Characterizing the Undergraduate Planetarium Learning Environment & Investigating Obliquity-Induced Changes to Heavy Ion Loss at Mars

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Three studies are described in this work detailing research efforts in two avenues of astrophysical and planetary science. PLUS (the PLanetarium Usage Survey) and PLOBS (the PLanetarium OBservation Study) investigated the use of the planetarium learning environment in order to characterize the environment's use in the education of undergraduate learners in the astrophysical and planetary sciences. PLUS, a nationwide survey and interview protocol, established an understanding of present-day collegiate planetarium use: what contents were shown, how often were planetariums being used, and how and why were particular content styles chosen for presentation to undergraduates. PLOBS, a university-specific survey and observation campaign, investigated how a university faculty used the planetarium: why did they integrate planetarium visits in their courses, how did their lessons commence, and how did the planetarium environment compare to its complementary classroom environment. Together, PLUS and PLOBS suggested a collegiate planetarium learning experience focused predominantly on non-major, lower division astronomy content presented to learners for the purpose of providing immersive, visual scaffolding. Learning processes in the planetarium showed a high degree of overlap with those in the classroom setting and a measurable decrease in certain reformed practices, suggesting planetarium lessons involve more passive learning strategies than those in the classroom. MOP (the Mars Obliquity Project) investigated the effects of the chaotic Martian obliquity cycle on the rate at which Mars loses its atmosphere to space. Using a multifluid, magnetohydrodynamic simulator engine to probe six experimental cases of the Mars-solar wind interaction, MOP analyzed the changes to the escape of three heavy ion species (O^+, $O_2{}^+$, and $CO_2{}^+$) from Mars with the remnant crustal fields on the planet's night side as the planet's obliquity angle was changed. Escape rate calculations demonstrated a measurable, but minor effect on heavy ion loss as a function of planetary obliquity angle, with the heaviest ions showing the greatest sensitivity to changing planetary obliquity. Implications of calculated escape rates suggest magnetic shielding of atmospheric particles is a minor player in the atmospheric evolution of a planet, with gravity being the dominating factor.

Dedication

For Paw Paw.

Acknowledgements

I would like to sincerely thank my two research advisors, Dr. John Keller and Dr. Dave Brain. My journey through graduate education has been an interesting one, both for better and for worse, and I am truly grateful to both for their help, wisdom, guidance, criticism, honesty, and occasional dad jokes. I would also like to thank my friends, both near and far, for helping me along during this journey. Graduate school would not have been remotely as much fun without seeing them every day in class, in the office, or the impromptu trips out to lunch. Lastly, I want to thank my family for their constant love and support. I hope I made you all proud.

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Chapter 1

A Letter to the Reader about this Dissertation

Dear Reader,

Before you continue, I'd like to have a word with you. The dissertation in your hands (or computer screen or whatever medium you happen to have) is perhaps a more unorthodox one than you might be used to? I mean, look at that abstract—two disjoint topical spaces in one doctoral thesis?! If I may, let me explain...

Discipline-based education research (DBER, for short) is the research of education by content experts like you and me. Who better to investigate the educational processes of a scientific discipline than the scientists who practice and teach it? It is this research that you will first encounter in these pages. DBER rejects the idea that "education is an art," or that instruction is too nuanced to be researched. As a consequence, DBER has enjoyed an undue stigma from others within our own disciplines as not being "real science." Such an attitude is rather dismissive, because due to the efforts of education experts like us, astronomy education research (which I'll get into in chapter 2) has already shown that the instructional practices of mankind's oldest science can be improved... and it did so (in its comparatively short life time) with observation and experimentation."Education is an art." Hardly—education is a *science.*

That being said, I am not just an educator—I am also an astronomer, physicist, and planetary scientist. As a practitioner of mankind's oldest science, I am still captivated by the Universe and ponder the processes that make it tick (see chapter 5 for details). Some might contend that my passion for these two seemingly disparate avenues of astronomy puts me between a rock and a hard place, and it would have been better to just pick one avenue and discard the other. I would disagree, as such a statement implies a disparity that in my mind does not exist... both halves of astronomy, its practice and its education, are of critical importance to our understanding of the Universe. As an aspiring educator, DBER practitioner, and astronomer, both these avenues of astronomy are important to me, so why wouldn't I pursue them both?

Thus, dear reader, in DBER's spirit of content experts investigating the education of their discipline, I commend to you this hybrid dissertation. The studies it contains are my efforts to advance my field, as an astronomer, astronomy educator, and an astronomy education researcher. It represents my desire to not only add to our collective understanding of astronomy, but to add to our understanding of how to instruct it so that our students might experience the same joy that we do when we practice it.

Daniel

Chapter 2

Astronomy Education Research - On Overview

In this chapter I will discuss my review of education literature and highlight the more important aspects that apply to the two astronomy education works presented in chapters 3 and 4. I will begin by establishing an understanding of constructivist learning theory, what I see as its two most important aspects for collegiate learners, and finally I describe the theoretical framework tool, LEPO (Learning Environment, Learning Process, and Learning Outcome), used to contextualize my studies in chapters 3 and 4. Next, I will discuss the aspects of learning that go into the LEPO framework, including formal definitions of what a learning environment is, how learning processes are affected by environments, a description of the general learning outcomes to provide context, and lastly a brief description of what assessments are and how they are used in education. Finally, I will discuss the two fields of education research that most closely align with the content in chapters 3 and 4, astronomy education and planetarium education, and what the findings of these two fields suggest about the learning. I will conclude with my synthesis of my review of the literature, the remaining research questions I was left with, and the definition of my own research questions which guided the studies in chapters 3 and 4.

2.1 Theory of Learning

“How people learn” is an old question, and as would be expected, there are many theories available to answer it. Going back to antiquity, the process by which people acquire new information like knowledge, attitudes, and skills has been an ever-present point of investigation and discussion. In modern times, two learning theories have emerged as the predominant cornerstone theories: behaviorism and constructivism. Behaviorism underscores instructor-centered learning styles, those in which an instructor is responsible for stimulating learners to acquire information by delivering points of fact, opinions, or insights to learners (e.g., those described by Gropper (1983) [93]). In so doing, behaviorism suggests that learners will acquire knowledge by having seen it delivered by the instructor, responding to that stimulus, and then having the appropriate reinforcement delivered [266, 54]. Constructivism underscores learner-centered learning styles, those in which learners bear the responsibility to acquire information through a lesson that is facilitated by an instructor. In so doing, constructivism suggests that learners' active participation in their own learning cements knowledge by having them answer questions or attack problems directly, rather than wait for an instructor to provide them the necessary knowledge through passive incorporation [30, 76, 39, 186].

Behaviorist-minded, instructor-centered theory has long stood as something of a “default” learning theory, at least as a matter of practicality [76]. Instructor-centered pedagogies are relatively easy to incorporate across many levels of education from grade-school to college. Behaviorism posits that learners learn via the expression of stimulated behaviors followed by the necessary reinforcements to cement their knowledge [266]. That is, learners are “trained” to know things by reacting to certain stimuli (practice problems, examples, statements by instructor) and then having that behavior reinforced [223, 266, 54]. Behaviorism was established as an excellent theory for describing the acquisition of base knowledge (factual recall, conceptual definitions, and performing predefined procedures), but could not truly explain the acquisition of higher knowledge like language development and critical thinking [93, 266, 76]. Perhaps the most important of behaviorism's failings was the lack of consideration of learner knowledge or how it was that learners were to think [266, 76]—elegantly stated by Winn (1990), “behavioral theory is inadequate to prescribe instructional strategies that teach for understanding” [266]. Research has instead demonstrated the superior aspects of constructivist theory (and its derived pedagogical principles) in reaching these higher levels of knowledge by focusing more on the learner, rather than the instructor [76, 39]. Consequently, constructivism will be the theory of learning discussed and implemented in this work.

2.1.1 Constructivism

In a nutshell, constructivism is the idea that learners acquire knowledge by actively assembling it themselves. Knowledge does not just fall from the sky (or straight from the mouth of a teacher)—rather, learners must actually build their own knowledge by discovery, revision, and cross-checking new information against a pre-existing base of knowledge and experience. Whether this contention happens individually or in a group setting is immaterial to the discussion here. The difference between individual and group contexts does have historical precedent within the learning theory, specifically from two vocal proponents of constructivism: Piaget, who advocated for an individual learner approach to the theory; and Vygotsky, who advocated for a social contextual approach to the theory. The discrepency between the two, in my opinion, is moot given that both approaches have been used and each has demonstrated merits as guiding theories. As such, in the following discussion I will not belabor the differences between the Piaget and Vygotsky approaches and consider constructivism-at-large [30, 223, 124, 149, 76, 186].

Critical to the idea of constructivism is that learners are not “empty pots” waiting to be filled with knowledge [21]. Rather, learners are possessed of a personal knowledge base and understanding that informs their own world view acquired from their own lives both inside and outside of formal learning settings like a classroom. Learners are most effective when they are actively engaged with their own learning (i.e., “active learning”), not just sitting and listening to an instructor deliver information. Talking with their fellow students, problem solving, discussing, and attempting higher-order learning outcomes are all indicative of active learning [30, 223, 31, 39, 186].

Among a learner's personal knowledge base is pre-existing, scientifically accurate information, sound models, and valid lines of reasoning. Unfortunately, this personal knowledge base is also replete with wrong inferences, poorly defined considerations, and generally inaccurate information. Together, both halves of this personal knowledge synthesize to form a person's understanding of a particular concept [257]. In the quest for content mastery, learners in a constructivist setting must keep their pre-existing accurate knowledge (called productive knowledge) while identifying and correcting their pre-existing inaccurate knowledge (called misconceptions) [235]. Misconceptions inhabit a unique position in a learner's explanatory framework in that while they are scientifically inaccurate, they are still sound inclusions to the learner in question because they have never been forced to meaningfully contend with them.

2.1.1.1 Conceptual Change in Constructivism

Constructivist pedagogies often focus on the identification and revision of these bodies of inaccurate knowledge, called "conceptual change." This change process was originally based on the idea of confrontation, where learners are forced to try (and ultimately fail) to reconcile their misconceived understandings with more scientifically accurate ones. In so doing, learners would then reconstruct a new, more accurate understanding more reflective of expert-level understanding [257, 63, 255]. Vosniadou (2002) remarked that learning science requires the integration of additional details onto a learner's pre-existing explanatory framework until a crisis is reached [255]. This crisis, described as a loss of coherence, is when a learner's framework can no longer support and explain all of the necessary information, due to a firmly entrenched misconception that has toxified the learner's framework. This crisis can be resolved by restructuring these learner frameworks to align them with scientifically accurate ones. Critical to this process is the necessity of a crisis between the learner and new information—if learners are never forced to meaningfully confront and reconcile their inaccurate frameworks with additional information, then learners will not shed their entrenched misconceptions and learning suffers [255].

Such a framework for conceptual change was functional, if a bit harsh. Criticisms pointed to the framework's single-minded reliance on identifying inaccurate or mistaken learner knowledge, but paid little attention to learner's productive knowledge [235, 256]; the framework's assumption that conceptual change is a sudden “all or nothing” replacement of knowledge; and that non-expert learners do not view their world as scientific experts so they are not prone to consider testing their own knowledge. More recent refinements to the idea of conceptual change have moved towards an understanding that learner knowledge could be composed of “synthetic models,” frameworks for understanding that combine both accurate and inaccurate information. Such a learner framework is not in need of full-blown crisis and replacement, but rather needs correction or revision of an otherwise sound underlying understanding [256].

For example, a commonplace astronomical misconception across learners of all ages is the “eclipse model of lunar phases,” a misconceived framework for explaining the phases of the Moon. The misconception invokes the fact that objects (like Earth) are able to throw shadows onto other objects otherwise immersed in sunlight making them appear dark. In this misconceived notion, Earth and the Moon are both objects immersed in sunlight—the Moon cycles through phases simply because Earth's shadow is being thrown onto the lunar surface as the Moon orbits, making it appear dark. A sensible enough explanation that seemingly invokes nothing but sensible propositions, yet this explanation is fundamentally false. Learners adhering to this misconception have likely never been challenged to explain their framework, specifically by reconciling their framework with a diagram showing the Moon at one of its quarter phases (90° from the Earth-Sun line). In this setup, Earth's shadow is falling nowhere near the Moon (the umbral cone is similarly 90° away from the Moon) leading a learner trying to use the eclipse model to explain the quarter phases to a loss of coherence. The learner's understanding of Earth's shadow being thrown is still preserved (and applicable to actual eclipses), but the failure to explain the Moon's quarter phase is now evident in a way that a non-expert would not normally consider.

2.1.1.2 The Concept of Scaffolding

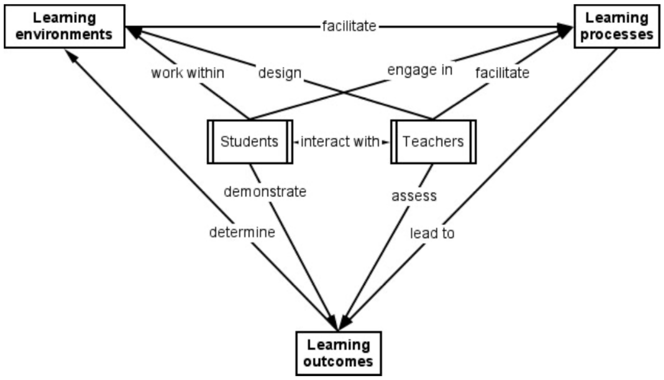
"Scaffolding" in the realm of constructivism is exactly as it sounds: just as a building needs initial physical support from an exterior scaffolding before it can stand alone, learners need initial pedagogical support from a guiding curriculum before content mastery can be achieved [120, 113]. What scaffolding looks like is often both context and learner dependent—a middle schooler learning the structure of Earth and a college student learning fault formation need different scaffolding aids, even though geology is the topic for both. A prime example of scaffolding aids are highly annotated (and sometimes animated or interactive) diagrams or simulations which offer far more information to a novice learner than an expert would need in a similar situation.

Scaffolding aids learners in concept mastery by providing extra mental resources that can relieve the learner of needing to "fill everything in" by themselves. Scaffolding offers learners a kind of "temporary expertise" that would allow them to engage with materials or discussions that would normally be beyond their skill set [120, 113, 226]. Like an actual edifice whose scaffolding is slowly removed as the building grows, pedagogical scaffolding slowly fades and is diminished as learning progresses. The rate at which scaffolding is removed is largely a question for how learning is assessed (discussed below). If a learner demonstrates a level of content mastery they did not have (or were presumed to have) at the beginning of learning, some scaffolding is removed. If mastery is not achieved, additional scaffolding might be provided [113]. An important aspect of scaffolding is the idea of learner control and intent: learners who do not need scaffolding aid (or who rapidly acquire content proficiency) may not need an instructor-designed scaffold anymore and continued use may stymie learning [218].

2.1.2 Framework for this Study: Learning Environment, Process, and Outcome (LEPO)

I decided to construct the works in this dissertation around a conceptual framework called "LEPO." LEPO (the Learning Environment, Learning Process, and Learning Outcome framework) is a constructivist mindset of learning that envisions three cornerstone learning items (the environment, the process, and the outcome) that are interacted with by two personages (instructors and learners) [190]. In this conceptual assembly, instructors and learners each interact with the three cornerstone items in the framework in unique ways. Instructors design the learning environment, facilitate the learning process, and assess the learning outcomes. Learners work within the instructor-designed environment, engage in the learning process, and demonstrate learning outcomes. These two personages interact with one another during the entire instance of learning. Importantly for LEPO, the three cornerstones themselves interact with one another. The learning environment facilitates the learning process, the learning process leads to the learning outcomes, and the learning outcomes determine the environment. The concept map of the LEPO framework in Phillips et al. (2010)'s discussion can be seen in Fig 2.1.

Figure 2.1: The concept map of the LEPO framework described by Phillips et al. (2010). Instructors and students each interact with the three cornerstone items of the framework to achieve learning. Figure source: Phillips et al. (2010), Figure 1, pg. 2497 [190].



Most critically for my choice of using LEPO for this study was the framework's generalizability. Many frameworks for learning existed in the various fields of education research; however, these frameworks often required a particular learning environment or a specific learning procedure in order to be applicable to a particular instance of learning. Thus, using a particular framework might have required a number of unjustifiable or indefensible *a priori* assumptions about the particular instances of learning that I was planning to study. LEPO makes few demands on learning *a priori*, and for a comparatively unknown pedagogical environment like the planetarium (which I will discuss below), LEPO offered a balance of a sufficiently detailed description of learning while maintaining a high degree of generalizability between learning contexts [190].

2.1.3 Related Learning Theories for the Planetarium: Multimedia Learning & Contextual Learning

Two learning theories applicable to the planetarium environment were specifically not chosen to serve as the theoretical framework of this study. However, given their import in other planetarium studies, I will briefly discuss them here. The first of these, multimedia theory, describes learning as the active process of filtering, sorting, and compiling input information from the ocular and auditory senses. This information is combined with pre-existing information already held by the learner to solidify a single understanding made from all of the experienced media. On its face, multimedia learning would be readily applicable to a planetarium environment given increased ocular and auditory sensory input in the planetarium theater. However, multimedia learning theory was very process-oriented and made little definition of learning outcomes [188].

The second of these theories, contextual learning, recognizes that learning does not "occur in a vacuum," and that where, how, and why learning happens can affect learning outcomes—learning that can link to a learner's real life is preferable to learning that does not. Like multimedia learning, contextual learning would have some advantages in the planetarium, but the theory's framework overstressed the process of learning with little definition of learning outcomes (e.g., [79]), much like multimedia theory. Both of these theories were well described for the learning process, but were also missing critical considerations that this study needed to describe learning as a whole. For future studies, these frameworks (or portions of them) might be incorporated, but for these studies I decided that the more generalized LEPO framework would offer greater flexibility in the formal planetarium learning environment.

2.2 Learning Environments & Processes

Defining the "environment" in which learning occurs can be a tricky affair. The word "environment" is a little vague as there are two sensible understandings of what an environment is. Is it referring to the physical setting where learning takes place? Perhaps it refers to the social context—the "vibe," if I may—and all of that context's associated processes? Or maybe a mixture of the two? What about the same physical setting used in different contexts—are those different? Do different social contexts have different processes—what makes a particular process appropriate for a given social context? For education research, the determination of "where" learning happens and "how" learning proceeds considers both of these traits when an investigation begins. Because of this apparently inevitable overlap between learning environments and learning processes, I will discuss the two of them together in this section. I will first discuss the two types of environments where learning could occur and then remark upon the processes that might occur in those environments.

2.2.1 Informal & Formal Environments

Informal learning environments are typically relaxed, low-stakes environments where learning is largely self-guided by a learner with an instructor acting as a facilitator or perhaps not even interacting with the learners at all. Museums, zoos, aquariums, planetariums, and field trips are all common examples of what an informal environment often looks like—the instructional authority accompanies their learners in these spaces, but they do not necessarily lead the learning process, the learner typically does [264, 62]. Outcomes in informal environments are articulable, but are rarely predetermined. During a field trip to a museum where numerous exhibits covering a wide variety of content is available, it would be impractical for an instructor to enforce a particular outcome in such a large, unstructured, self-guided environment. Doing so would kill the "vibe" of the informal learning environment. That's not to say that an outcome is not expected, only that it cannot be as practically predetermined nor compelled. Lastly, both learners and instructors in an informal environments are often absolved of any kind of assessment responsibility, whether formative or summative. Whatever is learned is learned; there is less assessable downside or penalty for not learning something [264, 193].

Conversely, formal learning environments, are typically stricter, high-stakes environments where learning is guided by an instructor with the learners taking a more passive, follower role. Classrooms and lecture halls are the obvious examples, and the structural traits of formal learning environments are evident from them. The instructional authority (or their slides) is often the focus of attention and the content being presented is a fairly well structured set of institutionally-defined material. Learners attend this presentation and are expected to achieve defined and usually predetermined outcomes. Less instructor-heavy environments, like an undergraduate laboratory, can also be formal—even though the learner is acting with temporary autonomy, the learner is still usually compelled by another authority (like a primary instructor or teaching assistant) to demonstrate a specific set of outcomes in the laboratory setting. For example, in secondary and tertiary education, the litany of expected outcomes is usually included in a syllabus or similar document in the form of statements like “the student will learn implicit differentiation” or “will understand the cause of the seasonal cycle.” Determination of achievement falls to the instructor who uses a rubric or similar grading scheme to reduce their learners’ work to “success” or “failure” [264, 193, 230].

2.2.2 Social & Situated Learning Processes

In more refined considerations of the learning process, several factors have been identified that might serve as arbiters of “how” learning is achieved. These factors consider learning as occurring within a particular surrounding and how that surrounding might influence when, if, or how learning is achieved. Social and situated learning recognizes that learning, in whatever form is takes, does not occur in a societal vacuum—learners acquire, adapt, process, and personalize information as active participants within their own societies or cultures and these societies and cultures exist in the real world. That is to say, learning occurs in particular real contexts or environments (like those discussed above), each of which offers specific ideas, tools, and real physical resources to learners who are themselves members of a present society or culture. Social and situated learning thus take the position that how the learning process occurs cannot be rendered strictly as a function of what is to be learned and how it will take place. Rather, how learning occurs is the union between a multitude of factors like who is doing the learning/instructing, what is the outcome (and how will it be determined), how does instruction occur, where/when does it take place, which values are associated with this learning (or outcome), and how will this learning advance the society or culture supporting it [10, 209, 22]. As outcomes are viewed beyond the scope of individual learners and towards an "ecological" view of learning, instructors and researchers must consider the entire set of social factors that constitute the learning process [125].

One exemplary feature of social and situated learning which has been documented towards greater learning and understanding is the concept of practice. Used here, "practice" means the actual "doing" of a scientific discipline or other subject discipline by learners during the learning process. This learning process is a cornerstone of inquiry-based instruction—instructional techniques where learners are guided to content mastery through practical execution of the scientific method (make observations, ask questions, formulate hypotheses, run experiments, debate results). Opposed to more traditional learning processes which guide learners through the fruits of the scientific practice (e.g., "the acceleration at Earth's surface is 9.80 meters-per-second-squared, and we know this because of X"), practical learning seeks to instruct learners by facilitating their participation in an actual scientific process [209, 22].

Such a learning process is not without its pitfalls, especially when used to instruct novice learners, as practical learning needs to maintain a level of meaningful authenticity in order to be effective. That is to say, practicing science for the sake of practicing science (as opposed to the sake of greater understanding) might not reap any meaningful learning from practicing students. Sadler (2009) points this out very succinctly with an example describing a high school learner practicing genetics by performing polymerase chain reaction (PCR) procedures to replicate DNA [209]. If appropriately guided (by instructions or a manual) a learner could likely, very easily, complete the practice of PCR—but upon completion of this practice, is it guaranteed to have produced deeper understanding of genetics? Unlikely, given that the learner did not really practice authentic genetics, but rather practiced *scripted* genetics. To provoke greater understanding, a learner must practice their discipline in such a way that their efforts are truly authentic and meaningful to the disciplinary community itself [209, 22]. The sense of authenticity goes hand-in-hand with the concept of learner identity, which I will discuss below in "Learning Outcome Domains & Taxonomies."

2.2.3 Expectations of Learning Processes

The last process point I will discuss here is not an actual learning process *per se*, but rather a mindset about learning held by both learners. In a given instructional/learning scenario, participants do not blindly walk into this scenario, nor is there a “come what may” understanding of the upcoming learning. Rather, each participant holds an internal expectation of the forthcoming learning process based on their own past experiences as instructors or learners. For example, imagine an undergraduate who is sitting down in a large lecture hall for the first lesson of a large-enrollment Physics 2 course. This undergraduate just recently completed the pre-requisite Physics 1 course (another large lecture hall, large-enrollment course) and will have as their instructor another member of the same faculty that instructed Physics 1. This undergraduate’s expectations towards the learning process would be fairly obvious—Physics 2 will proceed in a similar fashion to Physics 1 (all available clues suggest no reasonable alternative), only now the content is different.

What this means for us as education researchers is that how learning proceeds and how it is expected (or believed) to proceed are both considerations that need to be made when remarking upon a learning process. Learners beliefs about not only a scientific topic of interest, but also the learning of said topic can have an impact on how or if learning occurs [189, 4]. While learners’ beliefs about a scientific topic are not always within the sphere of control for educators, Adams et al. (2006) found that using teaching practices that specifically address learner beliefs about science (in their case, physics) can have measurable effects on the learners participating in the course [4]. I will revisit this idea of learner expectations below when I discuss affective learning outcomes.

2.3 Learning Outcome Domains & Taxonomies

It is oftentimes helpful (and currently commonplace) to consider learning through the lens of a desired outcome, that “thing” that a learner actually walks away with at the end of the learning period that they did not have before and how that “thing” would come to be. The term “outcome” can be used loosely, so its important to consider the context in which the term is presented. Discussed from an instructor standpoint, “outcome” is often synonymous with “objective,” the piece of knowledge that an instructor *plans* for their learners to acquire, and is usually the one articulated in documentation like syllabi [122]. Discussed from a learner standpoint, “outcome” usually means what the learner *actually* acquired, which may or may not be the same thing as the instructor-defined objective [5]. By and large, defining learning outcomes for learners at the beginning of a learning period is both popular and intuitive, as it provides both instructors and their learners a point of reference for what might be expected of them [122, 97]. Defining learning outcomes is a useful endeavor for educators as a framing tool for both individual lesson plans (what will be learned in a particular class meeting) and well as term-long learning goals (what will be learned over the course of a semester).

Defining learning outcomes is not without a bit of controversy in the various fields of education research. Havnes & Proitz (2016) point out in their commentary that defining an outcome might be an unintentionally restrictive process; that by enunciating “what is to be learned,” it could be the case that any other achievements outside this predefined window of success may not be accredited as learning or not given the same weight as an outcome than one that has been expressly determined [97]. Specifically, the commentary highlights four possible dilemmas that might arise: (1) unexpected learning, the acquisition of other learning outcomes achieved along the way towards a pre-defined one may not be attested as such; (2) abstraction, acquisition of knowledge that is too nuanced or ill-defined to be appropriately defined; (3) contestability, the inability of learners to challenge or question an established “truth” in a particular discipline; and (4) meta-level learning, learners learning about themselves is not well defined as a learning outcome.

These minor controversies aside, defining learning outcomes is still a useful pedagogical framing tool for the learning process, as doing so does aid in guiding the learning process for both instructors and learners. So long as outcomes are not maintained as the *only* allowable measure of successful learning (as an enunciation of absolute rigid policy pieces), defining outcomes is a beneficial process [97]. Outcomes are grouped into three overarching domains, each of which is organized into its own taxonomy. Each of these taxonomies is a rough hierarchy of domain-appropriate outcomes, beginning with a base level of simple learning outcomes (the easiest to achieve) and ascending through to the top level of the most complex or nuanced outcomes (the hardest to achieve). Unlike biological taxonomies which represent strict hierarchical structures, the taxonomies for each learning outcome are only approximately hierarchical due to the lack of a rigid system of definition within each taxonomy.

Still, each taxonomy remains a useful framework for establishing what kind of outcome a learning process achieves and what its complexity is compared to other outcomes. The three domains represent the different classes of "thing" that a learner acquires, and each outcome can be described as both nouns (outcome objects) or verbs (outcome actions) [28]. I would make one final semi-cautionary note here about learning outcomes before I discuss those considered in this work—what a learning outcome is and which of these domains it belongs to (if any) is typically subject to some interpretive bias. That is to say, you and I might consider the same outcome X as belonging to two different outcome domains because what it means to be outcome X is subject to our respective interpretations of X. Furthermore, these outcome domains may not be the only ones encountered in the literature

2.3.1 Cognitive Domain

The first outcome domain, the cognitive, is descriptive of outcomes concerning the acquisition of knowledge. Cognitive outcomes represent performance of the verb phrases "to know what," "to know how," or "to know why." This domain was enunciated by Bloom in the 1950s [29], and has served as a reliable cornerstone for education researchers and reformers. Bloom's taxonomy of cognitive outcomes underwent a light revision in the 2001 [6]. This revision (see below in Table

2.1) most importantly exchanged the highest levels of the original taxonomy, such that “Create” is now understood as the highest cognitive outcome in the domain with “Remember” still at the base level.

Table 2.1: Bloom's taxonomy of cognitive outcomes [29], revised by Anderson and Krathwohl [6]. Read from the top down, cognitive outcomes begin with the simplest (remember) and advance in sophistication to the most complex (create). Descriptions of each outcome are listed in the center column, expressed a verbal actions undertaken by a learner.

Cognitive Outcome Level	**Description**
1. Remember	Recall previously learned information
2. Understand	Grasp meaning; restate idea in one's own words
3. Apply	Use concept in novel situations
4. Analyze	Separate materials and demonstrate relationships between them
5. Evaluate	Judge worth/value against objective criteria
6. Create	Make new structure/pattern from existing elements

Cognitive outcomes are arguably the most recognizable for educators to identify, as it is these levels that most people envision when they think of "learning something." Furthermore, each level of the cognitive taxonomy can be reasonably probed using a test question or other administrable instrument, making them an effective tracer of whether learning has occurred. As a consequence, the learning objectives enunciated in education documents like syllabi are often constructed using cognitive outcomes as the objects of interest, as it is these pieces of knowledge that are the most convenient to express in written form. Cognitive outcomes are also arguably the most recognizable for education researchers to identify, as it is these kinds of learning outcomes that are usually measured in a study about education. Asking a learner the same question over time to see if they learned anything (the "pre-/post-intervention" method, described below) is a popular research method, and cognitive outcomes are typically the material lens that is used.

2.3.2 Affective Domain

The second domain, the affective, is descriptive of outcomes concerning the acquisition, assignment, or processing of attitude, belief, or emotion [126]. Affective outcomes represent performance of the verb phrase "to value" or "to commit." These outcomes are those which can modify existing behavior in learners, unlike cognitive outcomes which only modify existing knowledge. Of the domains I describe this chapter, this domain is perhaps the most expansive, as the past decades of education research have further described the considerable power of affect in learning. These outcomes are perhaps the least recognizable for educators, as these outcomes do not often have an efficient assessment instrument. After all, how do you measure whether a learner values something with a test? Even though the affective domain does not represent the same concrete knowledge principles that the cognitive domain does, it is nevertheless an important part of education as it is this domain that most directly applies to motivating and engaging learners.

In one of its earliest practical definitions, affective outcomes enjoyed a taxonomic structure like the cognitive domain—read from the top down, the affective taxonomy begins with the basic "receiving" and advance up to the most nuanced (characterization by value), representing the progressive complexity of attitudes that amount to a learner completely adjusting their preexisting ethical or value appraisal senses [126].

Table 2.2: Krathwohl's taxonomy of affective outcomes [126]. Read from the top-down, affective outcomes begin with the simplest (receiving) and advance in sophistication to the most complex (characterize). Descriptions of each outcome are listed in the right-hand column, expressed a verbal actions undertaken by a learner.

Affective Outcome Level	**Description**
1. Receiving	Being aware of something
2. Responding	Showing new behavior as a result of experience
3. Valuing	Showing definite involvement/commitment
4. Organization	Associating/integrating new value with one's priorities
5. Characterization by Value	Acting consistently with new value

While this taxonomy does, in my opinion, present the complete set of outcomes that describe affective achievement (that is, the complete integration and execution of a belief/value system), the importance of affective factors not expressly captured by this taxonomy has been well documented in constructivist-minded processes like those described in the above sections. Thus affective outcomes (and processes that promote them) take on a greater importance in the learner-centered environment, especially given the importance of learner belief and motivation in achieving other learning outcomes [4, 222, 150]. The additional aspects of learning affect that I will describe here are expectation, motivation, and belief. Each of these three *could* be considered as implicit in one of the outcome levels presented by Krathwohl and colleagues [126]—however, their individual importance in more modern research is such that each deserves a comment individually.

As I remarked on above, expectation is a factor that colors how learners experience the learning process. Expectations are an important affective aspect for educators and researchers to consider, as it is by these expectations that learners might either abandon or reconcile their feelings towards both the learning of a discipline and the discipline itself. If learners expectations towards a course are not met by instructors whose expectations lead them to instruct learners in a vastly different manner, learners might not achieve the higher learning outcomes desired by educators or may abandon the study of the discipline entirely [246, 167]. Expectations might be leveraged to promote greater affective gains in learners. Linder & Kung (2011) described this succinctly in their study which found that learners were influenced by their own context of "good teaching," and that learners developed or modified their own approach to the learning process accordingly [148]. The most important implication of this finding is critical for our discussion here about affect, because it implies that if instructors wish to provoke the greatest possible affective outcomes in their learners (like motivation and belief, below), instructors need to craft their lessons around those higher outcomes and the engagement strategies associated with them [148].

Motivation is the “drive” learners possess. Stimulating or promoting motivation is a critical affective outcome in education, regardless of learner level. At low levels, motivation keeps learners in school, driving them towards higher academic and scholastic achievements. At higher levels, like the university level, motivation keeps learners moving towards their graduation goals and can keep learners enrolled in their particular field (as opposed to unmotivated learners, who might abandon a field of study due to frustration, boredom, or other barriers). The positive correlation between motivated learners and academic success has been well established, and promoting learner-driven motivation remains a high priority for educators [191, 239, 150, 151], especially since externally-enforced motivation has been shown to negatively impact academic performace [165]. Motivation also helps educators and researchers by offering a window into learners’ value systems [239], which might offer insights into how/why learners choose particular educational or career paths in the STEM disciplines [71].

Beliefs are the last of these affective aspects I would like to discuss. Beliefs, particularly those held by learners, are an important characteristic for educators to understand, as it is the beliefs of the learners that might have the final say in whether a learner attaches personal value to the exercises, lessons, processes that educators guide them through. For example, Zwickl et al (2013) described a critically important learner belief concerning error analysis, one of the most important cornerstones of science itself. In their analysis of the CLASS (Colorado Learning Attitudes about Science Survey) instrument, learners held mixed views on the importance of error analysis in their personal practice of physics, even though the same learners reported that expert scientists would strongly agree with the notion that error analysis aids their practice and research [279]. Thus, physics learners recognize the usefulness of certain practices (like error analysis) for professionals, but might doubt the usefulness of the same practices to their own learning or understanding [279]. Such a mismatch between physics professionals and physics students is noteworthy, especially given the recorded importance of learner belief and conceptual gains in physics courses [189, 163].

2.3.3 Psychomotor Domain

The third domain, the psychomotor, is descriptive of outcomes concerning the acquisition of a physical or motive skill. Affective outcomes represent performance of the verb phrase "to know how to do" or "to perform." The psychomotor, although not originally part of Bloom's framework, was introduced by Elizabeth Simpson in the late 1960s [224]. This domain is the least widely used in collegiate education (the focus of this work)—most outcomes for tertiary education fall safely in the cognitive and affective domains. It is presented here as it completes the set of outcome domains; however, this particular domain will not be discussed much beyond this section. Read from the top down, psychomotor outcomes begin with the simplest "perception" and advance up to the most complicated, "origination," representing a complete acquisition of skill from a fully unskilled observer to a fully proficient master.

Table 2.3: Simpson's taxonomy of psychomotor outcomes [224]. Read from the top-down, psychomotor outcomes begin with the simplest (remember) and advance in sophistication to the most complex (create). Descriptions of each outcome are listed in the right-hand column, expressed a verbal actions undertaken by a learner.

Psychomotor Outcome Level	**Description**
1. Perception	Using sensory cues to guide motor activity
2. Set	Readies oneself to act
3. Guided response	Imitates action or conducts trial-and-error
4. Mechanism	Maintains basic, habitual (low-level) proficiency
5. Complex overt response	Maintains skillful, habitual (well-practiced) proficiency
6. Adaptation	Adapts proficiencies to novel requirements
7. Origination	Creates new motion patterns to fit novel situations

Psychomotor outcomes are perhaps taken for granted outside of educational programs that do not specifically instruct physical motions or actions (e.g., manual tasks like engine repair or food preparation), and many of the actions described in this domain can be reasonably inferred from an outcome in one of the other domains (usually the cognitive domain). For example, a level 4 psychomotor outcome (mechanism) like using a computer could be construed to be a level 2–3 cognitive outcome (understand or apply) if said computer use was programming the solution to a mathematical equation. Similarly, a level 3 psychomotor outcome (guided response) like following an example algebraic equation problem could also be construed as a a level 3 cognitive (apply) outcome. From the affective domain, the level 2 psychomotor outcome (set) and the level 2 affective outcome (responding) could be seen as demonstrating the same outcome, as both require a learner to identify a thing and then prepare themselves to contend with it.

In this work, I will be discussing upper division education at the university and college level which is not likely to include express psychomotor outcomes as a part of the learning process, so I will not spend more time on this outcome domain. However, certain aspects of upper division education like laboratory or observatory settings might include psychomotor outcomes, so it is important for the reader to be aware of this domain. For example, advanced astronomy learners who are learning how to operate an observatory telescope or a planetarium projector are likely not learning towards a cognitive outcome, but are rather learning towards a psychomotor outcome as they are learning “how” to work the telescope or projector, not “why” either works.

2.3.4 Learning Assessments

Up to now, I’ve discussed two aspects of learning: the process and the outcome. Before I continue to discuss the learning environment, I want to remark upon assessment: the procedure of determining how learning is or is not developing (termed “formative assessment”), or whether learning has occurred (termed “summative assessment”). Both assessment styles are critical for educators and education researchers, as it is with these instruments that we are able to probe where, how, and when learning occurs.

Formative (from the Latin, *formare*: “to form”) assessments are those procedures which “check up” on the learners as they experience the learning process. Educators use formative assessments to explore learners’ understanding while it is being compiled through the learning process. Formative assessments come in many flavors, from simple verbal discourse asking after a learners’ understanding to small tests or quizzes that prompt a learner to show more tangible proof of understanding as it is happening (or soon thereafter). Formative assessments are as much a tool for the educator as for the learner—if an instructor finds their learners are not grasping a particular piece of knowledge (or are so proficient in one that further instruction would simply waste time), a formative assessment not only informs learners as to their progress, but also informs the instructor about their own teaching (and how it might be corrected). Critically, these assessments are low-stakes procedures in the learning process, and while formative assessments can be graded, their purpose is to inform both learners and instructors as to the present-state of knowledge.

Summative assessments (from the Latin, *summare*: “to accumulate”) are those procedures which “look back” on the entire learning process (or set of processes) to determine whether or not learning has occurred after the learning period has finished. Summative assessments are usually encountered in the form of tests (like midterms or finals), but may also be presented as quizzes given after a single class period—many research studies use summative assessments like these when investigating the benefits of a particular learning style (I'll talk more about some of those later in this chapter). Summative assessments are critical aspects of higher education, as it is the results of these kinds of assessments which are ultimately used to determine a learners' success or failure upon completing a course. As a consequence, these assessments are high-stakes procedures in the learning process and are usually some kind of graded artifact that challenges learners to demonstrate their knowledge.

For either assessment style, someone must make the final determination of whether or not satisfactory learning has occurred. Usually, this responsibility falls to the instructor and is based on the learning objectives for the course the learner is in. As I discussed above, this can be a tricky prospect due to the potential disconnect between learning objectives and learning outcomes, and should an assessor retain too strict a consideration of learning, the learner might unduly suffer [5, 97]. Why I mention this here (even though assessments are not part of the research I will present in the next chapters) is that it is important to always be mindful of how successful learning is considered: in both chapter 3 and chapter 4, some of my interview subjects express their opinions in light of these assessment structures.

2.3.5 Assessment Tools for Research: Measuring Learning with g and d

Education research would not get very far if it did not have a means of measuring learning. But, unlike instructors who could grade using whatever measure of success they desired, researchers need to rely on a systematic measure of learning that can be compared with other instances. These gain-measuring assessment instruments are often delivered using a pre-/post- intervention strategy: learners take a pre-intervention quiz to test their existing knowledge; learners experience (or do not experience) a particular educational intervention; and learners take a post-intervention quiz to test their new knowledge gains some time after. The amount of time after the intervention is a critical piece of information to contextualize a study's findings. In some circumstances, a post-intervention quiz given immediately after the intervention shows noteworthy learning gains, but might not measure how well cemented these gains are. In other circumstances, a post-intervention quiz given a day, a week, or a month after the intervention could measure long-term learning gains, but the amount of time between the intervention and the assessment could be conflated with other interventions.

Measuring how much a learner learned is often expressed as one of two assessment-derived calculations: normalized gain (g, [96, 183]) and effect size (Cohen's d [49, 183]). Both of these are derived from an individual learner's score (or a group of learners' mean score) on the pre-intervention assessment (x_{pre}) and the post-intervention assessment (x_{post}). Normalized gain is calculated as $g = \frac{x_{post} - x_{pre}}{100\% - x_{pre}}$, where x_{pre}, and can be described verbally as "what one learned compared to what one already knew." Effect size is calculated as $d = \frac{x_{post} - x_{pre}}{s}$, where s is the pooled standard deviation of the pre- and post-intervention scores—unlike g, d is calculated using score averages from many learners [183]. Effect size can be verbally described as "did the class learn significantly more/less than when it started?"

Some controversy in the community surrounds the use of normalized gain. Studies about the measure have shown it possess a "prescore bias," such that using normalized gain as a measure of learning does not adequately capture the entire story [183]. However, normalized gain remains a popular scoring technique among education researchers and the argument over whether normalized gain is biased towards pre-intervention scores or some other ill-described variable remains contested [51]. Much of the astronomy and planetarium research described in the following sections have used both normalized gain and effect size as measures of learning, so a reader should keep in mind that even now researchers are not all on the same side of how to measure learning.

2.4 Astronomy Education Research

Discipline-based education research (DBER) is a more recent nomenclature identifying research into the education of a particular academic discipline, often by members or practitioners of that discipline. Physicists researching how physics is instructed, astronomers researching how astronomy is instructed, biologists researching how biology is instructed... the disciplines that participate in DBER are numerous, but the science, technology, engineering, and mathematics (STEM) disciplines are the most noteworthy for this work [101]. DBER maintains a certain advantage over traditional education research in that the researchers are experts in both general education content (e.g., the sections above about learning theory) and the discipline's specific content (e.g., chapter 5 of this dissertation). This research approach allows DBER researchers to examine the instruction of their craft from a viewpoint of a content expert who is attuned to the needs and goals of their field.

In this work, astronomy education research (AER) is the DBER field of interest (with occasional borrowings from physics and geoscience education for historical and practical reasons [14]). AER is as old as modern education, with the earliest recognizable AER works being presented in the 1920s [15]. However, as these early contributions were made before the more modern revival of constructivist theory and pedagogy, little of this early work will be considered here. Rather, I will begin discussion in the 1980s when AER served the astronomy education community a particularly stark reality check in the form of *A Private Universe*, a famous (read: "infamous") series of interviews with Harvard graduates who had recently received their diplomas. Almost all the interviewed graduates were incapable of describing an accurate explanation for the cause of the seasons or the phases of the Moon. Rather, the graduates expressed common misconceptions about the material and struggled to provide deeper explanations when pressed for greater detail [214, 15]. The situation highlighted by *A Private Universe* was not an isolated incident—further studies into learners across many experience levels in the 1990s and early 2000s continually reported that misconceptions about astronomy remained well entrenched in non-experts.

Astronomy has always been a historically difficult subject to teach, but the near-continuous report of persistent misconceptions made it obvious that in spite of instructors' best efforts, something was not working. Using an array of interviews, surveys, and concept inventories, researchers were finding that learners were retaining (and in some cases preferring) scientifically inaccurate descriptions of the Universe when tasked to demonstrate their understanding [277, 200, 271, 225]. Constructivism offered a potential solution to these seeming educational failures by restructuring learning away from the commonplace behaviorist, instructor-centered approach. Much of the work done for collegiate level astronomy learners concerns learners at the introductory or novice level, often under the guise of the "ASTRO 101" archetype [227].

Concept inventories (CIs) are one of the tools that DBER fields use to measure how learners have progressed during their respective learning processes. CIs are often short, multiple-choice test/quiz artifacts that probe a specific avenue of knowledge in a particular discipline—these items are used in a pre-/post-intervention style such that an instructor might establish what learners already understand about a particular topic (the pre-intervention) and what they have learned after the learning intervention (post-intervention) [13]. CIs can also be used as a yardstick for a particular group of learners to establish where said group's knowledge may be lacking or where learners are maintaining misconceptions as a part of their knowledge base (e.g., the Test Of Astronomy STandards, recently discussed in Slater et al. (2015) [225]) [276]. Items like CIs are important tools for educators and researchers at the collegiate level because undergraduate learners, in spite of their previous 12–13 years of education, still maintain a number of misconceptions and misunderstandings in their basic astronomical knowledge base. Such misconceptions or misunderstandings include: geological and cosmological time scales [41], macroevolutionary time [45], the structure of Earth and/or the Solar System [61, 144], light and spectra [277], lunar phases [249, 118], distance and dimension [118, 175], the cause of the seasons [250, 184], cosmology and the origin of the Universe [200], size and scale [248, 244, 213], and orbital motions [272] to name a few. Using concept inventories and test score analysis as guides, peer instruction and active engagement have made their mark on the present college education environment [78], so much so that some researchers have declared the concept of traditional behaviorist college lecture approaches untenable given the amount of research showing the clear superiority of constructivist strategies [90]. The techniques of peer instruction and active-learning has been demonstrated to help all collegiate learners both in content knowledge gains and to reduce attrition from astronomy [140, 198].

A useful tool in the promulgation of active learning strategies in the collegiate classroom has been the iClicker (or Clicker), a small handheld radio-frequency remote allowing a body of learners to anonymously respond to instructor questions in the classroom setting. The benefits of Clickers are multifaceted and appear to emerge in classrooms of all sizes and experience settings [220, 109]. Bachman & Bachman (2011) noted Clickers' popularity among learners in lecture settings and that learners perceived an increase in their own responsibility during a lecture [12]. DeBourgh (2008) noted on the system's ability to promote advanced reasoning skills in a nursing course [59]. Duncan (2006) and Kay & LeSage (2009) described in great detail the practical uses of Clickers and how their implementation can improve with time as instructors gain more experience in their use [70, 121]. Hunsu et al. (2016)'s meta-analysis of audience response system research showed that, used properly, Clicker systems were able to stimulate the active learner environment and aid the acquisition of cognitive and affective outcomes [109]. Clickers also provide a unique service as an instant formative assessment tool for instructors—by asking their classes a question in real time and recovering anonymous results, instructors can gauge the understanding of their learners (and adjust their lessons accordingly) without needing a formal test [59].

Nowadays, constructivist approaches like peer instruction, active engagement, and Clicker questions have made such an impact that manuals, articles, and instructor resources have been crafted to guide astronomy instructors (both new and old) in the practical use of constructivist reforms [16]. Exemplary works like Mazur's *Peer instruction: a user's manual*, Slater & Adam's *Learner-Centered Astronomy Teaching: Strategies for ASTRO 101* and Green's *Peer Instruction* *for Astronomy* each do this in such a way that guides instructors (most of whom will likely not be steeped in education research theory) away from their likely behaviorist pedagogies towards constructivist ones [170, 92, 229]. Additionally, learner resources for the classroom in the form of lecture tutorials have made inclusions in the astronomy lecture hall to leverage peer-instruction between learners with minimal direction from an instructor [199].

However, in spite of the widespread documentation in support of constructivist pedagogical approaches for collegiate education, widespread adoption of these approaches is a slow process as established instructors struggle (or even refuse) to incorporate constructivist strategies [99, 100, 102]. This barrier remains a danger to AER as a recent review of astronomy education by Lelliott & Rollnick (2010) stated, "It is recommended that future research should...aim to disseminate findings more effectively within the education systems" [143].

2.5 Planetarium Education: The Digital Fulldome Age

In spite of the long-standing popularity of planetariums as museum pieces and exhibitions, dedicated research concerning the efficacy of the planetarium environment towards reaching particular learning goals was initially rather dubious [40, 230]. Studies in the seventies, eighties, and nineties were not able to conclusively determine whether or not the planetarium was an effective instructional environment compared to a regular classroom. A general trend towards positive results began to unfold as more researchers using more reliable research methods continued their work in the planetarium environment, until a communal sense of clarity was provided by a suite of reviews and a meta-analytical study of the published planetarium works. Brazell & Espinoza (2009)'s meta-analysis of planetarium studies combined the findings of numerous studies of different sizes, learner populations, and results to synthesize a declarative trend from the variety of past results and occasionally contradictory studies. Their conclusion: "the planetarium has been an effective astronomical teaching tool" [40].

The progress of technology has made a profound impact on the planetarium community, specifically the progressively widespread emergence of digital fulldome planetarium technology [11, 267, 270, 42]. Planetarium technology (the projector) comes in two overarching types: analog, star ball projectors and digital projectors. Analog projectors were the first planetarium technology created and were meant to simulate the night sky by projecting points of light onto a hemispherical ceiling from a single, central projector in a planetarium chamber. These projectors, while perfectly effective in projecting points of light onto a hemispherical ceiling, were limited in their ability to create other visuals—mechanically it was not feasible, and planetarium learning spaces were somewhat limited in exactly what kind of content could be shown. The integration of standard 2D slide projectors into planetariums expanded their usefulness as presentation spaces, allowing for additional visuals to be displayed in the theater, but presentation technology was still restricted to an analog visual format. Digital fulldome projectors lifted this restriction by projecting light in a different way. Rather than shooting individual points of light simulating stars or pre-rendered 2D slides onto the ceiling, digital projectors render computer images onto the hemispherical ceiling. Since almost any image can be rendered by a computer, digital fulldome planetariums have a wider array of projection options available to them, including a greater capacity to render immersive visual environments (discussed below) [11, 267, 270, 42]. For larger theaters using more than one projector, this is accomplished by stitching together multiple projector images under the command of a single computer. Digital fulldome projectors can be built in portable formats by using an inflatable planetarium hemisphere—such planetariums open the possibility for learners normally barred from visiting a permanent planetarium from benefiting from the learning environment. Sumners et al. (2008) and Carsten-Connor et al. (2015) demonstrated just that with a group of grade school learners using a portable fulldome projector to instruct earth science concepts [241, 43]. Excluding portable fulldomes (where learners may need to stand), learners experiencing these powerful visuals are often seated in reclined chairs looking up at the ceiling. By the leaning the audience back, planetariums focus their learners' attention to a single point on the ceiling, called the "sweet spot," where central visuals are projected—although the entire hemisphere can have visuals projected onto it, it is this sweet spot which serves as a natural draw of learners' focus.

Due to the planetarium's somewhat unique position as an exterior setting to most proper educational contexts, planetarium education studies have taken an additional investigation route not normally encountered in astronomy education. Specifically, investigations into planetarium professionals (the persons responsible for the maintenance, upkeep, and execution of planetariums as places of public education) have made substantial contribution to the field as it is these frontline educators who are often responsible for ensuring meaningful planetarium experiences. Croft's interview protocol suggested that planetarium professionals struggle to make their message to the general public clear and impactful and were not overly compelled to provide an entertaining environment for their visitors [57]. Small & Plummer (2010) came to a similar conclusion in their study two years later, and also highlighted that planetarium professionals views on instruction seemed to be at odds with planetarium content producers' creation of passive planetarium content [231]. Plummer & Small (2013) reinforced this point by investigating planetarium professionals who found their instructional experience molded by the experiences of their visitors through a learner-centered perspective [194].

A substantial body of planetarium research investigations have used children as the learner groups of interest. Children often experience planetarium learning as a part of a field trip or similar informal learning environment outside the regular classroom [230]. Plummer et al. (2011) demonstrated that third graders were able to acquire more nuanced astronomical understanding after a planetarium visit [195]. Plummer et al. (2014) showed how younger learners were able to improve their understanding of daily celestial motions after a combined planetarium and classroom instruction regime [192]. A longitudinal study discussed by Small & Plummer (2014) suggested that active engagement strategies combined with planetarium use in young children was more likely to promote the acquisition of difficult concepts [232]. Combined with the findings of younger learners achieving substantial learning gains in the portable planetarium [241, 43], this suite of research continued to support the planetarium as a location for education younger learners.

At the collegiate level, important and proliferous research contributions in recent years have been the works presented by Drs. Ka Chun Yu and Kamran Sahami at the digital planetarium at the Denver Museum of Nature & Science. In their 2010 study, interview protocols were held with incoming undergraduate learners prior to any formal instruction and highlighted learners' misconceptions about orbital motions [272]. In 2015, Yu, Sahami, Sahami, and Sessions presented their work in teaching undergraduates seasons, using the immersive planetarium and the classroom as environments of comparison. Fielding an array quiz instruments, their findings showed greater gains for the planetarium group of learners. The proposed mechanism that helped these learners was the space's ability to free up cognitive resources during the learning process, and by leveraging the planetarium's ability to switch between egocentric and exocentric frames of reference [273]. Their 2016 study examined the learning gains for the same lesson in the classroom and immersive planetarium environments, using the same instructors and lesson outline between the two environments. Results showed superior learning gains by students in the planetarium compared to students in the regular classroom—the commanding display and large field-of-view of the planetarium lesson provided greater visual scaffolding than the classroom's comparatively weaker, 2D imagery [274]. Their 2017 study centering on learning the scale of the Solar System was a great addition to the literature by virtue of its long-term findings. Not only were planetarium learners making greater gains in short-term learning measurements, but those same learners were making measured making increased gains over time. Contrasted with the classroom control group, the study highlights the possibility that planetariums can instill lasting learning outcomes for collegiate learners, not just short-term ones [275]. In addition, contributions from outside the United States came from Turk & Kalkan (2015), a Turkish study that found similar results—their undergraduate planetarium learners were more successful in comprehending astronomical information requiring multidimensional thinking than learners who did not experience the planetarium [251].

2.5.1 The Power of Immersive Learning

The common thread binding all recent planetarium research together has been the power of immersion, specifically visual immersion in the planetarium environment. While both analog and digital planetariums are technically capable of rendering these environments, digital planetariums are usually considered as the theaters-of-interest when discussing immersive environments due to their ability to render 3D projections. These projections are not 3D in the strictest sense—they are illusory visuals that use parallax to emulate true 3D objects. What is it about immersion that offers such aid to learners? Immersive visualizations take advantage of two aspects of perception that are not always available to learners during their day-to-day experiences: changes in reference frame and commanding fields of view [177, 192, 273, 48, 275].

Table 2.4: The two frames of reference used in planetarium lessons for learners. In each frame of reference, learners are located somewhere in a particular scenario or setup that offers them a peculiar observational vantage point that defines relationships and mechanics based on a unique framework [48].

Frame of Reference	**Location of Learner**	**Relationship Frameworking**
Allocentric	Outside system; passive observer	Relationships and mechanics are defined between a system's objects
Egocentric	Inside system; active observer	Relationships and mechanics are defined using the learner as an anchoring reference

Reference frames in planetarium lessons come in two forms (summarized in Table 2.4), each of which offers an observer (a learner in this case) a different vantage point of a particular system from which they can consider the particular relationships between the system's various components. Allocentric frames are those offering a bird's-eye view of a particular system. Learners in an allocentric frame observe a scenario as a removed, non-participating party—allocentric frames highlight the relationships between a particular system's components, none of which include the observer. The advantage of this frame is its ability to offer learners a complete view of a system with ostensibly complete information about the system's inner workings, with learners being able to observe all possible relations between any set of a system's pieces. A disadvantage of this frame is a lack of direct relationship experience—while all parts of a system are available for learners to consider, all internal relationships between a system's components must be inferred. Additionally, allocentric viewpoints have no defined "origin," and relationships in an allocentric frame need to be expressly defined [48].

Egocentric frames are those offering an in-person view of a particular system. Learners in these frames observe a scenario as if they were literally "there" as an active participating party in the system. Egocentric frames highlight relationships within a system as they refer to the learner—the learner is anchor for which all relationships are defined. The advantage of this frame is its ability of offer learners a “peek inside” a particular system, even if that “peek” would remove some information available in an allocentric frame. Egocentric frames allow learners to experience a system’s internal relationships as if the learners were actual pieces of the system itself, directly offering learners information about a system’s internal workings without needing to infer them from an allocentric view. A disadvantage of this frame is the removal of information not directly observable from the egocentric location—relationships and mechanisms that may govern an entire system might not be directly observable from an egocentric frame and need to be inferred (when possible) from numerous interpersonal relationships [48].

As an example, consider a planetarium lesson exploring solar eclipses. In this scenario, the Earth-Moon-Sun system governing the eclipse can be experienced by the learner in two frames: (1) learners can experience the eclipse as they would on the ground looking up into the sky in an egocentric frame; or (2) learners can experience the eclipse as if they were up in a space ship looking back at the Earth-Moon-Sun system in an allocentric frame. In the first frame, learners observing the eclipse would define the system’s relationships (the positions of the various celestial bodies) using themselves as the central locus standing on Earth. As the eclipse progresses, the apparent positions of the Sun and Moon converge as the angle between the two closes to zero—the angle’s vertex is the learner. In this frame, an observer’s entire world is plunged in darkness until the Moon passes—if an egocentric observer did not know that the Moon and the Sun were different sizes, they might conclude that the entire Earth was briefly plunged into darkness. In the second frame, learners observing the eclipse would define the system’s relationships using whichever “origin” they desire; in this case, Earth is a “natural” origin for the various relationships to be defined, but this choice is not absolute. As the Moon orbits around Earth, the Moon passes in front of the Sun and blocks part of the incoming sunlight from reaching part of Earth’s surface. In this frame, an observer sees the comparatively small lunar shadow traveling across Earth’s surface as the natural consequence of the Sun being so much larger than the Moon. However, the allocentric observer must infer what an Earth-based observer would see depending on where they were standing on the planet.

Planetariums, specifically digital fulldome planetariums, offer learners both of these frames of reference. Additionally, digtal fulldomes are capable of illustrating the transition between these two by “flying” an observer between the two frames—in the above example, a digital fulldome could start a learner on the surface of Earth in the egocentric frame but the fly off the surface of the planet out to an allocentric frame where Earth, the Moon, and the Sun are all visible. Such a switch between the frames of reference is non-trivial exercise for non-experts and the planetarium’s ability to render both of these frames makes it a valuable instructional tool by helping learners switch from one frame of reference to another [177, 271, 192, 48]. Spatial thinking among undergraduates is an important skill to develop [103, 98], and the planetarium might offer the necessary scaffolding to make that development happen more easily.

As part and parcel with reference frames, fields of view are the second important contribution to planetarium instruction. Unlike a regular classroom chalkboard or projector screen which might occupy a scant 20° of a learner’s field of view (according to Yu et al. (2017), anywhere between 11° and 30 °), fulldome planetariums offer near complete command of a learner’s vision due to the large hemispherical dome spanning the entire field of view (180°) of a planetarium audience member [273, 275]. Such a commanding display can truly simulate the positions and motions of celestial bodies in the sky in such a way that a learner can take a visualization “as is,” without needing to further manipulate the visual to match their real-world experience. This lets learner focus on encoding information like positions and directions without spending cognitive resources attempting to stretch a non-immersive visual to real-world scale [275]. Which frame of reference is the best one for immersive instruction is still an active avenue of research, however recent work has proposed that the egocentric immersive experience is an important one for learners to experience during the learning process in the planetarium [273]. A 2014 study by Zimmerman suggested that fulldome instruction offered longer lasting gains that standard computer projection [278]. Additionally, the 2015 study by Price and colleagues showed that stereoscopic film presentations in a planetarium theater had the same short term gains as two dimensional film presentations, but learning gains from the stereoscopic film were longer lasting [201].

2.5.2 A Place for Spatial Reasoning

The past planetarium research works all shared a comparatively small content domain (that also happened to coincide with the content domain from AER classroom research). This domain included items like sky motions (diurnal and annual motions of celestial bodies in the sky), the annual seasonal cycle, Moon phases, and orbital motion [271, 142, 272, 195, 232, 251, 273, 274, 275, 230, 50]. All of these content items shared an underlying cognitive skill which is crucial for both astronomy and planetarium learning at large: spatial reasoning.

The term spatial reasoning itself refers not to a learner's knowledge of Space (capital "S," i.e., the Universe, the Milky Way Galaxy, the Solar System, etc.), rather to a learner's knowledge of space (small "S," i.e., the volume of existence, positions and motions through it, how objects within the volume relate to one another, etc.). While knowledge of Space is often acquired and practiced with knowledge of space, the two are distinct from one another. Another way of viewing this situation would be to consider knowledge of space as a true learning outcome with knowledge of Space being used as a scaffolding aid (and incidental learning outcome). Spatial reasoning describes a learners capabilities to envision and experience space as an abstract construct describing the relative positions, motions, sizes, and changes within a system.

Spatial reasoning is an expert-level practical skill and acquiring spatial reasoning proficiency requires the successful achievement of essentially the entire cognitive outcome taxonomy. It also happens to be critical to understanding astronomical content, as many observable phenomena require a proficient understanding of position and orientation to be fully understood [269, 238]. A marked difficulty in learning spatial reasoning for astronomy, however, is that many sizes and scales of astronomical content are so far removed from everyday experience for learners that the simple act of envisioning them is prohibitively difficulty [164]. This point is famously illustrated in *Powers of Ten*, an excellent instructional and scaffolding aid walks learners through astronomical scale sizes in a succinct video [116]. Given that spatial reasoning ability has been correlated to success in astronomy learning [103], the impetus for effective instruction is obvious. Guiding learners towards this cognitive proficiency using animations (both 2D and 3D formats) has been demonstrated to promote greater learning gains that with still images [269]. Using tablet-computer planetarium simulations, Schneps et al (2014) showed how manipulable animations helped reverse misconceptions about astronomical size and scale [213].

Yu and colleagues have speculated this to be the case via the planetarium relieving learners of some of the needed cognitive demand to make the necessary knowledge constructions [273, 275]. Digital planetariums represent a powerful resource in achieving proficient spatial reasoning for learners. The space's ability to render both an immersive and manipulable environment could offer learners a "double whammy" towards the acquisition of spatial reasoning [270, 213]. If combined with the classroom environment, the planetarium's instructional aids could be furthered even more by offering learners multiple contexts and different constructions of the same underlying astronomical constructs [192, 203].

2.6 Synthesis & Statement of Research Questions

Synthesizing the topics above, I can now make a general set of statements concerning the present state of astronomy education research at the collegiate level. Collegiate astronomy education currently recommends a constructivist mindset towards the education of undergraduate learners as a consequence of recent research endeavors demonstrating a clear weakness in behaviorist mindset theories—behaviorist pedagogies may still exist in the course of undergraduate education, but the bend towards constructivism demonstrates the transition towards a superior method of instruction. Classroom learning in astronomy may take advantage of any number of constructivism-based pedagogies—these active learning and interactive learning styles push learners to engage with astronomy material by building their own understandings of the Universe rather than absorb the understanding dictated to them by an instructor. These pedagogies aim to identify, confront, and unravel misconceptions to initiate conceptual change in undergraduate learners, usually those enrolled in an archetypical “ASTRO 101” course for non-majoring learnings. As a part of these pedagogies, response systems like Clickers are often used to provide instant feedback to both learners and instructors to facilitate the learning process for both parties. Learning outcomes in the formal collegiate astronomy classroom typically focus on the cognitive domain, with desired expressions of affective outcomes being comparatively rarer.

Planetarium visits also occur at the collegiate level during the course of astronomy education, and researchers have demonstrated that lessons therein are able to promote substantial learning gains in the undergraduate learners who visit there. Planetariums leverage the immersive environment and changing frames of reference to aid learners in constructing correct explanatory frameworks, many of which rely upon spatial reasoning as a core cognitive skill. Planetarium classes that have been subject to research have focused much of their efforts on “classical” planetarium lesson fodder like sky motions and seasons, both of which overlap with the “ASTRO 101” curriculum archetype. This content is often considered as novice level material for collegiate students, but nevertheless non-trivial to understand given the various spatial orientations and frames of reference needed for expert-level understanding. The digital fulldome theater offers learners the ability to learn in an immersive environment capable of jumping between two primary reference frames to help learners cement their understandings. Like the astronomy classroom, planetarium learning outcomes seem to focus principally on the cognitive domain; however, affective outcomes in the planetarium theater may be seen as more naturally available to learners given the environment’s immersive learning capacity.

My review of the literature has demonstrated that the collegiate planetarium is seen as an effective location for astronomy education, providing immersive learning experiences for undergraduate learners supporting their acquisition of astronomical content. However, my review has also highlighted some gaps which I will confront in this work. Published planetarium works are almost purely astronomy focused—a few have ventured into the closely related earth sciences, but otherwise astronomy is the only subject apparently using the planetarium at the collegiate level. Are other disciplines being instructed in the planetarium? Non-major, novice learners (the archetypical "ASTRO 101" learners) are apparently the only ones who have been widely studied—why is this the case? What outcomes are instructors wanting out of their planetarium learners? Presented research seems to set aside some of the pedagogical particulars of a collegiate planetarium lesson and focused on the immersive visuals; astronomy education from the classroom has demonstrated the clear advantages of constructivist-minded pedagogical practices. Are collegiate planetariums following suit by incorporating reformed practices or are other pedagogies governing planetarium lessons? Can these be observed and characterized?

These are the questions I will contend with in chapters 3 and 4 towards my goal of characterizing planetarium learning at the collegiate level. The first of these, presented in chapter 3, will describe my efforts in completing a survey and interview study of planetarium directors across the United States, called the Planetarium Usage Survey, or "PLUS" for short. The second of these, presented in chapter 4, will describe my efforts in executing a survey and observation protocol of planetarium instructors at a western American university, called the Planetarium Observation Study, or "PLOBS" for short. The third study, the Mars Obliquity Project, or "MOP" for short, is presented in chapter 5—this chapter describes my efforts in a more classical astrophysical study of the planet Mars and how the planet's changing obliquity will influence how its atmosphere is lost. I have placed the introduction to Mars research in that chapter, rather than incorporating it here.

Chapter 3

PLUS: The Planetarium Usage Survey

3.1 Foreword to PLUS

The primary purpose of the following work was twofold: (1) to provide a general sense of planetarium use for undergraduate learners, and (2) by doing so, to provide a contextual archetype allowing various planetarium education research efforts in perspective of a larger, national context. This second point was of most immediate importance for the second AER focused work in this dissertation, PLOBS, discussed in chapter 4. The contextual archetype in question was one that would allow me to place my results, findings, and inferences from my own planetarium studies in a larger, practical picture of planetarium use. That is to say, the archetype provided by PLUS would allow me to put the findings from future studies (like PLOBS in chapter 4) into an underlying framework such that planetarium researchers might get a sense of the broader practical implications of research studies. For example, if I were to innovate, research, and validate a piece of undergraduate planetarium curriculum using a particular planetarium as the research setting, how applicable would those findings be to another planetarium elsewhere which may or may not share the same technological, administrative, or material constraints as my particular planetarium? If particular instructional or pedagogical improvements were made in a planetarium setting, would they be widely usable by the rest of the collegiate instructional community?

PLUS would offer some guidance to these questions by providing an archetype planetarium construct that could be referenced for information about "typical" collegiate planetarium instruction. With periodic revision and redistribution of PLUS (detailed below in this chapter), this archetype could continually update itself such that instructors, researchers, and content developers might have a contemporaneous reference as both education research and technological advancement progress in the collegiate planetarium environment. DBER professionals who might produce content could reference critical information like typical course size, content domain, and technological availability provided by PLUS when considering their experimental parameters. Following the completion of PLOBS (chapter 4), additional pedagogy-focused question items were added to PLUS. These new items enhanced PLUS' investigative power by also offering details about how planetarium lesson delivery occurs.

At the time of submission of this dissertation, the work described in this chapter was subject to peer-review and accepted for publication in ***The Physical Review - Physics Education Research****. This work bears the formal title of "Survey of the academic use of planetariums for undergraduate education" and was published online on October 23, 2020. This work is referenced in the following chapter (PLOBS: The Planetarium Observation Study) as "Everding & Keller, 2020." [77]*

3.2 Abstract

We present the analysis of the Planetarium Usage Survey (PLUS)[1] , a two-part, mixed methods initial study investigating planetarium use in the United States by undergraduate learners. Seventy-seven planetariums situated on college or university campuses within the United States completed an online survey during the fall of 2018 with 11 of those participating in online/phone interviews during the summer of 2019. Planetarium representatives described how their facilities were being used, types of subject materials that were being taught, what content styles are used,

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[1] Institutional Review Board (IRB) protocol number: 18-0597. Granted exempt status for human subjects research on October 22, 2018.

and how often learners are attending lessons in the planetarium. Results suggest that undergraduate learners in a planetarium environment are: primarily novice, non-STEM majoring students; learning principally astronomy content; receiving instruction from a live presenter approximately once per month within a given course; and for the purpose of providing visualization-based scaffolding. Audience response systems like iClickers do not appear to be in widespread use in collegiate planetariums, and presented subject matter shows greater variety in planetariums with digital projector capacity as opposed to those with only analog projectors. Refinements to PLUS and future research plans are described.

3.3 Introduction

The extant literature for astronomy education research (AER) has shown that groups of students are able to improve their understanding of astronomical concepts in planetarium settings [40, 143, 230]. The planetarium environment, in both formal [273, 275] and informal contexts [142], uniquely provides an immersive visual experience that translates into greater learning for younger, elementary learners [241, 43] as well as more experienced, collegiate learners [273, 275]. The planetarium environment is also able to help students construct more complete views by presenting multiple frames of reference unavailable in typical classroom settings [192]. Fulldome environments could be highly useful, specifically to the education of undergraduate astronomy learners [270], who often actively maintain misconceived or incorrect visualizations of the Universe from traditional classroom environments [277].

The various perspectives, orientations, and vantage points needed to fully understand astronomical phenomena are usually beyond the two-dimensional (2D) presentation capacity of most classroom settings, making astronomy a historically difficult subject to teach [270]. Planetarium facilities are constantly renovating to keep up with the advances of technology, and many facilities are now equipped with the ability to render immersive, virtual environments in addition to showing traditional projected positions of the various celestial bodies [267, 270]. This allows for a learning space that can more fully illustrate astronomical concepts without leaving the learner to "fill in the gaps" between a 2D illustration in a textbook and an actual 3D phenomenon [270, 251, 273, 274]. The digital planetarium environment has been demonstrated to show measurable learning of both earth and space science concepts in young children [241], adding weight to the proposition of using planetariums for the instruction of non-astronomical content at the collegiate level [267, 57, 241].

In spite of these instructional benefits, planetariums seem to remain a "special occasion" educational setting for undergraduate astronomy learners, being visited by a given class no more than a handful of times a year, let alone in a given semester; these more informal trips to the planetarium are marked by visits that are typically shorter than a corresponding classroom visit [193]. Singular, self-contained planetarium visits have been discouraged since analysis by Sunal (1976) [242] found them to be inferior to alternate planetarium instructional strategies, and infrequent visits to unfamiliar settings like planetariums might induce a more difficult learning environment. The "novelty" of the planetarium setting can require more attention and cognitive demand than a typical classroom for learners stepping into an unfamiliar environment [187, 110]. Earlier assessments of planetarium use showed little-to-no benefit in the planetarium environment [242], but more recent evaluations of past planetarium studies have since demonstrated the benefits of planetarium instruction [40].

Viewing these findings with recent data demonstrating a planetarium's advantages over the traditional collegiate classroom [274, 275], we view these findings as incentive that further investigations are needed into how best a collegiate planetarium's benefits can be maximized, a point raised during a meta-analysis of planetarium studies presented by Brazell & Espinoza (2009) [40].

Evidence continues to mount supporting the gains provided by a collegiate learning environment that aligns with student-centered, peer-to-peer, and interactive instructional strategies [92, 70, 198]. These environments, often facilitated by the use of classroom technology (iClickers, for example), have been shown to promote better retention among learners and add to the traditional classroom experience [70, 121, 109] at both the undergraduate and graduate level for both large and small classes [220]. It is reasonable to ask how these technologies have also been integrated into planetarium environments, as part of the effort to more fully integrate interactive pedagogies into collegiate curriculum.

We contend that a general survey of undergraduate level, formal planetarium learning needs to be established, specifically to answer the following questions:

(1) How often are planetariums used in the education of undergraduate astronomy learners? Is a typical astronomy class visiting a planetarium regularly or rarely?

(2) What are planetarium learners being taught? Is astronomy the only subject planetariums formally instruct? How is content being presented to learners?

(3) How are planetariums trying to actively engage their learners? Are planetariums effectively utilizing interactive classroom technologies and what types?

(4) Which astronomical topics are seen as well instructed in planetarium environments? Which are seen as poorly instructed? How can these findings motivate and guide efforts to enhance astronomy learning in fulldome environments?

The answers to these questions can guide systematic efforts to examine planetarium effects on undergraduate astronomy learners by informing researchers of how planetariums are actually being used by university learners, why these learners are taking part in planetarium instruction, how instruction is being delivered, and by formally documenting how planetariums are currently being used to advance collegiate education.

3.4 Theoretical Framework

Our review of the existing research suggests that most, if not all, past investigations into planetarium learning rests upon a common assumption: a planetarium is a learning environment for astronomy [40, 143, 230]. The exclusion of other disciplines like physics or earth science was sound when planetariums were first constructed around analog star ball projectors, but the progressive incorporation of full or hybrid digital systems operating with dome mounted projectors may have expanded the set of possible material appropriate for a planetarium environment [267, 270, 241].

Learning environments may be broadly separated into two categories: formal and informal [264]. As collegiate learners are likely to be instructed in a primarily formal context with a well-defined set of learning outcomes, we have adopted the research guidance pertinent to a formal, in-dome environment where “a structured and controlled planetarium program” is the presumed method of learning [264, 193]. As a point of contrast for the reader, we offer astronomy classes and astronomy clubs as an exemplary pair of in-dome learning environments that typify the formal-informal axis outlined by Plummer et al. (2015) [193].

A truly generalized answer to “how students learn,” especially in planetarium environments, remains a topic of active research; however, for this study we will adopt an initial framework obliging the use of particular learning environments, like a planetarium, by instructors to promote specific learning outcomes in their students. We have adopted the learning environment, learning process, and learning outcome (LEPO) framework for this study [190]. Like many frameworks obliging an activity theory-mindset, LEPO considers the processes and outcomes of learning in the context of the learning environment. These three cornerstones are interacted with by both the learner and instructor during the act of learning [190]. While more complex frameworks exist in the context of technology-rich astronomy education (e.g., Barab et al. (2002) [18]), we have agnostically chosen this simpler framework upon which to build this baseline study.

This investigation assumes a framework for planetarium learners characterized by the following traits: learners are in a formal instructional setting where the learning process closely mirrors that of a usual collegiate classroom, with the instructor acting as a source or distributor of knowledge; learning outcomes are principally in the cognitive domain, such that students can be evaluated with some kind of definite assessment to gauge their learning; and presented content is often astronomy based and serves as a well-defined complementary instruction mode to the regular classroom. Thus, the planetarium forms the environment corner of the LEPO framework, with learners and instructors engaging with the environment through usual classroom processes to achieve the desired outcome [190].

3.5 Methods & Investigation

This initial study was constructed around a mixed-methods analysis, with study participants (representatives of higher education planetarium facilities) being asked both quantitative and qualitative question items using multiple instruments. This mixed-methods approach blended two investigation strategies previously employed in planetarium education research: a survey-style instrument (similar to Fraknoi (2004) [88]) and an interview-style instrument (similar to Croft (2008) [57] and Small & Plummer (2010) [231]). Fraknoi surveyed astronomy instructors at non-research institutions to gain insight into instructors "outside" the sphere of research institutions and top liberal arts colleges [88]. Small & Plummer explored the opinions of planetarium professionals about planetarium experiences, focusing on goals for children learners, via interviews [231]. Croft likewise interviewed planetarium professionals to explore an apparent conflict between educational and entertainment goals in a planetarium [57]. Like the above studies, this investigation collects primary data from campus professionals with direct experience about how instructors are using their facilities, with particular attention to higher education settings. Our approach offers three types of primary data that together serve to inform our research questions: quantitative data from closed-ended multiple choice survey questions; semi-quantitative data from trend coding open-ended survey questions; and qualitative data from open-ended interview questions.

This work sought to further our understanding of planetarium use for undergraduate learners by building a set of survey constructs around our research questions. These constructs are shown in Table 3.1 along with a description of the associated guiding survey questions used to test each construct. Following the distribution strategies in previous works [88, 231], we chose to distribute our survey to a large sample of appropriate participants.

The sample population was taken from the International Planetarium Society (IPS) catalogue, available to the public from the professional organization webpage. This catalogue contains self-reported information from IPS members, including information such as contact information, general institution information, and structural information describing the facility (theater seat counts, orientation, and projector capabilities). The sample population drawn from this catalogue were those institutions that identified themselves with the institution code “Univ/College,” describing planetariums located on university or college campuses.

Participants were representatives of planetarium facilities located on higher education campuses (e.g., planetarium directors and education coordinators). Participants were posed questions during an initial survey period and a subset of these participants volunteered for one-on-one interviews during the summer of 2019 to further explore trends emerging from the initial survey period. These additional interviews were to triangulate the initial findings emergent from the online survey data, and also to guide both validation efforts and development of a refined survey instrument for future use.

3.5.1 PLUS Survey Instrument - Fall 2018

Potential respondents were invited to participate en masse with a Qualtrics survey link embedded in an invitation email; approximately 261 institutions were invited to participate in the survey. Ninety-three such institutions (∼36%) were registered by Qualtrics as having opened the survey, with 77 of those (∼83%) fully completing the survey. Data from incomplete surveys are included in these analyses when available—blank entries were removed from each question's response data before any analysis was done. Respondents had 28 days to complete this survey and reminder messages were sent throughout this time to encourage survey completion.

Table 3.1: Survey constructs of the PLUS study. Constructs were constructed from our emergent research questions and were explored with both online survey question items and follow-up interview responses.

Research Construct	**Guiding Questions**
Learner populations and use-frequency	How often are planetariums used in the education of undergraduate astronomy learners? Is a typical astronomy class visiting a planetarium regularly or rarely?
Subject materials and projector-dependent content variety	What are planetarium learners being taught? Is astronomy the only subject planetariums formally instruct?
Interactivity strategies and perceived environmental traits	How are planetariums trying to actively engage their learners? Are planetariums effectively utilizing interactive classroom technologies and what types? How can these findings motivate and guide efforts to enhance astronomy learning in fulldome environments?
The nature of presented content	How is content being presented to learners? Which astronomical topics are seen as well instructed in planetarium environments? Which are seen as poorly instructed?

To verify the sample range of this study, a comparison was drawn between the listed seat counts in the IPS catalogue of all facilities listed under Univ/College and the facilities of PLUS respondents (Fig 3.5.1, blue and white distributions, respectively). This was accomplished by cross-referencing the PLUS respondents' contact information against the contact information in the IPS catalogue and extracting the corresponding seat counts—respondents were not asked to enumerate the seat counts of their respective planetariums.

Four descriptive statistics were drawn from the two distributions, shown in the legend of Fig 3.5.1. Assuming the IPS catalogue is the "true" distribution of seat counts, the distribution corresponding to the PLUS survey respondents closely maps that of the IPS Univ/College catalogue. A Kolmogorov-Smirnov (K-S) test was run between the two distributions, assuming the IPS Univ/College catalogue distribution was the true distribution. To a significance level of 0.05 ($U_{KS} = 0.084$, $p = 0.695$), a K-S test fails to reject the null hypothesis that the two data sets have the same distribution, allowing us to conclude the PLUS survey is a meaningful representation of the collegiate planetarium community.

3.5.2 PLUS Interview Instrument - Summer 2019

For the follow-up interviews, a selection scheme was devised to shorten the available contact list rather than send out an interview invitation to all original respondents. Invitations were sent out to those respondents who completed the Qualtrics survey and whose responses to three of the survey's questions were collectively deemed as "complete." This designation was made with the following scheme:

(1) For each completed survey, the number of distinct subjects taught (normalized by six subjects), the number of seats during a regular class visit (normalized by 180 seats), and the word count of the first free response question ("What subjects do you think are instructed well in a planetarium;" normalized by 114 words) were compiled as an ordered triplet.

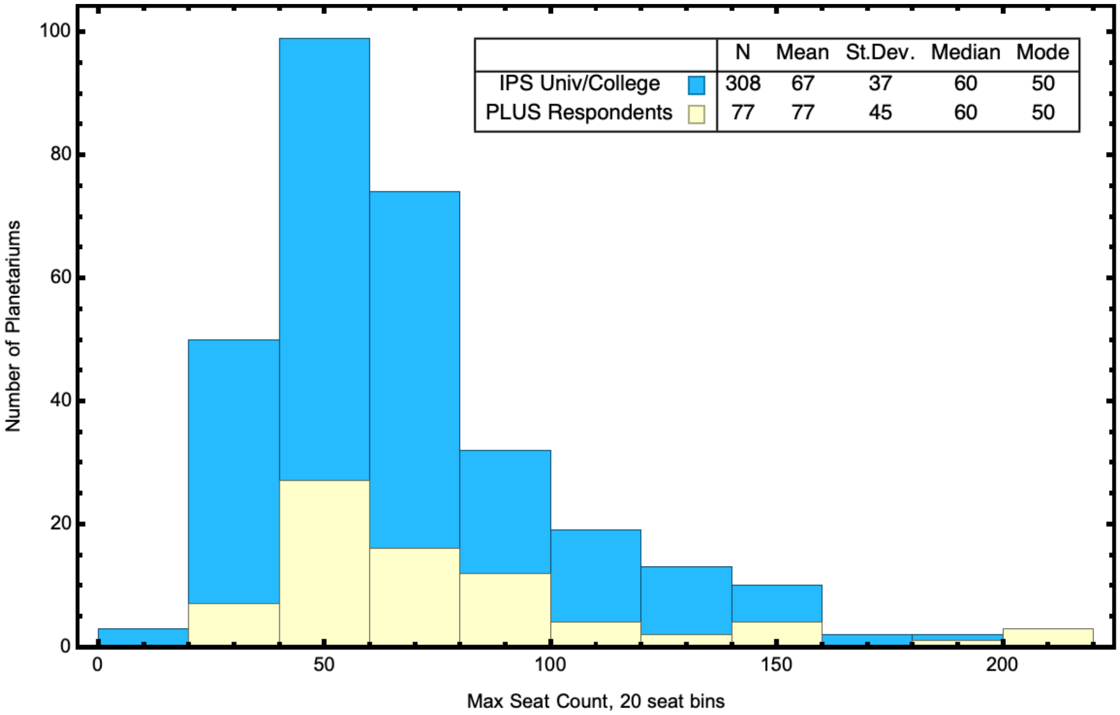
(2) Each ordered triplet had its Cartesian "completeness score," D, calculated as the distance from the "origin" of the three dimensional "completeness space." Quality scores could take any value between 0 and 1.73.

(3) The median quality score, D_{Med} , was determined for the entire respondent pool. Those respondents whose completeness score equalled or exceeded the median quality score ($D \geq D_{Med}$) were extended an invitation to be interviewed.

This strategy was used to identify prospective interviewees who might provide the most descriptive insight into how medium to large planetariums are engaging undergraduates both in astronomy and other content. While this strategy may have biased against respondents who were less descriptive in their written survey responses or who maintained smaller facilities, our choice of using the statistical median as the lower cut-off helped alleviate over-selection of outlying high-value quality scores.

This selection scheme selected 36 of the 77 valid respondents (∼47%). Invitations to be interviewed were extended to these 36, with the expectation that about half would be willing and available to be interviewed. Eleven of the 36 (∼31% of invitations; ∼14% of original 77 respondents) sat for an interview during the summer of 2019. The descriptive characteristics of the interviewees, as well as respondent pseudonyms, can be found in Table 3.2. Individual subject quotes and discussions will be prefaced by the respondent pseudonym in this paper.

Figure 3.1: Histograms of IPS catalogue seat count data for all respondents indicating “Univ/College” compared with IPS catalogue seat count data for facilities of PLUS respondents. Similarity in these distributions’ descriptive statistics supports this study’s findings as characteristic of the nationwide group.



Interviews occurred for each consenting participant in one sitting, and both interview notes and recordings resulted from each interview. Each interview took approximately 90 minutes to complete and followed a semi-structured procedure where participants were prompted with a question but were left to freely respond as they saw fit [57, 231]. Participants were asked 14 open ended questions, with possible follow-ups for clarification being asked as needed. The interview questions were crafted by the authors after discussion of the emergent trends from the survey data and were used to triangulate and validate the findings from the survey. Interview subjects were provided with both the interview questions beforehand and preliminary findings from the 2018 survey. Audio recordings of 10 of the 11 interviews were made—a recorder malfunction failed to record one of our interviews. We have included the text of our interview questions below in ”Data & Analysis” in the appropriate subsections for our research constructs (Table 3.1).

All respondents were asked to name their planetarium, the college or university at which is was located, their official position at the college or university, and a brief description of the technological capabilities of their planetarium. Each college or university was cross-referenced with the Carnegie Classification catalogue to establish the sampling diversity of this study [86]. Subjects’ institutions range from R1 (doctoral universities - very high research) to associate’s or community college. Five of the 11 (∼45%) institutions were doctoral degree granting institutions, three (∼27%) were bachelor’s degree granting institutions, two (∼18%) were associate’s degree granting institutions, and one (∼9%) was listed as both a bachelor’s and associate’s degree granting institution. Of the 11 interview respondents, 10 (∼91%) were full or partial instructor faculty at their respective institutes—the remaining interview respondent (∼9%) was formally rostered as the education director of their planetarium. Nine of the 11 respondent planetariums (∼82%) were partially or fully digital domes, with the remaining two (∼18%) being analog-only.

Table 3.2: Pseudonym, official title, home institution type, and general planetarium projector descriptions of this study's interview subjects. Institution types were determined by cross-referencing respondents' host institutions against the Carnegie Classification catalogue [86].

Pseudonym	**Official Title**	**Institution Type**	**Projector**
Dr. White	Planetarium director; associate professor of astrophysics	R2	Digital
Prof. Green	Planetarium director; instructor in mathematics	Bacc. College - A&S	Analog
Dr. Blue	Astronomy department chair	Bacc. College - A&S	Analog
Dr. Red	Astronomy faculty	CC / Assoc. College	Digital
Dr. Violet	Professor of physics and astronomy	CC / Assoc. College	Digital
Dr. Yellow	Planetarium director	D/PU	Digital
Dr. Indigo	Astronomy faculty; planetarium teaching coordinator	R1	Digital
Prof. Orange	Educational programs manager	R1	Digital
Dr. Black	Planetarium director; auxiliary faculty in astronomy	R1	Digital
Dr. Brown	Planetarium director; professor in physics and astronomy	CC / Bacc. College - A&S	Digital
Dr. Grey	Assistant professor in physics and chemistry	Bacc. College - A&S	Digital

Table 3.3: Counts of this study's respondent planetarium's projector descriptions. PLUS 2018 Survey projector types were found using respondent-provided planetarium names and institution extensions. Standard counting error ($\sigma_k = \sqrt{N_k}$) is assumed for each response bin. PLUS 2018 survey did not sample a measurably different distribution of planetariums than would be expected from the IPS Univ/College catalogue, but a slight bias against analog-only planetariums was introduced during the interview invitation process (described in text).

Group	**Respondent Count**	**Analog-Only**	**Digital-Capable**
IPS Catalogue - Univ/College Only	352	45.2%	54.8%
PLUS 2018 Survey	77	38.2%	61.8%
PLUS 2019 Interview Invites	36	27.8%	72.2%
PLUS 2019 Interviews	11	18.2%	81.8%

Lastly, we note here that this study showed a less favorable sampling of analog-only planetariums during the PLUS 2019 interviews (Table 3.3). When we consider the percent-equivalent counts of our four groups (with our assumed standard counting error applied ($\sigma_k = \sqrt{N_k}$)), the distribution of analog-only and digital-capable planetariums in the IPS Catalogue (Univ/College Only) is not statistically distinguishable from the PLUS 2018 Survey. Across the four groups presented in Table 3.3, the percentage of digital-capable respondents remains indistinguishable throughout this study. However, the number of analog-only respondents is measurably fewer as the study progressed. We do not believe that this has imparted undue bias to this study's findings for the following reasons: the IPS Catalogue (Univ/College Only) has a small, measurable preference for digital-capable planetariums; triangulation of the 2018 survey data was still possible with the sample of interviewees obtained; and the interview questions did not rely on a particular projector style in order to be considered by our participants.

3.6 Data & Analysis

The pool of available data used in this study was comprised of our primary data, collected during the online survey period in Fall 2018 and interview period in Summer 2019, and secondary data from the IPS catalogue, specifically the list of seat counts and projector types.

Quantitative data was collected by PLUS using multiple-choice and open-ended, free-response questions. Qualitative data was collected by PLUS free-response questions—free-response data were analyzed using an iterative identification of response trends. For each question's set of responses, trends were identified and coded with generally descriptive alphabetic codes and then re-analyzed and given additional numeric codes that further described the response. Descriptive codes were generated or consolidated as necessary throughout the iterative process. The PLUS survey asked a total of 10 required questions, with an additional 10 possible questions being displayed depending on the respondents selections of the required questions.

Given our comparatively small number of follow-up interviews (N = 11), analysis of the interview responses followed a more holistic approach similar to the approach presented in Croft (2008) [57]. Responses to each interview question were considered together and trends were identified as opposed to an iterative coding scheme. In most circumstances, our interview responses converged upon similar underlying themes or naturally partitioned themselves into distinctive groups.

We present this study's survey and interview data together for each investigation construct sought by this study. Survey and interview questions pertinent to each construct are presented in bold-face—for this presentation we adopt the style of "QX.Y" to denote survey question from section "X," question "Y," and "IQ" to denote interview questions. Finally, we refer to our initial survey instrument as PLUS 1.0 and the revised future survey instrument as PLUS 2.0.

3.6.1 Construct 1: Learner Populations & Use-Frequency

Our first construct exploring who is using a planetarium environment to learn was investigated by analyzing the responses to two survey questions (Q2.1 and Q2.2) and interview discussions.

Q2.1 - "Which of the following audience populations does your planetarium serve?"

During the PLUS 1.0 implementation of Q2.1 (Fig 3.6.1, “Primary service?”), respondents were prompted to select the audience populations served by their planetarium in a pair of side-by-side selection box columns. In the left column, respondents were asked to select all audience populations that make any use of their planetarium; in the right column, respondents were supposed to select a single audience population that the planetarium primarily served. Due to a misunderstanding concerning the Qualtrics platform, respondents were able to select more than one “Primary” selection, and thus were able to provide more data than should have been allowed. To compensate for this possibility, data were filtered and kept if they satisfied the following conditions: the respondent selected only one option in the “Primary” column and the same selected population was also one of the selected populations in the “Any” column. Such conditions avoided any respondents who selected more than one “Primary” selection while also ensuring that their choice of “Primary” was sensible (the choice had a corresponding “Any” selection). This data collection has been refined in PLUS 2.0 (described below).

Two immediate findings emerge from these filtered data (Fig 3.6.1). First, collegiate planetariums reliably serve almost every learner group, with the only distinct outlier being “graduate students.” Second, in spite of being on college campuses, these data suggest that the primary learner population served by the facilities surveyed is K-12 learners rather than four-year or community college learners. Also of interest is the complete loss of “pre-K” and “graduate student” learner groups in the set of “Primary service” responses. The wide selection of “Any” service populations is not surprising—we know of no planetarium that expressly excludes any of the considered learner groups from using their facilities. The “Primary” responses do not explain why collegiate planetariums are not primarily serving their own college students. These data required further probing during the interview portion of this study, described below.

Q2.2 - “On average, how often is your dome used by an undergraduate or graduate astronomy class during a typical term (quarter or semester)?”

Figure 3.2: Responses to Q2.1 concerning which learner populations (legend) are serviced by US planetariums on college or university campuses—respondents were asked to select all populations that their planetarium served at any time (left group) and which single population was their primary audience (right group). Standard counting error ($\sigma_k = \sqrt{N_k}$) is assumed for each data bin. An error in the data collection required the data to be filtered (described in text). Data reinforce findings about graduate learners' comparative lack of planetarium use, and suggest that collegiate planetariums are most commonly used by the K-12 learner group, not collegiate audiences.

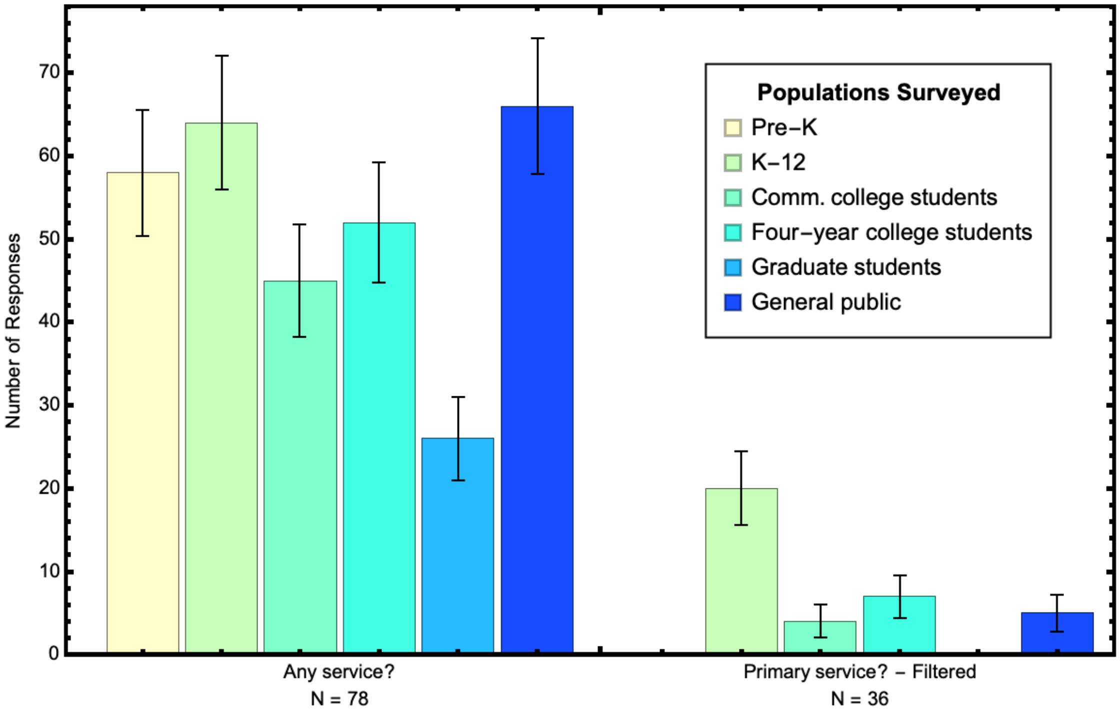
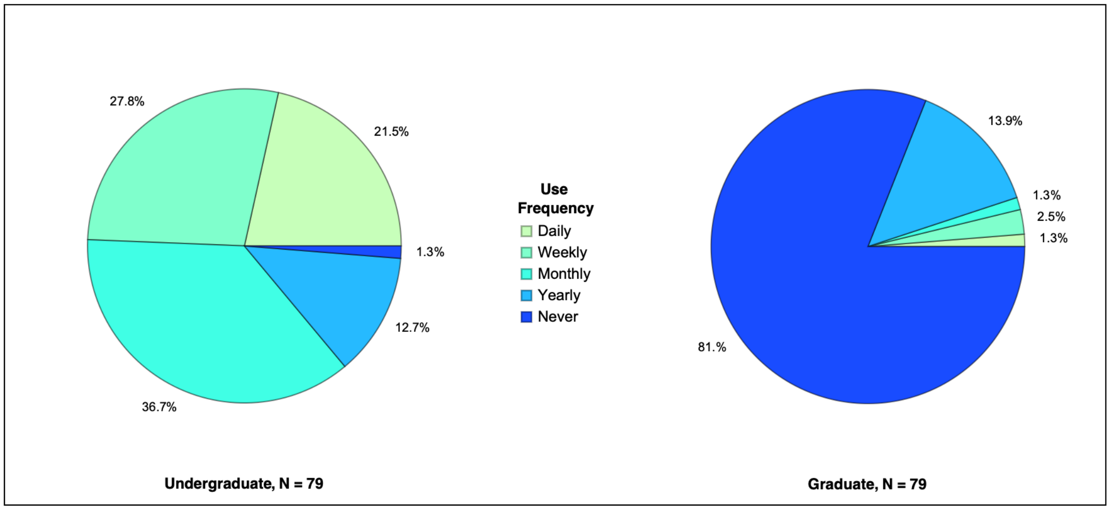


Figure 3.3: Responses to Q2.2 concerning how often undergraduate and graduate level astronomy students are using the planetarium during a typical academic term (quarters or semesters). Undergraduate data propose a characteristic frequency between weekly and monthly; graduate data strongly contend that graduate learners do not practically use a planetarium.



Data for undergraduate astronomy students (Fig 3.3, left) is the most numerous for a frequency of "monthly;" however, there is no statistical difference with the neighboring "weekly" bin. The "daily" frequency bin is also statistically indistinguishable from the "weekly" bin, but is significantly different from the "monthly" bin. Data for graduate students is more definitive (Fig 3.3, right): 81% of all respondents described the use of their planetarium by graduate level astronomy as "never," with the next largest frequency bin being "yearly." Both the "never" and "yearly" bins are statistically distinct from one another and from the remaining frequency counts, which are themselves statistically indistinguishable. Our conclusions from these data is that a typical undergraduate astronomy student on a campus with a planetarium is being instructed in that environment once every week to once per month during an academic term; graduate astronomy learners do not practically use a planetarium during an academic term, if ever. Collection of these data has been refined in PLUS 2.0 (described below).

IQ - What kind of undergraduate astronomy learner is coming to your planetarium?

To clarify the planetarium usage data gathered during the survey (Figs 3.6.1 and 3.3), respondents were asked to specify what kind of undergraduate astronomy learner is coming to their planetariums for instruction. All 11 respondents described their typical planetarium learner as "non-major," "non-STEM," "novice," "beginner," or a combination thereof. Three of the 11 (∼27%) made specific mention of expert level planetarium learners during their descriptions. These expert level learners were described as seeking their teaching credentials for STEM courses and were not in the planetarium to learn astronomy content specifically, but rather how to present it.

Dr. Blue: *"I suppose the wrinkle on that is that the advanced astronomy students are learning to use the planetarium and hone their teaching skills. ...they're not in there for a class, they're in there to learn how to give the class."*

The lack of use by more experienced astronomy learners may rest on an assumption that more experienced STEM learners would not benefit from planetarium instruction because they do not "need" it:

Dr. Indigo: *"...I specialize in students who are not going to be scientists, teaching them science and there, the planetarium is invaluable... we use the planetarium to teach general education astronomy... the planetarium is not as effective for a student that can do calculus because a student that can do calculus can think abstractly—they don't need a three dimensional visual representation."*

We stress to the reader that this assumption was inspired by the comments from one interview and may not be representative as a sample-wide trend. The contention above is that a more experienced learner should possess the ability to form the 3D constructs necessary for astronomy comprehension without the scaffolding aid of a planetarium. However, this ability could take several years of instruction to fully form [75], and assuming the spatial ability of a learner might not be advisable for an instructor. Furthermore, for astronomy specifically, even advanced learners in pre-service teaching training have been demonstrated to maintain misconceptions, even after instruction [118]. When this comment is considered alongside the small number of expert level learners and the near lack of graduate level learners (Fig 3.3), we contend that planetariums may be viewed as the near-unique purview of the novice, non-STEM major learner. The use of a planetarium for more advanced learners may be seen as unnecessary, but the veracity of this requires further dedicated study.

Respondents were also asked to explain why their planetariums were primarily used by their respective primary audiences. Respondents who selected "K-12" as their primary audience (∼64%) voiced one principal reason: population demand. K-12 learner groups, particularly younger learners, often partake in a planetarium visit during a field trip during their general science units. The inclusion of planetarium resources into K-12 curriculum for educational purposes has been recommended in the past [40]. More recent curriculum considerations for the K-12 learner population stress basic astronomical content knowledge [3, 181], for which a planetarium is almost uniquely qualified to serve as an instructional environment [11, 270].

<u>Dr. Yellow:</u> *"I think that a lot of people went to a planetarium when they were in grade school, so they think of a planetarium as being a place for field trips."*

This point is further reinforced when one weighs the financial considerations of a planetarium which may need to fund itself through ticket sales—the larger number of K-12 students could provide reliable revenue stream to a planetarium, and may thus be more heavily advertised to those learner groups as opposed to college faculty.

3.6.2 Construct 2: Subject Materials & Projector-Dependent Variety

To probe what materials are being presented and how a planetarium's projector type may impact the variety of those materials, our second research construct was initially probed with two "select all that apply" style questions. Respondents were asked to select which subjects are instructed in their planetariums and to specify how many students attend a typical class for each selected subject. As a follow-up for each subject, respondents were asked to further specify which disciplines for each subject were instructed in their planetariums:

Q2.3 - "Which, if any, subjects are taught in your planetarium? Where possible, please also include an approximate number of students instructed during a typical class period in the spaces included."

Q2.3a–f - "Which disciplines of [previously selected subject] are instructed in your facility?"

Table 3.4: Statistical measures of the data for the survey question Q2.3 asking how many students are in a typical class for each subject. The number of respondents is specified under "Counts." The mean, standard deviation, median, mode(s), and range are measured in number of students. Standard counting error ($\sigma_k = \sqrt{N_k}$) is assumed for each count bin. Values of the means and associated standard deviations imply non-normally distributed numbers of students—median counts are a more representative measure of class size.

Subject	**Counts**	**Mean**	**St. Dev.**	**Median**	**Mode**	**Range**
		(Number of students taught in typical class)				
Astronomical Sciences	72	47	30	40	30	165
Earth Sciences	31	46	32	30	25	130
Physical Sciences & Engineering	18	35	14	28	25	40
Life & Social Sciences	15	31	10	28	22	38
Fine & Performing Arts	9	28	14	24	24 & 30	48

For the purposes of this study, "subject(s)" will refer to the large, overarching academic categories shown in the left hand column of Table 3.4. These subjects are intentionally broad to capture enough descriptive information about what the general planetarium material is without getting prohibitively nuanced. In the development of PLUS 1.0, we did not provide formal definitions of each subject category (Table 3.4), opting to let our respondents interpret each subject as they saw fit. In PLUS 2.0, we have reformatted this question by providing a "definition though description" of each category by providing a list of topical examples of each subject. Further description of the revisions to PLUS can be found below in "Improvements to PLUS." "Discipline(s)" will refer to the smaller sub-categories of each subject listed along the left-hand axis in Fig 3.6.2. As partitions of the overarching subject, the discipline data allow for a more focused measure of what material each subject is dedicating instruction to in a planetarium environment.

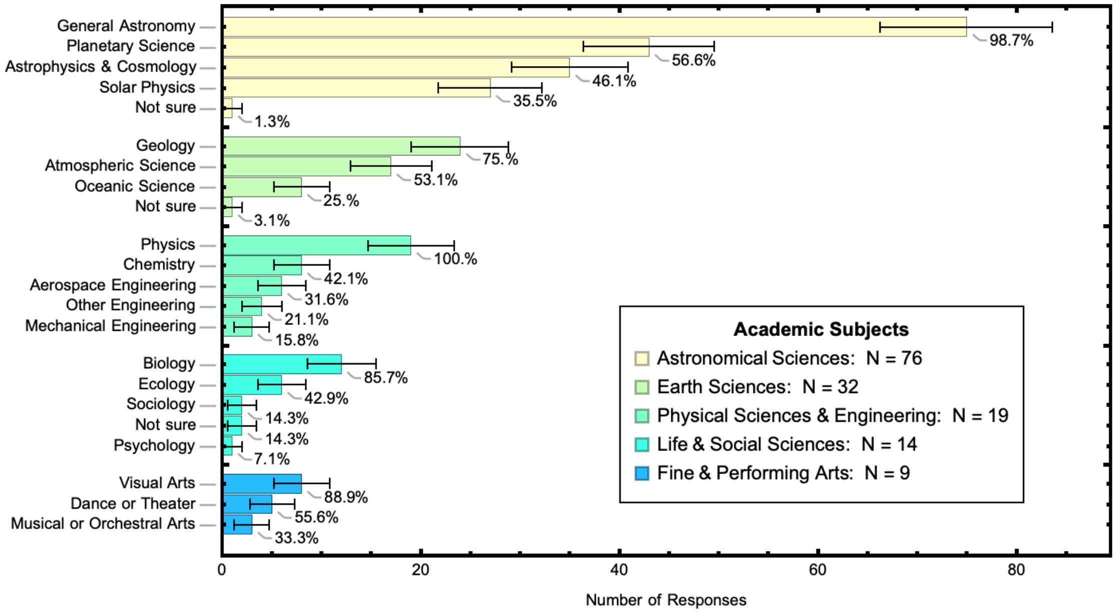
Statistical measures of the responses to Q2.3 can be seen in Table 3.4. The mean, standard deviation, median, mode, and range are all measured in number of students. Astronomical sciences is the most numerous subject being instructed; however, noteworthy counts appear in all remaining subject categories. As seen in Table 3.4, the statistical measures of these data suggest a typical planetarium class between 20 and 40 students (median counts). We have chosen to use the median here as opposed to the mean due to the handful of comparatively large student classes in the astronomical sciences and earth sciences subject categories as the median is more robust measure against outliers, exemplified in the large range values for those subjects.

Responses concerning the disciplines are presented in Fig 3.6.2. The overarching subjects are presented in the legend; the numbers adjoining the subjects are the number of responses for each group. The disciplines for all subjects are defined down the left-hand axis in Fig 3.6.2—the disciplines are color-coded according to their respective subject presented in the legend. The percentages next to each bar are that discipline's contribution to the entire subject's available responses. For example, of the 32 respondents who selected the subject "Earth Sciences" as an instructed subject, 24 of these (∼75%) chose "Geology" as a specific discipline instructed in their planetariums. As respondents were allowed to pick as many of the predefined disciplines as they desired, the percentages will not sum to 100%. We also note a small discrepancy between the numbers of responses for the academic subjects shown in Table 3.4 and Fig 3.6.2. This discrepancy is due to the survey engine not requiring a respondent to supply a seat count while answering Q2.3—they needed only select a subject(s) to continue with the survey, but could have left the seat count blank. The data shown in Table 3.4 is only for respondents who selected a subject and provided a seat count.

These data provide more clarity as to how planetariums are being used from the standpoint of academic subject matter. Specifically, planetariums overwhelmingly report instructing general astronomy as the subject material in question—98.7% of respondents to this question selected "general astronomy" as a discipline instructed in their planetarium. We stress to the reader that material which does or does not qualify as being "general astronomy" is still poorly agreed upon by the astronomy community and no prompt was provided to the respondents as to what they should consider as being "general astronomy." We have omitted this terminology from the revised PLUS 2.0, opting instead to offer specific examples of astronomical subject matter. For this study, we will consider "general astronomy" to be a loose category of material that includes topics like: sky motions, lunar phases, constellations, seasons, and naked-eye observations. We would also like to note that many studies in the past that concern planetarium learning have their topical focus within this category [15, 230]. The data for the remaining subjects suggest that material shown to students in a planetarium not under the umbrella of astronomy would likely belong to one of the natural sciences like the earth or physical sciences.

Further context is gained by binning the response data in Q2.3 into “astronomy-only” and “astronomy-plus” categories. Responses have been grouped based on the number of additional subjects selected in Q2.3 along with “Astronomical Sciences.” Additionally, responses have been split according to the projector capabilities of each planetarium (legend, Fig 3.6.2), as determined through cross-referencing with secondary data from the IPS catalogue. “Analog-Only” is assigned to respondents whose catalogue entries contained only a star projector; “Digital-Capable” is assigned to respondents whose catalogue entries contained at least one digital fulldome projector. A single respondent who did not select “Astronomical Sciences” as an instructed subject has been omitted from this binning scheme. These binned responses are shown in Fig 3.6.2, with the binning groups denoted along the horizontal axis—bars measure each group’s percent contribution to their projector group. For these binned data, “AS-only” corresponds to “Astronomical Sciences Only” and “AS + N” corresponds to the group of “Astronomical Sciences + N,” where “N” is the number of additional subjects. Respondents who selected four or more additional subjects have been grouped into one bin (”AS + 4+”). The number of true counts is listed along the horizontal axis beneath each column. The binning procedure described above was also performed on the counts from Q2.1 and Q2.2, but no distinction between the two projector groups could be drawn and have been excluded from this paper.

Figure 3.4: Responses to Q2.3a–f concerning which academic disciplines (left-hand axis) are taught in a planetarium environment in each overarching subject (legend). Standard counting error ($\sigma_k = \sqrt{N_k}$) is assumed for each data bin. Data are labeled with their respective percentage of the available response pool (corresponding "N" values in legend); the number of available responses per subject is specified in the legend. Noteworthy counts are seen across all the sciences, not just astronomy.



No reliable difference between analog-only and digital-capable planetariums is measured across the entire set of binning groups (Fig 3.6.2); however, we do note the measurably higher percent-equivalent counts for analog-only planetariums in the AS-only group and for digital-capable planetariums in the AS + 3 group. Analog-Only planetariums do show a sharp decline in the reported number of additional subjects after AS-only, but digital-capable theaters maintain a shallower decline as the number of additional subjects increases. Additionally, for both projector groups most of the contributions to the instructed subjects are in the first two sets of columns (AS-only and AS + 1)—Analog-Only planetariums contribute 89.1% and Digital-Capable planetariums contribute 63.8% of their respective responses to just these two. We also note here that PLUS respondents' planetarium projector capacities show a measurable preference towards Digital-Capable planetariums (29 Analog-Only compared to 47 Digital-Capable).

Viewing these data through a practical technology lens, the sharp decrease in Analog-Only counts beyond AS-only is expected—an analog star projector can only project points of light, so its ability to show other visualizations may be severely diminished. Digital-Capable planetariums do not share this technological barrier, and could be expected to exercise subject presentations outside astronomy more easily. However, at least 13 Analog-Only planetariums indicated they were able to use their planetariums for more than just astronomy. We conclude from these data that undergraduate students are going to planetariums to receive astronomy instruction but said planetariums are not definitively "astronomy-only" institutions. Furthermore, Analog-Only planetariums might suffer from a technological barrier against the presentation of other subject matter outside astronomy.

3.6.3 Construct 3: Interactivity Strategies & Perceived Environmental Traits

Our third research construct focuses around the planetarium as a physical learning environment and how the traits of that space impact instruction. We approached this by analyzing two survey questions (Q3.1 and Q3.2) and with interview discussions centered around respondents' opinions of the planetarium environment.

Q3.1 - "Which, if any, interactive technologies are installed in your planetarium?"

Q3.2 - "Please rate the approximate usage of your planetarium's interactive technology by instructors using your dome during a typical class period."

Figure 3.5: Responses to Q2.3, collected into ”astronomy only” (AS-only) and ”astronomy plus” (AS + N) bins, based on respondent selections of ”Astronomical Sciences” and any other N subject(s). Responses have been further binned according to respondent planetarium projector capacity and expressed as their percent-equivalent values. Standard counting error ($\sigma_k = \sqrt{N_k}$) is assumed for each data bin—raw counts for each bin are listed along the horizontal axis beneath each column.

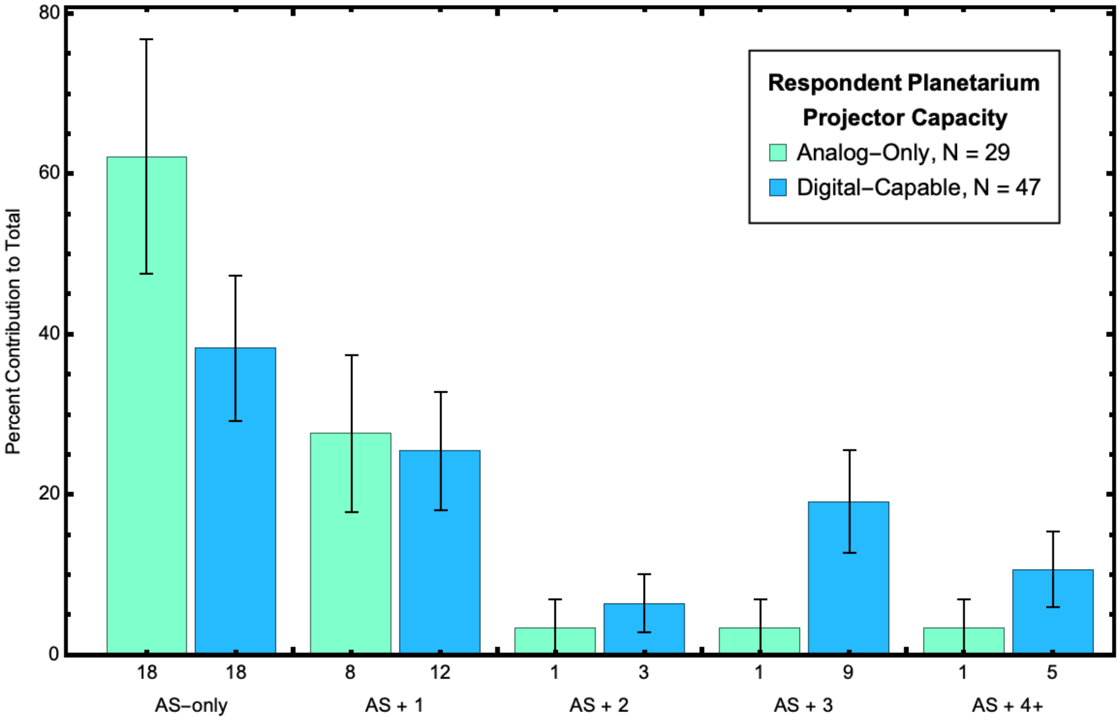


Table 3.5: Response counts to survey questions Q3.1 and Q3.2. Respondents were asked to rate how often interactive technologies like iClickers are used in their planetariums. Standard counting error ($\sigma_k = \sqrt{N_k}$) is assumed for each response bin. Counts strongly suggest an overwhelming lack of interactive technology use in planetariums, but those that have interactive technology do use them with some regularity.

Use Frequency	**Response Counts**	**Percent Equivalent**
None	62	80.5 %
Never	1	1.3 %
Rarely	4	5.2%
Intermittently	6	7.8%
Reliably	3	3.9%
Heavily	1	1.3%
Total	77	100%

Data for Q3.1 and Q3.2 have been shown together in Table 3.5. Q3.1's original text allowed for respondents to pick individual types of technology from the following list: "none," "iClicker or similar individual remote device," "armchair-embedded remote," "cell phone application," and "other" (filled in by the individual respondent). If a respondent picked any option except for "none," they were then asked to qualify their answer with Q3.2 which presented the following options as selections: "never - these systems are not used by instructors," "rarely - maybe once during a typical class," "intermittently - a few times during a typical class," "reliably - many times during a typical class," and "heavily - class cannot proceed without these technologies."

Only 15 (∼19%) of Q3.1's 77 respondents reported using interactive technology of any kind. No respondent offered their own "other" option. Of the 15 respondents who reported having interactive technology in their facilities 14 (∼93%) chose "iClicker or similar individual remote device," 3 (20%) chose "cell phone application," and 1 (∼6%) chose "armchair-embedded remote." The spread of use frequency of these 15 can be found in Table 3.5. The spread in usage frequencies is nearly symmetric around the "center" of the data ("intermittent" row), but due to the low number of counts for the five frequency ratings and corresponding uncertainties, we may only reasonably infer that planetariums equipped with some piece of interactive technology use said technology. We will discuss the implications of the large number of "none" counts below in the interview discussions.

IQ - Does your planetarium have an audience response system (ARS)? How often do instructors use it? If not, why and what do you see as the barriers to adding one?

IQ - Would you consider an ARS as a necessary component to produce a more interactive learning environment in your planetarium?

IQ - Why do you think a planetarium would or would not rely on an ARS?

When asked if their planetarium has an ARS, eight of the 11 (∼72%) interviews stated "No," and three of the 11 (∼28%) stated "Yes." These responses trends are in fair agreement with the survey responses displayed in Fig 3.5, if one considers all response groups excluding "No Interactive Tech" together. For the three respondents who possess an ARS in their planetarium, the descriptions of "daily," "commonplace," and "by almost every instructor," offer a positive, if ill-defined picture of how often such systems are used in a planetarium when available.

When asked if they view an ARS as necessary, three of the 11 (∼28%) stated that such a system was necessary, three of the 11 (∼28%) stated that such a system was not necessary, and five of the 11 (∼44%) stated that such a system is not necessary but possibly useful. All respondents, regardless of their personal facility's use or attitude towards an ARS, were asked to consider why a planetarium would or would not rely on one. Six of the 11 (∼55%) of respondents suggested that an ARS isn't appropriate for a planetarium environment. The reasons provided by the interviewees to explain these opinions include: not having enough students in the theater to warrant such a system; using other means of interactive learning like Q&A's, group discussions, and peer-to-peer instruction; and the use of "zero-tech" interactive technology like shows-of-hands and four-letter "ABCD" multiple choice cards.

<u>Dr. Blue:</u> *"Our classes will have maybe 25 to 30 people in them. If I'm in there with one of my intro classes where I've got 25 students, and I know them all, I'm interacting with them anyway. I can call them by name and ask them questions. I don't need clickers."*

Prof. Orange: *"...it's efficient and accessible, but it's certainly not a necessity. Well, probably my guess is that if you use some sort of response system, it does pull you out of the visuals for a moment. That's not a super accessible way for some people to learn and respond. So you put up a visual and then in a way that that removes you from that immersive space for a moment. I think there might even still be a tendency that even if you know about the research that active learning leads to better retention and things like that, that you feel like this space is impactful enough that maybe it'll do it on its own... ."*

Respondents that favored an ARS spoke confidently of its utility to those courses that use it, while respondents who did not favor an ARS were equally confident in their interactive strategies that did not use one. This mix of response trends suggest that ARS utility, which has demonstrated instructional benefits in the interactive classroom environment [70, 121, 220, 109], may still require further dedicated exploration specifically in promoting interactive planetarium environments.

IQ - Which traits about your planetarium do you think make it beneficial to the instruction of the astronomy disciplines? Why do you think this is the case?

IQ - Which traits about your planetarium do you think might make it useful to the instructions of disciplines outside of astronomy? Why do you think this is the case?

All of the responses to these questions were variations on the same theme—visualizations. Subjects considered this theme as the most beneficial trait their planetariums possess, satisfying both affective and cognitive classroom outcomes. Subjects highlighted the planetarium's visualizations as promoting interest in astronomy and positive student attitudes to learning through displays of the flashy "wow factor" visuals (principally affective outcomes). Subjects equally stressed the planetarium's ability as an instructional instrument by displaying detailed depictions of large scale structures and motions in two and three dimensions (principally cognitive outcomes). This simultaneous satisfaction of both classroom outcome types mirrors the audience content goals of informal planetarium professionals which showed no particular preference between the goals "interest/engage" and "education about content" for any particular audience type [194].

<u>Dr. White:</u> *"We spend a lot of time sharing pretty pictures in astronomy, and the planetarium is a great way to bridge the gap between reality—here's the horizon, here's stuff moving across the sky... and where the pretty pictures come from. ...So I think planetarium is great for giving context..."*

<u>Dr. Violet:</u> *"The planetarium exemplifies or animates what's in a book and it makes it come more alive for them. Since they can see things actually moving above them, then what they're reading makes more sense to them."*

<u>Dr. Red:</u> *"It's an immersive visual experience so that the dome essentially fills the field of view, so it's able to convey scale and proportion and directionality in a way that a figure on a printed page just doesn't do."*

When asked to consider traits that could benefit disciplines outside astronomy, the nine respondents whose planetariums were digital-capable converged upon the same theme of visualizations. These respondents also saw both affective and cognitive potential in a planetarium environment, similar to their reasoning for astronomy; these responses align with work by Sumners et al. (2008) [241], which highlighted the capacity of a portable digital planetarium to instruct earth and space science concepts. Our two analog-only respondents did not speculate upon the possible benefits to non-astronomical disciplines, making this question the only one in this study without substantive input from analog-only planetarium representatives.

<u>Dr. Brown:</u> *"It's a great space to have poetry readings, or banned book readings or things like that, because you can have somebody up there with a podium and we can put the software that we have that runs our planetarium. We can also put other content on the dome, we can put any video that we want up on the dome, which is really important... [all of the above] just takes a little bit*

more work to create that content."

<u>Dr. Red:</u> *"...a visually immersive show, and so it's different than something that they can just see on a classroom screen... it's also a way just to break up the pace of the class and bring the students to a different environment to maybe jog them out of old habits and get them thinking... we can make these connections in different ways, not only between disciplines, but also across the college—all of these disciplines have something to say to each other."*

These responses imply a deeper benefit across the various subject matters: scaffolding for students to better comprehend perspective, size, and scale. Past research has shown that these skills can be difficult for learners [244], but spatial comprehension, once learned, may correlate with student achievement [238, 103]. The use of electronic media during instruction, much like those found in a planetarium theater, has been shown to provoke greater student understanding [164] and to dissolve misconceptions [213]. Continued efforts to describe, measure, and refine this scaffolding should be undertaken for the instruction of undergraduates, especially those studying the sciences and engineering [238, 98, 273].

The response trends stressing both content and attitude goals are consistent with the analysis made by Small & Plummer (2010) and Plummer & Small (2013) [231, 194]. Furthermore, our interview respondents thoughts on other, non-astronomical subject materials being presented in a planetarium theater showed less apparent skepticism than was expressed in Croft (2008) [57]; however, we note that our interview respondents for this particular point uniquely operated digital-capable theaters. Arrayed with this study's survey data (Table 3.4, Figs 3.6.2 and 3.6.2), we propose that the same visualization capacities that have long promoted the use of planetariums for undergraduate astronomy education [274, 275] could also benefit other collegiate subject matters in the same planetarium environment [241].

IQ - Which traits do you see as detrimental to instruction in a planetarium?

Subjects were also asked to consider what traits they see as impediments to instruction in the planetarium environment. Unsurprisingly, the trait deemed as an impediment was inherent to the very idea of a planetarium theater: darkness.

Dr. White: *"...when I have undergraduates in there I have to be careful as I bring up the lights to say, 'Okay, wake up the person next to you,' because for better or for worse people fall asleep when you turn out the lights and start talking. It's kind of ironic because, as I said, I do a lot of school groups, and when these same people are in fourth or fifth grade I can't shut them up. ...then they come here again in 14th to 15th grade ten years later and they're falling asleep."*

Dr. Red: *"...we also of course get the students that were working late or studying late the previous night, and they're now in a darkened room with comfy seats, and we'll have some students actually nod off, simply because the environment is conducive to napping. ...the darkened environment isn't necessarily the best learning environment, but it is part and parcel of the technology of portraying the imagery on the dome."*

Numerous studies have measured the benefits of the planetarium [40, 230], but to our knowledge none have specifically explored how a planetarium's darkness may impact learning. We will accept the darkened environment as existentially necessary to the operation of a formal planetarium environment, and exploration of if or how lighting conditions impact planetarium learning warrants further investigation.

3.6.4 Construct 4: The Nature of Presented Content

Our last research construct seeks to confront the nature of content presented in planetariums. We approached this construct primarily with three survey questions (Q4.1, Q2.4, and Q2.5) and interview discussions.

Q4.1 - "Which of the following selections describes the content your facility uses?"

Response data for Q4.1 is shown in Fig 3.6.4. For each content style (listed across the horizontal axis), respondents were asked to specify whether they or a different facility produced that style of content used in their planetarium (Fig 3.6.4, legend). Respondents could select as many choices as possible, including an "Other" option for individualized responses. The number of respondents who had information to offer for each content style is specified along the horizontal axis under the corresponding content type. The percentage labels next to each bar denote that bar's contribution to that content style's total number of responses. The first three sets of bars are of greatest importance to this study as these three groups are structurally compatible with the learning process and learning environment corners of our conceptual framework. The last three sets of bars were asked for the sake of categorical completeness, but did not advance our investigations substantially will not be discussed further.

The data show a robust trend among the first three content types. Respondents to Q4.1 show overwhelming preference for live content being produced locally, by their facility, regardless of whether or not the content was presented specifically to students or the general public. Conversely, pre-recorded video content shows an overwhelming preference for content produced by other facilities. These data thus contend that planetariums may show near-complete preference for making their own content if they themselves are responsible for conveying it to their audience through a talk, lecture, or presentation. However, these data equally contend that if content is presented by "pressing 'play'," like a video, planetariums are more likely to source that content from an outside producer. These trends will be expressly explored during the interview discussions below.

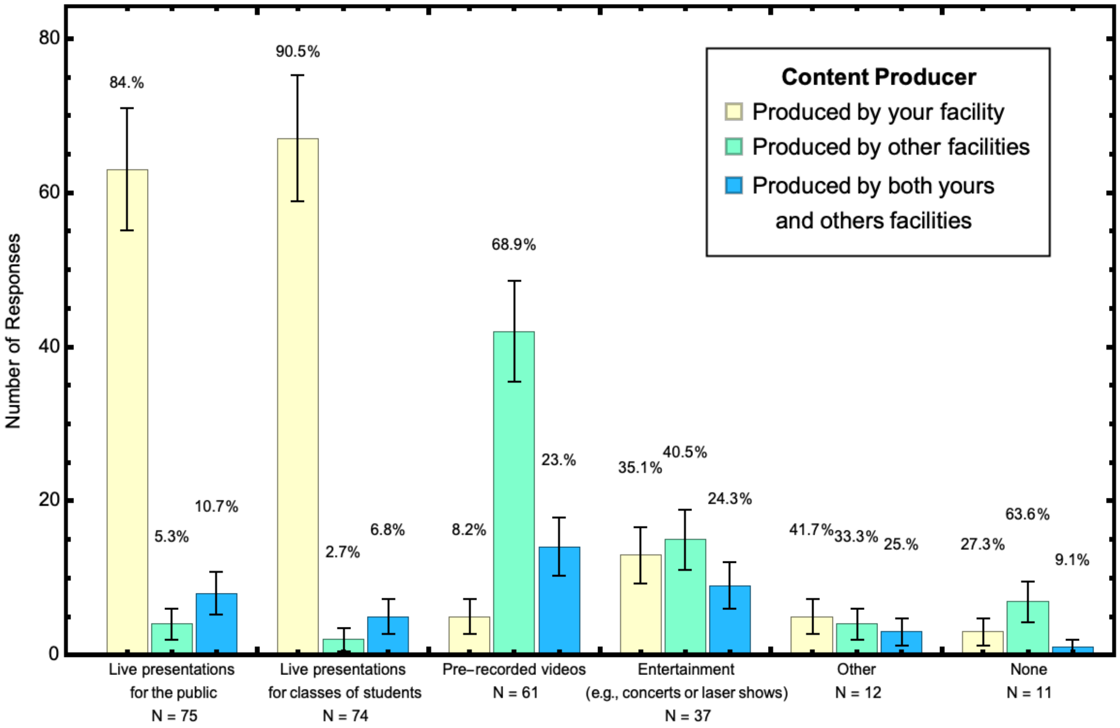
Q2.4 - Describe the topics, astronomical or otherwise, which you find are best or most effectively instructed in planetariums.

Q2.5 - Describe the misconceptions, astronomical or otherwise, which you find are being taught or potentially reinforced during instruction in planetariums.

The responses to these questions were analyzed using an iterative coding technique. In this technique, responses were read and given alpha-numeric code tags that described the constructs emergent from the data. These constructs were not pre-defined, so the group of responses was analyzed in successive sets of 10, with codes being created, merged, or destroyed as needed until the entire set of responses was analyzed. A final period of code merging was done on the complete data set to reduce the number of minimally descriptive or obsolete codes. Response codes were then counted and the resulting distributions interpreted. The resulting coding scheme can be seen in Table 3.6. General code themes are in the left-hand columns with more specific sub-codes and their descriptions in the adjoining center columns—the total number of responses qualifying for each general theme is also found in the left-hand column. Each sub-code's contribution to its general code theme is expressed in the right-hand column. We have omitted the inclusion of the following sub-codes which contributed 10% or less to their general code themes or had only a single count:

A3 (geographic effects), D3 (exoplanets), D5 (planetary systems), and E3 (timekeeping).

Figure 3.6: Responses to Q4.1 concerning what content types are used by planetariums and what entity produced said content. Percentage labels show each data count?s contribution to the entire content type; the number of respondents for each content type is specified underneath each content type along the horizontal axis. Standard counting error ($\sigma_k = \sqrt{N_k}$) is assumed for each data bin. Data propose that live presentations are more prevalent than any pre-recorded material, and that a planetarium is more likely to make their own live material and have someone else make their pre-recorded video content.



These data immediately oblige the ability of a planetarium to render immersive environments. Codes A1, A2, A5, A6, and C4 directly correspond to topical material that benefits from a full field-of-view projection or 3D "flying" simulation. Moreover, these five code groups map almost identically to the astronomical misconceptions held by undergraduate learners categorized by Zeilik et al. (1998) [277], bolstering the planetarium as an environment well suited to confront these [273, 274, 275]. This communal leaning towards topics benefiting from a planetarium's projection capacities will be discussed further in the interview discussion below. We also note here the relatively low tally of content that, while still in the academic domain of astronomy, does not appear to be held at the same level of "planetarium-worthy" content. For example, four of the five sub-codes in code group C (astrophysics), do not break a group fraction of 50%—the sole exception is C4 ("galactic and Universal structure(s)"). At this time, we are uncertain if these code distributions imply a lack of planetarium content availability, knowledge, or interest.

Challenges arose when attempting to code the responses to Q2.5, regarding possible misconceptions being taught or reinforced in a planetairum. Overall response counts significantly lower than Q2.4, and overall response quality and phrasing immediately implied that most respondents did not understand the question. Responses to Q2.5 were mapped to the code groups established in Q2.4 where possible, but additional codes pertinent to Q2.5 were innovated where necessary. Codes A1, A4, B1, X (references misconceptions held before planetarium visit), and Y (blank or rebuking answer) were the only codes to measure more than four counts (13, 4, 6, 4, and 12, respectively). After reflecting upon the responses from Q2.4 and Q2.5, we decided to avoid such open-ended question items in PLUS 2.0, discussed below.

We will expound upon some of the themes within the groups A1, A4, and B1 that respondents presented. Many of the stated misconceptions in A1 centered upon the nature of the celestial sphere, and how as a model of the sky it may reinforce the idea that all objects in the sky are the same distance away or do not otherwise change position. Themes in A4 focused upon potentially confusing aspects about constellations. Since a projector can be switched on and off (unlike actual stars), learners may become confused when a particular constellation or star field is shown on a certain spot on the dome, the projector is switched off and changed to another star field, and then turned back on with the new field on the same spot on the ceiling as the old one. This might lead to a misconception that constellations may be able to overlay one another or that the position of stars in the sky is entirely fluid and can be changed. Misconceptions surrounding B1 centered on the planetarium's ability to give a false sense of temporal and spatial scales. For example, a planetarium may simulate flying through several megalightyears of space in a few seconds (well in-excess of light speed). For content experts, this flying is obviously exaggerated, and experts have been shown to mentally jump between various size scales easily [248]. Such exaggerated displays might not be obvious to content learners who have been shown to hold intrinsically distorted conceptions of both temporal and spatial scales [277, 45, 238, 244], and may need more contextual support when experiencing scales well beyond their day-to-day experience [248]. These distortions, if left without appropriate confrontation and correction [255, 17], could damage learners' understanding of these materials and undercut the use of a planetarium as a learning environment.

IQ - Benefits and Drawbacks to Live/Pre-recorded Video content styles

To investigate the dichotomy between live and pre-recorded content styles emergent from the survey data (Fig 3.6.4), respondents were asked to consider the benefits and drawbacks of each of the content styles in a planetarium learning environment. We summarize the responses in Table 3.7. We also note here that two of this study's interview respondents did not possess the projector capacity to show pre-recorded video (PRV) content in their planetariums. We stress to the reader that we are considering each of the two content styles below as pure styles. We understand that the two may be combined with other one another for instructional or presentation purposes [231], but for the following discussions we will address each style as a "pure" mode of content presentation.

Table 3.6: Descriptive codes for survey question Q2.4. Response codes are sorted under by general category in the left column—the number of qualifying responses are adjoining. Descriptions of each sub-code are in the center-right column. Counts for each sub-group and their respective percentage of their code category are in the right column.

General code	**Sub-code**	**Description**	**Contribution to Code**
General astronomy (A), $N = 54$	A1	Sky motions (rise/set, retrograde motion); celestial sphere	42 (77.8%)
	A2	Lunar phases	20 (37.0%)
	A4	Constellations	19 (35.2%)
	A5	Seasons	19 (35.2%)
	A6	Sky coordinates (local, celestial, ecliptic systems)	21 (38.9%)
Spatial or temporal recognition (B), $N = 10$	B1	Sizes, distances, and/or scales (time and space included)	9 (90.0%)
	B2	2D/3D orientations	2 (20.0%)
Astrophysics (C), $N = 19$	C1	Compact objects (any)	4 (21.1%)
	C2	Gravity (Newtonian, Relativistic)	4 (21.1%)
	C3	Stellar evolution	3 (15.8%)
	C4	Galactic and Universal structure(s) (cosmology/CMB included)	12 (63.2%)
	C5	Orbital mechanics	3 (15.8%)
Planetary science (D), $N = 10$	D1	Comparative planetology	2 (20.0%)
	D2	Surfaces and interiors	6 (60.0%)
	D4	Minor bodies	2 (20.0%)
Ancient Astronomy (E), $N = 9$	E1	Historical interests	3 (33.3%)
	E2	Navigation	6 (66.7%)

Table 3.7: Summary of interview responses concerning the benefits and drawbacks of the pure content styles explored by survey Q4.1. PRV: pre-recorded video.

Content Type	**Benefits**	**Drawbacks**
Live	Instantly adaptable to audience. Content can be changed instantly. Interpersonal engagement with audience.	Needs informed presenter or content expert. Presenter or audience may get distracted. Additional technical expertise required.
PRV	Reliable and reusable content package. Well-defined content and duration. High production value. “Press ‘Play’ ” ease-of-use.	No interpersonal engagement. Audiences are mostly passive. Questions must be held until finished. Expensive to produce and acquire.

In regards to the benefits of live presentations, all 11 respondents described variations on the same underlying theme—live presentations have a human aspect that other content styles simply do not. A live presenter has a level of interactivity and adaptability that cannot be replicated—they are “there” with their audience in the moment they are learning. Questions from the audience can be fielded immediately, allowing for misconceptions to be confronted as they emerge. Live presenters can engage with their audience, adapting or altering their presentation as audience members provide feedback—additionally, live presentations can be guided by the audience members themselves, the live presenter serving more as a learning facilitator than a content presenter.

When discussing the drawbacks of live presentations, responses complemented the benefits described above. A live speaker holding a presentation needs to be informed about the presented content—experience in public speaking is beneficial, but if a speaker does not possess the content knowledge necessary to instruct the audience, learning could suffer. Live presenters may also get sidetracked as questions from the audience divert the discussion away from the established lesson goal. While a learner guided discussion does have its benefits, we contend that such an impromptu diversion in an uncommon learning environment like a planetarium theater could be considered a drawback, at least for formal learning environments. Finally, live presenters may require a second person with the technical expertise needed to operate the planetarium as it is not guaranteed that an instructor at a particular college or university has the expertise necessary to operate a planetarium's systems.

Concerning the benefits of PRV content, most respondents saw the production value as its greatest benefit. Video content is typically of a higher visual caliber than any live presentation concerning the same material, and such visuals are of a definite duration and content depth. Videos do not change between presentations and are usually easy to use for a presenter, requiring little more than a "Play" button, and are reliable resources for an instructor who knows exactly what they want to show their learners and how much time they want to spend. Finally, PRV content, having usually been made with the collaboration and input of research institutions and content experts, may be used as content presentation in the absence of having an actual expert. The famed *Powers of Ten* video highlights the utility of PRV content, delivering an effective instructional message with measurable increases in learner knowledge [116].

The discussed drawbacks for PRV content were centered on the lack of a human component that live presentations are built around. Video content does not interact with its audience, and such a presentation style renders an audience functionally passive, with little engagement beyond what the video itself is able to engender. Questions formulated by the audience need to wait until the end of the presentation, by which time they may fade or the audience loses interest. The last drawback noted by the respondents is cost. The high production quality of planetarium videos is typically accompanied by a high cost that some planetariums simply can't afford.

A particular point was raised during the interviews that we are presently disinclined to categorize as either a benefit or drawback to PRV content: a planetarium with video projection capabilities is very similar to a movie theater environment, and learner groups may take behavioral cues from being in such an environment. This point was raised specifically in light of younger learners who comport themselves in a planetarium environment much the same way they would in a traditional movie theater space.

Dr. Yellow: *"So when you have young kids they understand watching a movie? They're familiar with watching movies so it's just a little bit different format of a movie. I've had some really loud rambunctious groups of middle schoolers usually and when I'm talking they don't pay attention but as soon as you hit 'Play' they're quiet because they know, 'Oh, the movie's playing, we need to listen."'*

We note this here for this particular study because it raises the possibility that undergraduate planetarium learners might also comport themselves like their younger counterparts, eschewing their active learner tendencies like asking questions or discussing in favor of passive learner tendencies like watching and listening; however, further study is needed to confront this supposition.

The interview subjects also discussed some of the challenges and possible solutions to obtaining or creating new content, not just for astronomy, but for other subjects as well (Table 3.4 and Fig 3.6.2). The largest challenge or barrier against the wider use of planetariums was the availability of content. This challenge has both financial and existential facets: some planetariums are simply not able to afford the expense of certain content styles (like high production value PRVs); or content that is desired to be shown has not been innovated (full-dome presentations for biological content, for example). These interview responses partially oblige the data for Q2.4 (Table 3.6) by suggesting that topics like planetary science or ancient astronomies (code groups D and E, respectively) could be more widely instructed in planetariums if the content was available.

These challenges echo the investigation undertaken by Fraknoi (2004) [88], in which instructors voiced challenges to the instruction of astronomy at non-research institutions, particularly community colleges. That study found a common, non-administrative difficulty between its participants that we could describe as academic isolation. That study's participants voiced desires to ask other instructors for advice, to have time to innovate new materials for instruction, and to have a network of other instructors in similar situations who could coordinate or exchange strategies and materials [88]. We note these points here to highlight that the same difficulties for astronomy instructors may also translate to those attempting to use planetariums, and that the continued effort towards easier and streamlined access to planetarium educational materials should continue [267].

3.6.5 Theoretical Synthesis & Future Work

We now address our findings in light of our theoretical framework, LEPO [190]. Collegiate planetarium learning occurs in a formal learning environment, which is characterized by darkened illumination conditions and immersive visualizations. These visualizations may be either presented as live or pre-recorded video content, with each having perceived strengths and weaknesses as content styles (Table 3.7). Learning processes appear to unfold in a manner similar to a “typical” collegiate lecture setting, characterized by an instructor-centered information delivery dynamic. This procedural dynamic is likely not supported by commonplace classroom technologies like iClickers to promote student interaction and engagement (Table 3.5). Learning outcomes seek to leverage the environment to the fullest, with visualization-based scaffolding for astronomical content being the principal outcome (Table 3.6), with outcomes outside the topical domain of astronomy being less common, but not negligible (Fig 3.6.2).

Our continuing investigations will focus on cornering the learning process and learning outcomes in collegiate planetarium environments. We plan to conduct a small sample study using the validated undergraduate classroom observation protocol COPUS [236] in the planetarium environment. This protocol has been demonstrated to measure undergraduate STEM classroom behaviors across wide a sample of lecture settings [240], and doing so in a planetarium would allow behavioral information to be gathered without the use of self-reporting instruments. Additionally, future iterations of PLUS (described below) will collect information descriptive of the broad learning process trends throughout the United States.

3.6.5.1 PLUS 2.0 - Improvements & Revisions to Survey

The results of this study have allowed us to implement a set of revisions to our original PLUS 1.0 survey instrument. Future distribution of the revised survey will further our goals of maintaining a contemporary measure of planetarium use for collegiate educational purposes. Here, we present our revisions for each of our original research constructs as well as emergent constructs.

New Construct. Respondent Characterization: The use of the IPS catalogue as a source of secondary data demonstrated a possible pitfall in future distributions of PLUS, specifically using data that may not be as up-to-date as possible or which may have missing entries. In light of this we have implemented changes to the opening section of PLUS. These changes ask respondents: to provide their host institutions Carnegie Classification from a shortened list of possible descriptions [86]; to give the approximate population of their immediate surroundings (letting us provide context for learner populations); and to select a description of their planetarium's projector (giving us information for other constructs as well as tracking facilities' transitions to digital technology).

Construct 1. Learner Population and Use-Frequency: Questions probing this construct have been separated into individual questions to avoid the data collection difficulties with Qualtrics, described above. We have separated the original "K-12" learner population into "elementary (K-8)" and "high school (9-12)" populations, and provided definitions of each group for respondents to consider. Additionally, we have expanded the use-frequency question to explore learner populations as an entire group and as individual classes within that population.

In the college-specific portion of the survey, we have added two "select all that apply" questions for respondents to describe the type of undergraduate student coming to their planetarium and how learning commences in undergraduate classes from a list of descriptive archetypes. These archetypes have been crafted around discussions held during the PLUS 1.0 interviews in 2019 and will help establish a more accurate picture of which students are being instructed in planetarium environments and how that instruction takes place.

Construct 2. Subject Materials & Projector-Dependent Variety: We have decided to simplify this section from the previous incarnation of PLUS. We have removed the free-response sections (Q2.4 and Q2.5 described above) entirely and removed the discipline follow-up questions. We have used our free-response analysis and subject/discipline question to restructure a single question asking respondents to select the subject material shown in their planetarium and how large a class learning that material is. Additional subject material categories and descriptions of each category have been added to provide more topical constraint each category without becoming prohibitively nuanced. This information, coupled with our respondents' projector types, will allow further tracking of "astronomy-only" and "astronomy-plus" planetariums.

Construct 3. Interactivity Strategies & Perceived Environmental Traits: We have revised our original question surrounding interactive strategies in college classes. The range of possible use frequencies for interactive technology has been simplified following our analysis of Q3.1. We have also defined other interactive technologies that we would like our respondents to consider—these additional definitions have been made following our interviews in 2019.

Respondents would be asked to describe how the interaction between instructors and planetarium staff unfolds during a college-level class, using a list of "select which best describes" options. These options will contrast the responsibilities for planetarium operation and content presentation between planetarium staff and instructors. This information, combined with that described under "Construct 2," will also allow a more narrowed view of the learning process in planetarium environments.

Construct 4. Nature of Presented Content: As is seen in Fig 3.6.4, the dichotomy between locally produced live content and outside-sourced pre-recorded content is stark, and our interview discussion (Table 3.7) highlight the reasons as to why. Barring some major shift in planetarium resource paradigms, we see greater value in probing our respondents further about what kind of content is used, rather than continued investigation of who is ultimately responsible for producing it. Thus, we have partially merged this aspect of Construct 4 into Construct 3, by integrating a more detailed list of content types into our question about technology usage. Combining this updated construct with the other three will further our understanding of the learning environment and the learning outcome of collegiate planetarium visits.

Additionally, we have added a question tasking our respondents to describe what kind of learning environment they have been asked to provide for our list of learner populations. We have chosen to provide brief descriptions of formal, informal, and entertainment environments for the survey takers to consider when answering this question [264, 11, 267, 270, 193].

It is our intention to distribute this new survey pending Institutional Review Board approval for human subjects research. This revised PLUS 2.0 has been included as supplementary material to this paper.

3.7 Conclusions

An initial study has been conducted to investigate the use of planetariums by undergraduate astronomy learners in the United States. Responses to an online survey and follow-up interviews have been analyzed to establish trends among college-serving planetariums and to further develop the Planetarium Usage Survey (PLUS) instrument.

Responses concerning audience populations (Fig 3.6.1) propose that the primary learner group serviced by college and university planetariums is K-12 learners, not their own college learners. These higher counts of younger learner groups compared to college-level learners seem to rest upon curricular demand, as more K-12 instructors are requesting the use of a planetarium on a local college or university campus compared to that college's or university's instructors.

Survey data concerning audience populations (Fig 3.6.1) and the follow-up interview responses strongly indicate that undergraduate astronomy learners in a planetarium environment are typically non-STEM major, novice science learners. These learners are being instructed in a planetarium to take advantage of the space's visual scaffolding capacity, with instructors using a planetarium's projection capabilities to produce an immersive learning environment. Learning outcomes expected of these learners may be either affective or cognitive, but no conclusive preference has been determined by this investigation. Instruction of these learners in a planetarium environment happens between once-per-week to once-per-month (Fig 3.3); however, there is significant variation within that characteristic frequency range. An exception to these novice learner trends is for more experienced learners who are receiving training to teach future science learners—this group of planetarium learners is not using a planetarium to learn astronomy content, but rather to learn pedagogical approaches.

This study has shown that planetariums are not uniquely the domain of astronomy instruction and that other subject material, particularly the natural sciences closely aligned with astronomy (Table 3.4 and Fig 3.6.2), are instructed at the collegiate level in planetarium spaces. However, content most widely seen as well instructed in planetarium environments is within the field of astronomy, specifically the widely defined "general astronomy" (Table 3.6). Technology is a factor in how varied this subject material may be, with digital-capable planetariums reporting measurably more varied subject materials than their analog-only counterparts (Fig 3.6.2). Content presented to planetarium learners favors live content, presented by an in-house speaker and produced at the presenting planetarium itself. Pre-recorded content is used less widely than live content (Fig 3.6.4), and is typically produced outside the planetarium using it. Regardless of style, content is often not being presented using the aid of an audience response system (ARS) (Table 3.5). Instructors who do use an ARS are most commonly using a iClicker or similar remote-style system. Reliance towards or against using an ARS presently shows no definite theme. The continued development and distribution of a revised usage survey is planned for the future to further explore the planetarium as a collegiate learning environment.

3.8 Supplemental Material

As a part of this work's submission to *The Physical Review* [77], supplemental material describing the revised PLUS instrument was created. It can be found in this work in Appendix A.

Chapter 4

PLOBS: The Planetarium Observation Study

4.1 Foreword to PLOBS

The purpose of the following work was to extend the original idea of PLUS—to purposefully examine the use of planetariums for undergraduate education. But, instead of investigating planetariums at-large, PLOBS would examine the use of one single planetarium and use the findings from PLUS to help contextualize it. This research strategy is contrasted with PLUS, which left much of the planetarium learning process unexplored. A localized study was crafted that would examine instructors at a single planetarium and attempt to generalize my findings, using the implications of PLUS and other DBER faculty-centric studies, when possible.

While PLUS made certain suggestions as to how the learning process occurs in the planetarium (especially during the follow-up interviews), no outside observation protocol was completed on the PLUS respondents—how the process of learning unfolded in the planetarium was all self-reported by planetarium directors about themselves or their peers. Additionally, many undergraduate planetarium research studies did not directly address how it was that planetarium lessons occurred—those research studies (discussed in chapter 2) focused their attention on how the planetarium could produce learning gains typically greater than those from the classroom environment alone. These findings, while certainly of import, left a substantial factor of learning, the actual process, aside. Additionally, since it is most likely that the majority of planetarium using instructors were not themselves education researchers, it stood to reason that how learning unfolds in the planetarium and why instructors were taking their learners there should be scrutinized.

Why would someone care about how your everyday planetarium instructor uses the planetarium? In my estimation, the highest goal of AER, PER, or any DBER field is the investigation, production, validation, and promulgation of practical pedagogical artifacts—the actual "things" that I might recommend to other peer educators that they, as non-DBER faculty instructors, could use which have clear, demonstrable, and superior effects on college instruction. Like the benefits of AER reformed classroom practices, immersive planetarium lessons have been reliably beneficial to collegiate learners. Given the findings of PLUS that suggested that most collegiate instruction occurred in the classroom setting (with occasional visits to the planetarium), it stood to reason that instruction in the planetarium might share much of the same pedagogical processes as the classroom setting; however, what this potential mix of reformed practices and immersive visuals might have been had yet to be explored. Investigating why collegiate instructors took their learners to the planetarium setting and how it was their lessons proceeded might provide insight into refinements or revisions of planetarium instructional practices that could provide further benefit to learners.

At the time of submission of this dissertation, the work described in this chapter is in preparation for submission to the ***Journal of Astronomy & Earth Science Education*** *for peer-review, with potential publication in 2021. This work will bear the formal title of "Study of Faculty Instructors in Undergraduate Classroom and Planetarium Learning Environments."*

4.2 Abstract

A two-part, mixed-methods study[1] exploring the undergraduate planetarium learning environment was conducted during the 2019–2020 academic year at a western American university.

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[1] IRB protocol number: 19-0453. Granted exempt status for human subjects research on August 21, 2019.

Survey responses from university faculty, observational data using the Classroom Observation Protocol for Undergraduate STEM (COPUS), and faculty interview responses were collected and analyzed to investigate how and why collegiate undergraduates were being instructed in a planetarium environment and how this environment compared to a traditional classroom counterpart. Results suggest that planetarium use is viewed by instructors as an integrated learning experience with the classroom environment, with affective learning outcomes in the planetarium complemented by cognitive learning outcomes in the classroom. COPUS observations of planetarium instruction show broad similarity to classroom instruction; however, reductions in active-learning behavior archetypes measured in the planetarium environment suggest a trade-off between interactive learning strategies and visually immersive content presentation. Implications concerning the collegiate planetarium environment and future work are discussed.

Keywords: astronomy education; planetarium environment; COPUS; undergraduate education

4.3 Introduction

The use of the planetarium setting has long been associated with astronomy instruction as a place to enhance learners' experience with astronomical content. Given astronomy's historical record as a difficult discipline to both instruct and learn, the planetarium environment is seen as providing a unique and immersive visual experience that aids learners in constructing and cementing the understandings necessary for astronomical comprehension [40, 230]. The progressive increase of immersive projections in a digital fulldome planetarium has offered greater opportunities for visitors to learn in a three-dimensional (3D) simulated environment [267, 270]. Such environments can help learners of any age by providing different spatial perspectives and fully rendered 3D simulations of concepts that can relieve learners of cognitive load and enhance learning [241, 43, 251, 48]. For collegiate learners specifically, those who experienced lessons in the planetarium have been shown to not only achieve greater learning gains than their classroom-only contemporaries but also to better retain those gains over time [278, 273, 274, 275].

Collegiate learners are a group of particular educational interest—these learners have been notorious for maintaining particularly entrenched misconceptions of basic astronomy concepts which must be undone if meaningful instruction is to occur [61, 277, 249, 200, 175]. Collegiate instruction in astronomy has undergone a metamorphosis in recent years [258]. Education research in physics and astronomy have previously highlighted a shortcoming with classical instructional techniques in the lecture hall setting: they were not particularly effective towards achieving the desired learning outcomes. These ineffectual strategies were far too "instructor-centered," relying upon old (and sometimes ancient) suppositions about the learning process where an instructor filled their otherwise knowledge-devoid learners with information and the learners would then internally synthesize this information into a perfectly accurate knowledge base [228]. Needless to say, that supposition was wildly inaccurate, infamously illustrated by Schnep's interviews of Harvard graduates' astronomical misconceptions in A Private Universe, where recent graduates of the prestigious institution were incapable of providing scientifically accurate explanations for basic astronomical phenomena [214, 15].

Learners do not enter classrooms as empty vessels, intellectually speaking. Rather, they have entire lives' worth of experiences, perceptions, and knowledge that already informs an individualized physical or astronomical worldview. While this worldview may not be scientifically accurate, learners will remain attached to it unless they are forced to contend with false explanations, misconceptions, or inaccuracies and reach a new, refined understanding of the world around them [276]. Informed by the discipline-based education research (DBER) communities, guidance for instructors has made significant inroads into collegiate teaching pedagogies. Learner-centered pedagogies [229, 198], peer instruction techniques [78, 92, 198], classroom materials like lecture tutorials [199], and audience response systems like iClickers [70, 121, 109] have all made noteworthy impacts on learners, both in assessable gains and in attitudes towards learning itself. Critical to these techniques' success is the active participation of learners with their own learning, rather than waiting for instructor-delivered knowledge to be passively absorbed.

Classroom studies lean heavily into topics like pedagogical strategies and the use of particular classroom materials to elicit learning gains. However, most of the past investigations into planetarium efficacy have focused on its capacity to increase the content knowledge of the learners who partake in the setting; noticeably fewer have investigated the teaching strategies made therein [230]. For example, comparison studies like Yu et al. (2015) and Yu et al. (2016) remark upon learners receiving lecture instruction as part of the study (with their test groups all receiving the same lecture, but in different settings to isolate the planetarium visuals as the variable of interest), but the pedagogies used in this lecture remained unspecified [273, 274]. Small & Plummer (2014) suggested that children benefit from a combined planetarium-active learning instructional regime, but the study was restricted to a small number of child-aged learners learning about the motions of the Moon [232]. Thus, we encounter something of a disconnect between the bodies of education research in the two settings most associated with collegiate astronomy: the classroom, where research focuses on what and how instructors do; and the planetarium, where research focuses on what and how instructors show. Even though the planetarium is the less frequently used of the two settings [77], both are still components of collegiate instruction and investigation of the planetarium setting should include considerations of its classroom counterpart. Is how a lesson unfolds as important as what is shown as a part of that lesson? This study seeks to confront this proposition by answering the following research questions:

(1) What are the characteristics of faculty and undergraduate learners making use of the planetarium environment?

(2) Why do faculty choose to use or not use the planetarium environment in their curriculum?

(3) What do faculty planetarium users perceive as the benefits and drawbacks of the planetarium environment and why do these faculty see them as such?

(4) How does a typical day of instruction in the planetarium proceed and what makes it similar or distinct from the regular classroom environment?

4.4 Theoretical Framework

The implementation of this study was built using the Learning Environment, Learning Processes, and Learning Outcomes (LEPO) conceptual framework [190]. This framework describes learning as the mutual interaction of instructors and learners with three cornerstone constructs: the environment (both physical and contextual) in which learning occurs, the processes that are used therein, and the outcomes which are produced and assessed. For this study concerning both classroom and planetarium environments, LEPO offers a broad, descriptive framework of learning appropriate to collegiate contexts without becoming too prescriptive about the specific environment or the processes and outcomes accompanying them [190].

This study will restrict itself to formal collegiate learning environments, that is those in which learning occurs during the official execution of an undergraduate course. These environments are made to achieve instructor-defined or institution-defined course goals with learner progress being ascertained through assessments by the instructor, usually ending with a final summative assessment resulting in a letter grade or final score for each learner [264, 230]. Additionally, this study will follow both the in-dome and out-of-dome ends of the planetarium research spectrum posed by Plummer et al. (2015), focusing on the planetarium as a place to improve learning and on how the planetarium and classroom environments compare [193].

This study will examine learning in two separate physical environments for comparison purposes to achieve our research goals: the classroom environment and the planetarium environment. The processes that occur in either space are assumed to be consistent with others found in American collegiate settings, such as those described by the Classroom Observation Protocol for Undergraduate STEM (COPUS) [236], discussed in greater detail below under "Methods & Investigation."

Similarly, the outcomes expected in either setting are assumed to be identifiable as belonging to one of the taxonomic groups common in describing learning outcomes [29, 126, 6, 28]. Excluding these reasonable assumptions for collegiate learning, our only restrictive assumption is that learning in these spaces is entirely formal.

For descriptive purposes in this work, we will use "environment" or "setting" to denote instances of learning combining an actual physical environment (classroom or planetarium) being occupied in the context of the formal learning procedure being attended to. "Space" will be reserved for considerations of the literal environment, i.e., the actual physical space being occupied.

4.5 Methods & Investigation

To provide structure to our later analysis we have defined two principle research constructs derived from our guiding research questions. The constructs and their input questions are presented in Table 4.1. The first construct, the "calculus" of using the planetarium, is informative of the decision making process that faculty instructors make when deciding where, when, or how to integrate the planetarium environment into their curriculum. Presuming that a college level classroom is more likely to spend most of its time in a regular classroom or lecture hall setting during the learning process, the decision to relocate a group of learners to the planetarium should follow some general decision-making framework where an instructor makes cost-benefit analyses concerning the planetarium environment against the classroom environment.

The second construct, discriminating the classroom and planetarium environments, is informative of the presumed differences between the two learning environments including the implied differences between the learning processes and learning outcomes, per the LEPO framework [190]. Some similarities between the environments should be expected, as the two learning environments are both contextually formal. These differences and similarities should be identifiable to an outside observer, but given our weak assumptions about how the learning process should unfold in either environment, a more general observation protocol should be preferred to a more specific one, thus our choice of the COPUS observation protocol is sound [236].

Critically, we did not approach this study as an evaluation of the efficacy of instructional practices in either the classroom or planetarium environments—observed practices and behaviors might be indicative of particular practice archetypes or preferences, but this study made no effort to categorize them as effective or ineffective.

Guidance for the construction of this study came from previous investigations exploring planetarium use, specifically those that examined use through the lens of planetarium directors and instructors [87, 57, 194, 77]. The structure of this investigation contained two portions: (1) a survey portion using an online instrument to collect data; (2) and an observation portion using a classroom observation protocol, pre-observation questionnaires, and post-observation interviews to collect data. Survey data collection is a commonplace tool in astronomy and planetarium education [87, 88, 231, 77], and allows for the bulk collection of responses from a wide range of respondents. Observational data is commonplace at the collegiate level for professional development—instructors may inaccurately describe their own teaching methods using self-report instruments like a survey, so validated observation protocols may be used to collect an unvarnished measurement of instruction [119, 72]. Interview data provides more content rich discussion by directly interfacing with planetarium instructors that would not normally be emergent in survey-only or observation-only data sets [194, 77].

Survey data was collected using the online Qualtrics survey platform and distributed using institution email. Faculty instructors from five of the institution's constituent colleges were invited to participate in the survey. The choice of colleges was made based on the variety of past planetarium users at the institution's planetarium (private communication with planetarium director) and from the planetarium content results in our recent survey study [77]. All faculty, both those with past planetarium experience and those without, were invited to participate in this survey held during the fall of 2019. Faculty who had never instructed a class in the planetarium were directed to answer a shorter survey instrument, taking approximately five minutes to complete. Faculty who had instructed a class in the planetarium were directed to answer a longer survey instrument, taking approximately 15 minutes to complete. This longer survey instrument was also used to roster participants in this study's observation portion.

The observation portion of this study was completed in two stages. Six consenting faculty instructors were observed during two lessons, one in the classroom environment and the other in the planetarium environment. Due to scheduling constraints, three faculty were observed during the fall of 2019, and the remaining three were observed during the spring of 2020. The pseudonyms of our observed faculty, a brief description of their respective courses, and the approximate number of enrolled students are shown in Table 4.2. Faculty participants chose the days they would be observed, but were asked to pick days that could be described as “usual” or “typical” lessons such that our observations would minimize recording any spurious or unnecessarily singular interactions that would not be meaningfully representative of a lesson in either environment.

Table 4.1: Research constructs of this study. Constructs were formed by considering the guiding research questions and were explored during the two portions of this study.

Research Construct	**Guiding Questions**
The "calculus" of using the planetarium	Why do faculty choose to use or not use the planetarium environment in their curriculum? What do faculty planetarium users perceive as the benefits and drawbacks of the planetarium environment and why do these faculty see them as such?
Discriminating the classroom and planetarium environments	Which kinds of faculty and undergraduate learners are making use of the planetarium environment? How does a typical day of instruction in the planetarium proceed and what makes it similar or distinct from the regular classroom environment?

This study investigated the use of one specific planetarium by the surveyed faculty, which we will describe here. The planetarium comprises a 206 seat theater with the seats arranged in an epicentric pattern with the inclination of the seats focusing an audience's attention to a "sweet spot" approximately 30 above the dome's perimeter. Beneath the sweet spot is an elevated stage for a speaker to stand on if desired—the navigator's booth is opposite the stage and contains the controls for the planetarium's audio and visual systems. The line connecting the stage to the navigator's booth divides the audience approximately into halves. The theater possesses a hybrid projector system, with both an analog star ball projector and a digital fulldome projector. The analog projector occupies the center of the room and is surrounded by a central walled pit that separates the projector itself from the audience. The digital projector is composed of multiple smaller projectors mounted around the perimeter of the dome and coordinated by the navigator's computer. Audiences may enter or exit the theater through two antechambers, each on opposite sides of the theater. The antechambers are meant to separate the well-lit lobby of the planetarium from the darkened environment of the theater so audiences are not disturbed by brief, vision-impairing bursts of bright light during a show.

Observation protocols are powerful tools in the classroom learning environment, both for instructor reflection and education research on class practices [212, 105, 236, 152], but to our knowledge there has yet to be a study using these tools in the collegiate planetarium environment. COPUS was selected as the in-class data collection instrument for the observation portion of this study. Developed to provide an efficient and validated means of measuring classroom behaviors and procedures, COPUS characterizes the behaviors of both instructors and students using a set of 26 codes, 13 codes for each group. Codes are descriptive of particular actions, behaviors, or interactions within a collegiate STEM course—we direct the reader to Smith et al., 2013 for the full description of the observable codes [236]. As is raised by Hora & Ferrare, 2014, coding schemes can accidentally hide instructional behavior nuances by using overbroad codes that try to cover too many behaviors at once, so research concerning collegiate education should use a protocol that is as descriptive as possible [106]. However, given the lack of prior guidance concerning observations in a planetarium environment and the desire to not prescribe that a particular style of instruction would occur in either the classroom or the planetarium environments, we decided against protocols like the Reformed Teaching Observation Protocol (RTOP) [212] or the Teaching Dimensions Observation Protocol (TDOP) [104].

Measurements occur in successive two minute windows of time during a lesson. If a behavior is observed within a given two minute window, that code is assigned to that block of time—if not, no assignment is made for that code [236]. In addition to the 26 behavioral codes, COPUS also includes a metric to measure student engagement during each two minute window. However, given the heavy reliance on visual cues which are difficult to discern in the darkened planetarium and the more subjective nature of determining student engagement, we decided to not use the three engagement codes for this study.

Table 4.2: Pseudonyms of this study's observed faculty participants along with descriptions of each participant's course and approximate enrollment. All instructors were members of the same university department.

Pseudonym	**Course description**	**Approx. Number of Students**
Dr. Monday	Non-major, non-sequenced introductory astronomy. Lower division. University's analog of "ASTRO 101."	200
Dr. Tuesday	Non-major, sequenced introductory astronomy. Lower division. Similar material domain as "ASTRO 101." Has a lab component.	200
Dr. Wednesday	Non-major, non-sequenced intermediate astronomy course concerning exploration of life in the Universe. Lower division.	120
Dr. Thursday	Non-major, non-sequenced intermediate astronomy course concerning space exploration and policy. Lower division.	100
Dr. Friday	Major-track, sequenced "ASTRO 101." Focuses on the nature of science, naked-eye astronomy, and planetary science. Has lab component. Lower division.	100
Dr. Saturday	Non-major, non-sequenced introductory astronomy. Lower division. University's analog of "ASTRO 101."	120

Rather than exclude the engagement coding framework completely, we adapted the three engagement codes in the protocol as a rough measure of illumination conditions during each observation. This study involves comparison between two physical environments (one of which presumably maintains low-light or zero-light conditions), so during each 2-minute window, the ambient lighting was recorded as either low (L), medium (M), or high (H) using the same recording procedure as the engagement codes. The rough framework used to determine which lighting level to record in the two environments can be seen in Table 4.3. Lighting conditions were determined by considering the illumination intensity of dedicated lighting fixtures, not incidental illumination caused by projector screens or fulldome projections.

As this study was not meant to explore or refine COPUS itself, but rather to investigate with COPUS, efforts were made to preserve as much of the original code scheme as possible without unnecessarily innovating new protocol codes. These efforts were of particular import in the planetarium environment, specifically with regards to the use of the planetarium's projection systems and the DV instructor code. DV, or "Demo/Video," is descriptive of instructors using experimental demonstrations, simulations, videos, or animations as a part of their lesson [236], which fits the description of using the planetarium projector very well. However, as the planetarium dome is also equipped with a standard, flatscreen projector like ones found in lecture hall spaces, a distinction needed to be made as to when a particular projection shown to students qualified as DV. Since the regular classroom space is usually lacking in a planetarium projector system, innovating a new code specific to using a planetarium projector would have been impractical as no comparator code would exist in the classroom observations, so preserving the DV code structure was desired. For this study, the assignment of DV was made when the planetarium was "on," with either the fulldome or analog starball projections providing an immersive visual presentation. In situations where the planetarium was "off," such as when standard slides were projected up onto the ceiling, the assignment of DV was not made. In such scenarios where instructors were using regular slides in the planetarium, the Lec instructor code ("Lecture") was assigned, just as if it was a slide presentation in the classroom space.

COPUS observations in both the classroom and planetarium environments were recorded digitally using the Generalized Observation and Reflection Platform (GORP), an online data collection platform hosted by the University of California Davis (https://gorp.ucdavis.edu/). The GORP platform uses a system of selection icons to record the behaviors measured by COPUS, with the set of selected icons automatically saving and resetting every two minutes to keep with the COPUS recording procedure [236]. The data product generated by GORP was an array recording the tabulations of the 26 behaviors: rows contained the 26 behaviors (plus three rows for the engagement codes) and the columns were generated for each two minute observation window. For a given column (two minute window), each behavior was recorded as a “1” if the behavior was selected in GORP and as a “0” if the behavior was not. Thus, an entire observed lesson is expressed as a table of ones and zeroes measuring when the predefined behaviors were or were not observed. Observations in the two environments were made from the back of each classroom environment and from the navigator’s booth in the planetarium environment. Between the six instructors, four unique classroom spaces were used, with two pairs of instructors sharing the same physical classroom space. Classrooms ranged from medium-sized (100 seat capacity) to large-sized (200–300 seat capacity). The same planetarium theater (206 seat capacity) was used for all six instructors. Only in-person observations were made for this study—video recordings of planetarium lessons were too difficult to produce in the darkened environment and trying to overcome that optical limitation could have unduly disrupted the observed lessons.

COPUS data was principally collected by the author—two observations needed to be made by an alternate COPUS observation from the host institution’s professional development office due to scheduling conflicts. The author was trained in the use of COPUS by their host institution, per the institution’s professional development guidelines for observation protocol training. A training session with an institution trainer followed by independent test codings of several pre-recorded example lessons was completed to be trained in COPUS. Proficiency in the trained protocol is achieved when a trainee is able to achieve and inter-rater reliability (IRR) score of 0.80 or greater on at least two of their independent test codings when compared to an institution standard. If a trainee does not merit a high enough IRR, additional training and feedback is given and alternate independent test codings are made until a sufficient IRR is achieved. The author achieved an IRR score of 0.92 during training and was deemed proficient in the COPUS protocol, and the alternate observe was already proficient.

Compiling COPUS data was done by correcting miscodes that were accidentally or mistakenly made during each observation, with typical miscodes occurring due to the GORP platform automatically saving a miscoded behavior before it could be removed by the observer. These miscodes were identified by comparing handwritten observer notes made contemporaneously with each observation, and correcting the observation record accordingly. Additionally, a period of approximately 10 minutes (five observation windows) was removed from the COPUS data for Dr. Friday's classroom observation—this 10 minute period was an unavoidable time where the students were completing an institutionally obliged faculty evaluation questionnaire.

Supplementing the COPUS protocol, each instructor was asked to complete the same pre-observation questionnaire before each observation period. These questionnaires tasked the instructor to describe the material they intended to cover during the observed lesson, outline their goals or outcomes, and what preparations had been made by the instructors or their students to achieve those stated goals or outcomes. Additionally, a post-observation interview with each observed faculty was conducted after both observations were completed. Interviews were conducted as soon as possible after the COPUS observations, usually a day or two after the second observation. Interviews were conducted in the campus offices of each faculty participant, with each interview taking approximately one hour to complete.

4.6 Data & Analysis

In this paper, we present some of our data using box plots. To avoid any uncertainty of how we are using these presentation tools, we specify here how each box element is rendered. Each box is representative of a distribution of data points such that each box is rendered with the lower and upper box edges defined by the respective lower (Q1) and upper (Q3) quartiles of the data, with the intervening space between them being shaded. This shaded space is the interquartile range (IQR), with the horizontal white lines denoting the median (Q2) of the data. The sloped notches beginning on the median in each box denote the 95% confidence interval (CI) of the median for the presented data, with the transition to vertical sides denoting the end of that 95% CI—for many of our presented boxes, the notches span the entire box, indicative of a wide spread in the presented data. The lower fence (a horizontal line) is placed on the smallest data value between Q1 and 1.5*IQR below Q1; the upper fence is similarly defined using the largest data value and Q3. The two fences bound the space containing all of the meaningful data within a given distribution—all data in a distribution outside this fenced boundary are considered outliers and are plotted as individual points [128].

This study investigated both faculty instructors who used the planetarium environment as well as those who did not. For the sake of convenience, we will refer to faculty with past planetarium use experience as “users” and those who have not as “non-users.” Rather than present all this study’s data at once, we will present data products as they are used to explain this study’s research constructs (Table 4.1).

4.6.1 Construct 1: The “Calculus” of Using the Planetarium

4.6.1.1 The “Calculus” of Non-User Faculty

To confront our first construct, we began with our probe into why faculty might not use the planetarium environment, investigated using this study’s short-form survey. Non-users were asked to select reasons why they had yet to include a planetarium in their curricula from a predefined list of options, each describing a particular barrier against planetarium use. Participants could select as many options as they felt appropriate, and participants could also provide their own reasons in a fill-in-the-blank box if they felt none of the predefined barriers adequately described them, though none did. The five non-user archetypes presented below represent a roughly hierarchical progression of barrier complexity, beginning with the simplest barrier, awareness of the planetarium (A), and ending with the most nuanced barrier, procedural or administrative difficulties (PrAd). Where appropriate, barrier archetypes were subcategorized to explore differing dimensions within each archetype. The five non-user barrier archetypes (and associated sub-archetypes) provided can be found in Table 4.4.

Table 4.3: Repurposing of the COPUS engagement coding framework to record illumination conditions during the observed lessons.

Original COPUS Code	**Repurposed Code**	**Description of New Code**
Engagement - H	Lighting - H	Lights are "up" or at maximum brightness. An example would be a well lit classroom during lecture or a planetarium theater with the lights around the dome on full intensity.
Engagement - M	Lighting - M	Lights are dimmed and/or chromatically altered to conserve low-light visibility. Examples include dimming a classroom's lights to darken the area near a projector screen or turning on low-intensity red lights in a planetarium.
Engagement - L	Lighting - L	Lights are fully "down" or completely off—blackout or pitch-black conditions.

Characterizing the non-user responses (Table 4.4) suggest that the major barrier impeding planetarium use is either not considering the planetarium environment as a possible venue (A3) or not knowing if appropriate subject matter exists for their instructed subject (P1). The first of these major barriers, A3 (65% of respondents), is indicative of non-users assigning limited or no value to the planetarium environment for their discipline. This barrier may be suggestive of the planetarium being "guilty by association" with astronomy content. Instructors from another subject field like chemistry might never need to consider the planetarium, because the planetarium is perceived to be an exclusive place to instruct astronomy. This astronomy associated barrier is given further weight when considering the noteworthy percentage of the L1 barrier (discussed separately below). The second major barrier, P1 (56% of respondents), is suggestive of a lack of communication or lack of marketing between the planetarium, content producers, and prospective instructors.

The A3 and P1 barriers are not unexpected as the most prominent measured in this study. Historically, the planetarium's attachment to astronomy content was a matter of technological practicality—in fact, almost all past planetarium research has used astronomy content as the learning medium of choice [230]. Prior to the widespread installation of digital planetariums, presentations in a planetarium relied upon older, analog-only starball projectors and static slide projectors to present visuals to the audience. Content that did not make effective use of these presentation tools (particularly the starball projector) was likely not considered cost-effective to show in the planetarium theater. However, the steady installation of fulldome projectors coupled with the progressive diversification of fulldome content development would suggest that planetariums be relieved of their perceived exclusivity to astronomy content instruction [267, 270, 77]. The potential of the immersive learning experience in a planetarium has been demonstrated to benefit undergraduate students in astronomical contexts [273, 274, 275]; but, immersive content for the fulldome planetarium that does not center on astronomy has been produced for some time (e.g. Dynamic Earth, Expedition Reef, The Body Code, Supervolcanoes, Exploring Limits, The Green Planet 3D, or Whale Superhighway [83]). Using the innovation-decision process framework presented in

Rogers (2003), these results are indicative of an inefficient or ineffective communication channel between the planetarium stakeholders (directors, content creators, etc.) and instructors not already using the planetarium environment [207]. In spite of the advancements offered by the planetarium environment, non-user faculty have not been made aware of them (knowledge-level communication) or have not been convinced of their usefulness (persuasion-level communication) as instructional implements [207]. Communications may need to be re-examined and possibly recrafted to better “sell” the planetarium, as instructors do not appear to quickly or regularly attempt to integrate new technologies in their pedagogical framework [107]. Planetarians and content creators seeking to diversify the variety of college classes instructed in the planetarium space may want to direct communications towards specific academic departments, rather than to university-level administrators [123, 169].

Two minor barriers (A2 and L1) amounted for 32% and 30% of respondents, respectively, considerably fewer responses than A3 or P1. The first of these, A2, represents a straightforward barrier—instructors did not know they could use the planetarium. Taken with the discussion above, A2 could indicate an imperfect communication channel like the one described above for A3 and P1. The second, L1, represents a concept similar to A3, but describes an instructor that has made a minimal consideration of the environment, but has been otherwise prevented from exploring the environment due to resource constraints concerning how a lesson might actually unfold. The L1 barrier alone could suggest that the planetarium environment is a more novel consideration than other pedagogical innovations, and that instructors who are open to the idea of the planetarium environment may benefit from assistance in turning the idea of a planetarium lesson into a reality. We contend that this barrier rests somewhere between persuasion-level communication and decision-level communication, suggesting that L1 identifying instructors are “almost there” in being convinced of the planetarium’s usefulness [207]. Coupled with the low counts from L2, L1 suggests that non-user instructors by-and-large would have no trouble getting their students physically into the planetarium, but would face a higher barrier in deciding what to do once their class was there.

The remaining barriers offered to the respondents did not record substantial returns and are not discussed further here.

4.6.1.2 The "Calculus" of User Faculty

Next, we present our probe into why faculty do use the planetarium environment as a part of their curriculum. To answer this question, respondent faculty were asked five free-response questions during the long-form version of the online survey. These questions asked the respondents to explain: (1) why they used the planetarium at particular times during the academic term; (2) why they chose to incorporate planetarium visit into their curriculum; (3) what outcomes they expected their students to reach; (4) their own cost-benefit analysis to using the planetarium; and (5) how a typical lesson in the planetarium unfolds for their classes. The responses to these five questions were aggregated and coded in concert—a brief analysis of the responses showed that some respondents answered parts of one question in the response to another, thus combining all five during coding preserved the necessary information.

Unlike the non-user barriers described above, the coding analysis of the user responses was a mix of predefined (code classes E, T, and W) and emergent codes (code classes S, C, L, and F). Emergent codes were created and revised as needed to describe the responses as accurately as possible—emergent codes that did not merit at least 10% of users were discarded or reincorporated into larger codes.

Table 4.4: Response archetypes investigated for non-user faculty instructors ($N = 88$). The percentage of non-users who chose each archetype is shown in the right-hand column, rounded to the nearest percent. Standard counting error is assumed in each response bin $\sigma_k = \sqrt{N_k}$. Respondents could pick as many options as they felt appropriate to describe themselves, so percentages will not sum to 100%.

Usage Barrier Archetype	**Sub-Archetype**	**Percent of Non-User Responses**
Awareness of Planetarium (A)	A1: Did not know planetarium exist	1 ± 1
	A2: Did not know planetarium could be used by any faculty at the institution	32 ± 6
	A3: Had not considered the environment before, but knew of existence and possible use	65 ± 9
Logistics of Planetarium Lesson (L)	L1: Knew of planetarium, but had not explored the uses of the environment	30 ± 6
	L2: No time for class to make trip to planetarium, regardless	7 ± 3
Financial Constraints (F	F: Monetary restrictions existed against using the planetarium	6 ± 2
Presentation of Content (P)	P1: Unknown if appropriate subject matter exists to be shown	56 ± 8
	P2: Existing content is too sparse or nuanced	0 ± 0
Procedural / Administrative Barrier (PrAd)	PrAd1: Had considered using planetarium, but had not reached out to try	10 ± 3
	PrAd2: Had tried to use planetarium in the past, but encountered difficulty coordinating	0 ± 0

We first discuss our three predefined codes in Table 4.5: E, T, and W. Code E (outcome-based choice of environment) is illustrative of what instructors described as the outcomes they wanted their learners to achieve by attending instruction in the planetarium. Outcome identification was completed by analyzing instructors responses and comparing their use of particular verbs and nouns to the key-word descriptions of the affective (code E2) and cognitive domains (code E1) [29, 126, 6, 28]. A minority of respondents described both the affective and cognitive domains (E1 and E2) in their desired learner outcomes (code E3). The two remaining codes were assigned to responses that specifically cited the environment as a complement to the regular classroom (code E4) and when instructors described the planetarium as "cool," either in their own capacity or attesting that description to their learners' experience (code E5). We make a brief note here of E5, given the possibility of overlap with the affective domain code E2. E5 exists as a separate code due to the implication of words like "cool" or "exciting" in the context in which they were provided by respondents, the implication being that their learners were entertained or amused by the planetarium experience. We do not doubt that entertaining or amusing lessons are possible vehicles for outcomes like those described by codes E1 and E2, however they are not per se an outcome.

Counts of E1, E2, and E3 suggest no particular preference towards either outcome domain across the group of surveyed instructors; assuming standard counting error ($\sigma_k = \sqrt{N_k}$), E1 and E2 are not distinguishable from one another and E3 is a distinct minority. This collection of count trends suggest that neither outcome domain was seen as clearly preferable for users; thus the counts for codes E1–E3 did not uniquely explain why the planetarium space was used in terms of desired outcomes. However, counts from E4 and E5 offered possible insight into why the environment is used. Half of the respondents were descriptive of their use with specific reference to the classroom environment, either by referencing specific pieces of classroom content or referencing the classroom setting generally. Similarly, half of the respondents expressed that the planetarium environment is "cool" or "exciting," either by their own estimation or as had been expressed by their past planetarium learners.

These counts suggest that the reasoning for users contained both a content-specific consideration (codes E1–E3), but also a “coolness” value judgement that went beyond the normal constraints of classroom outcomes. This might imply that instructors using the planetarium as a formal learning environment are making similar value judgments about the setting as planetarium professionals who generally create informal learning environments. Specifically, users are making judgments about the planetarium with the clear goal of educating, but also wanting to leverage the setting to inspire their learners to continue exploring after the presentation ends [57, 231, 194].

Such a value judgment might not be inappropriate for users to make, given that holding a lesson in the planetarium does require additional administrative and logistical concerns that the classroom does not. However, it could suggest that instructors are knowingly presenting course material in a different, more informal context when moving to the planetarium space during the execution of a formal collegiate course. This switch to a more informal setting might be detrimental to an instructor’s planned learning outcomes. Learners in informal environments are typically responsible for their own learning with little-to-no expectation of an assessment after the learning period is completed [264]. Informally presenting planetarium content as a part of formal instruction might cause a conflict of expectations between instructors and learners, possibly hampering learning [167]. Instructors might present content in so informal a manner that learners feel relieved of their responsibility towards meaningfully confronting the content. In the worse case scenario, learners might consider the planetarium a “zero-stakes” environment and participate in distracting behaviors like talking or sleeping [77].

Code T (typical lesson description) is illustrative of how instructors described the procedure and delivery of their planetarium lessons. Three archetypes were presupposed as to what an instructor might describe as their typical lesson, each of which has characteristic qualities that help distinguish it from its companions. Code T1 describes a lesson resembling the regular classroom with mention of the planetarium's technology. Usually included are mentions of classroom procedures or materials like lecture slides, the use of the planetarium's iClicker system, and the collection or distribution of material like homework or worksheets. Code T2 describes a lesson resembling a visit to a movie theater or cinema, described through express mention of playing particular fulldome films or a learner audience that would look identical to a group of general public moviegoers. Code T3 describes a lesson resembling a lecture-only setting, usually through mentions of a presentation that is almost entirely presenter or content focused with few mentions of audience interaction or typical classroom materials like those described under T1. The potential overlap between T1 and T3 is evident from their descriptions, given that many facets of each code have some similarity in the other—we discuss the differences between the two below. This crossover between the two is highlighted in code T4, where an instructor's description of their lesson had aspects of both T1 and T3. Finally, code T5 represents a described lesson that doesn't fit well into any other group, usually describing something like an exhibition or a conference poster session where the environment is not definitively formal or informal.

Lecture-only settings (T3) and augmented classroom settings (T1) do share procedural similarities like a primary lecturer presenting content to an audience in a formal setting; however, the two settings do maintain exclusive aspects that help distinguish them from one another. Chief among the exclusive aspects is the implied behaviors of the learner audience in the two settings. In T1, the implied behaviors of the learners are more active, engaging and interacting with the instructor to reach the lesson's desired outcomes. In T3, the implied learner behaviors are passive, with learners only responsible for listening and paying attention. The high degree of overlap between T1 and T3 could suggest a planetarium lesson that blends the procedures from an interactive classroom with a lecturer-centered classroom. We explore this implication in greater detail below in "Construct 2."

Code W (when to incorporate planetarium visits) is illustrative of when in the course of their overarching semester lesson plan an instructor chooses to make use of the planetarium. Two types of "when" were considered when defining the two subcodes for W. Code W1 describes a more figurative "when" that is defined by the arrival of content within an academic semester, i.e., the class has reached a particular body of content or knowledge that is seen as usefully instructed in the planetarium. Code W2 describes a more literal "when," and is denoted by the use of calendar dates or events not ascribed to bodies of content. For example, an instructor who uses the planetarium to present sky motions would be denoted with W1, but an instructor who uses the planetarium when they are personally absent from class would be denoted with W2.

The distribution of W codes is rather one-sided, with 77% of respondents describing the "when" of their planetarium use as occurring when particular content is encountered during the course of the academic term, as opposed to particular calendar dates during the term (described by 18%). Since a course's schedule for an academic term (i.e., the syllabus layout or calendar) is likely written in advance of the course in question, it follows that planetarium use is not likely a spontaneous affair at the collegiate level. Rather, a user who has defined their content goals for their course must then decide which of these content goals will be presented in the planetarium well in advance of the actual presentation. Additionally, by scheduling a visit so far in advance, the actual learners who will experience a lesson in the planetarium would have given no input as to what would actually be presented during that visit. However, since learners are likely to struggle with the same concepts term after term, an instructor using their past teaching experience to schedule future planetarium visits is likely a sound decision. Lastly, this administrative necessity of scheduling visits well in advance of their occurrence might unduly hamper innovation in the planetarium environment, or at the very least dissuade users from trying new pedagogies or content presentations. If the availability of the space is likely to be limited, a user may not deviate from well-established or well-practiced instructional patterns in the space since chances to revisit or revise such patterns do not happen within a reasonable time. We note for the reader that this administrative process of scheduling planetarium visits well in advance of actual visits may or may not be commonplace in other college or university settings.

We will now discuss our four emergent codes shown in Table 4.5: S, C, L, and F. Code S ("seeing it") is illustrative of instructors using the planetarium for its visualization capacities, literally allowing their learners to "see" some body of content that might not otherwise exist in such a format. Code S1 describes instructors who specifically cited the planetarium's immersive projection capacity. Code S2 describes instructors citing the ability to animate or actually show particular effects or motions in the planetarium theater, typically to show "how things work." Code S3 describes instructors who specifically noted how the planetarium compares and contrasts with the classroom as a content delivery environment for their lessons.

S1 focuses the power of the planetarium upon its arguably most unique trait as a learning environment—the ability to produce immersive learner experiences for students. The benefits of immersive learning are well described across numerous modes of presentation like planetarium theaters [241, 201, 48], virtual-reality (VR) platforms [64], and even interactive crime scenes [20]. S2 stresses the animation qualities, which may or may not themselves be immersive. Animation provides learners assistance by showing "how something works," and the learning benefit provided by animations is described across broad educational contexts [269, 204, 24]; however, animations are not entirely understood as to the precise mechanisms that aid learning when they are used [215, 127, 44]. S3 could be the most critical emergent code of our survey respondents, as this code reinforces the idea that the planetarium does not exist as a truly separate setting from the classroom, but is seen as an integral piece of the whole, as discussed above for code E. S3 could suggest that for the purposes of undergraduate education, the classroom/planetarium pair may be uniquely powerful in confronting learner misconceptions by granting learners two settings in which to confront material, similar to computer simulation experiences [233]. Such an attitude towards the planetarium highlights a prospect from astronomy education that we feel needs greater consideration—the planetarium as a laboratory setting [85].

Laboratory classes provide additional opportunities for learners to confront course materials in a "hands on" setting with greater social aspects than the classroom environment [171]. Unlike experimentation-driven disciplines like physics or chemistry, observations drive astronomy, and most astronomical observations require prohibitively expensive equipment [166]. Disciplines like physics are usually replete with experimental setups for a physics laboratory course to choose from, but astronomy laboratories have comparatively limited options [85]. Like computer simulators [166], digital planetariums might offer a feasible work-around by simulating astronomical phenomena that can then be confronted by learners. Learner-driven exercises like the manipulation of three-dimensional astronomical orrerys on a tablet computer have shown gains when learning about astronomical sizes and scales [213], and direct interaction by students with a zoom-in/zoom-out interface has been suggested as aiding learners grasp of sizes and scales normally beyond everyday human experience [164]. With appropriate technical assistance, learners might use the planetarium in a similar fashion "hand on" for laboratory exercises, enhancing learners' agency with the environment and allowing more impactful confrontation of misconceptions [17].

Code C (specific content referenced) is illustrative of what concrete content examples instructors chose to provide when describing what they showed in the planetarium during their lessons. Code C1 describes the "usual" use of the planetarium, e.g., showing sky motions like the diurnal, monthly, and annual motion of the celestial objects in the sky, naked eye observations, or other ground-based, technologically unaided sky observation. Code C2 is the contextual complement to C1, describing content that does not fall into C1, including a wide span of content ranging from the surface of Mars to the edge of the observable Universe. Code C3 describes instructors who overlap both C1 and C2 in their descriptions. Codes C4 and C5 split C2 into two broad categories of "other content." C4 is descriptive of astrophysical content like the scale of the Universe, the exploration of black holes, and "flying" through the Milky Way Galaxy simulation. C5 is descriptive of planetary science content like examining other planets (including exoplanets), "flying" though the Solar System orrery simulation, and visiting the surface of Mars. C4 and C5 are not mutually exclusive for a given instructor—if an instructor described other content that qualified as both astrophysics-centered and planetary science-centered, they were marked as both C4 and C5. Lastly, not all content was describable by C4 and C5, but since no broad theme was emergent from these final descriptions, they have been left incorporated into C2. Assuming standard counting error ($\sigma_k = \sqrt{N_k}$), C1 and C2 aren't distinguishable from one another, and the overlap between the two is substantial (C3). This distribution of C subcodes highlights that planetarium users continue to attach high value to the planetarium's classical instructional uses (like sky motions and naked-eye phenomena) and that value is similarly attached to the technology-dependent materials that need digital fulldome projectors (like "flying" and 3D simulation).

Code L (learner types/experiences distinguished) is the smallest of the emergent categories, but does highlight a point worth mentioning. L is illustrative of instructors who expressed some kind of discrimination in their descriptions of planetarium use based on what particular class they were instructing (e.g., "ASTRO 101" compared to "ASTRO 400"). The low number of L counts suggests that instructors using the planetarium do not see the need to distinguish between learners of different experience levels when considering the use of the planetarium, but may rather be relying upon a different decision schema that may be based upon presented content. We continue our discussion of the implications of code L below in Construct 2.

Code F (costs associated with planetarium use) is illustrative of instructors who expressed some kind of cost or tradeoff (or lack thereof) in using the planetarium for their lessons. Code F1 describes a logistical cost in using the theater, like needing to relocate a class to the planetarium theater. Code F2 describes a pedagogical cost incumbent in planetarium use, like learners not being able to take notes in the theater or being restricted in their personal movement through the space due to the orientation of the audience. Code F3 describes instructors who countermanded the premise of the question, and specifically mentioned there being no cost towards their use of the planetarium in their lessons. Interestingly, three of the four (75%) F3 responses also counted as E5, possibly suggesting that their use of the planetarium is satisfactory, so long as an entertaining experience is had by their learners. None of the three F codes are distinguishable from one another, assuming standard counting error ($\sigma_k = \sqrt{N_k}$); however, the theme of the two material codes (F1 and F2) does highlight a particular difficulty that users may encounter that are worth discussing.

F1 represents a cost not likely typical to the usual classroom setting, namely the cost of movement to the space. College classrooms are identified and assigned by administrators well in advance of an academic term, let alone an individual lesson, and the classrooms themselves are likely not prone to switching, barring some externally imposed need. The planetarium space is likely not one of these regular spaces, and exists functionally outside the regular assignment framework for a college. As such, for classes that do not routinely meet in the planetarium (or in the most extreme case, only meet in there), learners will need to relocate to the planetarium, which may not be at a location as readily accessible as another building on campus. When there, more time is needed to get seated and situated, delaying the start of class. As late-arriving students make it to the planetarium theater (mostly at the beginning of class), the presentation must be temporarily paused so learners are allowed into the theater and situate themselves. As a consequence, college classes in the planetarium are likely to be temporally shorter than their classroom counterparts (similar to Plummer et al. (2015)'s statements concerning visits to informal planetarium learning settings) [193], meaning the true cost described by F1 is actual class time.

F2 is representative of the planetarium space being incompatible with an instructor's preferred presentation style, specifically how the planetarium space does not oblige particular actions, strategies, or techniques that would be available to an instructor or their learners in the regular classroom. Examples mentioned by our respondents include actions like moving through the learners during group discussions or being able to have learners take notes on the content shown in the theater. If an instructor views such activities as necessary to reach their course goals, but they are unable to do so in the planetarium, then they might feel compelled to have their learners "make up" those activities in the classroom setting rather than attempting to include them in the planetarium. Like F1, the true cost of F2 is time, but rather than being a cost of time in the planetarium, F2 is instead a cost of time in the classroom.

Complementing our user survey responses, we now discuss the post-observation interview responses from our six observed instructors. Given the small number of interviews, a coding scheme like the one in Table 4.5 was not advisable for analysis. As such, we will discuss our interview responses in a holistic manner such as the interview discussions presented in Croft, 2008 and Everding & Keller, 2020 [57, 77]. Interview topics were contextualized for each interviewee based on their responses to their pair of pre-observation questionnaires; these topics and the group responses are shown in Table 4.6.

Table 4.5: Coding scheme of the user responses ($N = 22$) concerning why/how/when they incorporate a planetarium into their curriculum. Four responses were left blank or were otherwise not adequate for analysis. Percent of users is based on the total number of valid responses ($N = 22$).

Code Classification	**Sub-Classification & Description**	**Number**	**Percent**
Outcome-based choice of environment (E)	E1: Cognitive gain/outcome	12	54.5
	E2: Affective gain/outcome	10	45.4
	E3: E1 and E2	5	22.7
	E4: Complement to classroom material/environment	11	50
	E5: Planetarium is "cool," "exciting," "interesting," etc.	11	50
"Seeing It" (S)	S1: Stresses immersive experience	5	22.7
	S2: Shows/animates "how things work"	9	40.9
	S3: Information shown in different or alternate ways compared to classroom	6	27.2
Specific content referenced (C)	C1: Sky motions (daily/annual/etc.) or closely related	10	45.4
	C2: Other content	14	63.6
	C3: Both C1 and C2	8	36.3
	C4: C2 with astrophysics-centered content	8	36.3
	C5: C2 with planetary science-centered content	5	22.7
Typical lesson description (T)	T1: Describes an augmented classroom setting	9	40.9
	T2: Describes film/movie/cinema	0	0
	T3: Describes a "lecture-only" setting	7	31.8
	T4: T1 and T3	5	22.7
	T5: Other learning experience (studio/exhibition/etc.)	3	13.6
Learner distinguished (L)	L: Describes benefits applying to different, defined groups of learners	4	18.1
Costs associated with using planetarium (F)	F1: Logistical cost (e.g., movement of learners to planetarium)	6	27.2
	F2: Pedagogical cost (e.g., no notes in darkness or difficulty delivering lesson)	4	18.1
	F3: Specifically refutes idea of a cost	4	18.1
When to incorporate planetarium (W)	W1: Planetarium use meets specific content delivery goals	17	77.2
	W2: Planetarium use meets specific calendar dates	4	18.1

The response trends concerning the choice of materials/content in the two environments resulted in an interesting partition, seen in the first row of Table 4.6. Classroom material was typically well described in terms of how a particular lesson would unfold—specific action items like Clicker questions, board writing/note taking, or group discussions were clearly enunciated as a part of classroom material content. Conversely, planetarium material was well described in terms of what a particular lesson would contain—specific projections or animations like sunrise/sunset simulation, exocentric Solar System orrery projection, or fulldome pre-recorded movie content were mentioned. Content presentation that made use of note taking or class discussion was decidedly preferred in the classroom space, as the planetarium space was not considered conducive to these "regular" classroom activities due to the lowlight conditions and seating arrangement in the theater.

Critical among these responses was the emergent, if loosely defined, concept of "planetarium worthy" content and how that content did not exist in a pedagogical vacuum. Contents worthy of the planetarium generally centered on immersive projections not available in the classroom space. The immersive projections were seen as helping learners build more complete understanding of the presented material and offering a complement to the presentation styles used in the classroom. Thus, "worthy" content fulfilled two principle traits, according to our observed instructors: (1) "worthy" content is capable of being rendered as an immersive visual experience; and (2) the content exists in another format in the classroom environment, such that the same underlying information is present in both content presentations. Interviewees converged upon the idea that any content shown in the planetarium (the setting held to be non-conducive to regular classroom activities) must invariably be discussed or confronted again in the classroom setting, where regular classroom activities could touch upon said content. This confrontation in the classroom environment could happen either before or after confrontation in the planetarium. Incorporating our interviews with the discussions made by Yu et al. (2015) and Rau (2017), "worthy" content was characterized as follows [273, 203]. "Worthy" content was content which was presentable in a visually superior format in the planetarium (visually immersive and resolved); but, "worthy" content was also presentable in the classroom in a visually inferior format (non-immersive, like a projector slide), likely supported by deeper verbal discourse, textual accompaniment, or both.

Response trends concerning the goals/outcomes in each environment are seen in the middle row of Table 4.6. Described goals in the classroom stressed low-to-mid level cognitive outcomes, with no explicit mention of affective ones [28]. Goals in the planetarium were general low level outcomes across both the affective and cognitive domains. Interview discussions helped distill these responses further, with instructors generally seeing the classroom setting as the appropriate venue for cognitive outcomes and the planetarium setting for affective ones. Described reasons as to why fell along the same lines of discussion concerning the course content discussed above. Instructors held that when their learners are stripped of the practical ability to take notes, make calculations, or engage in group discourse the ability of the lesson to achieve cognitive outcomes is stifled. Such mentally (and possibly physically) rigorous activities were thus held as more appropriate for the classroom setting. Desired affective outcomes were discussed as not necessarily needing these more rigorous activities, thus the planetarium would more naturally align with the affective domain; any cognitive outcomes that occurred in the planetarium were seen as positive, but were not the primary focus of the environment.

Difficulties described by instructors in reaching their enunciated goals fell mostly upon the planetarium environment. Classroom difficulties discussed were very nuanced and no group trend among these difficulties emerged. For example, Dr. Friday's classroom difficulties centered around time constraints and not being able to present all the desired content for that day's lesson. Conversely, Dr. Saturday's classroom difficulties centered on how a class-wide discussion technique did not unfold as anticipated. Planetarium difficulties across the group were more cogent. This group of instructors described a level of physical movement through the classroom space that is perceived as facilitating their preferred instructional styles (many of which were descriptive of reformed practices), but the planetarium's physical restrictions on movement (low lighting, crowded/cramped space) placed a pronounced hindrance upon them from presenting content in their classroom-practiced style.

The trends concerning the procedures in each environment are shown in the last row of Table 4.6. The described preparations for each lesson showed noteworthy overlap, with preparation strategies like reviewing or correcting old slide sets and studying content notes being common for the two settings. However, descriptions of classroom preparations made greater mention of planned reformed/active-learner practices like Clicker questions and group discussions than in the planetarium preparations. Unquestioned among the interviews was the perception of planetarium lesson preparation needing more time than classroom lesson preparation—this perception was emergent from all interviews, regardless of past user experience. Moreover, preparation for a planetarium lesson was seen as itself requiring the planetarium. All classroom material described in the interviews revolved around a set of slides that would be shown during a lesson—slides could be reviewed anywhere via a personal computer, so reviewing for a classroom lesson required little more than an instructor's computer and course notes. Planetarium preparation was seen as needing a rehearsal with a planetarium staff member in the planetarium environment—such a constraint on preparation required the coordination of a third party and was restricted to a single location on campus. Instructors were not pessimistic about this additional demand on their time, but all were able to identify it as a difficulty they encountered.

Unique among the interview points was the idea of a "script" for classroom lessons that did not generally exist in the planetarium. This script, the collection of projector slides used during the lesson, "mapped out" the lesson's content into small, sequential quanta of information for both the instructor and their learners. This script thus provided a procedural framework that not only laid out the lesson's procedures but also served as part of the content delivery system. Fulldome visuals in the planetarium were not similarly discretized, and the "map" of a lesson could be more easily lost without the comparatively more ordered slide set framing the lesson delivery.

Synthesizing the analysis of this construct's data, the "calculus" of using the planetarium environment may now be described. An instructor considers a course's available content and determines if any would be "planetarium worthy." This worthy content is seen as benefiting the learners by being shown in two ways: as an immersive visual spectacle in the planetarium, shown without any contemporaneous "regular" classroom material (notes, calculations, discussions); and as a weak visual like a 2D projection in the classroom, where regular materials are available for the learners. These materials could be from the planetarium's well-established content profile (e.g., sky motions or Moon phases) or from its more recent, digital fulldome content profile (e.g., flying through the Universe). Visits to the planetarium are made around a course's content schedule, not around any individual personal schedule. Additional time must be allotted to preparing for a planetarium lesson in order to coordinate with a planetarium operator who will aid the instructor in delivering the lesson in question. Furthermore, lesson preparation must take into account a likely loss of class time as the planetarium space requires extra temporal expenditures like transit time to the planetarium and early-lesson interruptions to seat late arrivals.

4.6.2 Construct 2: Discriminating the Classroom & Planetarium Environments

4.6.2.1 Discriminating the Two Environments: Survey Responses

To confront our second research construct, we examined our respondents' self-reported prior teaching experience. Respondents were asked to identify how many years each had spent instructing at the various instructional levels common in the United States, ranging from pre-K to four-year university/college. By and large, survey respondents reported experience only at the university/college level, with minimal, but varied, experience at other instructional levels (Table 4.7). This trend holds when examining users and non-users as separate groups (not shown separately in table), with a Kolmogorov-Smirnov test failing to reject the null hypothesis that the two groups have the same distribution of collegiate teaching experiences at the 5% significance level $(\alpha = 0.05; U_{KS} = 0.167; p = 1.0)$.

Table 4.6: Summary of post-observation interview responses from the six observed user instructors. Interview discussion topics are presented in the left column, and the holistic findings from interviewees are presented in the right column.

Post-Observation Interview Topic	**Group Response Trends**
Choice of material/content in each environment	Classroom described as the appropriate setting for "regular" classroom material like note-taking or calculation. Planetarium described as the appropriate setting for less strenuous course material not needing notes, calculations, or contemporaneous discussions. Described content-specific actions undertaken by learners suggest a more instructor-centered/passive-learner planetarium experience. Suggested instructors held an idea of "planetarium worthy" content.
Goals/outcomes in each environment	Classroom goals stressed low-to-mid level cognitive outcomes. Planetarium goals stressed low-level cognitive and affective outcomes. Classroom seen as favorable venue for cognitive outcomes; planetarium is seen as favorable for affective outcomes. Instructors encountered difficulties incorporating interactive strategies in the planetarium environment due to physical layout of the space. Planetarium outcomes required coordinating with a third party planetarium staff member to orchestrate learning.
Procedure to achieve goals/outcomes in each environment	Instructor preparation strategies for the two environments showed significant overlap (e.g., study notes or review/update old slides). Classroom preparations showed greater planning towards active-learner pedagogies compared to planetarium. Planetarium preparations seen as decidedly more time-intensive and focused more on what visualizations would be shown. Posits the existence of a ?script? for the classroom environment that does not generally exist for the planetarium.

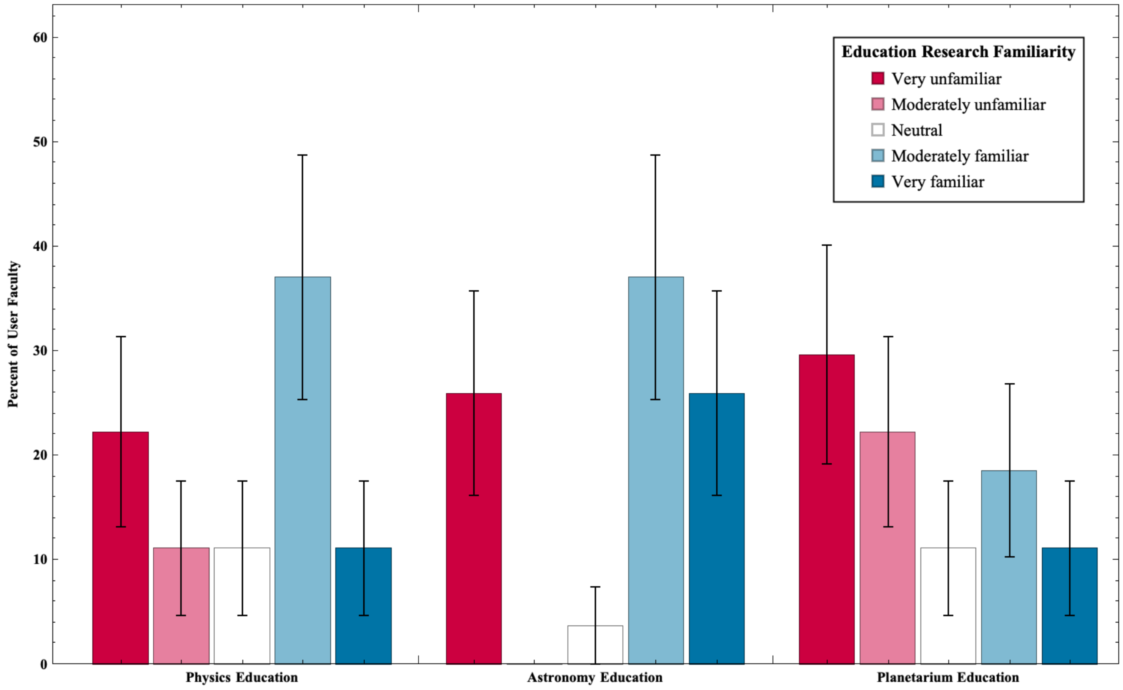
Table 4.7: Statistical measures of survey respondents' ($N = 113$) teaching experience across American instructional levels, measured in years. Results strongly suggest that none of this study's respondents have much experience outside the formal, university/collegiate context.

Instructional Level	**Mean ± St. Dev**	**Median**	**Range**
University/college	15.3 ± 11.2	12	0–41
Community college / Junior college	0.2 ± 0.7	0	0–4
High school (grades 9–12)	0.5 ± 2.7	0	0–25
Middle school (grades 5–8)	0.2 ± 0.8	0	0–5
Elementary school (grades 1–4)	0.1 ± 0.6	0	0–4
Kindergarten or younger	0.1 ± 0.6	0	0–6

Respondents were also asked to rate their familiarity with the fields of education research (physics, astronomy, and planetarium) that typically confront the planetarium as an investigable venue of education. Respondents were allowed to enter another discipline-based education research (DBER) field they were familiar with (e.g., chemistry, biology, and engineering), but few did so. The reported familiarity with these fields is presented in Figure 4.6.2.1.

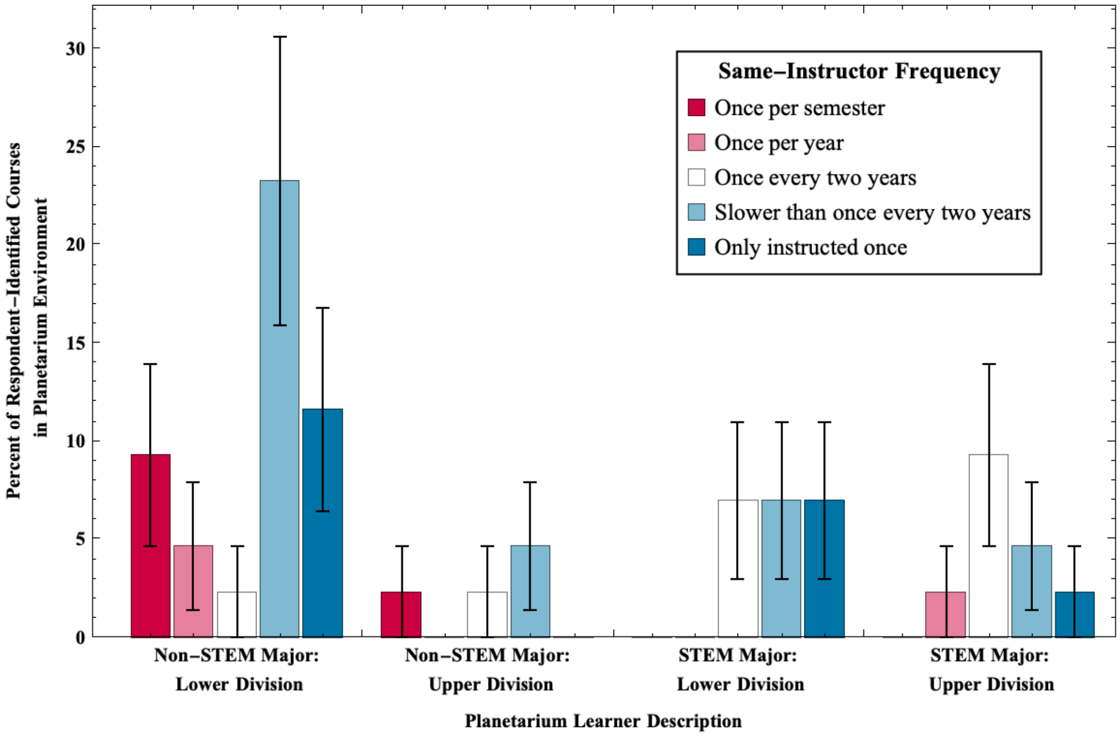
Expectedly, non-users rated mostly as “very unfamiliar” with all three education fields (not shown), suggesting non-users experience a complete detachment from the planetarium as a formal researched educational venue. Users rated greater familiarity with the three fields, particularly with astronomy education. However, the lower measure of “very familiar” and “moderately familiar” counts in the planetarium education category compared to the physics education and astronomy education categories could suggest that user faculty are more likely to be abreast of education research findings derived from the regular classroom or laboratory setting than the planetarium, specifically. This distinction could be of great importance for future endeavors in the planetarium space. Instructors are likely to pay greater attention to education research findings that would have the greatest impact on their usual instructional practices, such as those found in the regular classroom setting where most of their instruction would occur (e.g., active-learner/peer-instruction strategies, iClickers, etc.). However, instruction in the planetarium space is not the commonplace locale of collegiate instruction, so innovations originating in that setting might not make as great an impact on users’ pedagogical considerations as one originating from the lecture hall. By extension, users could be transferring their classroom instructional practices directly into the planetarium without consideration of whether those practices would be as impactful or achieve similar outcomes in the planetarium environment.

Figure 4.1: Planetarium users' ($N = 26$) self-identified familiarity with three DBER fields commonly investigating planetarium learning during the survey portion of this study. Users are generally familiar with physics and astronomy education findings, but generally unfamiliar with planetarium education findings.



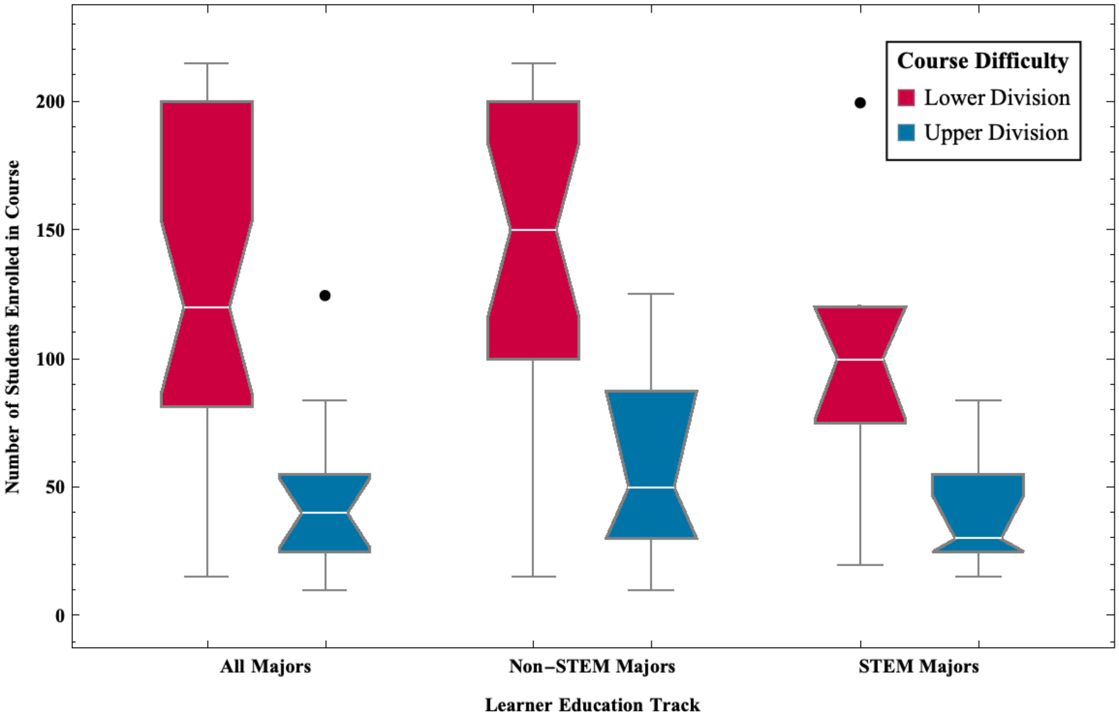
Users were also asked to identify with what frequency they teach a particular course in the planetarium (e.g., “ASTRO 101” or “PHYS 301”). The frequency with which instructors taught these courses is denoted by the colors in the legend of Figure 4.6.2.1. Courses are separated by learners’ educational track (Non-STEM/STEM major) and course difficulty (lower/upper division) along the horizontal axis. Responses suggest that a particular planetarium user is not instructing the same course (and accompanying body of content) in the planetarium environment at frequent intervals (once every two years, or slower, on average for the four learner descriptions). Such a slow rate of repetition could suggest that instructors might maintain a “default” presentation style in the planetarium, possibly the presentation style maintained in the classroom environment, as they are so rarely forced to contend with the same or similar lesson delivery. Additionally, once instructors have established a particular repertoire of planetarium worthy content (discussed above under “Construct 1”), the slow rate of repetitions might suggest that instructors would be unlikely to consider other content presentations in the space. Part of the “calculus” of the planetarium environment (discussed above) is preparation time for a particular lesson; if planetarium instruction occurs so infrequently, instructors might not consider innovating upon their established repertoires due to the time commitment necessary. A possible exception to this might be instructors who instruct similar, but not identical, courses with greater frequency. An example of this might be two courses which overlap in presented content but are distinguished from one another only by the presence of a laboratory requirement in one that is not shared in the other.

Figure 4.2: Distributions of the frequency of instruction of planetarium classes by the same instructor between 2016–2019, as reported by user faculty, separated by learner education track (Non-STEM Major / STEM Major) and course division (Lower / Upper). Forty-three unique instances of a particular course were described by respondents. Response trends suggest that planetarium use for a particular instructor teaching a particular course is rather infrequent, further suggesting that planetarium use (or any changes thereto) do not propagate quickly within this body of planetarium instructors.



In addition to identifying the frequency with which a user instructed a particular course, users were also asked to identify the number and education track of that course's learners, separated into non-STEM majors and STEM majors. These data, along with the course difficulties, are shown in Figure 4.6.2.1, with the course difficulties identified in the legend and learner education tracks across the horizontal axis. Forty-three unique instances of a particular course were described by respondents. Upper division courses for all majors are distinctly smaller than lower division courses for all majors (Figure 4.6.2.1, left pair of boxes) as determined by the t-Test ($\alpha = 0.05$; $t = 5.77$; $p = 1.37 \times 10^{-6}$), against the null hypothesis that the two divisions had the same mean class size. This distinction holds when courses are separated by education track [Non-STEM: ($\alpha = 0.05$; $t = 2.43$; $p = 0.023$), Figure 4.6.2.1, center pair of boxes; STEM: ($\alpha = 0.05$; $t = 3.37$; $p = 0.004$), Figure 4.6.2.1, right pair of boxes]. However, differences in class size are not distinct between the education tracks for a particular course difficulty (Figure 4.6.2.1, center-and-right pair of red (lower division) or blue boxes (upper division)). Reflecting back upon our discussion of the user response code L under "Construct 1" (Table 4.5), we contend that these data indicate that the planetarium environment is viewed by our respondents as the province of lower division courses, without regard to those learners' education headings. In light of our interviewees' discussions concerning classroom and planetarium materials, the implied rigor of upper division courses would suggest that the planetarium is not considered as valuable to those learners as regular classroom instruction. As was discussed in the interview portion of Everding & Keller (2020), this supposition about more experienced learners not "needing" the planetarium space may not be an advisable position.

Figure 4.3: Enrollment, learner experience, and learner education track of planetarium classes between 2016–2019, as reported by user faculty. Forty-three unique instances of a particular course were described by respondents. Upper division courses are distinctly smaller than lower division courses, but differences in class size are not distinct between the education tracks for a particular course difficulty.



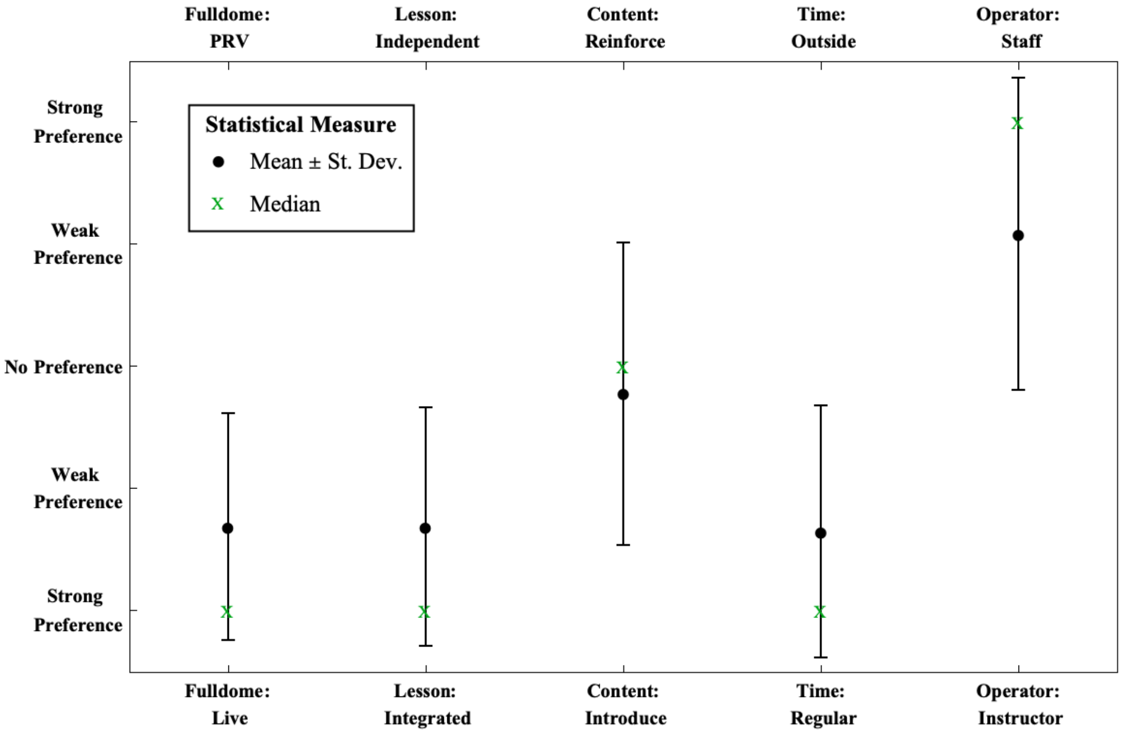
To establish how users preferred their planetarium lesson to proceed, respondents were asked to select their preference towards a particular presentation mode with each of five presentation facets, each facet being presented as a dipole choice between two approximately-exclusive end members. These five presentation facets concern the following: (1) whether the fulldome projector is used for pre-recorded video (PRV) content or live presentation content; (2) whether a planetarium lesson is independent or integrated into an instructor's semester-long lesson plan; (3) whether content is introduced or reinforced from previous introduction in the planetarium; (4) whether lessons occur during the regular class meeting time or outside the regular class meeting time; and (5) whether the planetarium systems like the projector are operated by the instructor themself or by a member of the planetarium staff.

The distributions of preference counts are shown in Figure 4.6.2.1. Means (black points with standard deviation bars) and medians (green X's) were calculated by assigning an integer value ranging from -2 to +2 to each of the preference values within each facet. For example, under the fulldome facet, a strong preference towards "live" would have a score of -2, a weak preference would be -1, no preference would be 0, a weak preference towards PRV would be +1, and a strong preference towards PRV would be +2 . Both means and medians show strong polarization for four of the presented facets (fulldome, lesson, time, and operator) and minimal polarization for the fifth (content). The disjoint locations of the means and medians demonstrate that most of the counts in each facet are in one of the two extreme ends ("strong preference"), except for the minimal polarization in the content facet.

In a large collegiate classroom setting, live presentation (that is, presentation made by a real person in the room with the learners) is likely the commonplace mode of instruction [240]. Semester-long lesson plans typically schedule out every week of instruction as part of an integrated whole to reach the course's semester-long learning goals—few instances of independent or disjoint lessons confronting non-assessable content would be expected. Content in the classroom is both introduced and reinforced throughout the semester. Lastly, the time the instructor and their learners meet in the classroom is usually defined by a collegiate administration, so that the lesson presented therein has no schedule conflicts with other courses' lessons. The distribution of preferences in Figure 4.6.2.1 strongly aligns with this "typical" classroom description, and suggests that as a practical matter user faculty prefer planetarium lessons that closely mirror their classroom counterparts, with the exclusion of the operator facet. In this case, there is a strong preference for having a separate operator in the planetarium to control the projector system while the instructor presents—this preference is in distinct contrast to the classroom setting where the instructor is usually both the presenter and the projector operator. The distribution of preferences also suggests that the planetarium is perhaps not seen as a unique learning space in its own right, but is instead seen as augmented or alternate classroom.

4.6.2.2 Discriminating the Two Environments: COPUS Data

Figure 4.4: Responses of users ($N = 23$) regarding their preference towards particular facets of lesson delivery in the planetarium. Statistical measures presented are specified in the legend. Distributions within the five facets (described further in text) are suggestive of faculty who prefer planetarium lesson delivery to closely resemble classroom lesson delivery, excluding the operation of the planetarium projectors where preference favors a third-party operator. Skewed locations of the mean and median suggest heavy preference towards one end of each dipole, except for the "Content" facet.



Further insight into this supposition is gained by directly examining the distribution of COPUS behaviors in the two environments recorded during our joint classroom/planetarium observations. Because COPUS codes are recorded every two minutes, it is possible for multiple behaviors to be recorded within the same time window, even when such behaviors would be indicative of distinctly different instructional or learning modes. For example, in our planetarium observations, the instructor codes Lec (instructor lecturing or presenting content) and DV (demo/video) often coincide with one another in the same two minute observation window—such dual coding is exemplary of an instructor lecturing on a piece of material and then showing a short simulation on the planetarium dome pertaining to that material, or showing a separate simulation to introduce the next discussion in the space. The percent-of-lesson data distributions presented in Figure 4.6.2.2 were calculated as follows: (1) for each individual instructor or individual student group, each particular behavior was tabulated based on how many two minute observation windows that particular behavior was recorded using COPUS; (2) each particular behavior tabulation was then divided by the maximum number of possible two minute observation windows available for a given observation period and multiplied by 100%, thus producing a percent-of-lesson value for each behavior; and (3) the percent-of-lesson values for each instructor and group of students was plotted for the two separate environments, producing the 26 pairs of data distributions shown in Figure 4.6.2.2.

The similarities and differences between the two environments were qualitatively apparent based on the location and spread of either environment's percent-of-lesson distributions; however, to qualify the differences between the two environments beyond a simple qualitative judgement of these distributions (Figure 4.6.2.2), t-test calculations for each of the 26 distribution pairs were made, using significance levels (α values) of 5% and 10% as the calculation cutoffs. T-tests were run against the null hypothesis that the difference in means between the two environments for a particular group's behavior distribution was zero. We remind the reader that the COPUS data in this study represent six faculty instructors and their entire corresponding student bodies (N=6), so statistical inferences from these small data sets are not as robust as inferences garnered from a larger set of data. Results of the tests suggested significant differences between the expressions of the instructor behaviors AnQ (instructor answering student questions; $p = 0.04$), DV (instructor using demonstration or video; $p = 0.001$), and PQ (posing questions to class; $p = 0.06$) and expressions of the student behaviors CG (student clicker group(s); $p = 0.08$) and SQ (student question to instructor; $p = 0.03$). All other differences between behavior expressions were not significant. AnQ, PQ, CG, and SQ were expressed in greater percentages in the classroom, and DV is expressed in a greater percentage in the planetarium. On the whole, our COPUS observations do not fit perfectly with the lesson code archetypes presented by Lund et al. (2015) nor the actor/action code archetypes in Smith et al. (2014) [152, 237]. As a group our observed classroom lessons were somewhere between "Socratic with slides" and "Limited Peer Instruction with slides" with a larger percentage of the Lec behavior [152]. Similarly, our observed classroom actors could be described as presenting instructors and receiving students with some smaller contributions from interactive or reformed practices [237].

The four classroom-favoring behaviors are indicative of greater interpersonal communication between the instructor and their students, suggesting a more interactive or active-learning environment [84]. Compared to the archetypes of instructors and students presented in Smith et al. (2014), these behavior measurements are also indicative of a guiding instructor and working/conversing students [237]. The AnQ/SQ behavior pair especially highlights this, as the interaction described by these two behaviors can be directly interpreted as the learners asking more questions (and the instructor similarly answering) in the classroom compared to the planetarium. At the less significant level, the PQ instructor behavior further supports a more instructor-focused environment in the planetarium, suggesting that instructors pose fewer verbal questions to their classes. Similarly, the difference in CG behavior suggests that when questions are asked to groups of learners using a Clicker, planetarium lessons are less likely to involve peer-to-peer or think-pair-share interactions incumbent with a Clicker question. The lower measure of CG in the planetarium, without a corresponding drop in CQ (instructor presenting Clicker question) or Ind (student responding to Clicker individually), further suggests that while Clicker questions are used, the content or difficulty of such questions has been chosen only to quickly scan the learners' understanding of a concept without an expectation of meaningful discourse after the question is completed. Clicker use of this kind does comport with student attitudes about the devices [220], however it may also represent a lost opportunity for instructors to engage with their learners instead of "just checking" that everyone is still responsive. Clicker use can be a challenging process for college classrooms, and creating and executing effective Clicker questions is a non-trivial task for instructors under the best circumstances. Our COPUS measurements might suggest that Clicker question items need to be refined for the planetarium environment using a framework appropriate to the environment that takes into account the darkened conditions and restrictive seating.

The single planetarium-favoring behavior is indicative of a more visually compelling environment, one in which instruction is supplemented by significant immersive visual aids via the planetarium dome. As described in "Methods & Investigation," the DV code is used to identify when the planetarium projectors are "on," and the percent-of-lesson counts in Figure 4.6.2.2 show that during a lesson in the planetarium, roughly 65% of the lesson is presented using the planetarium's projectors. When compared to the roughly 10% occurrence of DV in the classroom, the percent-of-lesson counts clearly demonstrate a sizable shift in presentation style in the planetarium, from one relying on few visual aids in the classroom to one using them almost two-thirds of the time. Moreover, the variance within the planetarium DV code percentages propose that there may be a very wide range or opinions among users as to what amount of a lesson "needs" to be held with immersive visuals. Even so, we note the lack of significant difference between the two environments of instructor code Lec (instructor lecturing or presenting content) and student code L (listening to lecture or taking notes), which occurs roughly 85% and 95% of the time during a lesson, respectively. This apparent reliance on lecture-based, didactic instruction as the primary means of discourse is not unexpected, given the large class sizes and instructor-described barriers to movement throughout the planetarium space [240].

Taken together, these data suggest that in the planetarium, instructors are lecturing and learners are listening just as they do in the classroom. Combined with our survey data concerning instructor presentation preferences in the planetarium (Figure 4.6.2.1), the large lack of COPUS differences (excluding those discussed above) is illustrative of a planetarium learning environment that is by-and-large procedurally identical to the classroom learning environment. However, the differences in interactive learning behaviors and the instructor code DV suggest that a trade occurs when learning moves into the planetarium environment: the loss of interactive learning in exchange for more time in a visually immersive environment to supplement lecture material. Such an exchange could be of great significance, as it would indicate that instructors are knowingly choosing to give up some of the advantages of interactive pedagogies to make use of the planetarium's immersive presentation advantages.

Both immersive and interactive instruction are well documented to be superior modes of instruction compared to their personal counterparts. Immersive planetarium instruction is routinely shown as assisting learners achieve greater gains, both immediately after instruction and over time [274, 275], when compared to instruction using static or two-dimensional content presentation (like a textbook figure). Similarly, learner-centered techniques have demonstrated a potent advantage over older instructor-centered techniques [78, 198, 90], so much so that there have been calls to eliminate instructor-centered pedagogies from collegiate use entirely [90]. We conceive of no reason that interactive instruction in the immersive learning environment should not still reap at least some of the demonstrable benefits of both pedagogical strategies. However, we would also comment here about the findings in Andrews et al. (2011), who showed that implementations of active learning strategies do not always correspond to learning gains in collegiate settings [7]. Faculty who are not active DBER researchers do not always approach active-learner strategies with the same care and nuance to elicit the strategies" maximal benefits [7]. Since the expression of active learning strategies were reduced in the planetarium (as measured using COPUS), we are skeptical of the impact of active-learning strategies when used with such low frequency in that setting. That is to say, we are skeptical toward the benefits of using active-learning strategies in potentially "token" amounts. Does the class benefit from including a single Clicker question and discussion, or would more time in the immersive visual environment have been a better use of time? We are also unsure as to what the appropriate "mix" of active-learning and immersive pedagogical strategies should be and the variance in the planetarium DV code (Figure 4.6.2.2) might also suggest that planetarium instructors may not have a well-defined sense of such a mix either. However, narrowing the scope of this question would most likely require longitudinal observation campaigns examining multiple instances of different course content, which are beyond the scope of this work's "snapshot in time" approach. We revisit this possibility of future work below, under "Theoretical Synthesis & Future Work."

Figure 4.5: Distribution of COPUS code counts for instructors (a) and students (b), expressed as percentages of the observed lesson for the two environments (legend). A description of box plot rendering can be found in text under "Data & Analysis." In each pair of boxes, the left one is the measurements from the classroom (red) and the right one is the measurements from the planetarium (blue). Results suggest that planetarium learning environments are measurably more passive than their classroom counterparts, typified by the reduced percentages of active-learner indicator behaviors ((a): AnQ, PQ; (b): AnQ, CG, SQ).

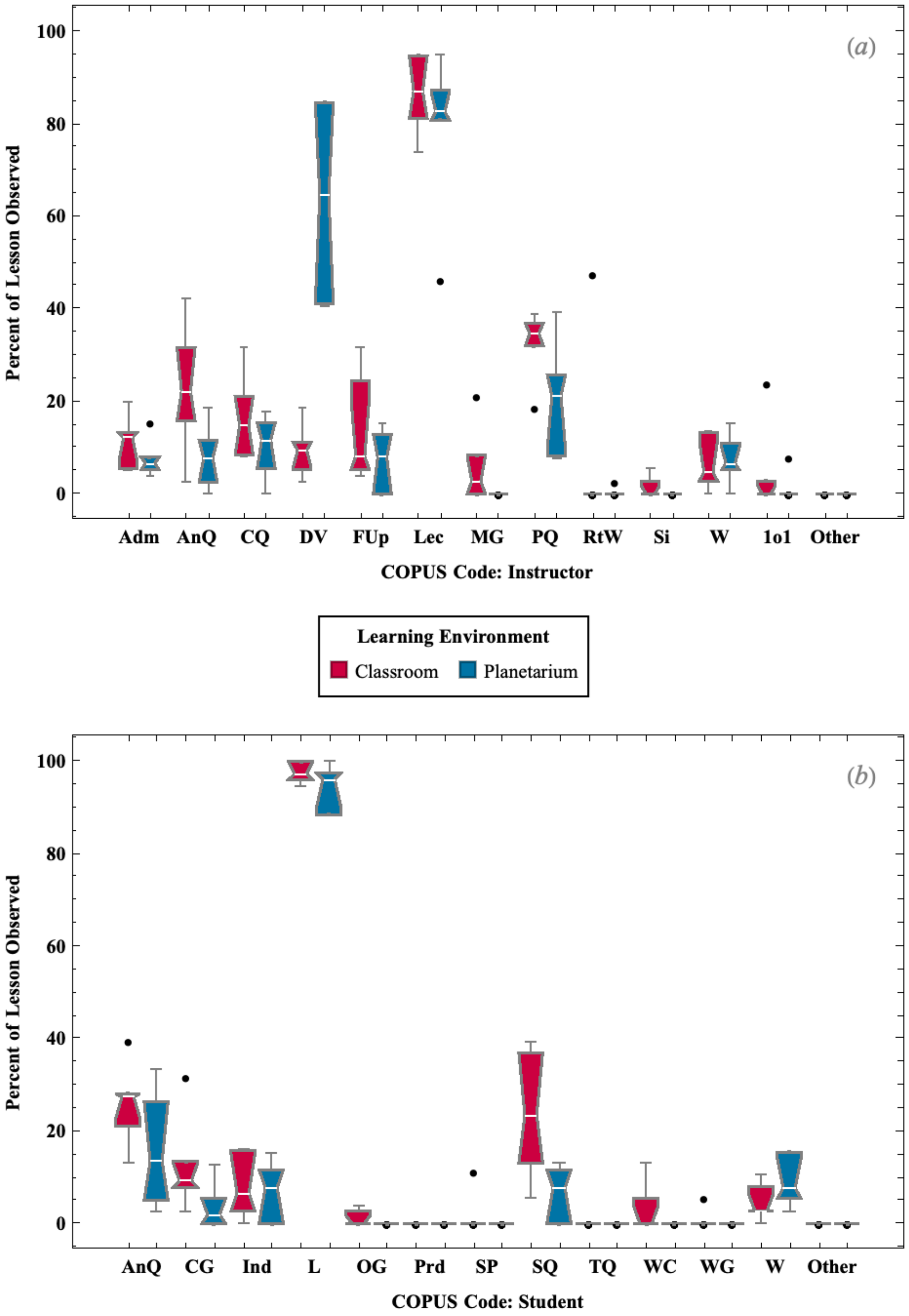
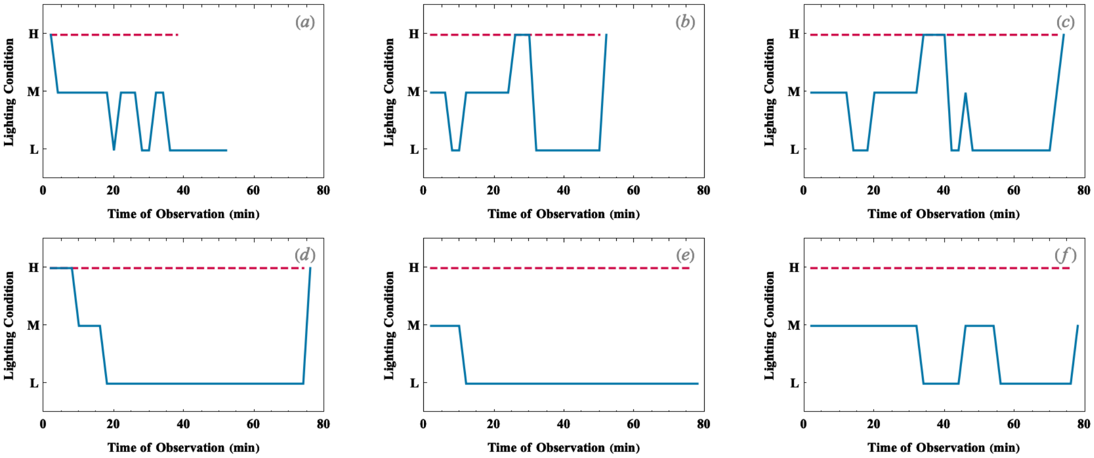


Figure 4.6: Time series of the lighting conditions during the COPUS observations (classroom: red dashed lines; planetarium: blue solid lines). Lighting conditions (H, M, and L) are described in Table 4.3. Classroom lighting shows no variability during the observed classes. Planetarium lighting shows variability, but no robust trend across the six observations is evident.



Finally, we turn our analysis to the environments themselves and how the classroom and planetarium spaces are distinct entities. During the course of our observations, the COPUS engagement framework was used to record illumination conditions in the observed environments (described above in Table 4.3 and in supporting text). Lighting conditions throughout the 12 observations demonstrated no pattern of interest in either environment (Figure 4.6.2.2). In the classroom environment (red dashed lines), the lighting condition never changes—all entire classes are held in high lighting conditions throughout. In the planetarium environment (blue solid lines), a variety of lighting conditions were recorded with lighting variability showing as little as one shift (panel (e)) to as many as seven shifts (panel (c)) in ambient illumination. In spite of the variance shown in our six planetarium observations, no real correspondence between lighting shifts and COPUS behaviors was observed—changes to lighting conditions appear to be too instructor-specific. Generally, lighting changes occurred when an instructor was attempting to engage interactive or active-learner strategies like a clicker question (CQ) or during a question/answer session (Figure 4.6.2.2, panels (a)–(c)). However, not all instructors raised the lighting conditions during occurrences of these behaviors and left the lighting conditions on low once the class had gotten underway (Figure 4.6.2.2, panels (d) and (e)). Excluding brief windows at the beginning and end of instruction (to facilitate learners finding/leaving their seats) and two periods in panels (b) and (c), lighting conditions never exceed medium, which in the observed planetarium is relatively bright, but low energy red lights around the perimeter of the planetarium dome (Table 4.3). These data did not point to instructors' consideration of lighting conditions towards a particular pedagogical strategy, per se, but rather towards maintaining a minimally disruptive lesson delivery. Lights were brought up-and-down only as necessary to facilitate the lesson delivery, but not always for all observed instructors. Examples of this included: bringing up lights to heighten visibility during lecture, bringing up lights to allow students to move to their seats or the door, and bringing lights down to enhance the visibility of the star projector or fulldome projectors. Of these examples, only the last one was rigorously observed in all six instructors.

Uniting these discussions, we confront our second research construct: discriminating between the classroom and planetarium environments. By-and-large, the two environments shared broad pedagogical process overlap, as is measured by our COPUS observations (Figure 4.6.2.2), survey responses (Figure 4.6.2.1), and interviews (Table 4.6). Instructors using the planetarium presented content with much the same procedure used in the classroom setting; however, COPUS behaviors indicative of interactive or active-learning strategies were significantly reduced. Interview responses placed more value on the classroom setting for cognitively rigorous course materials, such as those perceived as needing notes, calculations, or discussion. The planetarium is seen as helping learners via the immersive and animated visuals, providing visualization scaffolding not available in the classroom setting. However, both survey responses and interviews suggest that the cognitive aid of the planetarium is secondary to the affective goals, like engaging learners with material via the spectacle of planetarium presentation. Survey responses concerning class size (Figure 4.6.2.1), learner experience (Figure 4.6.2.1), and instruction frequency (Figure 4.6.2.1) suggest that the planetarium setting was perceived as more conducive to lower division learners. Coupled with the emergent cognitive-classroom/affective-planetarium value system described by users, planetarium use at the upper division, though clearly possible, might fail to achieve more widespread use as the environment is not perceived as helpful towards aiding experienced learners to meet course content goals.

4.6.3 Limitations of this Study

Lastly, we highlight the limitations of this study and their potentially adverse effects on our findings. First, the planetarium considered in this study is a partial outlier when one considers all the other planetariums available in the United States. The classes observed in this planetarium were quite large (100–200 students) when compared to the median class size of 30–40 students measured in Everding & Keller (2020) [77]. Additionally, the availability of audience response systems like Clickers in planetariums is not widespread, making this planetarium an outlier in interactive technology availability. This limitation is not as restrictive, given the portability of Clicker technology, but other studies that examine pedagogical implications of the planetarium may or may not have an audience response system available.

Secondly, this study relied on a "snapshot" approach to classroom and planetarium instruction, by using a single observation of each instructor in each environment. Such a strategy could unintentionally mischaracterize how instruction unfolds in either environment, however we believe we have reduced that danger by considering observed trends of the group of instructors as opposed to individual instructors. Additionally, the instructors in this study all made efforts towards using reformed practices, something which may not be commonplace on other campuses or collegiate planetariums. Moreover, the observation portion of this study had just six participants. As was discussed under "Construct 2," our statistical comparisons of behavioral differences should be taken with some care, as the low number of observation points makes rigorous statistical inference possible, but not as strong as if we had observed a larger number of instructor participants.

Finally, this study does not include a student/learner survey or interviews concerning either environment. Only COPUS data concerning the students observed and instructor-relayed information has information about the learners. The implied limitation is obvious—this study has limited information concerning the other half of the collegiate learning experience, leaving us to rely on alternate data implications, rather than relying on the learners themselves. As a practical matter, such a limitation is not surprising, as interviewing six instructors is markedly more feasible than interviewing approximately 900 students (assuming they all consented to be interviewed). However, it does represent a missing piece of information that a future study concerning the planetarium environment would be advised to make.

4.7 Theoretical Synthesis & Future Work

Using the LEPO framework [190], collegiate planetarium learning is attained in two complementary formal environments: the planetarium setting itself and the regular classroom setting. The learning processes in both environments share a high degree of similarity based on our COPUS measurements and can be broadly described as mostly instructor-centered with noteworthy inclusions of learner-centered pedagogical processes. Classroom processes make greater use of interactive and active-learner strategies like Clicker questions, peer-to-peer instruction, and group interactions. Assuming the classroom process template is the "usual" state of affairs, planetarium processes make predominant use of immersive visualization strategies at the expense of interactive and active-learner techniques used in the classroom. The reason for this exchange is the perceived incompatibility of the planetarium setting with interactive and active-learner techniques which rely on a degree of mobility by the instructor or their learners which is not feasibly attained in the planetarium theater. Outcomes in the two environments show a weak preference for an affective-favoring planetarium and a cognitive-favoring classroom.

Further observations using COPUS would better refine the implications of this study's "snapshot" approach at investigating planetarium use. Longitudinal observation campaigns following the same faculty instructor (or group of instructors) over multiple planetarium visits would provide additional points of observation as well as demonstrating how or if planetarium use changes over the course of a given academic term. We might propose to follow the advice from Smith et al. (2014) and unite the investigative power of COPUS with an instrument like the Teaching Practices Inventory (TPI), developed by Wiemann & Gilbert (2014), but modified to include planetarium-specific aspects [237, 265]. Such an observation/inventory combination would offer planetarium users or content developers a window into instructors' use of the planetarium space while also generating externally observed use practice catalogues with COPUS [237]. Additionally, by incorporating both instructor opinions and experience into such a study, it might be possible for any pedagogical innovations created as a consequence of such studies to diffuse more easily to other instructors, alleviating some of the slow pace of collegiate practice reforms [102, 185].

Our analyses suggest that there is a shift in pedagogical strategies between the two environments, with the classroom embracing more active learning strategies than the planetarium, which itself embraces immersion-visualization strategies. These two points leave us with two questions concerning if such an apparent exchange of strategies is necessary: (1) can the benefits of both interactive and immersive strategies be achieved in the planetarium environment; and (2) what is the correct "mix" of the two strategies to achieve the greatest learning outcomes? We suspect that the answer to the first question is "yes" [241], but we are uncertain as to the second. Future studies might focus their efforts on investigating how the effects of both pedagogical strategies can be maximized for formal collegiate learning, similar to the hybridization approach discussed in Swap & Walter (2015) [243].

4.8 Conclusions

A mixed-methods investigation combining an online survey instrument and in-class COPUS observation protocol campaigns has been completed as a western American university. Twenty-six faculty members with planetarium experience and 87 faculty members without planetarium experience completed an online survey measuring the characteristics and procedures of their planetarium use, or lack thereof. Additionally, six user faculty were observed in both the formal collegiate classroom and planetarium environments using the COPUS observation protocol [236], and were then interviewed about their classroom and planetarium instructional experiences.

Non-user survey responses suggest the existence of an ineffective or inefficient communication channel between non-user instructors, who might maintain an outdated conception of the planetarium's capabilities, and planetarium professionals including planetarium staff or content developers. Using the innovation-decision process tree presented in Rogers (2003), our analysis suggests that the first (knowledge) and second (persuasion) communication channels might not be effectively leveraged to inform non-user instructors of the potential materials and instructional benefits of the immersive planetarium space [207].

Survey responses from users suggest that planetarium lessons occur for both STEM majoring and non-STEM majoring learners, but said learners are mostly in the lower division. Content examples provided by respondents suggest that users attach value to the planetarium for both its older display capabilities (e.g., sky motions or Moon phases) and its newer display capabilities (e.g., immersive Solar System orrery or navigable galaxy model). Described learning outcomes in the planetarium and classroom environments suggest a weak dichotomy between the two, with the planetarium being valued as an affective outcome-stressing environment and the classroom as a cognitive outcome-stressing environment. Crucially, planetarium lessons are not considered as isolated or "one off" occurrences, and are seen as integrated into a course's overarching curriculum.

Interview responses from users suggest the existence of a broad framework for what makes a particular body of content "planetarium worthy," and thus worth the investment of time in the planetarium setting. Worthy content is visualization-based curricular materials that can be presented in both the classroom and planetarium settings. Presentation of worthy content in the planetarium leverages that space's projection capabilities to provide scaffolding aid for learners via immersion visuals and animation. Presentation in the classroom instead leverages that space's structural advantage promoting "regular" classroom activities like active-learner strategies and note-taking. Worthy content is thus perceived as needing student confrontation twice: once in a style that stresses a visual representation and once in a style that stresses a more abstract representation. The reported rate of same-instructor-same-course frequency in the planetarium combined with interview responses concerning planetarium lesson preparation suggest that user faculty may be unlikely to innovate outside an established pattern of planetarium worthy content. Additionally, interview responses suggest that the planetarium space itself is a hindrance to the application of active-learner strategies as the darkened environment and seating arrangements make navigating through the planetarium space difficult for instructors and learners.

COPUS observational data comparisons between the two environments suggest that planetarium instruction is broadly similar to classroom instruction, typified by a mostly instructor-centered lesson delivery with inclusions of learner-centered behaviors. The planetarium environment is the more passive of the two, based on the differences between behaviors typifying interactive or active-learning strategies measured by COPUS. Instructors exchange interactive instructional practices for immersive visual presentations when learning moves from the classroom environment to the planetarium. Use of immersive visualizations is varied across the observed planetarium lessons, with immersive fulldome content being shown approximately 40%–85% of the observed lesson. However, the implementation of interactive strategies does not reduce to zero in the planetarium, suggesting that instructors are attempting to merge the benefits of both interactive and immersive strategies while making as efficient use of the planetarium space as possible.

Chapter 5

Mars Obliquity Project

5.1 Foreword to MOP

The purpose of the following work was to explore a hypothesis concerning the planet Mars. As will be described in greater detail below, the planet Mars represents the union of two particular physical properties which make the planet a place of research interest to me: the astrophysical property of a wobbling planetary body and the geophysical property of a partially magnetized terrestrial world. Could the combined effects of these two have had a marked effect on atmospheric loss? Might this effect be important in the long-term habitability of the planet? These were the questions I confronted in this study.

Since the presentation of this work, additional data has been simulated to confront these same questions under a complementary physical scenario to the one described below. In this work, Mars' crustal fields were on the night side of the planet. In this new, additional data, the crustal fields were on the day side of the planet. The analysis of this new data continues (as of the submission of this dissertation) and will serve as a contextual counterpart to the study described below.

At the time of submission of this dissertation, the work described in this chapter was in preparation for submission to ***The Journal of Geophysical Research*** *for peer-review. This work will bear the formal title of "Obliquity-induced changes in simulated Martian heavy ion loss."*

5.2 Abstract

The effect of obliquity angle on heavy ion loss at Mars is described. A simulation campaign utilizing the Block-Adaptive-Tree Solar-wind Roe-type Upwind Scheme (BATS-R-US) multifluid magnetohydrodynamic (MHD) model for six idealized obliquity and interplanetary magnetic field (IMF) conditions is used to probe the changes to heavy ion loss from Mars with the strong remnant field on the night side of the planet. Calculations of escape in the planetary magnetotail of O^+, ${O_2}^+$, and ${CO_2}^+$ ions suggest a general decrease in heavy ion loss as the obliquity angle increases from 15° to 45°. Compared to a 25°, "present day" standard calculation, average ion loss varies by approximately 6.5% for O^+, 5.5% for ${O_2}^+$, and 24% for ${CO_2}^+$ over the simulated obliquity angle range. Modification of the near-Mars magnetotail could suggest an increased probability of nightside reconnection events at low obliquity angles when the crustal fields are impeding the smooth draping of IMF lines. Implications of loss reduction at high obliquities may suggest additional constraints concerning the formation and evolution of the early Martian atmosphere and surface.

5.2.1 Key Points:

- Heavy ion loss shows general decrease as obliquity angle increases for nightside crustal fields.
- Escape shows minor dependence on IMF orientation.
- Heavier species (${CO_2}^+$) are more sensitive to obliquity than lighter ones (O^+ & ${O_2}^+$).
- Obliquity-dependent behavior might offer additional constraints for early Mars evolution.

5.3 Overview of Mars

Mars has always been a source of mystery for humans on Earth. Like the other planets known from antiquity, Mars was one of the peculiar objects in the night sky that did not behave like the other stars, and its bright red color marked it as particularly special. The planet's size and distance from the Sun have long proposed that life as we know it (that is: carbon-based, water-requiring organisms) might arise on the Red Planet (see Melosh (2011) [174]). Naturally, Mars has always has enjoyed a certain mystique among human cultures and has often been the setting for works of science fiction, especially for works concerning the potential for alien life. Needless to say, the limits of Earthlings' imagination were summarily quashed as missions to Mars sent data back for analysis. A cursory survey of the Martian surface would identify a host of ancient aquatic features like canyons, river channels, lake beds, and shorelines. However, a similarly cursory survey would identify a distinct lack of liquid water anywhere on the surface, suggesting that while Mars might have looked like Earth in the ancient past, present-day Mars was little more than the desiccated remains of a formerly aquatic planet [245, 174].

Martian air, made mostly of chemically inert CO_2, is very thin, and surface pressures are typically no greater than 7 mbar. This extremely low air pressure makes the liquid phase of water unstable on the surface of Mars—any volume of liquid water splashed out onto the surface would quickly evaporate into the gaseous phase, leaving nothing behind to carve the host of aquatic features observed today. Estimations of the past Martian atmosphere suggested that as much as 1–2 bar of gas pressure was needed at the surface to sustain liquid water long enough to produce the present day landscape, thus it would seem that the Martian atmosphere needs to have been thicker in the past but has suffered some process that removes gas from the atmosphere [211].

In broadest terms, an atmosphere can be lost by two means: it can go down, being deposited onto the surface or chemically bound into surface minerals; or it can go up, being lost to interplanetary space (see Fig 1 in Lammer et al. (2013) for a more nuanced diagram [129]). In spite of the present day dry conditions, chemical analyses of the surface have found substantial reservoirs of both H_2O and CO_2 (in the form frozen glacial/permafrost deposits and of minerals like clays, sulfates, chlorides, and carbonates [178, 117, 74, 73]). However, these reservoirs are not estimated to contain enough material to account for the present day atmospheric conditions. Consequently, these underestimations of available surface or subsurface reservoirs suggest an additional explanation as to how present day Mars came to be is invoked: the Martian atmosphere has been (and continues to be) permanently removed to space [130, 211, 129, 146, 115].

5.4 The Loss of the Martian Atmosphere & Ionosphere

5.4.1 Atmospheric Escape Processes

The loss of a planet's atmosphere can occur through numerous physical mechanisms (Fig 5.1), all of which result in the same end effect: an atmospheric gas particle moving with sufficient velocity to escape a planet's gravity well [46, 211, 32]. These mechanisms are distinguished into two categories based on the way a potentially escaping particle is energized: thermal and non-thermal. The thermal mechanisms, Jeans escape and hydrodynamic escape, are consequences of thermodynamic and hydrodynamic energizing processes inherent to a thermal gas. Jeans escape is the slow, progressive loss of particles through the exobase, the "top" of an atmosphere where the gas behavior switches from a collisional to collisionless. At exobase altitudes, the minor number of gas particles from the high velocity tail of the gas' Maxwellian velocity distribution have enough kinetic energy to escape the planet's gravity well; since collisions at these altitudes are so rare, nothing will stop their escape and the atmosphere is slowly thinned. Presently, Jeans escape is the commonplace escape channel for the lightest gasses H and He from terrestrial worlds whose gravity is simply too low to ever restrict the escape of these gasses. Hydrodynamic escape is the collective escape of atmospheric particles as the gas is heated and accelerates itself into space as the gas "puffs out" due to the increased temperature. Because this escape mechanism involves collective flow of all an atmosphere's gasses, hydrodynamic escape is capable of removing atmospheric particles that would normally be incapable of Jeans escape due to their prohibitively large mass. The flux of lighter particles is capable of dragging heavier particles away with it via collision effects which energize the heavier particles to escape energy. In the present era, thermal escape from Mars is dominated by the Jeans escape of hydrogen—all other atoms are too heavy to be thermally energized to escape the planet in significant amounts [46, 211, 130, 32].

Non-thermal mechanisms encompass all other energizing processes which the above two do not describe. These are frequently electromagnetic in nature (even though both charged and neutral species can be removed) and result in providing a particle(s) with suprathermal energies (energy which cannot be attributed to thermal processes alone). At Mars, these mechanisms are: photochemical escape, sputtering, ion escape, and solar wind pick-up (Fig 5.1). Photochemical escape encompasses the processes that involve the creation of suprathermal particles via chemical or photoelectric reactions. These reactions are able to donate energy to heavy ion species via the severing of chemical bonds, producing particles that would otherwise lack the requisite energy to escape the planet [130, 211, 147]. Sputtering is a "sandblasting" effect, where particles are removed after being subject to a particularly energetic collision from a separate incoming energetic particle (e.g., those from the solar wind) [46, 211, 146]. Ion escape (or outflow) occurs when an accelerated ion is able to directly leave a region without being subject to any possible hindering effects—given the sensitivity of ions to any electric or magnetic field, this process occurs most prevalently when ions are accelerated along open magnetic field lines (discussed below), shunted through cusp regions, forced across magnetic field lines (triggering the $\vec{J} \times \vec{B}$ Hall term, i.e., the magnetic pressure and curvature forces), or lost in bulk removal scenarios where large volumes of ions are removed in impulsive events [46, 211, 146, 32]. Pick-up processes occur when an ion is generated in a location where an external magnetic field is moving past it. As it is not in the frame of the moving field, the ion feels the convective electric field of the mobile magnetic field and is accelerated into the same direction the external field is moving (it is "picked up" and carried away by the mobile field). Depending on where an ion is "picked up," it might be carried away from the planet or is forced to precipitate back into the atmosphere [130, 211, 146, 147].

5.4.2 The Martian Ionosphere

Clearly, ions and electrons are of critical importance for these removal mechanisms by virtue of their net electric charge, so a discussion needs to be had as to where these mechanisms are likely to occur: the ionosphere. Ionospheres mark the region in a planet's atmosphere where the ionizing effect of the Sun's high energy radiation (ultraviolet and X-ray) can meaningfully alter the composition of a planet's neutral atmosphere by creating a large population of free charge species—this population is numerically inferior to the neutral atmosphere, but nevertheless an important contributor due to the possibility of modification by outside electromagnetic forces. Ionospheres are usually described in terms of the free electron density (since all ions, regardless of species, will be accompanied by electrons), and are typically of greatest density at altitudes between 100–120 km at Mars. Above this "ionospheric peak," ion densities drop off exponentially as the originating neutral atmosphere continues to drop off exponentially with altitude. Which ion species compose an ionosphere is a question of what the underlying neutral atmosphere is made of. Counterintuitively, CO_2 dominated atmospheres do not produce predominantly ${CO_2}^+$ ionospheres. Rather, as has been measured at both Mars and Venus [46, 211], ${O_2}^+$ makes up the bulk of the ion species available, then ${CO_2}^+$ and O^+, a consequence of the preferential generation of ${O_2}^+$ through atom-ion interchange and charge transfers [46]. Figure 5.2 illustrates this with both simulation and spacecraft data for Mars [160]. In this work, contributions from minor chemical and ion constituents (like N_2 or NO^+) will be ignored and discussion will consider only the three named ions (O^+, ${O_2}^+$, and ${CO_2}^+$) as the species of interest.

Figure 5.1: Atmospheric loss processes at Mars. Interactions with solar radiation, solar wind, and eruptive solar events can trigger the removal of atmospheric particles from the Martian atmosphere. Removal processes affect both neutral (blue) and ionized (red) atmospheric particles. EUV: extreme ultraviolet; CME: coronal mass ejection; SEPS: solar energetic particles. Figure source: Laboratory for Atmospheric and Space Physics, MAVEN - STATIC (https://lasp.colorado.edu/home/maven/files/2011/03/Escape-processes.jpg).

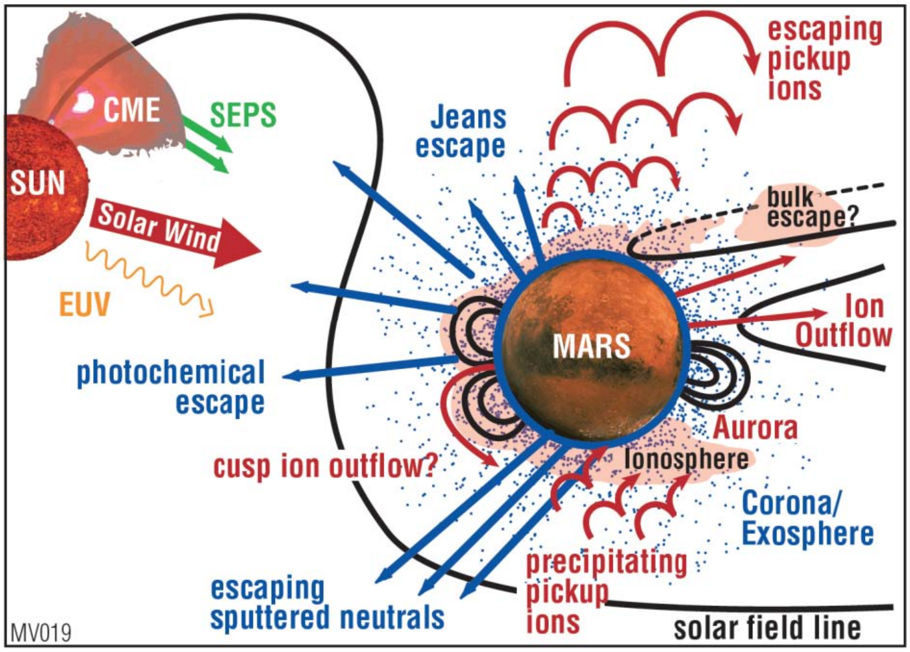
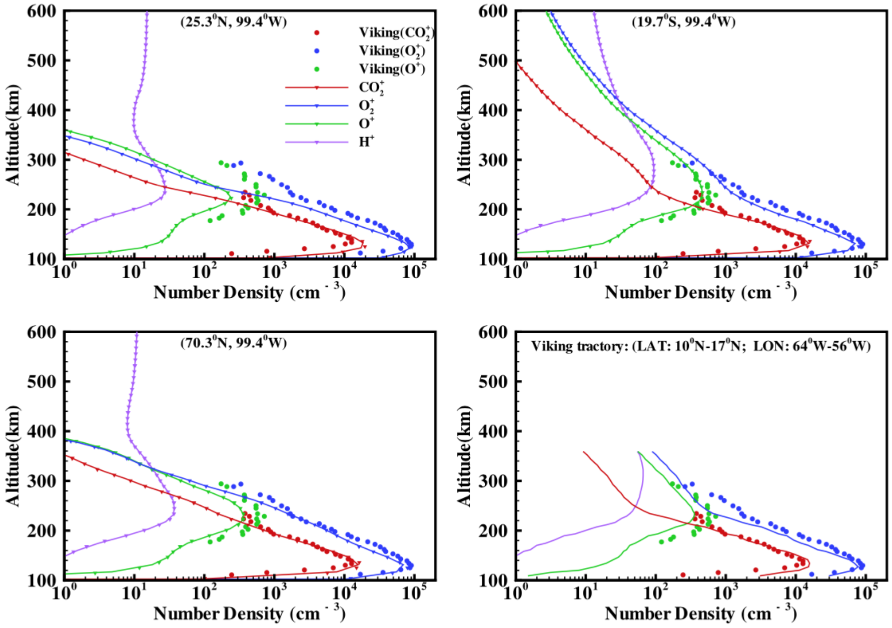


Figure 5.2: Ion density profiles for Martian ion species. Shown are comparisons between simulated atmospheric profiles (solid curves) and descent data from the *Viking* spacecraft (individual points). Simulated and observed ion species are specified in the legend in the upper left panel. Figure source: Figure 8, pg. 7, Ma et al. (2004) [160].



O_2^+ and CO_2^+ densities both follow an exponential decrease as the altitude increases away from the ionospheric peak. O^+ follows a more nuanced density profile due to a unique generation mechanism not shared by the other two ions. As mentioned above, the dissociative recombination of an ionized molecule is able to donate suprathermal energies to its constituent pieces. When this process happens to O_2^+, a pair of energized O atoms is created—these newly created neutrals fly away from Mars without regard for any electromagnetic forces. However, sunlight still permeates the space surrounding Mars, and there is a chance that these liberated O atoms can be ionized at locations well removed from the bulk ionosphere, creating an ion corona around the dayside of the planet. This O^+ corona extends the spatial availability (and range of removal mechanisms) of only O^+, but its existence relies upon O_2^+ [172, 60, 66, 55].

Due to the extremely low particle densities at ionospheric altitudes, the constituent particles of the atmosphere (whether neutrals or ions) do not collide with one another very often. As a consequence, the collisionally well-mixed atmosphere at low altitudes begins to diffusively separate at higher altitudes. What this means for the Martian ionosphere is that the heavy ion species largely behave separately from one another, with each acting like its own chemically unique ionosphere overlapping with the others. By virtue of their mass-dependent scale heights ($H = \frac{kT}{\mu g}$), ions like CO_2^+ ($\mu = 44.01$ amu) are more tightly bound to Mars than ions like O^+ ($\mu = 16$ amu) [46, 211], meaning that loss mechanisms may not affect all of an atmosphere's ion species equally, depending on where particular mechanisms are most effective.

5.5 The Martian Magnetosphere and the Remnant Crustal Field

5.5.1 A Comparison of Magnetospheric Archetypes

As a crude approximation, magnetospheres come in two general flavors: intrinsic (Earth-like) or induced (Venus-like). Intrinsic magnetospheres, like those enjoyed by Jupiter, Saturn, and crucially Earth (Fig 5.3, subfigure (a)), are characterized by an interaction between an internally generated magnetic dipole moment and the incoming solar wind. These actively generated magnetospheres are typically quite large in spatial extent (much larger than the planet generating them), and are able to fully encompass a planet's atmosphere and ionosphere in a single magnetic bubble, excluding two small polar regions where the intrinsic magnetic field lines emerge and reenter the dipole source. The comparative lack of "holes" leaves few points for the solar wind to attack a planet's atmosphere directly, and thus provide a functionally unbreachable shield against atmospheric loss via direct solar wind interaction. This near-complete defense comes from an intrinsic magnetosphere holding off the incoming solar wind well upstream of the planet by: (1) balancing the dynamic pressure of the solar wind with magnetic field pressure and (2) deflecting the stream of solar wind particles (protons and alpha particles) away from the magnetosphere via the Lorentz force [208].

Opposite to intrinsic magnetospheres, induced magnetospheres are characterized by a single, externally induced magnetic field and the incoming solar wind (Fig 5.3, subfigure (c)). Unlike intrinsic magnetospheres which could exist independent of the solar wind, induced fields exist as a consequence of the solar wind. When an unshielded conducting object (e.g., Venus' ionosphere) is subject to the approach of an external magnetic field (like the interplanetary magnetic field (IMF) in the solar wind), Maxwell's equations tell us that the change in magnetic flux through the conductor will force the generation of currents within the conductor in an attempt to cancel the effects of the initial incoming field [19, 208]. This generation of countercurrents within the conductor halts the unimpeded approach of the IMF and forces the incoming field lines to bend around the obstacle. This results in a draping of the IMF lines around the obstacle, producing a spatially small region (approximately the same size as the planet itself) where the now induced magnetosphere is only as large as it needs to be to stop the free passage of the solar wind. Induced magnetospheres push back against solar wind dynamic pressure through gas pressure—the conducting ionosphere generating the canceling currents is at its core a thermal gas that will attempt to puff out against the external pressure of the incoming solar wind [179, 25, 208].

Major structural landmarks of both magnetosphere archetypes are the bow shock, magnetosheath, magnetopause, and magnetotail, though the formation and location of each may differ between the two. First, the bow shock, denotes the location where the supermagnetosonic solar wind first "feels" the planetary obstacle and attempts to flow around the barrier rather than smash into it—the "front" of the planet's magnetosphere. Here, the solar wind begins a drastic slow down and compression (and commensurate heating) as the flow has to redirect itself around the planetary barrier. Behind this first landmark is the magnetosheath, the volume of space between the bow shock and the underlying magnetic obstacle the solar wind is trying to slip past. Magnetosheaths are populated by the shocked solar wind (mostly protons and alpha particles) and are denser than the unshocked wind just outside the bow shock. Underneath the magnetosheath is the magnetopause, the "official" barrier separating the region of solar wind dominance from the region of planetary dominance [179, 25].

Magnetopauses are where the two archetypes have their first practical difference. In intrinsic magnetospheres, the magnetopause is where the planet's internal dipole field completely halts the advance of IMF lines via magnetic pressure—the open field line configuration of the IMF lines switches to the closed field line configuration of the planet's dipole field. This region is also comparatively devoid of particles, as most of the planet's atmosphere is well removed from this region (For Earth, this "stand off" occurs about 10 Earth radii away in the direction of the Sun). In induced magnetospheres, the magnetopause is where the IMF lines have draped around the planetary obstacle, but may typically push no further into the obstacle due to the generation of countercurrents in the planet's ionosphere (described above). The strength of this boundary might become permeable to incoming IMF lines depending on the exact ionospheric conditions like ion density and conductivity—as the ionosphere becomes more conductive, the less penetration by the IMF occurs. Unlike intrinsic magnetopauses which are low in particle density, induced magnetopauses are comparatively high in particle density as it is this density that is responsible for generating the necessary countercurrents and gas pressure to hold off the incoming solar wind. This is also the region where the draped magnetic field lines run into each other, resulting in a region called a "magnetic pileup region." This pileup region extends down to the top of the planet's ionosphere where the pileup region is finally stopped by induced currents. The pileup region is the most important location in an induced magnetosphere, as it is here that the solar wind appreciably "meets" the planet's ionosphere and has access to a substantial population of ions [179, 25].

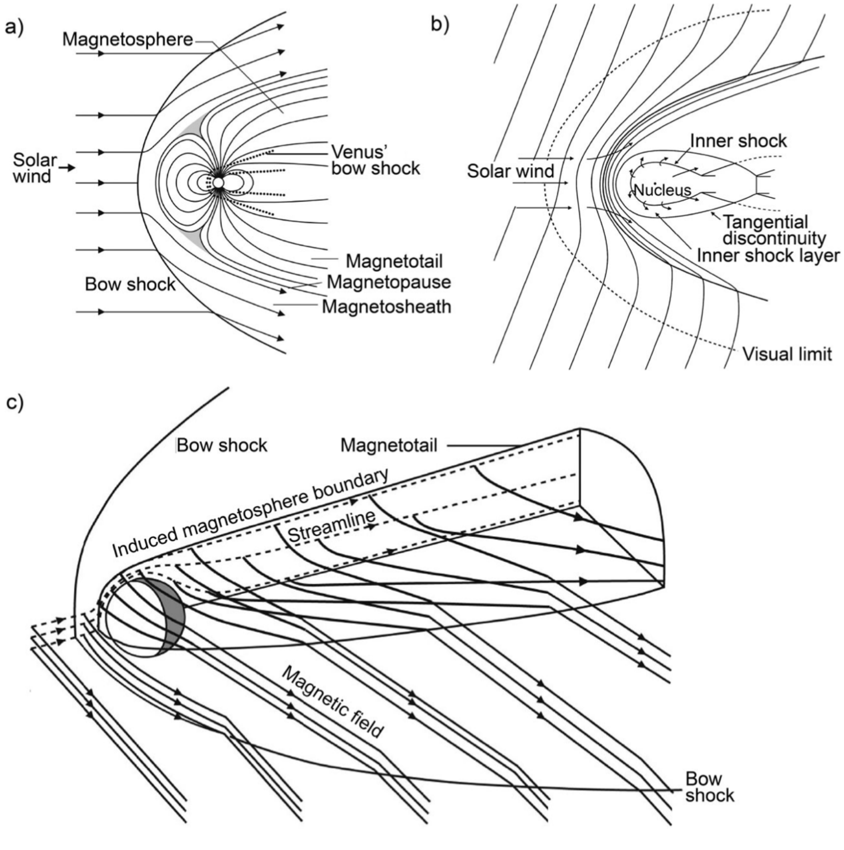
Finally, the magnetotail marks the last landmark of interest in the magnetosphere, representing the final location of interaction between the solar wind and the planetary obstacle. Here, the two magnetospheres have both similarities and differences. Both magnetotails are divided into to lobes, each with a magnetic field orientation opposite the other with a current sheet separating the two. Intrinsic magnetotails are sourced from the planet's dipole field, and the location and orientation of the magnetotail lobes depends on how the planet's intrinsic dipole is oriented. For

Earth, whose dipole is only slightly offset from the planet's rotation axis (by 11°), the two lobes are roughly separated by the planet's equatorial plane, with the northern lobe magnetic field pointing towards the Sun and the southern lobe magnetic field pointing away from the Sun. Induced magnetotails are sourced from the draped IMF, and the location of each lobe depends on the orientation of the IMF itself. For Mars, as the IMF is draped around the planet (Fig 5.3, subfigure (c)), the direction of the magnetic field in each lobe depends on how the IMF arrives at the planet. In the example magnetosphere shown in Futaana et al. (2017) [91], the dayside IMF (pointing towards Mars' dusk terminator) results in a nightside magnetotail with a "western" lobe pointing towards the Sun and an "eastern" lobe pointing away from the Sun. If the dayside IMF were reversed, so to would the magnetotail lobes. Both tails may also experience reconnection events when the two lobes are able to cross the current sheet separating them. In these situations, plasma in the magnetotail may be pushed out into the solar system or trigger the onset of an aurora event in the planet's atmosphere as particles precipitate back along the field line [252, 19, 25, 208, 91].

5.5.2 Mars: Somewhere In-Between

Unlike its two siblings, Mars does not fall neatly into either the intrinsic or induced magnetosphere descriptions due to the presence of the remnant crustal field anomalies dotting its surface. These anomalies were discovered relatively recently by the Mars Global Surveyor (MGS) spacecraft, which measured numerous magnetic fields jutting out of Mars' crust at orbital altitudes [2, 1, 53]. These crustal sources are not uniformly distributed around the planet, nor are they all of comparable strength with one another [2]—the largest and strongest crustal sources are located in the southern hemisphere, spanning the two classical regions of Terra Cimmeria and Terra Sirenum [1, 53]. Presently, these fields are believed to be remnants of an ancient internal dipole field that died out early in Martian history [1], held as permanent magnetism in iron-rich crustal material [53], from earlier in Mars' history when it had large scale tectonic activity like Earth [52]. The presence of these anomalies and their asymmetric distribution complicates the Martian magnetosphere to a point where it can not be easily categorized as either an intrinsic or an induced magnetosphere everywhere (Fig 5.4). Over the northern hemisphere, Mars is mostly magnetically barren [1] and the magnetosphere here closely resembles the induced magnetosphere described at Venus. However, over the southern hemisphere, Mars is a patchwork of crustal anomalies protruding out of an otherwise unshielded atmosphere [1], exhibiting force balances descriptive of both the terrestrial and Venusian archetypes, depending on exactly where one is measuring. Among the most critical of these is the crustal fields' ability to modify the magnetosphere's pileup boundary from below—the strong crustal fields are able to exert an outward pressure (much like Earth's global dipole field) and lift the pileup boundary off of the underlying ionosphere [56].

Figure 5.3: The two planetary magnetospheric archetypes: (a) Earth's intrinsic magnetosphere; and (c) Venus' induced magnetosphere. A scale replica of the Venusian magnetosphere in (c) is overlain on Earth's in (a). The cometary archetype (b) is not directly applicable for Mars due to the differences in formation between the Martian ionosphere and the cometary coma. Figure source: Figure 5, pg. 1460, Futaana et al. (2017) [91].



The resulting assemblage of magnetic fields means the ion escape channels discussed above take on a new level of nuance at Mars, because depending on where an ion is located, the kinds of forces available to move it may differ. In front of the planet in the dayside corona, O^+ ions are generated by the ionization of O atoms released by the destruction of ${O_2}^+$. ${O_2}^+$ and ${CO_2}^+$ are not numerous enough out here to worry about. O^+ ions are picked up by the solar wind and are accelerated back towards Mars by the convective electric field ($\vec{E} = -\vec{u} \times \vec{B}$). These pickup ions might escape around Mars into the tail region or they might impact the Martian ionosphere, possibly being lost or colliding with other particles [66, 55]. Closer to Mars, the extended ionosphere (containing all three ion species: O^+, ${O_2}^+$, and ${CO_2}^+$) is able to be accelerated away from the planet in a unidirectional plume structure, caused by the acceleration of the convective electric field carried by the solar wind. Here, the solar wind is still the dominant source of electromagnetic forces, as the induced magnetosphere has not formed enough to weaken the effects of the IMF. Once one reaches deeper into the magnetosheath (and eventually reaches the magnetopause) the effects of mass loading can become apparent as draped IMF field lines have access to Martian plasma of appreciable density. This is also the region where the Martian crustal anomalies come into play—as the most powerful localized source of magnetic field, crustal anomalies are able to hold IMF lines away from denser regions of the ionosphere, acting as "mini-magnetospheres" much like Earth's and keep the ionosphere beneath them safe. Additionally, for crustal fields on the dayside of the planet, the crustal fields are able to exert a global effect on the magnetosphere by pushing up the entire magnetopause However, the numerous crustal sources create a plethora of cusps and transition regions where IMF lines might find locations for reconnection events or where outflows might vent plasma into the upper ionosphere along crustal field lines [268]. As IMF lines try and pass through and around this region, the bend formed by the IMF draping induces a curvature force on ionospheric plasma which accelerates plasma away from the planet and into the magnetotail [208, 91]. Once in the magnetotail, ions continue escaping down the tail with the IMF lines. Some backflows and asymmetric structures can occur in the tail, but by and large once an ion has made it into the magnetotail a sufficient distance, it will escape permanently from Mars.

The location of these magnetic fields and their effect on heavy ion escape has been investigated before, oftentimes using a computer simulation (this work also uses simulated data, described below). As Mars rotates, the effects of the crustal anomalies rotate with the planet, changing their location relative to the incoming solar wind, modifying the escape of heavy ions by changing the underlying electromagnetic environment. Modelling efforts by Fang et al. (2010) proposed that escaping Martian ions are controlled by the location of electromagnetic fields in the ionospheric environment [80], and that the control exerted by crustal fields has global effects on heavy ion loss [81]. Lundin et al. (2011) considered this point directly using data from the *Mars Express* spacecraft—their findings suggested that Martian crustal fields impose a substantial barrier to the free movement of ionospheric plasma and can act as traps for dayside ions, preventing their transport across the terminator and into the magnetotail [156]. Most pertinent to this work, Dong et al. (2015) explored the dependence of heavy ion loss on crustal field position along with solar input conditions and Martian season by comparing the results from three different species of simulator. Their results suggested that, in addition to solar input and Martian season, crustal fields generally reduced heavy ion outflow when on the dayside of the planet by diverting the flow of dayside plasma towards the nightside and down the magnetotail [156, 65]. The findings were supplemented Fang et al. (2015), who directly examined how the time dependence of the Martian crustal field anomalies impacted the flow of ions around the planet. In their findings (which will be discussed in greater detail below with our own), the motion of the crustal anomalies between the nightside and dayside of the planet during one planetary rotation has a significant effect on the ion loss rate. When on the day-night terminator, crustal anomalies open a “vent” down the flank of the planet by pushing up the underside of the induced magnetosphere and increasing the cross-sectional area that dayside ions might flow through to the nightside [35, 82]. In general, Martian crustal fields appear to provide a protective barrier against unimpeded ion loss, but under some circumstances these fields might comparatively increase ion flow.

5.6 The Evolution of Martian Obliquity

Over the course of thousands to millions of years, gravitational interactions between the Solar System's masses in the form of resonant orbits, spin-orbit resonances, aligned precession rates, and net torques provide minuscule shifts in a planet's Keplerian orbital elements (eccentricity, inclination, etc.) and planetary elements (obliquity, precession, and rotation) [196, 26, 133]. These interactions build upon one another, imperceptibly during the course of the human lifetime, and ultimately lead to the chaotic evolution of a planet's various elements. Mars is no exception to this chaos, and the planet's unique situation within the Solar System might make it particularly vulnerable to wild behavior over comparatively short time frames. Of particular importance for this work is the variation in obliquity, the angle made by a planet's rotation axis and the normal direction of the orbital plane.

Obliquity, also called "axial tilt," is paramount among the planetary parameters in describing how a planet's surface and atmosphere interact with the Sun. Obliquity determines how solar energy is distributed over the sunlit side of a planet, and effects the physics of both the lower and upper atmosphere by forcing a preferentially deposition of energy on one side of a planet. On Earth, obliquity is the ultimate source of the seasonal cycle, resulting from the unequal absorption of sunlight at the surface between the Northern and Southern hemispheres. Climatological records like ice core samplings tell us that, by and large, Earth enjoys a comparatively well-behaved obliquity cycle, varying between 22.0° and 24.6° over the recent geological past. Currently, Earth is inhabiting a middling value of 23.3° [137]. Earth's rather small obliquity variance comes principally from the presence of the Moon. Lunar gravity acts to alter Earth's rate of precession (how quickly Earth's north pole points somewhere else in space), consequently stabilizing the terrestrial obliquity against any wild swings towards minimal or maximal axial tilt [137, 58].

Mars does not have a satellite like the Moon—Deimos and Phobos, a pair of very small asteroidal bodies, are far too small to exert the same kind of stabilizing effect on Mars, leaving the planet at the mercy of the rest of the Solar System [135]. Mars is also not the most massive terrestrial world, weighing in at roughly one-half Earth masses—smaller planets are generally easier to perturb compared to heavier ones. Compounding the problem, Mars is noticeably oblong: it's southern hemisphere is areographically higher than its northern one, and tectonic features near the Martian equator (particularly the Tharsis igneous province) give the planet a uniquely pronounced moment arm for gravity to act upon [234, 173, 168]. Further compounding the problem, changes in volatile mass distribution and the unknown characteristics of Mars' interior add poorly constrained parameters to the Martian system [27]. Combined, these north-south, east-west, and volatile mass asymmetries result in comparatively more pronounced moment arms for gravity from other masses to pull on. The sum of these interactions wreaks long-term havoc on the planet's axial tilt—Martian obliquity could be described as one of long-term chaotic behavior with short-term periodic (or quasi-periodic) behavior superimposed upon it. The stability of this short-term cyclic behavior was originally estimated to be as short as 1 Myr [259], but better calculations have since refined these estimations to be about 10–20 Myr [263, 247, 136].

5.7 Synthesis & Definition of Research Questions

Uniting the points of fact discussed above lead to the establishment of the following three-part framework. First, Mars possess numerous fossilized features on its surface indicative of a warmer, wetter, and more hospitable past that can only be reasonably explained through atmospheric loss. Currently, the necessary atmospheric loss to produce present-day Mars requires the loss of heavy atmospheric gasses to interplanetary space through erosive interactions with the solar wind. Second, Mars' magnetosphere exhibits particular asymmetries not found in other "pure" magnetosphere archetypes like Earth or Venus. Studies investigating the effects of the crustal field on the erosion of the upper atmosphere strongly suggest that the crustal field has a significant effect on the loss rates and escape processes involved in the removal of an atmosphere via heavy ion loss. Third, Mars' astrophysical evolution, vis-à-vis its obliquity cycle, suggest a wide variability in possible orientations of the planet during its lifetime. While calculations are still unable to describe Martian obliquity over the entire 4.5 billion year lifetime of the planet, solutions concerning Mars' recent geological past provide a reliable range of possible obliquity angles likely enjoyed by the planet. Combining these three leads to a necessary consideration which has heretofore not been explored: which effects, if any, does the Martian obliquity cycle impart on the atmospheric loss rate of the planet as is measured by the loss of heavy ion species (O^+, ${O_2}^+$, ${CO_2}^+$), given the asymmetric distribution of crustal field sources and the natural variability in the solar wind. This guiding point is punctuated by four primary research questions which will guide the following analysis and discussion:

(1) Which changes to heavy ion loss are incurred as the Martian obliquity angle changes, if any, and why?

(2) Which changes to the general structure of the Martian magnetosphere-solar wind interaction are incurred as the Martian obliquity changes, if any, and why?

(3) What implications about the historical loss of the Martian atmosphere are implied by these findings and why?

(4) What generalizations about planetary atmospheric evolution can be made by using the varying obliquity of Mars as a case study?

We make a special note here about a particular side effect of changing the Martian obliquity that we did not implement in this study: the alteration of the underlying Martian neutral atmosphere as the obliquity angle is changed. Milankovitch first showed that Earth's climatic history is inherently tied to the planet's astrophysical history—geological data recording ice ages in Earth's recent past were shown to be strongly correlated with Earth's cycles of precession, nutation, and eccentricity [111, 23, 112, 137]. Mars should behave no differently [260], and glacial depositional features on Mars are speculated to record the same paleoclimatic information in the Martian polar regions [138]. As mentioned above, Mars possesses a thin, carbon dioxide atmosphere which grows and shrinks over the course of the Martian year as the global temperature rises and falls with the planet's eccentric orbit. Obliquity changes also trigger global temperature shifts, with high obliquity conditions corresponding to increased surface temperatures everywhere on the planet, thus it stands to reason that Mars should have a different underlying neutral atmosphere in our simulations when the obliquity angles are high as the volatile carbon dioxide ice sublimates back into the gaseous phase [262]. By the estimations presented in Ward et al. (1974), shifting between the 15° and 35° obliquity values could results in an approximately 100 times increase in the surface air pressure [262]. Numerical simulations by François et al. (1990) propose that the entire solid reservoir of CO_2 might be destroyed at high obliquities, dumping all available gas into the atmosphere [89]. Calculations by Haberle et al. (1994) [95] and Jakosky et al. (1995) [114] further expounded on the possibility of an increase in the Martian atmosphere by considering how the sublimation of carbon dioxide allows for the sublimation of water ice, suggesting that high obliquity conditions could significantly increase the quantity of atmospheric particles as the two volatile substances retake gaseous form. Simulation campaigns of Mars general circulation models (MGCM's) come to a similar conclusion, suggesting temperature variation of approximately 50 K at the surface [219], and that the increase of available atmospheric gas could provoke greater dust storm generation [94].

The implied changes to the Martian neutral atmosphere, while likely resulting in a more accurate study, represent corrections that were too prohibitive to incorporate. The implied changes would require assuming particular evolution schemes for the Martian volatile compounds that may or may not be true, or may require invoking particular volatile sources or concentrations in order to "correct" the underlying neutral atmosphere for each iteration of this study. We have omitted "correcting" the underlying neutral atmosphere for each simulation case and utilized the same Martian atmosphere in each case. The simulated ionosphere "naturally" adjusts to the change in obliquity (solar zenith angle dependent calculations, the location of magnetic fields, etc.), but the underlying neutral atmosphere remains the same across the six simulations.

5.8 Methods & Investigation

For this study, we implemented a suite of six performed simulations using the BATS-R-US (Block-Adaptive-Tree Solar-wind Roe-type Upwind Scheme) simulator for multi-fluid magnetohydrodynamics (MHD). This simulator has been described in detail in Najib et al. (2011) [180], however we offer a summary of the simulator's features here. BATS-R-US solves the below equations governing the conservation of mass (5.1), momentum (5.2), and energy (5.3) for each ion species, "s," included in this study (O^+, ${O_2}^+$, ${CO_2}^+$):

$$\frac{\partial \rho_s}{\partial t} = \nabla \cdot (\rho_s \vec{u}_s) = S_{mass_s}, \tag{5.1}$$

$$\frac{\partial \rho_s \vec{u}_s}{\partial t} + \nabla \cdot (\rho_s \vec{u}_s \vec{u}_s + \mathcal{I} P_s) = n_s q_s (\vec{u}_s - \vec{u}_+) \times \vec{B} + \frac{n_s q_s}{n_e e}(\vec{J} \times \vec{B} - \nabla P_e) + \vec{S}_{momentum_s}, \tag{5.2}$$

$$\frac{\partial P_s}{\partial t} + \nabla \cdot (P_s \vec{u}_s) = -(\gamma - 1) P_s (\nabla \cdot \vec{u}_s) + S_{energy_s}. \tag{5.3}$$

For a particular ion species "s," ρ_s, n_s, q_s, $\vec{u}_s$, and P_s are that species' mass density, number density, electric charge, velocity, and gas pressure, respectively. $\vec{B}$ and $\vec{J}$ are the magnetic field and electric current density, $\mathcal{I}$ is the identity matrix, e is the electron charge, and γ is the ratio of specific heats (assigned as 5/3). The electron pressure (P_e) in equation 5.2 is not separately solved for in this simulation and is assigned to equal the ion pressure. Governing the evolution of the magnetic field, the induction equation (5.4) used is expressed as:

$$\frac{\partial \vec{B}}{\partial t} - \nabla \times ((\vec{u}_+ - \frac{1}{n_e e}\vec{J}) \times \vec{B}) = 0, \tag{5.4}$$

where $\vec{u}_+ = \frac{1}{n_e e}\sum_s n_s q_s \vec{u}_s$ and $n_e = \frac{1}{e}\sum_s n_s q_s$. The source terms for mass, momentum, and energy of a particular ion species "s" are:

$$S_{mass_s} = S_s - L_s, \tag{5.5}$$

$$\vec{S}_{momentum_s} = \rho_s \vec{g} - \rho_s \sum_{t=neutrals} \nu_{st}(\vec{u}_n - \vec{u}_t) + S_s \vec{u}_n - L_s \vec{u}_s \tag{5.6}$$

$$S_{energy_s} = K_{energy_s} + V_{energy_s} + G_{energy_s}, \tag{5.7}$$

such that:

$$K_{energy_s} = 2 \sum_{t=neutrals} \nu_{st} \frac{m_s}{m_s + m_t} n_s k(T_n - T_s) + 2 \sum_{t=ions} \nu_{st} \frac{m_s}{m_s + m_t} n_s k(T_t - T_s), \tag{5.8}$$

$$V_{energy_s} = \frac{2}{3} \sum_{t=neutrals} \nu_{st} \frac{m_s m_t}{m_s + m_t} n_s (u_n - u_s)^2 + \frac{1}{3} S_s (u_n - u_s)^2, \tag{5.9}$$

$$G_{energy_s} = k \frac{S_s T_n - L_s T_s}{m_s} + \frac{n_s}{n_e} k \frac{S_e T_n - L_e T_e}{m_e}; \tag{5.10}$$

where S_s and L_s are the production and loss rates for ions (subscripted e for electrons); $\vec{g}$ is the local gravitational acceleration; T_s and m_s are the ion temperature and mass; T_n and u_n are the neutral temperature and velocity; m_e and k are the electron mass and Boltzmann's constant; and ν_{st} is the collision rate between colliding species s and t. Additionally, the energy density, $U_s = \frac{1}{2}\rho_s u_s^2 + \frac{P_s}{\gamma - 1}$, of species "s" evolves according to:

$$\frac{\partial U_s}{\partial t} + \nabla \cdot ((U_s + P_s)\vec{u}_s) = (\frac{n_s q_s}{n_e e}(\vec{J} \times \vec{B} - \nabla P_e) + n_s q_s(\vec{u}_s - \vec{u}_+) \times \vec{B}) \cdot \vec{u}_s + S_{U_s}, \tag{5.11}$$

where S_{U_s} is the energy source term. The energy density is critically important for the calculation of shocks, which are normally not captured in non-fluid style simulators [180]. Additional sets of equations governing the evolution of planetary protons and solar wind protons (H^+) were also included to complete the necessary calculations; however, these two ion fluids were not included in this study. Hydrogen (H) escapes easily, and principally, from the Martian atmosphere through thermal Jeans escape as neutral atoms [32], thus we do not consider protons in our analysis of obliquity dependent escape. The inclusion of the Martian crustal magnetic field is made using the spherical harmonic representation described in [8]. The simulator solves these equations in MSO (Mars-Solar-Orbit) spherical coordinates (Fig 5.5) using a variable spherical evaluation grid centered on Mars—solutions are converted to MSO Cartesian coordinates during output.

Figure 5.4: Magnetogram of the radial component of Mars' remnant crustal field, constructed from magnetometer data from the Mars Global Surveyor spacecraft. The north-south and east-west asymmetries are readily apparent, with the strongest magnetic sources localized in the south-eastern quadrant of the Martian crust. Figure source: Figure 3, pg. 792, Acuña et al. (1999) [1].

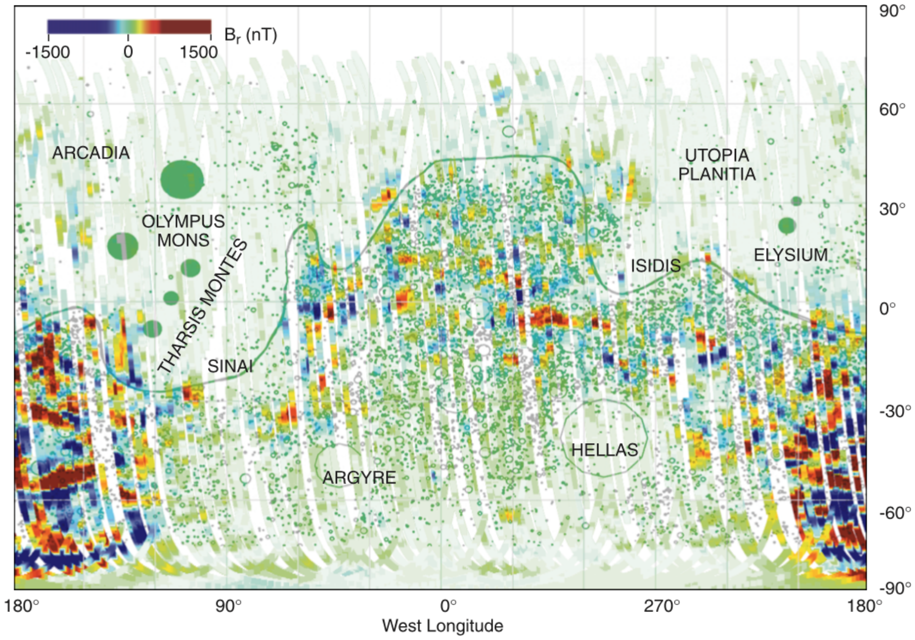
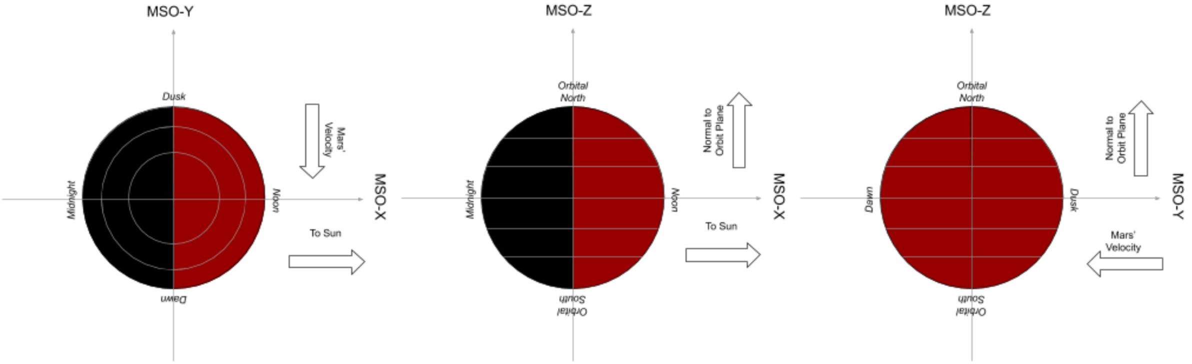


Figure 5.5: Mars-Solar-Orbit (MSO) coordinate system of the BATS-R-US simulation, displayed as the three two-dimensional coordinate planes (XY, XZ, and YZ). MSO-X is along the line connecting Mars to the Sun, MSO-Y is antiparallel to Mars' instantaneous velocity, and MSO-Z completes the right-handed coordinate set, pointing parallel to normal for Mars' orbital plane. Mars' sunlit hemisphere is colored red—a latitude grid for MSO is superimposed on Mars in gray. Landmark positions (denoted by italic script) for each of the three coordinate directions are specified: Noon-Midnight (MSO-X); Dawn-Dusk (MSO-Y); and Orbital North-Orbital South (MSO-Z).



The simulation domain extends from $-24R_M \leq X \leq 8R_M$, $-16R_M \leq Y \leq 16R_M$, and $-16R_M \leq Z \leq 16R_M$ and is solved using Mars-Solar-Orbit (MSO) coordinates. The MSO coordinate system is a three dimensional Cartesian system defined as follows: the MSO-X axis is directed along the line connecting the center of Mars to the Sun (positive X values are towards the Sun); the MSO-Y axis is directed along the direction anti-parallel to Mars' instantaneous orbital velocity (positive Y values are "behind" the planet as it orbits around the Sun); and the MSO-Z axis completes the right-handed set, and is directed towards along the normal direction of Mars' orbital plane (positive values are "up," pointing in the same general direction as Martian areographic north). This system can be seen in Fig 5.5, where the three axes are shown in the three primary coordinate planes. Landmark locations on the planet along each of the three axis can be seen in Fig 5.5, identified with italics: the noon-midnight line contains the MSO-X axis, the dawn-dusk line contains the MSO-Y axis, and the orbital north-orbital south line contains the MSO-Z axis. The expansive simulation domain ensures that regions of meaningful interest near the simulated Mars are independent of the outer simulation boundaries [158].

The experiment is shown schematically in Fig 5.6, where the two variables of interest are the obliquity angle (θ) and the IMF orientation (ϕ). For this experiment, the changes in obliquity lean Mars "back," with the northern hemisphere experiencing its winter season and the southern experiencing its summer season. For all six simulations (Table 5.1), the crustal magnetic field sources were on the night side of Mars, with the strongest field sources projecting into the negative MSO-X (midnight) direction. The upstream solar wind had a velocity of 486 km/s in the $-X$ direction with a particle density of $2.7\,cm^{-3}$; solar conditions were set to solar moderate for all six simulations. The upstream IMF was a 3 nT, 57° Parker spiral field with two orientations, depending on the simulation: spiral-out ($< -1.634, 2.516, 0 >$ nT) and spiral-in ($< 1.634, -2.516, 0 >$ nT). Implementation of the numerical procedure followed that presented in Najib et al. (2011)—a non-uniform spherical grid was used, with radial resolution varying from 10 km (near the lower boundary) and 630 km (at the outer boundary). Angular resolution varies from 1.5° to 3.0° degrees in the MSO latitude/longitude angular directions [180]. The lower boundary condition was enforced at 100 km altitude above the surface of Mars ($\sqrt{X^2 + Y^2 + Z^2} = 1$ in MSO coordinates)—here, the three heavy ion densities (O^+, ${O_2}^+$, ${CO_2}^+$) were set to be equal to their photochemical equilibrium values. Additionally, the lower boundary enforced a reflective boundary condition for the velocity field, such that velocities near the lower boundary would not pass below the 100 km altitude limit [180].

As with other MHD simulators, the motions of individual plasma particles are assumed to be negligible, and the choice of the fluid approximation means that this experimental setup tacitly assumes fluid characteristics for the simulated ion species everywhere in the simulation domain. For plasma dynamics, this means that scale length for calculations (the resolution of the local grid) must be much larger than the gyroradius of a given ion species ($r_g = \frac{mv_\perp}{qB}$) [141], the scale height of the atmosphere, or the spatial variability of the crustal fields. In the real world, this assumption for the Martian plasma environment is not ironclad, and there are situations in the environment where the fluid approximation does not *technically* hold as individual particle motions become a roughly equal (or more dominant) dynamic than fluid ones. In the upstream direction, the gyroradius of O^+ is larger than the planet Mars (radius of 3390 km), meaning individual particle motions are more important than bulk fluid ones (the situation would be worst for ${O_2}^+$ and ${CO_2}^+$ due to their larger mass). Lower in the Martian atmosphere, both the atmospheric scale height (approximately 44, 22, and 16 km for O^+, ${O_2}^+$, and ${CO_2}^+$, respectively) and the spatial variance of the crustal fields (approximately 100 km, see Fig 5.4 [1]) are both of the same numerical order as (or greater than) the 10 km radial resolution of the simulator. As a consequence, the accuracy of the fluid approximation is certainly strained, but not completely broken in these regions.

That being said, regions such as these do not unduly hamper the simulator from providing reasonable results. Most of the ions in the simulation are in the near-Mars environment, where the fluid approximation holds more reliably—generally speaking, the lower flow velocities and stronger magnetic fields near Mars (including the magnetic pileup region [180]) can keep ion gyroradii small. Additionally, this simulation style also treats each ion species as a separate fluid, preventing the various species from blurring their individual behaviors together as one bulk fluid—situations where O^+, ${O_2}^+$, and ${CO_2}^+$ each break or adhere to the fluid approximation are more accurately captured than if one used a single ion fluid [141, 180]. Thus, the choice of multifluid MHD simulation does set aside certain physics that more accurately describes the plasma interaction at Mars [141], but the assumptions inherent to the simulation do not unduly hamper its use as an investigative tool for processes like global ion escape [141, 34, 180].

Figure 5.6: Schematic of the MOP experimental setup. For each simulation run, an obliquity angle (θ) and IMF orientation (ϕ) is selected and the simulation runs until steady-state convergence. The solar wind (yellow arrow) carries the IMF lines (purple rays) and convective electric field (not shown) into the negative MSO-X direction where it encounters the Martian obstacle.

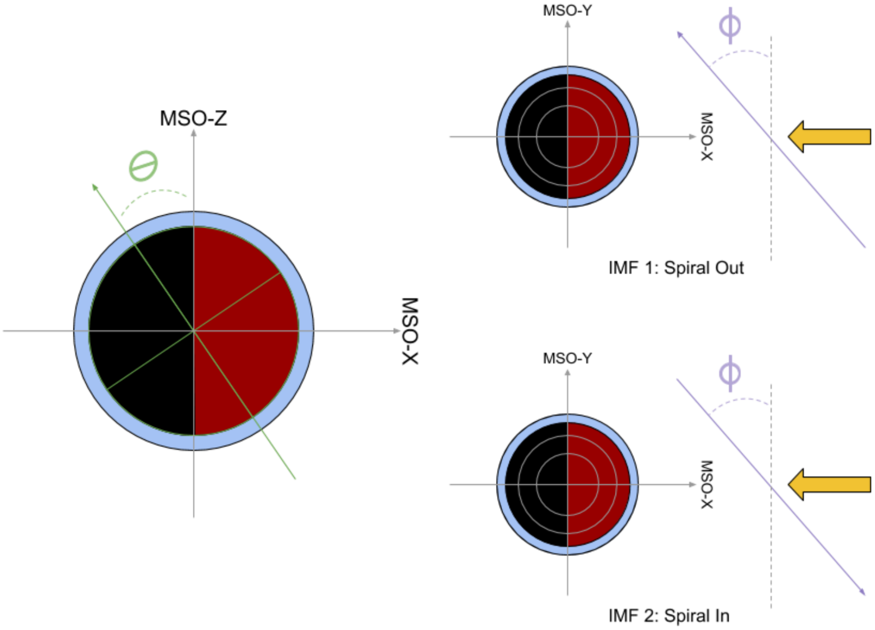


Table 5.1: The six simulations in this experiment, expressed as combinations of the parameters of interest. In each simulation specified in the right hand column, an obliquity angle (middle column) and IMF orientation (left-hand column) is set and the simulator is run to convergence. Obliquity angles result in Mars "leaning back" from the Sun, such that the southern hemisphere is more directly in the subsolar region.

Simulation Number	**Obliquity Angle (degrees)**	**IMF Orientation**
1	15	3 nT, Spiral-Out
2	15	3 nT, Spiral-In
3	25	3 nT, Spiral-Out
4	25	3 nT, Spiral-In
5	45	3 nT, Spiral-Out
6	45	3 nT, Spiral-In

The choices of obliquity parameters were taken from Laskar et al. (2004)'s study using an update obliquity calculation and statistical studies meant to extend their precise calculations into a probability space that would describe the planet's obliquity cycle over the life of the Solar System [136]. However, we decided that restricting our considerations to the more precisely calculated obliquity extremes indicative of the recent geological past were more reasonable to use and the 15° minimum and 45° maximum were chosen as the two simulation bookends. The present day value of 25° was included such that any derived results would have a meaningful point of comparison with current calculations. The choices of IMF parameters were taken from other MHD studies simulating the effects of the solar wind—the decision to switch the IMF orientation between pairs of simulations was made based on both observation and simulation data showing the Martian magnetosphere's sensitivity to the externally imposed IMF conditions [37, 68, 182].

5.8.1 Limitations & Caveats of this study

Critical to the context of the following results is a consideration of the parameters that were not chosen to vary in the simulation runs. First, this simulation was run in steady state mode—the simulated Mars was "frozen" in space and not allowed to rotate. Such an enforced modeling constraint was a practical experimental choice to make—other simulation studies (e.g., Ma et al. (2014) showing a small time lag between dynamic pressure enhancements and changes in ion escape

[157]) have made a similar choice and their results were not unduly hampered by doing so. But, due to the asymmetric distribution of crustal magnetic sources, the effect of Mars' rotation should impart effects on the calculated ion loss not captured by these calculations as the crustal field rotates between the dayside and nightside of the planet. Fang et al. (2015) explored this effect by expressly comparing a set of steady state runs (each with a different orientation for the simulated Mars) to a continuous, time-dependent simulation [82]. In that study, steady-state calculations (like those presented below) reliably underestimated ion loss when compared to the time-dependent simulation calculations for similar parameter conditions. The discrepancy between the two calculations was most pronounced for O_2^+ and CO_2^+ (time-dependent producing approximately two-times the ion loss compared to steady-state), with O^+ showing little difference between the two simulation styles (practically no difference between the two styles) [82]. Additionally, recent simulation results by Ma et al. (2019) point to the importance of the electron pressure gradient (and corresponding ambipolar electric field; ∇P_e in equations 5.2 and 5.11) as an important source of energy for escaping ion species, with the inclusion of the ambipolar field amplifying ion loss from 50–110%, depending on exact model conditions [162]. The model style used here does not include a separate electron pressure calculation [180], so this mechanism is missing from these results.

The choice of our multifluid MHD simulation has precluded the consideration of particular physical processes that could not be described using the multifluid approach [34]. Chief among these were magnetic reconnection events, the union between the open IMF lines carried by the solar wind and the closed crustal field loops on Mars. Such events could be critical to ion escape, as the temporary joining of IMF and crustal fields could provide intense energy to ion species (released during the instant of field-line reconnection), possibly provoking greater escape. Additionally, reconnection events offer a temporary flow path for plasma attached to closed crustal field lines to leave the Martian ionosphere and escape down the tail by connecting the two magnetic regions. Per the orientation and extent of the regions of magnetic reversal shown in Figs 5.19 and 5.20, low obliquity scenarios might offer the greatest opportunity for nightside reconnection events as the draped magnetic field line encounters opposing lines from the crustal field or cusp regions were reconnection might be more likely to occur [37, 36, 33, 145, 38]. Additionally, the various spatial scales for the Martian magnetosphere (e.g., species-dependent cyclotron radii) made the fluid approximation in MHD a functional, but not completely physically accurate representation of the physical system. The combined effect of Mars' smaller physical radius and the weaker IMF magnitude mean the Martian magnetic obstacle is too small for the multifluid MHD approximation to hold everywhere reliably all the time [91]. Lastly, our choice of a BATS-R-US model precludes the addition of a reliable error estimation scheme for our calculated results. As the model self-modifies the spatial scales needed for calculation based on internally generated criteria [197], the results lack a meaningfully generalizable “yardstick” against which they could be compared save actual real-world data. While such comparisons to real-world data have upheld the model's accuracy (e.g., Ma et al. (2015) [161]), we do note here that these results should be read with appropriate sobriety as to their presumed accuracy.

This study ignored the changes to Mars' other planetary parameters, each of which might meaningfully alter the simulated planet's steady-state ion loss [65]. Eccentricity and the argument of periapsis would likely be the most important of these, as these parameters controls how much energy is available to be absorbed by a planet and how the crustal field obstacle would be facing the solar wind at a particular spot along the planet's orbit. The combined effect of these two parameters might add or subtract from the obliquity-induced ion loss changes described below, depending on how each of them cycles with respect to one another. For example, a high obliquity planet might have its preference for ion retention partially counteracted by a more eccentric orbit as the increase in energy input by moving the planet closer to the Sun amplifies loss mechanisms. Similarly, our calculations have Mars directly leaning “back,” with the north areographic pole pointing away from the Sun. But what happens six months later, when Mars is on the other side of the Sun? The obliquity angle does not change—the planet is just now facing the other way at noon. Are ion loss rates enhanced here, or has another process emerged that modulates their escape to a more reasonable amount? These considerations were set aside for this work, which instead focuses on obliquity angle and IMF orientation instead.

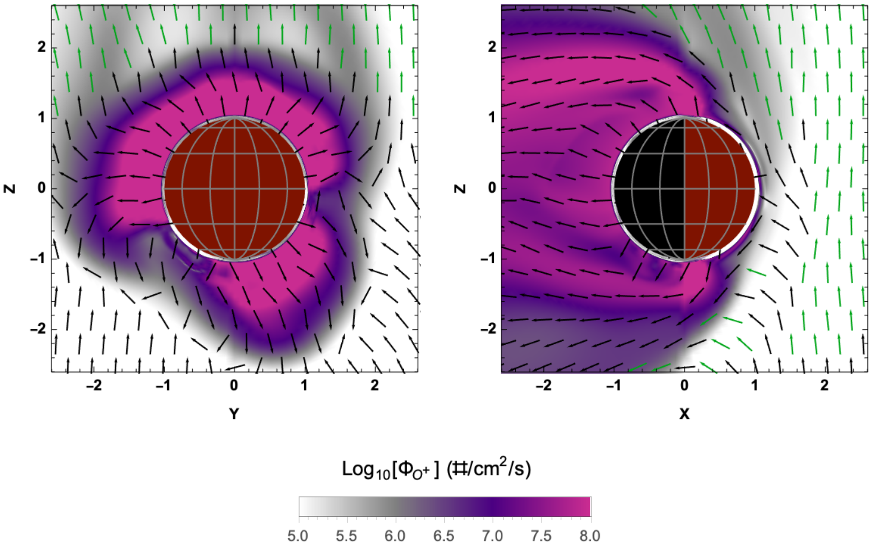
Lastly, the modification of the neutral atmosphere by changing the planet's obliquity was ignored, in spite of ample theoretical evidence that an obliquity change should alter the underlying atmosphere. Recent calculations presented by Ramstad et al. (2017) could propose present-day ion loss at Mars is production limited [202]—enough energy exists for any particle potentially escaping, but the number of potentially escaping particles controls the amount of escape. It might follow that changing the available number of ions by virtue of changing the obliquity (from the consequent changes to the underlying neutral atmosphere [46]) could result in a similarly altered ion loss rate. Additionally, Mars' peculiar surface conditions might trigger the release of additional volatiles like H_2O as the surface temperature is modified by the changed obliquity angle. This release of additional gaseous species would modify the available populations of neutral species in the Martian mesosphere and by extension modify the populations of potentially escaping ions.

5.9 Data & Analysis

As an aid to the reader for the figures and discussions to come, a pair of example figures will be discussed concerning the flux field for O^+ in simulation 3 (Table 5.1: 25° obliquity, spiral-out IMF) generated by BATS-R-US. This pair of figures is displayed in Fig 5.7. In the left panel, the flux of O^+ ions within the MSO-YZ plane (dawn-dusk plane, observer is "looking" at Mars' dayside with the Sun at their back) is displayed, with the vectors showing the local flow of the ions within the plane—the vectors have been colored such flow velocities less than 100 km/s are rendered in black and those exceeding 100 km/s are rendered in green. The colored scalar density (specified in the legend) denotes the magnitude of the flux field at a given point. A similar setup is shown in the right panel, with the perspective now looking at the MSO-XZ (noon-midnight, observer is "looking" at Mars' dawn terminator with the Sun to their right) plane. The white/gray annular regions immediately surrounding Mars is the simulated low-altitude ionosphere, including the 100 km simulation cutoff point. Data displayed within the disk region containing the planet itself is covered by a Mars mask, colored red or black to denote where the planet's sunlit or darkened faces are pointing.

As a point of clarification, there exists an artificial structure along the MSO-Z axis within these data that a reader should not mistake as real. In Fig 5.7, this manifests as a slight vertical extension of the indigo coloring of the flux field along the line at $Y = 0$ in the left panel; this artifact can be seen in the right panel as a distinct break in the outflow pattern along the line at $X = 0$. These artifacts are an unforeseen side effect of two factors. First, as BATS-R-US runs all its calculations in MSO spherical coordinates and then converts them to MSO Cartesian, conversion from radial-angular space to rectangular coordinates in high resolution regions may have accidentally assigned multiple physical values (like density or velocity) to the same point in space. This assignment is suspected to be a consequence of the coordinate converter routine's precision limited calculations—when converting into MSO-XYZ coordinates, closely packed unique radial-angular positions were assigned the same rectangular coordinates due to the converter chopping off digits of precision (such as those near the MSO-Z axis, the coordinate origin for the polar angle in spherical coordinates).

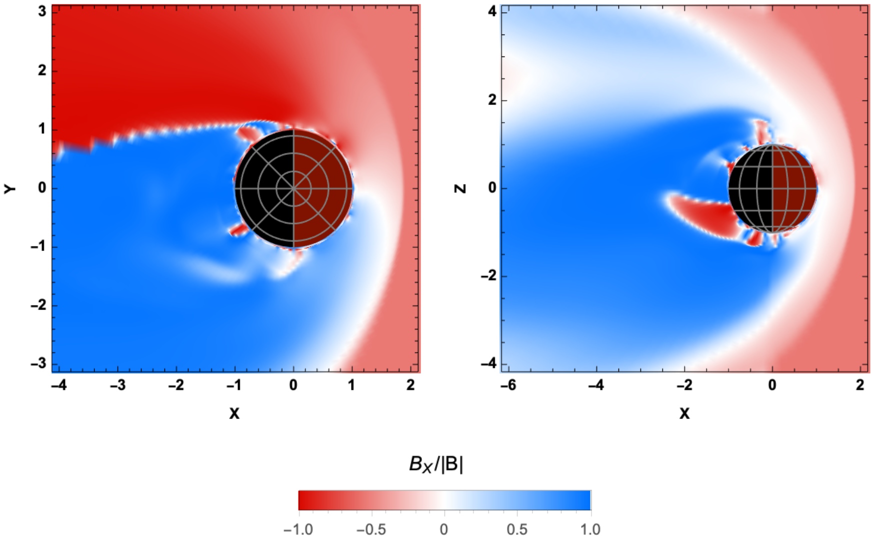
Figure 5.7: Flow fields of O^+ ions escaping Mars in the MSO-XZ plane and MSO-YZ planes for simulation 3 (Table 5.1), set aside for exemplary purposes. The background color density denotes the magnitude of the flux specified in the legend. The vectors denote the direction of flow in the plane. Vectors have been colored such that flow speeds less than 100 km/s are black and speeds greater than 100 km/s are green.



To accommodate this unforeseen output error, for any point in MSO-XYZ space that had multiple values for the same physical parameters, the average of these parameters was made before any subsequent calculations took place. As a consequence, artificial extensions or reductions in the plotted output data were manifested. A brief point-by-point investigation of the data was made for these points which had multiple values for the same spatial position to ensure that calculations were not combining drastically different physical values within the same point in space. Within a given set of physical values for the same spatial position, values varied within small factors of one another, typically between a factor of 2–5 between the greatest and least physical values. Thus, while this averaging scheme did introduce artificial plotting features, we do not consider the scheme to have introduced any extreme artifacts in any of the calculated values used in this work.

Escaping ion flux field patterns in these two planes clearly showed the two primary outflow channels: tail flow and plume flow. Tail flow was characterized by comparatively slow, dense ion movement leaving the planet along the day-night terminator traveling towards the tail away from the Sun (down the negative MSO-X axis); plume flow was characterized by fast, low density ion movement leaving the planet from the space on the dayside of the planet. Tail flow was always from the day side to the night side, with the densest flow at the terminator. Plume flow was in the same direction as the convective electric field ($\vec{E} = -\vec{u} \times \vec{B}$) and has a distinct wedge-shape morphology away from the dayside of the planet—in the example figure (Fig 5.7), this wedge structure is the light gray region whose vertex is near the extreme subsolar point of the planet. The two dominant outflow region characterizations are also seen in the overplotted vector fields—tail outflow is slow (black vectors) and plume outflow is fast (green vectors). Each of the three ion species in this work has its BATS-R-US data displayed in a similar fashion. In the MSO-YZ data figures, readers are directed to bring attention to the lower-left of each panel—it is in this region that crustal field interactions will be most readily apparent due to changes in obliquity angle.

Figure 5.8: Draping direction of the simulated magnetic field in the MSO-XY and MSO-XZ planes for simulation 3 (Table 5.1), set aside for exemplary purposes. The color denotes the draping direction of the magnetic field, expressed as the MSO-X component of the field divided by the field magnitude—values range from -1 (red, pointing away from the Sun) to 1 (blue, pointing towards the Sun.



In addition to flux fields for the heavy ion species, the structure of the magnetic field via the draping direction was also considered for each simulation. We show a brief exemplary pair of figures in Fig 5.8. In the left panel, the draping direction is shown in the MSO-XY plane (north-south plane, observer is “looking” down at Mars from a position hovering over the planet with the Sun to their right). In the right panel, the draping direction is shown in the MSO-XZ plane. The actual data being displayed in both panels is a calculated expression of magnetic field draping direction (as described above in the introduction, Mars’ magnetosphere is formed when IMF lines are forced to drape around the planet while passing by). Calculations were made by taking the MSO-X component of the magnetic field and normalizing it by the total magnetic field magnitude—these values, ranging from -1 to 1, were then colored on a red-white-blue color scale. Cooler, blue values denote magnetic field lines pointing towards the Sun (positive MSO-X) and warmer, redder values denote magnetic field lines pointing away from the Sun (negative MSO-X axis).

The general structure of the draped field is readily apparent in the left panel—using $Y = 0$ as a guideline, there is a split between the oppositely aligned halves of the induced magnetosphere, with a protrusion of positively pointing field lines into the otherwise negatively pointing dominated upper half of the figure. In both the left and right panels, the bow shock and magnetopause are also apparent as the two sudden transitions in draped field direction along the subsolar line. The complete magnetospheric cavity (everything inside the bow shock) has the expected generally parabolic shape. Lastly, the regions of crustal field interaction are easily recognizable as the protrusions of opposing field alignments in both the left and right panels—the strongest nightside crustal sources are manifested in the large extension of negative draping direction with cusps and shunts of positive draping (red region with blue intrusions attached to the lower-left of Mars). Draping calculations and structural considerations like these were carried out for all six simulations, seen in figures 5.19 and 5.20, discussed further below.

Figure 5.9: Flow field of O^+ ions escaping Mars in the MSO-XZ plane. The background color density denotes the magnitude of the flux. The vectors denote the direction of flow in the plane. Vectors have been colored such that flow speeds less than 100 km/s are black and speeds greater than 100 km/s are green.

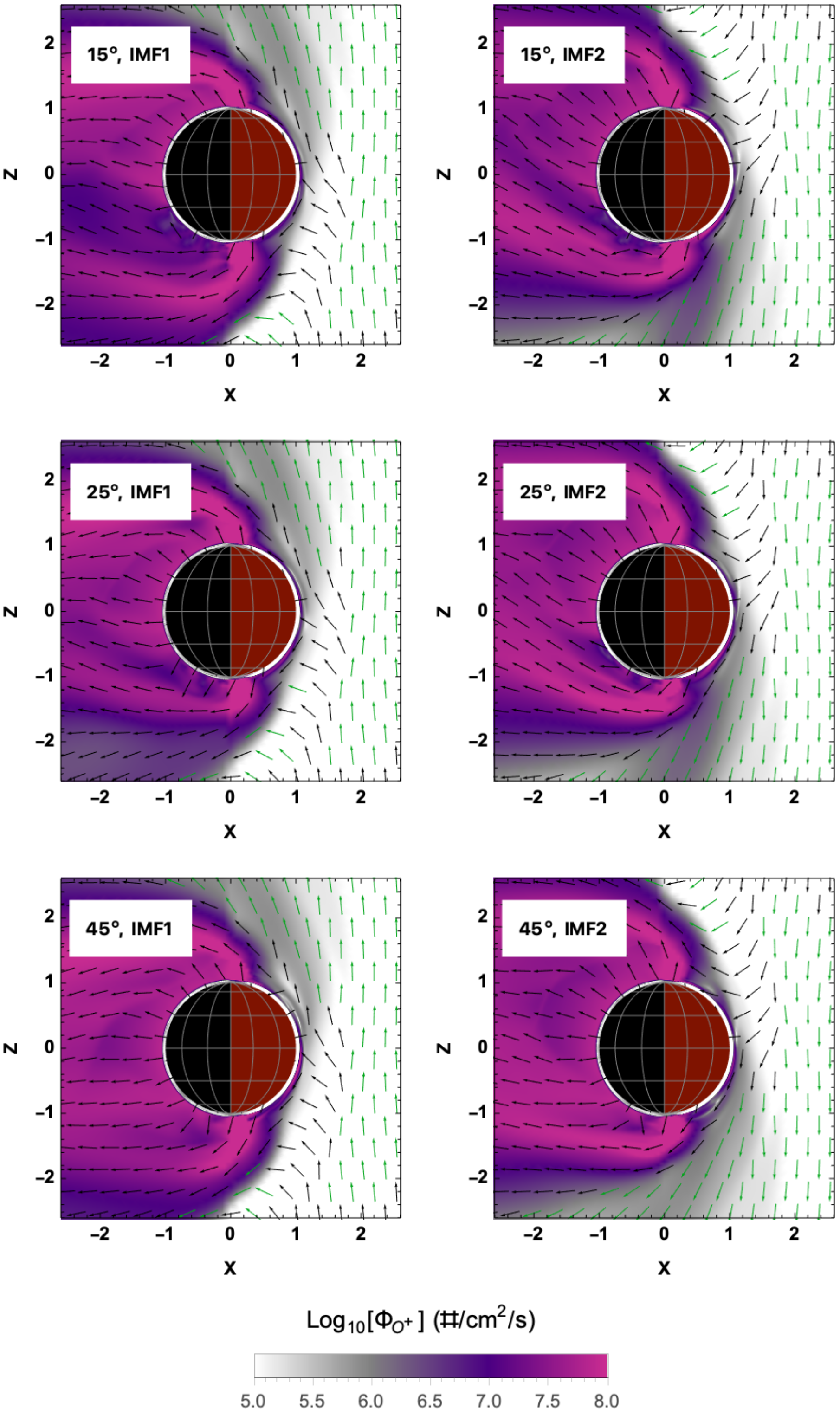


Figure 5.10: Flow field of O^+ ions escaping Mars in the MSO-YZ plane. The background color density denotes the magnitude of the flux. The vectors denote the direction of flow in the plane. Vectors have been colored such that flow speeds less than 100 km/s are black and speeds greater than 100 km/s are green.

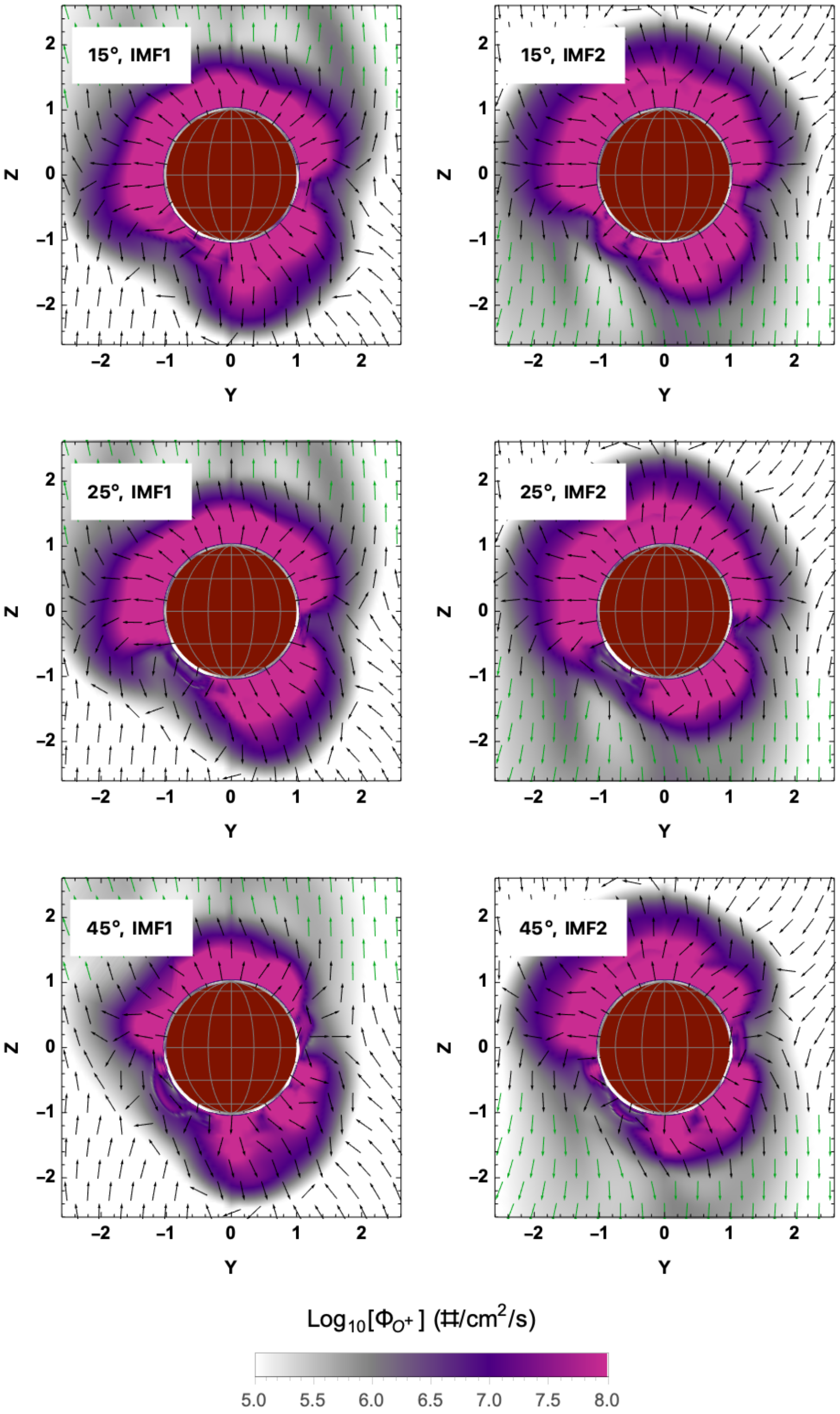


Figure 5.11: Flow field of $O_2{}^+$ ions escaping Mars in the MSO-XZ plane. The background color density denotes the magnitude of the flux. The vectors denote the direction of flow in the plane. Vectors have been colored such that flow speeds less than 100 km/s are black and speeds greater than 100 km/s are green.

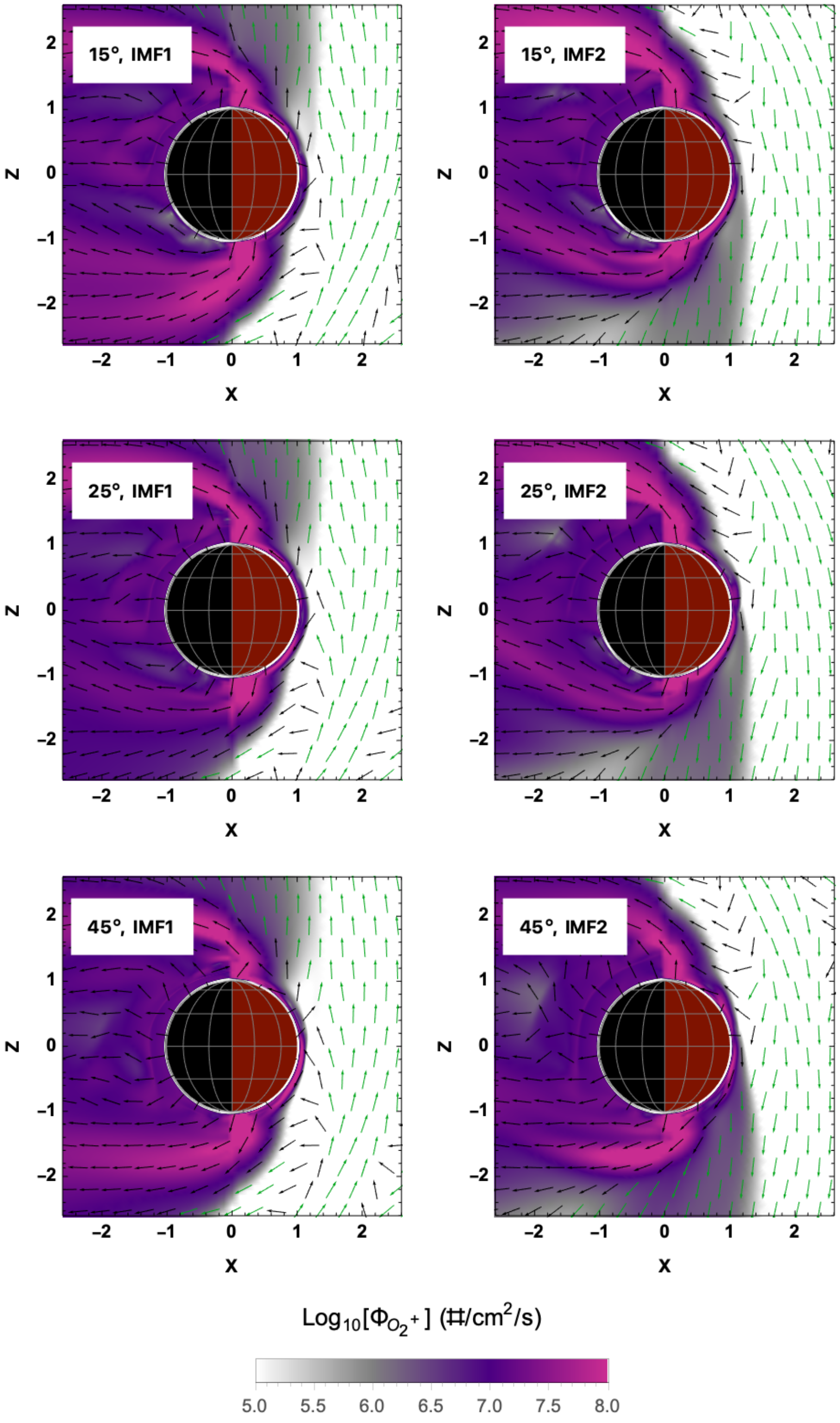


Figure 5.12: Flow field of O_2^+ ions escaping Mars in the MSO-YZ plane. The background color density denotes the magnitude of the flux. The vectors denote the direction of flow in the plane. Vectors have been colored such that flow speeds less than 100 km/s are black and speeds greater than 100 km/s are green.

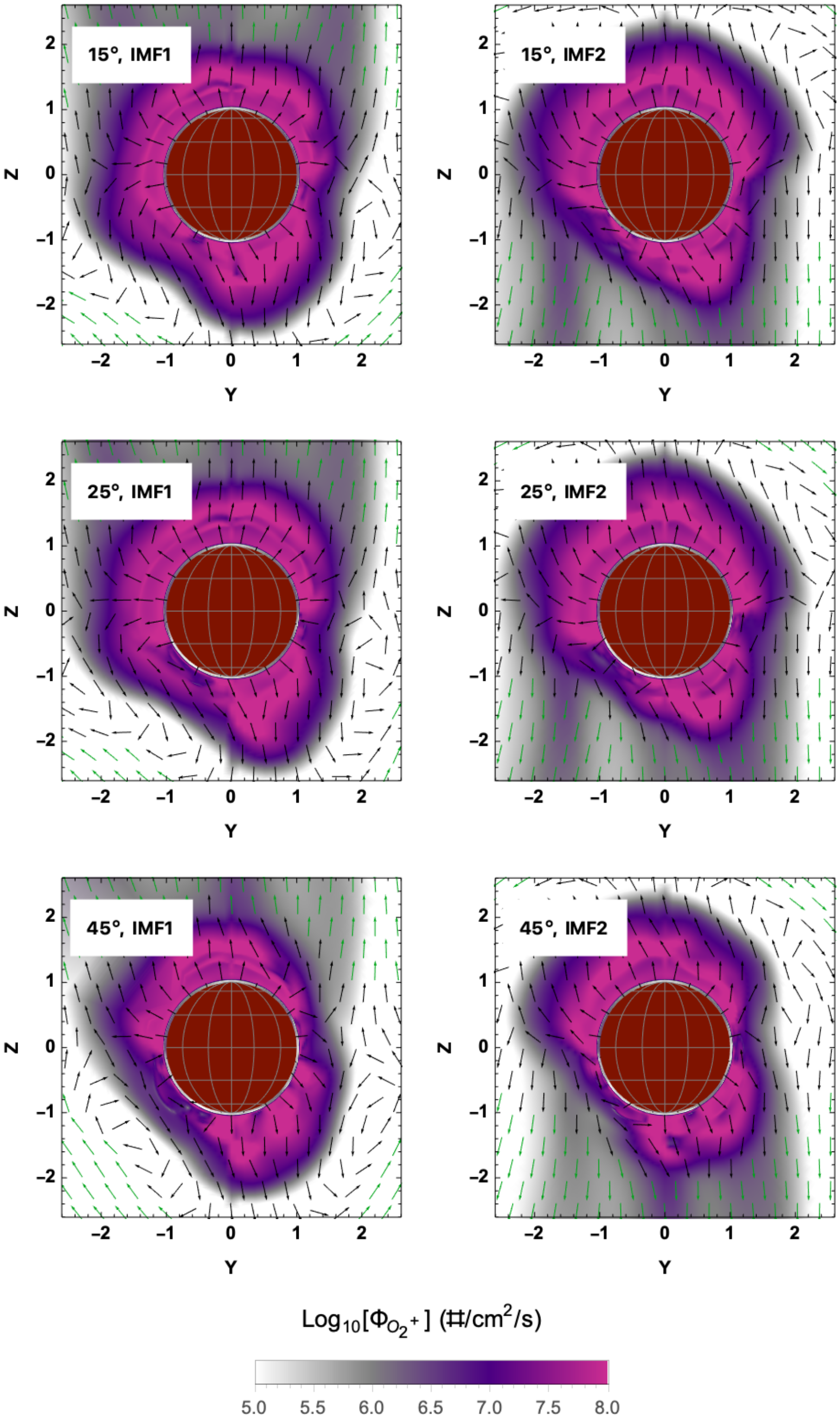
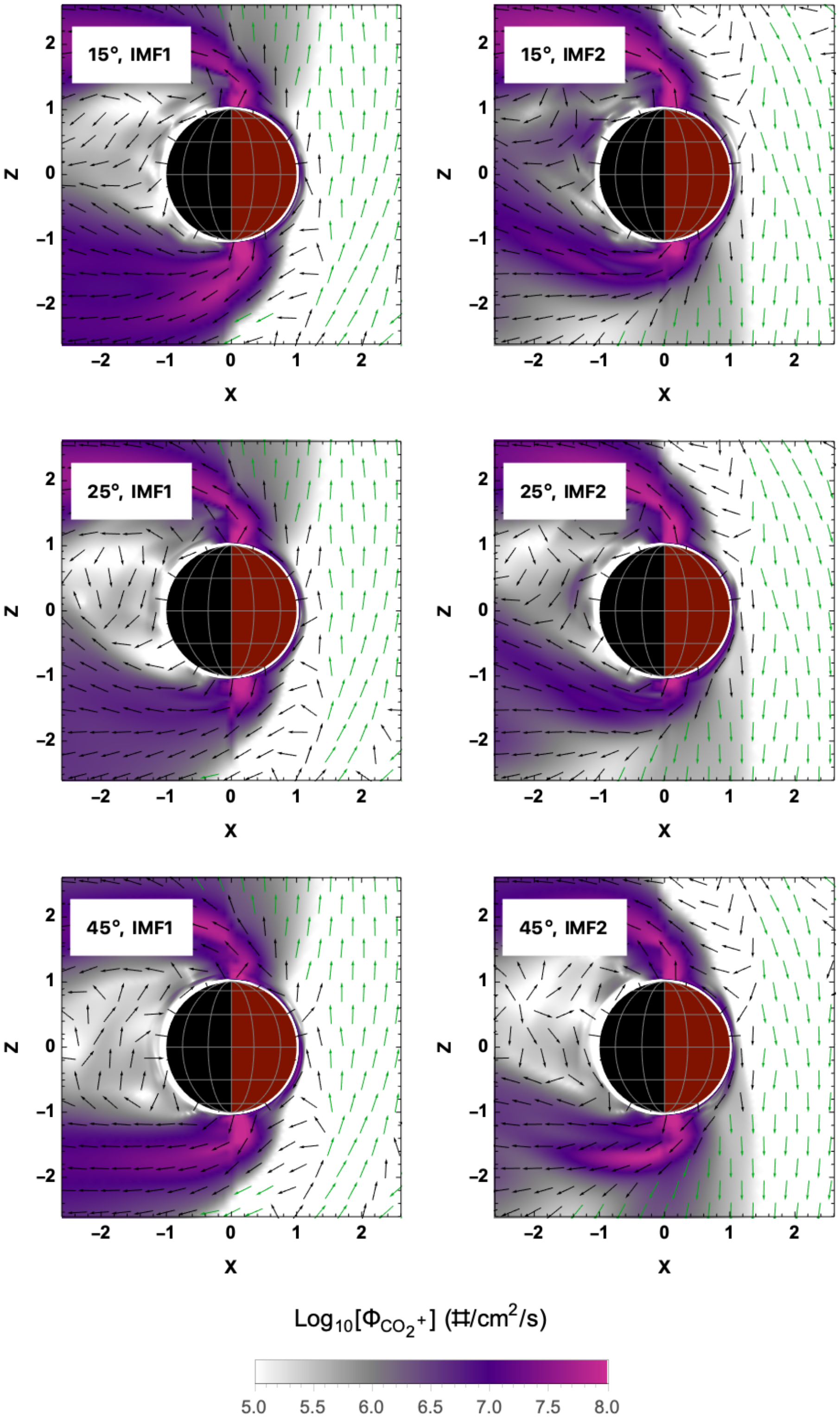


Figure 5.13: Flow field of CO_2^+ ions escaping Mars in the MSO-XZ plane. The background color density denotes the magnitude of the flux. The vectors denote the direction of flow in the plane. Vectors have been colored such that flow speeds less than 100 km/s are black and speeds greater than 100 km/s are green.



Absolute escape rates from the planet were calculated by using a large flux surface in the deep magnetotail for each of the six simulation cases to ensure that all escaping ions were adequately accounted for. A 10 $R_M \times 10\ R_M$ square surface was erected along the MSO-X axis centered at $X = -4\ R_M$—the large integrating area was chosen to include ion escape from both the more narrowly confined magnetotail as well as the more expansive ion plume generated by the convective electric field ($\vec{E} = -\vec{u} \times \vec{B}$). Absolute escape rates through this surface are shown in Fig 5.15, with the obliquity angle specified by the horizontal axis and the IMF condition specified by the plot markers in the upper legend. Ion species are identified by the color scheme denoted in the lower legend. Heavy ion escape showed a small dependence on the obliquity angle of the planet, with absolute escape rates (in particles per second) not substantially varying from approximately 8×10^{25} for O^+, 3.5×10^{24} for ${O_2}^+$, and 1.5×10^{24} for ${CO_2}^+$. Additionally, absolute loss rates show minimal reliance upon the IMF condition used in each simulation.

Figure 5.14: Flow field of CO_2^+ ions escaping Mars in the MSO-YZ plane. The background color density denotes the magnitude of the flux. The vectors denote the direction of flow in the plane. Vectors have been colored such that flow speeds less than 100 km/s are black and speeds greater than 100 km/s are green.

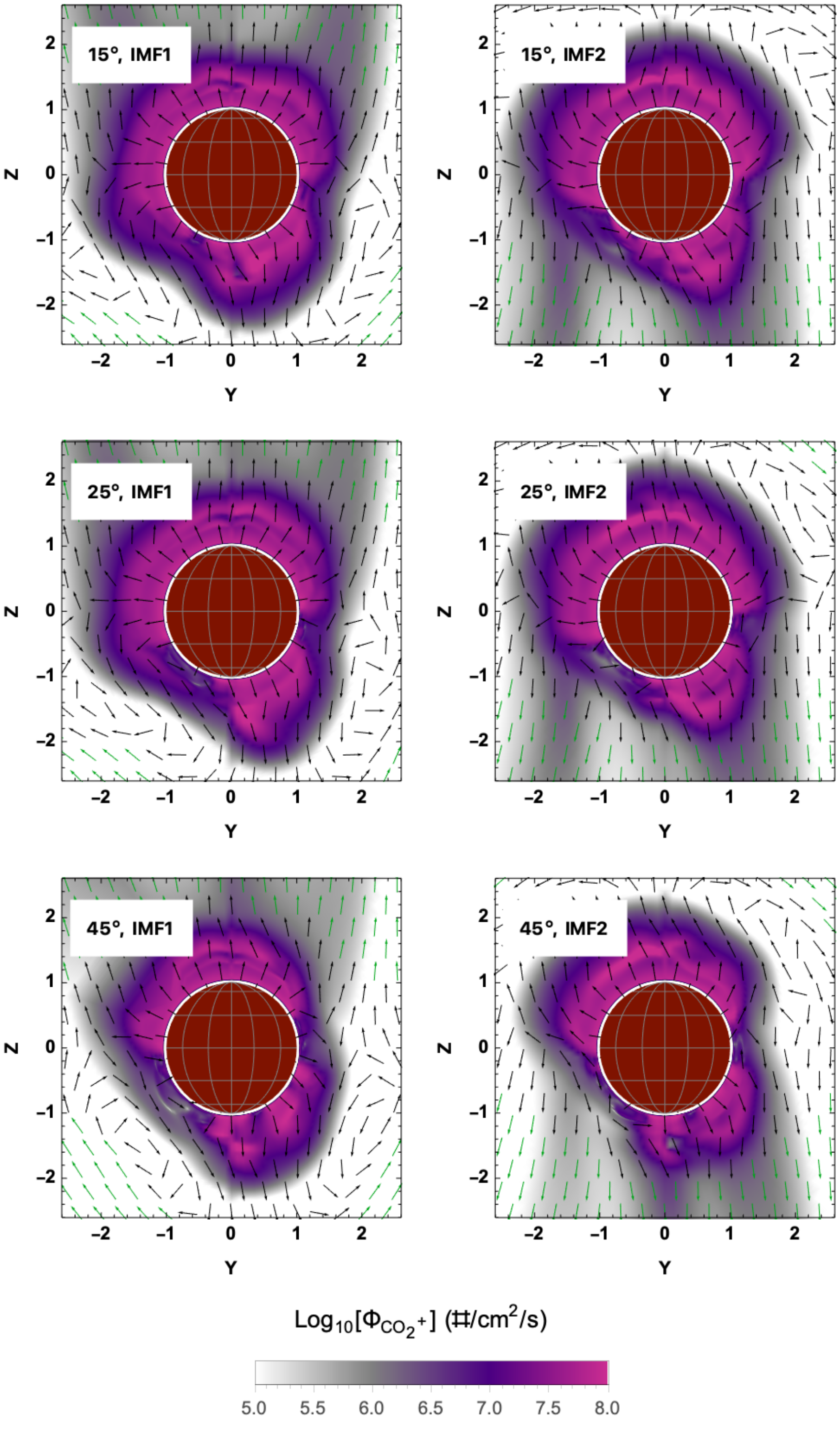
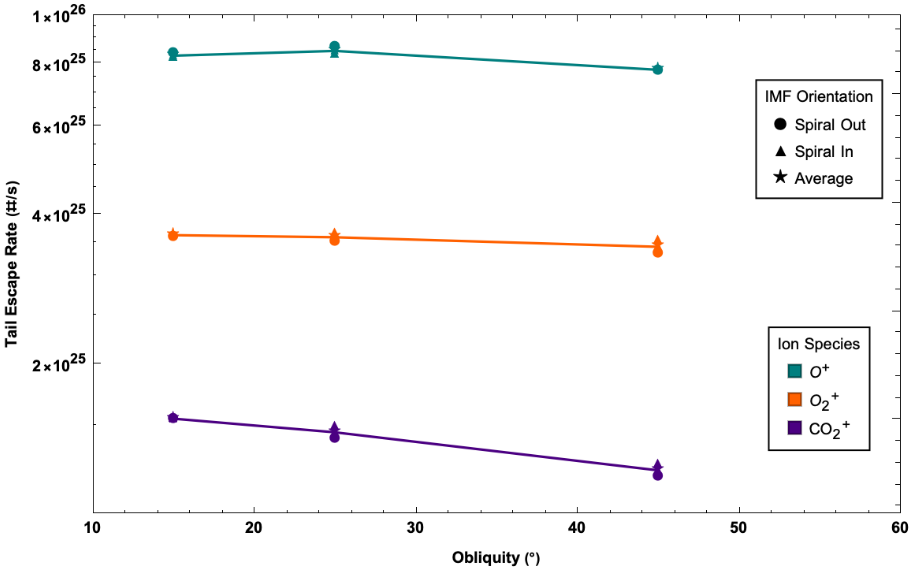


Figure 5.15: Escape rates through a 10 R_M × 10 R_M integrating surface in the deep magnetotail ($X = -4\ R_M$). IMF orientations and ion species are specified by the colors and icons in the legends. The average between the two IMF orientations is denoted by the ⋆ icons. Escape rates show comparatively little sensitivity to the change in obliquity angle or the IMF orientation.



For comparative context, each species' absolute escape rate was recalculated as a percent-difference from the three escape rates calculated for simulation 3 (Table 5.1)—the choice of simulation 3 was its similarity to present-day Mars conditions. Using these new percent-difference values (Fig 5.16), greater insight was seen in the changes in loss rates. Low obliquity conditions favored the loss of $O_2{}^+$ and $CO_2{}^+$ by 3% and 9%, respectively. High obliquity conditions favored the retention of $O_2{}^+$ and $CO_2{}^+$ by 5% and 17%, respectively when compared to our standard. The retention of O^+ was favored for all simulations when compared to our standard, suggesting that the loss of O^+ was not a linear function of obliquity alone.. A weaker dependence on IMF orientation was also evident from our calculations, which showed enhanced escape of $O_2{}^+$ and $CO_2{}^+$ for spiral-in IMF orientations compared to spiral-out. Loss of O^+ was again a behavioral anomaly, showing a preference for spiral-out conditions excluding the most extreme obliquity cases.

Tail outflow was calculated by using a standard $4R_M \times 4R_M$ integrating square centered on the MSO-X axis located at three successive positions in the magnetotail ($X = -1.5$, -2.5, & $-3.5\,R_M$). Plume outflow was calculated by using a standard $1\,R_M \times 2\,R_M$ integrating rectangle, aligned such that the short length ran along the MSO-X direction from $X = 0.5\,R_M$ to $X = 1.5\,R_M$ and the long length ran along the MSO-Y direction from $Y = -1\,R_M$ to $Y = 1\,R_M$. The MSO-Z location of the plume integration rectangle was either positive or negative depending on the direction of the convective electric field of the upstream solar wind (positive values for spiral-out conditions; negative values for spiral-in) and was located a three successive positions in the plume ($|Z| = 1.5$, 2.0, & 2.5 R_M). The succession of positions for both tail escape and plume escape is shown in Figs 5.17 and 5.18 as triplets of points for a particular ion species and obliquity angle. For example, in Fig 5.17, consider the escape rates through the square control surface for O^+ at 15° obliquity (teal points, triangles, and stars in the upper left corner). The left set of points, offset by -1.5°, are the calculated escape rates at $X = -1.5\,R_M$; the center set, offset by 0°, are the calculated escape rates at $X = -2.5\,R_M$; and the right set, offset by 1.5°, are the escape rates at $X = -3.5\,R_M$.

As expected for both outflow channels, outflow decreases as the integrating surface was moved further away from the planet—the slight expansion in the outflow pattern in the magnetotail meant progressively less flux was captured using the same, consistently-sized integrating surface at deeper positions. For tail escape (Fig 5.17), rates through the square control surface decreases as the surface was centered at positions deeper in the magnetotail. Such behavior was expected as the magnetotail (and the escaping ion populations trapped inside) asymptotically expands away from the MSO-X axis as one moved deeper into the tail. For plume escape (Fig 5.18), rates through the rectangular control surface decreases as the surface was moved higher from the planet away from the MSO-XY plane. This behavior was also expected, as the convective plume was naturally deflected into the negative MSO-X direction as the accelerated ions became entrained in the solar wind.

Figure 5.16: Escape rates through a 10 $R_M \times 10\, R_M$ integrating surface in the deep magnetotail ($X = -4\, R_M$) expressed as percent-differences from the 25°-Spiral Out standard (three overlapping points located at (25°, 0)). IMF orientations and ion species are specified by the colors and icons in the legends. The average between the two IMF orientations is denoted by the ⋆ icons. The average between the two IMF orientations is denoted by the ⋆ icons. Compared to the standard, ion loss among the heaviest species (O_2^+ & CO_2^+) shows a roughly linear decrease as the obliquity increases. O^+ follows a roughly quadratic trend, with the standard measurement being the maximum.

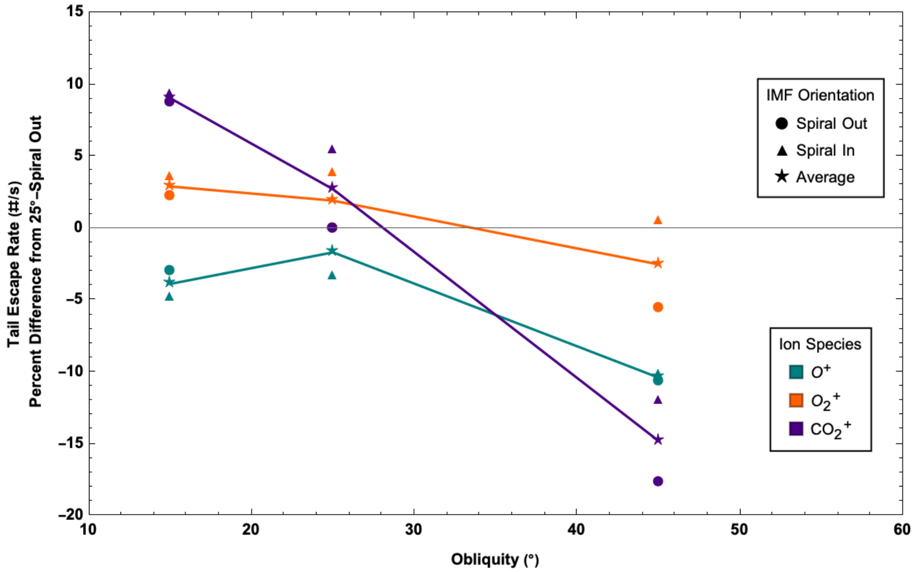
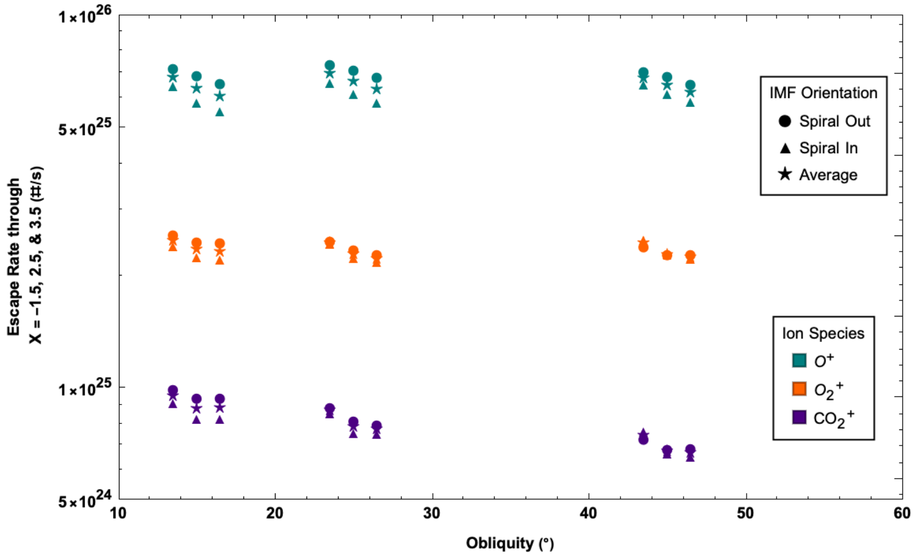


Figure 5.17: Escape rates through a $4R_M \times 4R_M$ square integrating surface at progressive locations in the magnetotail ($X = -1.5,\ -2.5,\ \&\ -3.5\ R_M$) as a function of obliquity. IMF orientations and ion species are specified by the colors and icons in the legends. The average between the two IMF orientations is denoted by the $\star$ icons. Obliquity angle is specified along the horizontal axis—for illustrative purposes, the escape rates for $X = -1.5\ R_M$ are offset by 1.5° to the left of each primary obliquity value. Escape rates for $X = -3.5\ R_M$ are offset by 1.5° to the right of each primary obliquity value. IMF orientations and ion species are specified by the colors and icons in the legends. The average between the two IMF orientations is denoted by the $\star$ icons.



Tail outflow (Fig 5.17) demonstrated roughly constant behavior for O^+ and ${O_2}^+$, and notable decreasing behavior for ${CO_2}^+$. Additionally, the discrepancy between the two IMF conditions is reduced for the two heavier species, but was preserved for O^+. Plume outflow (Fig 5.18) generally steady for the two heavier species, but O^+ shows a substantial drop in calculated rates across the range of obliquities. Lastly, the absolute escape rate of the three species in the tail ($\sim 10^{25}$ particles per second) was commensurate with other MHD simulations considering solar maximum conditions [158, 159]—even though this work used solar moderate inputs for EUV flux and solar wind velocity, we did not consider any of the calculated escape rates to be absurdly or anonymously large.

Obliquity-induced modification of the magnetosphere was explored by calculating the draping direction and comparative field intensity in the MSO-XY and MSO-XZ planes. Similar calculations in the MSO-YZ were performed, but were not provided in figure format in this work. The two sets of calculations can be see in Fig 5.19 for the MSO-XY and in Fig 5.20 for the MSO-XZ. The general magnetospheric structure is evident from both figures, with the bow shock, pileup boundary, and magnetotail fully formed in all six simulations. The localized effects of the Martian crustal fields can be identified as the small protrusions of opposing field alignments in the otherwise uniform background along the edges of the Martian disk. Structural modifications to the magnetotail appeared in a greater extent for low obliquity simulations than in high obliquity ones, characterized by lengthy regions of oppositely aligned magnetic fields from the draping of the IMF.

Figure 5.18: Escape rates through a 1 $R_M \times 2\ R_M$ rectangular integrating surface at progressive locations in the convective electric field direction ($|Z| = 1.5, 2.0, \& 2.5 R_M$) as a function of obliquity. IMF orientations and ion species are specified by the colors and icons in the legends. The average between the two IMF orientations is denoted by the $\star$ icons. Obliquity angle is specified along the horizontal axis—for illustrative purposes, the escape rates for $|Z| = 1.5\ R_M$ are offset by 1.5° to the left of each primary obliquity value. Escape rates for $|Z| = 2.5\ R_M$ are offset by 1.5° to the right of each primary obliquity value. IMF orientations and ion species are specified by the colors and icons in the legends. The average between the two IMF orientations is denoted by the $\star$ icons.

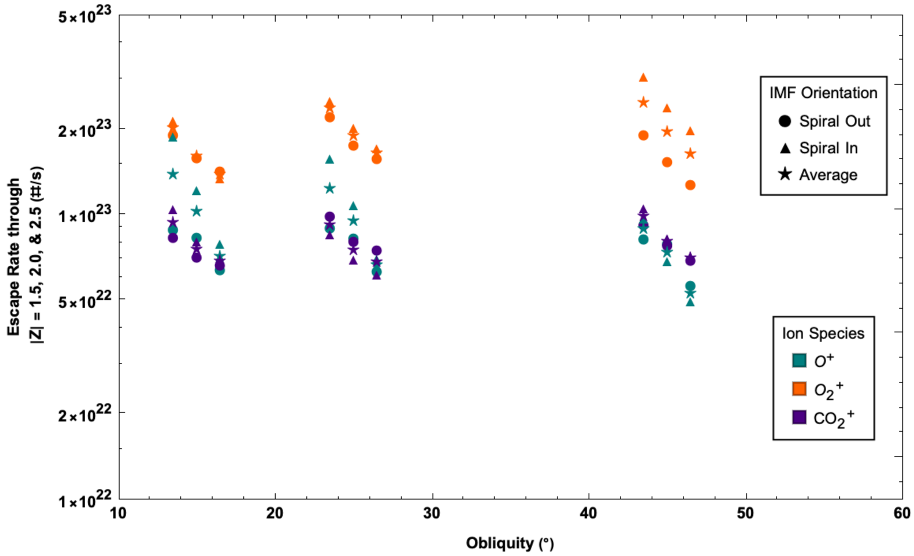
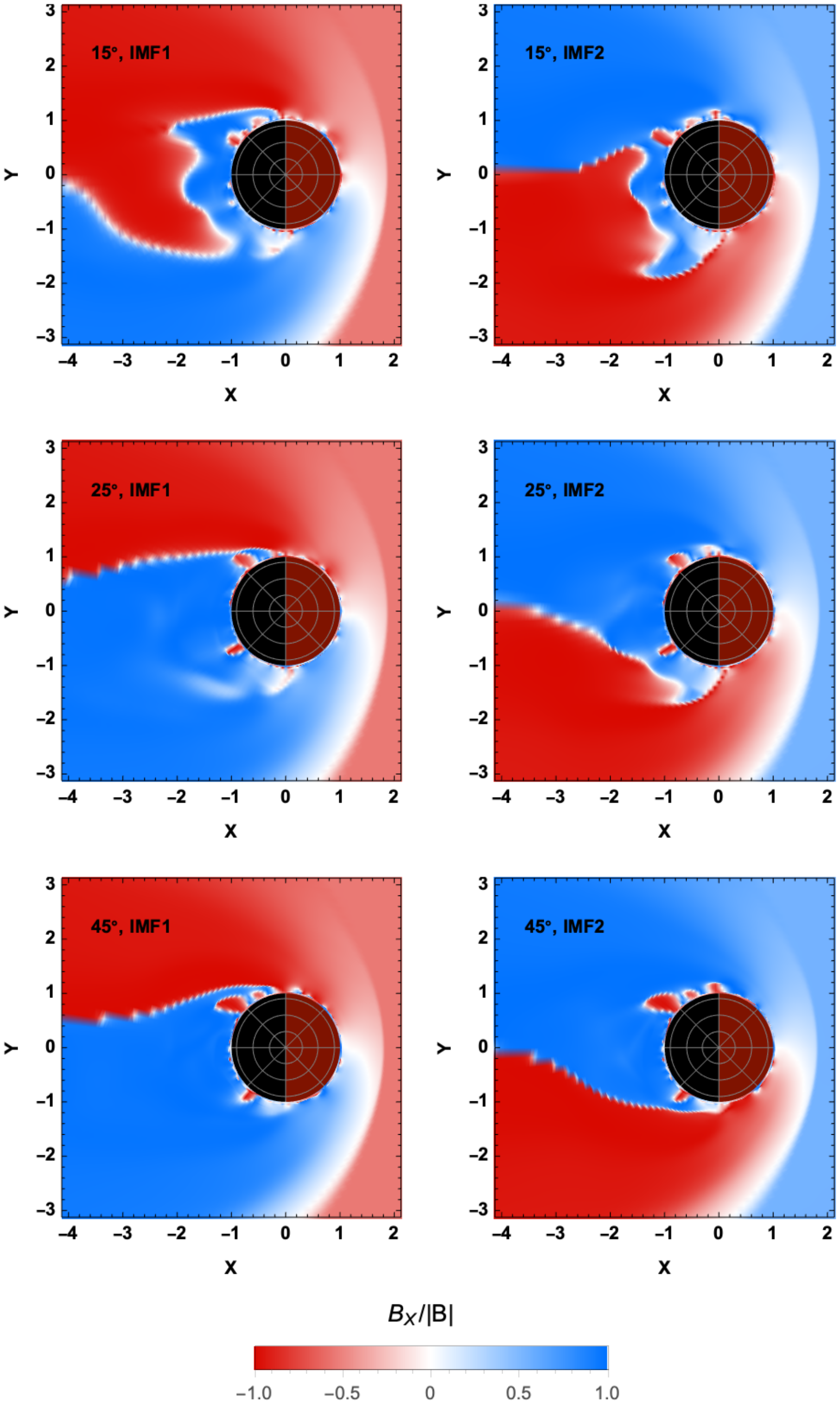


Figure 5.19: Draping direction of the magnetic field in the MSO-XY plane, expressed as the X component divided by the field magnitude. Obliquity angle and IMF condition are specified in the upper-left of each panel. Blue regions denote where the magnetic field is directed towards the Sun; red regions denote where the magnetic field is directed down the tail.



5.10 Discussion

Escape of the three heavy ions showed both symmetric cometary escape structures [155, 69, 153], and asymmetric electric field driven escape structures. Cometary patterns were characterized by the near radial flow patterns in the MSO-YZ plane (Figs 5.10, 5.12, 5.14), where high magnitude fluxes are carried by slow velocity fields, indicative of mass-loading field lines by Martian plasma. Electric field driven loss (via the plume) was characterized by the low density, high velocity flux magnitudes drawn from the dayside of the planet on the positive electric field side, indicative of ion pickup by the solar wind—in Figs 5.9, 5.11, 5.13, this structure was demonstrated as the gray wedge structure with green velocity vectors. Additionally, flow morphology in the tail region showed acceleration by Hall effects in the space immediately behind Mars for O^+ and ${O_2}^+$—${CO_2}^+$ showed minimal flux in the immediate tail region. The effects the crustal fields are readily evident in Figs 5.9 and 5.11, where tailward flows in the MSO-XZ plane showed a distinct reduction by a factor of approximately 10 in the night-south quadrant (lower-left) of the 15° and 25° obliquity runs. Moreover, the heavy ions also showed flow suppression patterns characteristic of trapped flow in regions containing the strong crustal fields. Seen in Figs 5.10, 5.12, 5.14, flow away from the south-dawn terminator region (lower left quadrant of all subfigures) showed progressive reductions in both flux magnitude and spatial extent for all ion species as the obliquity angle increases.

Tail-specific and plume-specific calculations through control surfaces (Figs 5.17 and 5.18) suggested that ion escape occurred principally through the magnetotail (escape rates of $\sim 10^{25}$ particles per second) with plume escape from the dayside of Mars acting as a minor contribution to the planet's total ion escape (escape rates of $\sim 10^{23}$ particles per second). This could have been a consequence of the choice of control surfaces used to calculate each escape rate—that is, the control surface was not spatially extended as much as it could have been in the MSO-X or MSO-Y directions and captured a correspondingly lower amount of particle flux. However, our choice of integrating surface was well removed from the day-night terminator outflow and captured the majority of the flux field in the dayside plume "wedge" seen in Figs 5.9, 5.11, and 5.13. Outflows showed no particular horizontal asymmetries (not shown in figures) that would not have been captured by the integrating surfaces. Given our choice of simulation parameters for the input solar wind (solar moderate), such a comparatively small contribution to total ion loss might follow from Dong et al. (2017)'s analysis of MAVEN data suggesting the ion plume outflows are reduced during higher EUV periods [67]. But, their measurements suggested plume contributions to the total ion loss were to the order of 20–30% [67], not the approximately 1% calculated here. We are presently uncertain as to the ultimate cause of this substantial reduction in plume outflow for this set of simulations. Species-dependent behavior for the two outflow channels showed well-behaved outflows through the tail (Fig 5.17), but peculiar patterns through the plume (Fig 5.18). Tail escape for ${O_2}^+$ and ${CO_2}^+$ showed a smooth decline in loss rates as the obliquity increased, and IMF-dependent losses slowly converged with one another. O^+ showed general convergence towards the IMF-averaged escape rates but did not have a smooth decline with obliquity—like the absolute escape rates (Fig 5.15), O^+ in the tail showed a slight increase then decrease as obliquity varied.

Plume escape was less well behaved, and no trends held for all three species, save for escape rates declining within each set of integration surfaces. That is, for each obliquity angle and IMF orientation, escape rates declined as the integrating surface moving away from Mars. Such behavior is expected as the plume flow field is diverted away from the MSO-Z axis and down into the tail [67]. ${O_2}^+$ was the most well behaved, showing a general increase in plume escape with obliquity and a preference for spiral-in IMF conditions (convective electric field directed in negative MSO-Z). This behavior is peculiar, as the combined obliquity and IMF conditions would suggest that the population of accessible ions should have been the most protected from direct acceleration by the convective electric field, yet these measurements proposed the opposite case. The lack of a similar trend among the other two ion species offered no additional clarity. As the dominant loss channel through the tail accounted for essentially all ion loss from the planet, the variation in plume loss might be ultimately negligible; however, a satisfactory mechanism for the variable flows through the plume surfaces remained indeterminate.

These results stand in partial opposition to the time-dependent MHD simulations discussed in Fang et al. (2015) [82]. Specifically, Fang et al. (2015) suggested that ion loss should be enhanced by the presence of the crustal field across the day-night terminator (YZ plane in MSO) due to an increase in cross-sectional area between the outer and inner magnetospheric boundaries—these crustal field induced vents offer a temporarily larger outflow region as the crustal fields swing around the dawn terminator into the day side (similar function at dusk). Our simulations for 45° obliquity angles resulted in the nightside crustal field being as obtrusive as possible, increasing the cross-section by pushing the magnetospheric boundary out away from the ionosphere at the terminator [35, 82]. However, our simulation cases showed the greatest reduction in ion loss rates occur for the largest obliquity angles (Figs 5.15 and 5.16), suggesting that the high obliquity obstacle acts more appropriately like an ionosphere-trapping "mini-magnetosphere" by impeding the transport of dayside plasma to the nightside for escape rather than enhancing it by opening up a magnetospheric vent [159, 156, 82, 32]. Similarly, the dayside intrusion created by the nightside crustal fields during high obliquity angles might not exert enough influence on the dayside subsolar regime to make the necessary modifications to the subsolar magnetic pressure environment. The magnetic pressure in the 45° region surrounding the subsolar point acts as an excellent proxy for day-to-night escaping ion flow [82]. Thus, while the obliquity changes in our simulations should increase the cross-sectional flow area across the MSO-YZ, the ion source region on the dayside remains unaltered by the obliquity change. On the other hand, these simulations held the crustal anomalies on the nightside and leaned the planet back, allowing greater intrusion of the crustal fields preferentially into the negative MSO-Z direction. Draped field lines exert a comparatively stronger curvature force ($\vec{J} \times \vec{B}$) on plasma near the MSO-Z poles; it is here that draped IMF lines finally "slip around" the Martian obstacle into the tail, but before they do they have been maximally bent by combined action of the solar wind and ionospheric obstacle [208, 91]. On the negative MSO-Z pole, the obliquity induced protrusions of the crustal field shield progressively more ionosphere from direct interaction with the induced magnetosphere, meaning the curvature force has both less material to act upon and may be reduced in strength by the presence of the crustal field.

Consistent with past measurements from spacecraft [254, 253] and MHD simulations exploring the effects of the crustal fields [159, 160, 34, 82], our results showed that the location of the bow shock was insensitive to the magnetospheric modifications caused by changing the planet's obliquity angle (abrupt transition in $B_X/|B|$ at extreme right in all subplots in Figs 5.19 and 5.20). Given the nightside position of the strongest crustal sources in this experiment, this lack of dayside magnetosphere modification was not surprising. Moreover, the pileup boundary on the dayside showed limited modification by the changing obliquity, and was most severely altered during the 45° obliquity runs (when the crustal fields were most intrusive along the MSO-YZ terminator plane). However, modification of the nightside magnetosphere and magnetotail was readily apparent from the simulations, shown in Fig 5.19 and Fig 5.20 as the MSO-X component of the magnetic field normalized by the field magnitude. Fig 5.19 shows the magnetic draping in the MSO-XY plane for the six simulations. During the lowest obliquity simulations (top pair), the draping of the magnetic field around Mars formed a peculiar magnetic reversal in the space immediately behind the planet extending to approximately 3 Mars radii in the tail. As the obliquity increases, the reversal structure is diminished (middle row) until almost completely suppressed a maximum obliquity (bottom row). At the same time, changes in the MSO-XZ plane suggest that the magnetic structures could be protrusions of the crustal field extended out into the magnetotail. Such extensions (and corresponding regions of magnetic reversal) might be characteristic of reconnection sites caused by the warping of crustal field loops, triggering bulk atmospheric loss through detached plasmoid creation [33]. As this study cannot capture reconnection (explained below), this supposition may or may not bear out in simulations capable of reconnection calculations.

5.10.1 Implications for early Mars & Mars as a planetary archetype

According to past calculations of the Martian obliquity cycles extrapolated to the beginning of the Solar System, Martian obliquity could have been as high as 75° earlier in Solar System history [136]. If the obliquity-induced suppression of ion loss demonstrated here holds, it would suggest that following the collapse of the Martian global dipole field, the remaining crustal field may have offered some protection against the loss of atmospheric particles which were likely subjected to the increased effects of solar-driven removal processes [47]. The early, young Sun was not the same star Mars experiences today—though the Sun's luminosity was approximately 30% dimmer than it is today, the Sun was also a more violent generator of extreme ultraviolet (EUV) radiation. Such a combination of an overall dimmer Sun with a greater amount of EUV radiation suggests that past Mars had both: more atmosphere to provide the necessary surface conditions for liquid water [47]; and suffered a faster ion loss rate due to the greater effects of ionizing radiation [154]. As present-day Mars has shown, this small-scale magnetic protection could never completely halt atmospheric escape no matter the season, crustal field orientation, or solar wind conditions [65]; however, obliquity-induced reductions in loss might offer additional constraints on how energetic the early, young Sun needed to be in order to remove the requisite volumes of atmosphere to reach the present-day atmospheric conditions [131]. Similarly, as was discussed above in the introduction, the ability of the Martian atmosphere to support condensable liquids at the surface (i.e., water) requires enough neutral gas pressure to keep said liquids stable. Obliquity-induced reduction to atmospheric loss rates might offer the Martian hydrosphere more time to modify the surface before the atmosphere had become too drastically altered to support liquid water [47].

Remarks about contrary or controversial points concerning Mars also need to be considered when attempting to generalize the results of this study. The entire onus of this work rests on the uniqueness of the Martian remnant crustal field compared to the other planetary magnetic environments like Earth or Venus. However, to our knowledge there is no general description of how this particular arrangement of crustal magnetic sources came to be (or would come to be in a simulated clone of the Solar System). Assuming that Mars used to possess a global dipole field and the crustal fields are the permanently magnetized remains of that field, it follows that the evolution of Mars is generalizable to other planetary objects if the processes that lead to the current distribution of magnetic sources and demagnetized regions is similarly generalized. However, this exact evolution is still debated, specifically as to when the Martian dipole needed to collapse for the planet to evolve to its current state [47, 217]. More recent MHD simulation findings presented by Sakata et al. (2020) further suggest that an intrinsic Martian dipole might actually enhance ion outflow rather than suppress it, depending on exactly how strong the dipole field is [210]. Permanently magnetized objects may be stripped of their permanent dipole moment in two general ways: the object can be heated above its Curie temperature, allowing random thermal motions to randomize the internal magnetic domains; or the object can be impacted with enough impulse to shake its magnetic domains loose into a random pattern. For a planetary object carrying permanently magnetized crust, these two processes would likely manifest as a geophysical process (tectonics or volcanism generating the necessary heat for Curie demagnetization) or an astrophysical process (asteroid impact depositing sufficient energy into a planet's crust) [221, 176, 9]. But is a Mars-like distribution of crustal anomalies (one with a dominant region and several smaller regions here and there [2, 52, 176]) an inevitable result of global demagnetization? Are other remnant field distributions more or less likely for a planet evolving under similar conditions? Answers to these questions are still being sought, so while the results presented here are appropriate for our planet Mars, their generalizability to any partially magnetized planetary object might not be sound.

Additionally, as mentioned above during the discussion of Martian obliquity, Mars does not have a large natural satellite like the Moon to act as a gravitational anchor against chaotic axial swings, [137, 58]. If Mars did, it would stand to reason that its obliquity cycle might be less severe in its extreme changes (like Earth's obliquity cycle), so much so that these results might show more negligible changes in ion loss over geologic time. However, the commonality of comparatively large planet-moon pairs remains poorly constrained. Considering just the major planets in our Solar System, only Earth possesses a comparatively large satellite, suggesting that such large planet-moon pairs may be unlikely elsewhere in the Universe. Mars itself may still be subject to major redistributions of internal mass [205], or may have suffered particular formation processes resulting in the present day distribution of mass that might not be likely in other circumstances [234, 206, 217]. Either of these formation processes would alter the Martian moments of inertia and corresponding spin rates, possibly to such a degree that the planet is no longer a generalizable archetype.

Lastly, the comparatively small magnitude of the changes incurred by the changing obliquity angle (Fig 5.15) could provide context to the question "do magnetic fields really matter?" These results would suggest the answer is "no," if one were to consider only first-order effects on atmospheric escape. While it has been shown that in the absence of the crustal fields, Mars' present day loss rate could be twice as large, obliquity-induced enhancements to atmospheric protection are not enough to overcome a more critical measure: the lack of gravity. At only one tenth of Earth's mass, Mars simply does not have enough pull to keep enough of its atmosphere close enough to the planet. Contrast this with Venus, which like Mars has no global dipole magnetic field, but is otherwise capable of retaining its atmosphere via its higher gravitational pull [217].

5.10.2 Future work

Future work that would further benefit this analysis centers principally on examining the unexplored parameters of this study including: the other Martian planetary parameters; alternate simulation styles that can capture time-dependent effect or additional physical processes like reconnection events; and the underlying modifications to the Martian atmosphere caused by changing planetary parameters like obliquity. While obliquity was considered the most important of the planetary parameters considered during the setup of this experiment, other planetary considerations like eccentricity (how close/far would Mars be to the Sun) or argument of periapsis (how Mars rotation axis is pointing with respect to the equinox) would likely also have an effect on heavy ion loss. Such modifications

Critical to the context of these results is a reconsideration of the parameters that were not chosen to vary in the simulation runs. First, this simulation was run in steady state mode—the simulated Mars was "frozen" in space and not allowed to rotate. Such an enforced modeling constraint is a practical experimental choice to make—other simulation studies (e.g., Ma et al. (2014) showing a small time lag between dynamic pressure enhancements an changes in ion escape [157]) have made a similar choice and their results were not unduly hampered by doing so. But, due to the asymmetric distribution of crustal magnetic sources, the effect of Mars' rotation should impart effects on the calculated ion loss not captured by these calculations as the crustal field rotates between the dayside and nightside of the planet. Fang et al. (2015) explored this effect by expressly comparing a set of steady state runs (each with a different orientation for the simulated Mars) to a continuous, time-dependent simulation [82]. In that study, steady-state calculations (like those presented here) reliably underestimated ion loss when compared to the time-dependent simulation calculations for similar parameter conditions. The discrepancy between the two calculations was most pronounced for O_2^+ and CO_2^+ (time-dependent producing approximately two-times the ion loss compared to steady-state), with O^+ showing little difference between the two simulation styles (practically no difference between the two styles) [82]. Combined with our calculations' apparent opposition to Fang et al. (2015)'s described above, future studies concerning the obliquity-induced effects might benefit from time-dependent simulations replicating a full rotation of the planet to help unravel this disagreement such as those presented in Ma et al. (2015) [161]. Additionally, recent simulation results by Ma et al. (2019) point to the importance of the electron pressure gradient (and corresponding ambipolar electric field; ∇P_e in equations 5.2 and 5.11) as an important source of energy for escaping ion species, with the inclusion of the ambipolar field amplifying ion loss from 50–110%, depending on exact model conditions [162]. The model style used here does not include a separate electron pressure calculation [180], so this mechanism is missing from these results—future work would likely benefit from the inclusion of this explicit forcing term when considering obliquity-induced effects.

The choice of our multifluid MHD simulation has precluded the consideration of particular physical processes that could not be described using the multifluid approach [34]. Chief among these were magnetic reconnection events, the union between the open IMF lines carried by the solar wind and the closed crustal field loops on Mars. Such events could be critical to ion escape, as the temporary joining of IMF and crustal fields could provide intense energy to ion species (released during the instant of field-line reconnection), possibly provoking greater escape. Additionally, reconnection events offer a temporary flow path for plasma attached to closed crustal field lines to leave the Martian ionosphere and escape down the tail by connecting the two magnetic regions. Per the orientation and extent of the regions of magnetic reversal shown in Figs 5.19 and 5.20, low obliquity scenarios might offer the greatest opportunity for nightside reconnection events as the draped magnetic field line encounters opposing lines from the crustal field or cusp regions were reconnection might be more likely to occur [37, 36, 33, 145, 38]. Additionally, the various spatial scales for the Martian magnetosphere (e.g., species-dependent cyclotron radii) made the fluid approximation in MHD a functional, but not completely physically accurate representation of the physical system. The combined effect of Mars' smaller physical radius and the weaker IMF magnitude mean the Martian magnetic obstacle is too small for the multifluid MHD approximation to hold everywhere reliably all the time [91]. Lastly, our choice of a BATS-R-US model precludes the addition of a reliable error estimation scheme for our calculated results. As the model self-modifies the spatial scales needed for calculation based on internally generated criteria [197], the results lack a meaningfully generalizable "yardstick" against which they could be compared save actual real-world data. While such comparisons to real-world data have upheld the model's accuracy (e.g., Ma et al. (2015) [161]), we do note here that these results should be read with appropriate sobriety as to their presumed accuracy.

Finally, this study ignored the changes to Mars' other planetary parameters, each of which might meaningfully alter the simulated planet's steady-state ion loss [65]. Eccentricity and the argument of periapsis would likely be the most important of these, as these parameters controls how much energy is available to be absorbed by a planet and how the crustal field obstacle would be facing at a particular spot along the planet's orbit. The combined effect of these two parameters might add or subtract from the obliquity-induced ion loss changes, depending on how each of them cycle with respect to one another. For example, a high obliquity planet might have its preference for ion retention partially counteracted by a more eccentric orbit as the increase in energy input by moving the planet closer to the Sun amplifies loss mechanisms. Similarly, our calculations have Mars directly leaning "back," with the north areographic pole pointing away from the Sun. But what happens six months later, when Mars is on the other side of the Sun? The obliquity angle does not change—the planet is just now facing the other way at noon. Are ion loss rates enhanced here, or has another process emerged that modulates their escape to a more reasonable amount? Lastly, the modification of the neutral atmosphere by changing the planet's obliquity was ignored, in spite of ample theoretical evidence that an obliquity change should alter the underlying atmosphere. Recent calculations presented by Ramstad et al. (2017) could propose present-day ion loss at Mars is production limited [202]—enough energy exists for any particle potentially escaping, but the number of potentially escaping particles controls the amount of escape. It might follow that changing the available number of ions by virtue of changing the obliquity (from the consequent changes to the underlying neutral atmosphere [46]) could result in a similarly altered ion loss rate. Future simulation studies may want to follow a similar procedure to Brain et al. (2010), by using a Martian global climate simulator to create a new neutral atmosphere for each choice of planetary parameters which is then passed to an MHD model like BATS-R-US for calcualtion [34].

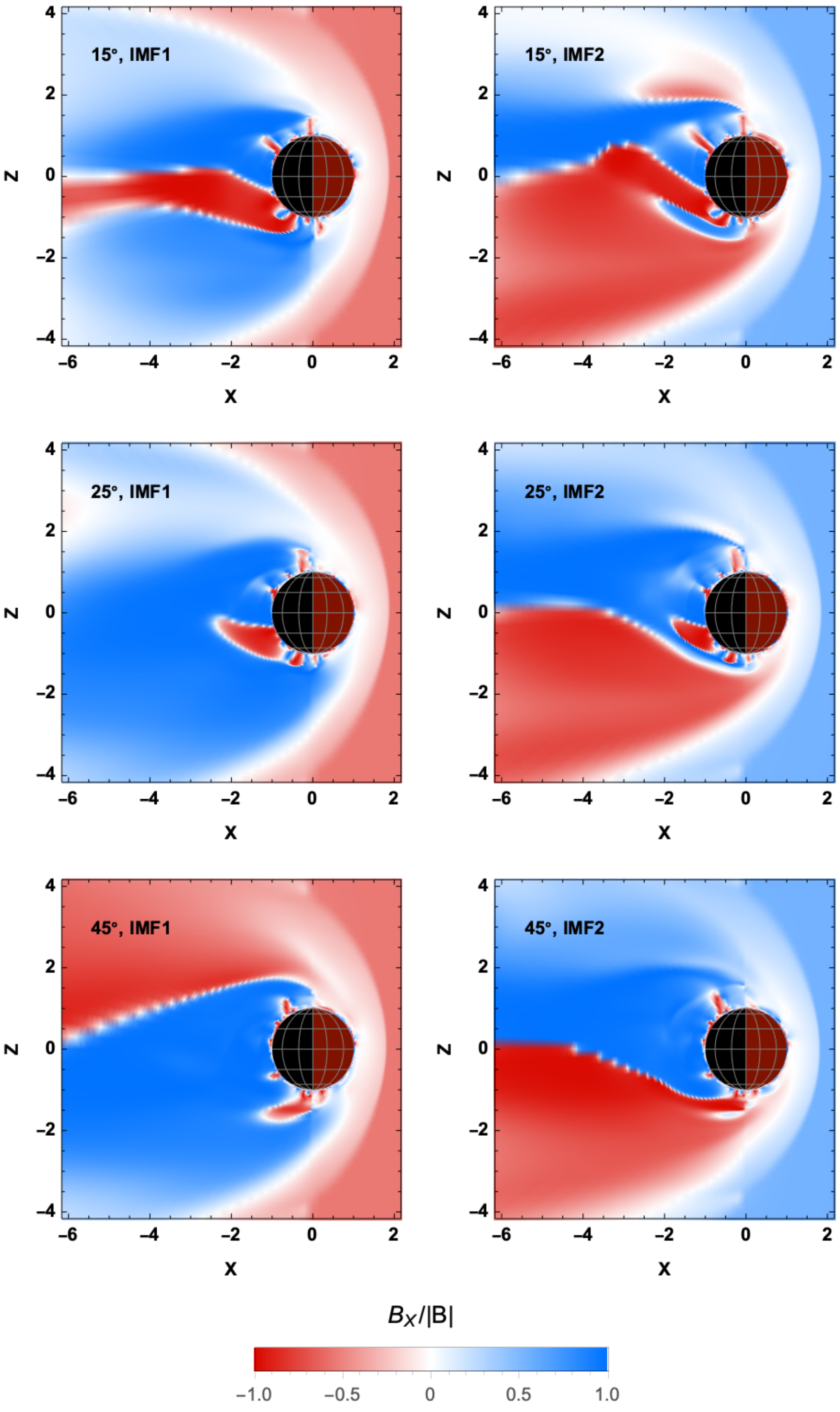
5.11 Conclusions

An investigation into Martian heavy ion loss using a multifluid MHD simulation campaign has been completed. Six simulations exploring the combined effects of planetary obliquity and IMF orientation on O^+, $O_2{}^+$, $CO_2{}^+$ were run with Mars' strong crustal fields on the nightside of the planet. Results suggested that obliquity has a minor, but measurable effect on the absolute escape rate of heavy ions from Mars (Fig 5.15), with obliquity angle and loss rates being anti-correlated. Expressed as percent-differences from a standard calculation (Fig 5.16), $CO_2{}^+$ showed the greatest comparative change over the simulated obliquity range—O^+ showed the least comparative change. Ion loss for all three species suggested that outflow through the tail as the dominant loss channel (Fig 5.17) for any obliquity; plume escape offered a minor contribution for all three species (Fig 5.18). Outflow patterns suggest that high obliquity conditions increase the dayside shielding effects of the nightside crustal magnetic field by hiding increasingly large regions of the Martian magnetosphere from directly interacting with the induced magnetosphere, thus suppressing cold ion outflow channels.

Changes in IMF orientation (and corresponding convective electric field) showed minimal effect on loss rates at low obliquity angles, but larger differences at high obliquities (Fig 5.16). Additionally, low obliquity angles resulted in a chaotic near-Mars magnetotail suggesting that draped field lines are disturbed by the presence of the crustal fields protruding into the MSO-XY plane and are prevented from smoothly forming a symmetric draped structure (Figs 5.19 and 5.20). Extended regions of oppositely aligned magnetism in the magnetotail at lower obliquities compared to higher ones suggest that reconnection events between the crustal fields and the IMF may be more likely to occur during low obliquity conditions as the remnant fields are lifted into the plane containing the draped field lines; however, the choice of a multifluid MHD simulator for this study leaves this question for future experimentation.

Implications of these results suggest that for Mars-sized worlds, partial magnetization via remnant crustal fields would not offer permanent protection for heavy ion species over the lifetime of the planet. Magnetic defenses for small terrestrial planets are likely a second-order adjustment to atmospheric escape, with gravity being the likely and ultimate determiner of a planetary atmosphere's lifetime survivability. However, modification of loss rates by obliquity changes contend that partially magnetized worlds might have temporary reductions to the loss of heavy ion species as the planet swings through its obliquity cycle.

Figure 5.20: Draping direction of the magnetic field in the MSO-XZ plane, expressed as the X component divided by the field magnitude. Obliquity angle and IMF condition are specified in the upper-left of each panel. Blue regions denote where the magnetic field is directed towards the Sun; red regions denote where the magnetic field is directed down the tail.



Chapter 6

Conclusions

6.1 Characterizing the collegiate planetarium environment

First, I conclude the PLUS and PLOBS projects and their findings and detail future studies that could follow. I will then discuss a third, and sadly cancelled, planetarium research study that was stopped by the emergence of the COVID-19 pandemic. Two studies, the Planetarium Usage Survey (PLUS) and the Planetarium Observation Study (PLOBS) have been completed to investigate the use of the planetarium environment for the purpose of collegiate instruction. Collegiate planetarium learning is characterized by the following procedural, pedagogical, and material traits:

- Instruction centers principally on astronomy content, with minor inclusions mostly from the sibling natural sciences like the earth sciences and physics.

- Analog-only planetariums are unlikely to present any content outside the sphere of astronomy. Digital-capable theaters show wide variance in presented materials.

- Instruction occurs fairly regularly, with planetarium lessons occurring every few weeks; however, frequency is widely varied depending on individual planetarium circumstances.

- Planetarium instruction is not viewed as a "time sink" or "one off" occurrence, and instruction therein is integrated into larger lesson plans.

- The planetarium environment is widely viewed as an immersive scaffolding tool for learners.
- Novice learners are the normal audience of learners; advanced learners are seen as not "needing" the scaffolding aid of the space.
- Outcomes from planetarium instruction are not perceived as uniquely affective nor cognitive; however, a preference for affective outcomes in the planetarium is favored over the cognitive favoring classroom outcomes.
- Presentation style closely mirrors the regular lecture-hall or classroom. Observed instruction suggests a didactic, instructor-centered pedagogy, but this may be specific to the investigated planetarium.
- Presentation in the planetarium is not likely to include many expressions of constructivist pedagogies. Instead, presentation relies heavily on immersive presentation coupled with classical lecture techniques.

These characterizations suggest that planetariums (and the instructors who use them) might find themselves at a bit of a crossroads when it comes to college education. On the one hand, the immersive planetarium theater alone has been demonstrated to aid learners, but it is not used every day so lessons therein should be as impactful as possible to make use of the space. On the other hand, classroom learning has also shown its demonstrable benefits to learners using constructivist-minded, active learner pedagogies like peer instruction. However, the observed overlap between planetarium and classroom pedagogical techniques would suggest that these two separate bodies of instructional techniques have yet to be meaningfully reconciled, and that instructors are taking their regular classroom pedagogies and holding them in the different immersive planetarium environment. Whether or not this is the most effective pedagogical use of the collegiate planetarium has yet to be determined.

6.1.1 Future Work: Continuation of PLUS

As discussed near the end of chapter 3, PLUS did not fully end with the termination of my study. Rather, PLUS was revised and restructured such that the survey instrument can be redistributed once every 3–5 years. The purpose for this is twofold. First, the planetarium environment itself evolves, and keeping track of the time-series changes to projector capacity, material variety, and instructional uses is important for the long-term characterization of the planetarium space. Second, as planetarium research continues to evolve, new aspects can be added to PLUS to keep up with the demands of the field. The most recent revision, PLUS 2.0, has integrated new questions that probe instructional styles (not just instructional contents) that can keep the field appraised of the more detailed nuances to planetarium use.

6.1.2 Future Work: Evolution of PLOBS

To my knowledge, PLOBS was the first instance of a classroom observation protocol making its way into the planetarium theater for research purposes. In demonstrating this, PLOBS has opened a door to planetarium research which was hitherto not used—validated third-party observations. The procedure demonstrated by PLOBS served as a proof-of-concept for the strategy, and has opened the space to greater research investigations beyond the power of immersive versus non-immersive visuals. The future for PLOBS, or for any sibling research studies that follows, is to improve upon the original design and continue the observation efforts at other planetariums at other universities.

Additionally, the study presented in chapter 3 was completed using a "snapshot" approach—examining a single instance of planetarium instruction for each instructor. Future iterations of PLOBS would benefit from a more longitudinal approach by observing the same instructor (or group of instructors) over multiple occasions of planetarium instruction. Such a campaign would offer both a greater sample size for statistical interpretations, but would also refine understanding of how planetariums are used over time. At a large university (like the one used in PLOBS) where multiple instructors might use the planetarium to instruct the same course (e.g., ASTRO 101), longitudinal campaigns over multiple semester or years would further describe the variance in how a particular planetarium over both a longer period of time but also across a wider roster of instructors. If such a study campaign could be coordinated with other colleges or universities, the same characterization scheme described in PLOBS would allow an expedient and effective means of observations across the planetarium community.

6.1.3 Cancelled Work: Planetarium Innovation Case Studies (PLICS)

The Planetarium Innovation Case Studies (PLICS)[1] protocol was an investigation into the innovation process of curricular strategies and artifacts in the collegiate planetarium space. Three faculty (listed in Table 6.1, along with a description of the innovation being experimented with) were of varying experience and were identified from the body of consenting faculty in the PLOBS project.

Table 6.1: The pseudonyms of the consenting faculty for the cancelled PLICS protocol. A description of each faculty's course is in the center column, and a description of the innovation case study for each faculty is in the right-hand column.

Faculty	**Class Description**	**Description of Innovation**
Dr. Uno	Upper-division education	Modified laboratory exercise for future teachers
Dr. Due	Lower-division astronomy	Retooling pre-recorded video content to enhance engagement strategies
Dr. Tre	Lower-division astronomy/geology	Redistribute seating arrangement of class for instructor mobility

The purpose of PLICS was to probe some of the potential barriers that exist against the wider incorporation of the planetarium environment in higher education via a curriculum revision

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[1] IRB protocol number: 19-0841. Granted exempt status for human subjects research on January 15, 2020.

or innovation. The initial results of PLUS demonstrated that while the astronomical sciences were the primary user of the space, other academic disciplines were also making use of the space for education purposes. Furthermore, PLOBS data from respondent non-users suggested that the planetarium was perceived as an “astronomy only” setting, and other subject disciplines had no reason to be instructed there. When these points were viewed in light of the long-running relationship between the planetarium and astronomy, it did not strain credulity to think that a barrier (perceived, practical, or otherwise) existed between more widespread planetarium use and certain faculty instructors. To that end, three faculty instructors, two users and one non-user, were recruited for a suite of small, case-study style curricular innovations.

The investigation protocol for this study followed the same general template for all three instructors: pre-interview, discussion, collaboration-towards-innovation, implementation, and post-interview. The order of the template steps was made by following Roger’s theory of diffusion and Henderson & Dancy’s work with physics faculty [207, 102]. During the pre-interview and discussion section, Roger’s theory was satisfied by having the three faculty enunciate the “prior conditions” outlined in the innovation-decision process—these conditions articulated “the thing” about their respective curricula that they felt were inefficient, undesirable, or otherwise needing a change [207]. The collaboration-towards-innovation portion made as many possible inclusions from the faculty as possible to avoid the barriers associated with an outside researcher presenting material to an instructor and expecting their immediate compliance in its use [102]. Incorporating the input and experience of the faculty during the process of curricular creation facilitates the completion of steps I and II of Roger’s decision process. The post-interview completed Roger’s process chain by confirming the innovation, either positively (allowing for revision or reuse) or negatively (abandoning the innovation) [207].

The first case study, Dr. Uno’s, was an innovation for an upper-division education course training future STEM instructors at the middle and high school level. The purpose of the innovation was to allow the learners to experience the planetarium space such that they might consider the space (or other spaces outside the classroom) for their future students. The innovation itself was a modified version of a pre-existing piece of curriculum from an undergraduate laboratory exercise for the planetarium environment. In this exercise, learners were posed to locate their location on Earth using their knowledge about the motions of the celestial bodies (Sun, Moon, etc.) by simulating the various sky conditions via the planetarium dome. Before they were challenged to do this, learners were guided through a brief, inquiry-style presentation to inform them of the aspects of sky motions necessary to complete the challenge. Dr. Uno's desire to try a planetarium exercise was not out of a particularly well-defined dissatisfaction with their current course curriculum—rather, Dr. Uno expressed a desire to expand upon the existing repertoire of problem-based learning exercises that their students could use in concept mapping similar exercises in the future. After the exercise was completed in the planetarium, Dr. Uno's learners then participated in a group discussion in the planetarium lobby where they dissected their experience as learners using their experience as educators. Part of this discussion was the construction of concept maps exploring how the planetarium space might be a "jumping off' point for a broader lesson plan, such that these future educators might use the planetarium space as a single cornerstone lesson from which an entire suite of learning objectives could be defined.

The second case study, Dr. Due, was an innovation for a lower-division astronomy course for non-majors. The purpose of this innovation was to incorporate more opportunities for reformed practices (peer-instruction, active engagement, etc.) into Dr. Due's regular planetarium lesson. Dr. Due's past experience in the planetarium highlighted great proficiency and satisfaction with planetarium lessons delivered using live content as the method of delivery, but also demonstrated a comparative dissatisfaction with video content. The lesson in question, using the fulldome video *Dynamic Earth* as a part of the course's objectives towards instructing comparative planetology, was a reliable planetarium excursion for Dr. Due's classes, but the use of the video was perceived as somewhat disconnecting. The video was typically played in one unbroken sitting (approximately 20 minutes long), with no pauses for discussion or reflection upon its contents until the very end.

Dr. Due expressed a desire to keep the underlying content of *Dynamic Earth*, but also wanted a chance to incorporate pauses in the fulldome video so the class might participate in engagement strategies while the video was playing, rather than wait until the end of the video. Thus, Dr. Due's case study would morph the current presentation strategy of a 20 minute video followed by a 20 minute lecture/discussion period into a synthetic lecture/video/discussion period for the entire class period.

The third case study, Dr. Tre, was an innovation for a lower-division astronomy/geology course for non-majors exploring the potential of life in the Universe. As a multidisciplinary class, Dr. Tre's course needed to call upon four cornerstone disciplines (astronomy, geology, chemistry, and biology), but could not spend too much time in any one of them. The planetarium, perceived as a valuable instructional resource for the astronomy cornerstone by Dr. Tre, was integrated into this class; however, Dr. Tre found a pedagogical barrier to its use in the form of the planetarium's physical setup. Unlike the regular classroom at their disposal, Dr. Tre was unable to freely move throughout the planetarium space during discussions or question/answer sessions due to the tight rows of reclined seats and comparative lack of clear aisles. Dr. Tre's class numbered only approximately 120 students, thus the innovation was not to invent a new piece of curriculum to circumvent this problem. Rather, the large seating capacity of the planetarium in question did allow for the possibility of simply reorganizing the students such that empty rows could be maintained for instructor mobility. This reorganization strategy would have allowed for learners to still be seated together for discussions and questions, but would have also allowed Dr. Tre (and their TA) to more freely move throughout the space, facilitating the lesson like the regular classroom.

Unfortunately, the emergence of the COVID-19 pandemic in the United States during the Spring 2020 academic semester put a functional stop to all three of these case studies, due to state-wide orders against congregations of students. At this time, PLICS had already completed one trial run of Dr. Uno's case study, and a revision and repeat was planned for the Fall 2020 semester, but was not materialized due to the pandemic; Dr. Due's case study had completed a formalized a strategy to retool the *Dynamic Earth* video into 5–10 minute clips with a corresponding suite of Clicker questions and class discussions, such that Dr. Due's planetarium lesson would be transformed from a 20 minute video followed by a 20 minute lecture to a 40 minute video/lecture hybrid; Dr. Tre's case study had completed a dissection of the planetarium environment and had identified locations in the planetarium where empty rows could be maintained while still seating the entire class of learners. The pandemic made all of these a practical impossibility, but their potential as future pieces of research remained unhampered. Dr. Uno's desire to use the planetarium as a location of teacher training was in alignment with the findings by Everding & Keller (2020), showing that more advanced learners in the planetarium space are future educators [77]. Dr. Due's desire to incorporate more engagement strategies in their planetarium lessons when using video content also highlighted one of the perceived "cons" of pre-recorded content in interviews with planetarium directors [77]. Dr. Tre's desire to enhance their mobility to maintain their facilitation capacity in the planetarium theater was a commonplace barrier discussed by the instructors participating in PLOBS. Every one of these desires for change generalizes, thus even though these case studies were not completable for this work, they should certainly survive into the post-pandemic educational environment.

6.1.4 Reflections upon PLOBS & Advice to Planetarium Instructors

Though PLOBS made no attempts to characterize any particular instruction as good or bad, the data presented and analyzed in chapter 4 did demonstrate lesson procedures that generally aligned with more traditional instructor-centered collegiate pedagogy. Such alignment with these pedagogies was not unexpected *per se*; however, the persistence of these instructor-centered lesson styles is discouraged by current AER findings. To that end, I would reflect upon the more practical findings from PLOBS and offer some possible advice to planetarium instructors.

First, I would remark upon instructors' perceived difficulties in incorporating active learning strategies in the space, specifically those difficulties that centered on physical movement through the planetarium space. Since the completion of PLOBS, the studied planetarium in question has undergone interior renovations which will likely impact how the space could be or would be used in the future. In the original planetarium setup (as existed during PLOBS), a large circular pit in the center of the planetarium theater contained an elevator system to raise or lower the planetarium's analog starball projector into or out of position for projection. This pit excluded a large amount of floor space from being used by instructors or learners—the floor, literally, did not exist to be stood upon. Renovations have since reduced the size of this pit containing the analog projector, freeing up more floor space for instructors to walk through or to present in. I would recommend that future instructors in this renovated space make purposeful use of this new area and present their planetarium lessons from this newly created "front" that was previously unavailable. Where feasible, instructors might also use this space for activities to include learners in the newly available space.

During my observations of planetarium lessons, most of the observed faculty presented their material from a relatively confined area near or inside the navigator's booth in the planetarium, as opposed to the dedicated presentation stage on the opposite side of the theater. Since the planetarium's seating arrangement draws the audience's attention to the "sweet spot" on the ceiling above the stage, learners generally needed to direct their attention around to another direction in the theater should they have wanted to make a line-of-sight to the speaking instructor. Additionally, I might recommend that instructors actually rehearse their planetarium lessons as they prepare for them in the theater. As was discussed during PLOBS, instructors did make use of the theater itself when preparing lessons for the setting. I would advise that given the newly designed floor plan instructors block out their lesson delivery during their review of lesson material to more concretely envision not only what a lesson will cover, but also how and where the instructor plans to facilitate said material.

Second, it is commonplace for curricula, notes, and lesson materials to be shared by faculty instructors within a particular department (or closely aligning departments) whenever a particular faculty is assigned a course they have not instructed before (or for some time). Planetarium materials should behave no differently. However, the degree to which particular planetarium materials are shared between instructors is unknown, and given the comparatively slow rate of planetarium use, it could be the case that planetarium lesson materials or strategies are not readily shared between instructors. Instructors who make more frequent use of the planetarium might create or experiment with certain lesson materials more often than instructors who do not. The collective experiences of various instructors' planetarium lessons might warrant a reconsideration of how these materials are memorialized and passed between instructors, especially active-learning materials like clicker questions and discussion prompts. Finally to this point, instructors who use the planetarium may want to consider an end-of-term group reflection period where all instructors who had used the planetarium revisit their lessons as a team of teaching professionals. In this group setting, instructors might discuss, reenact, critique, and dissect their experiences as peers. Sharing and documenting their experiences might offer critical insight into both individual instructors' pedagogical strategies and to future instructors who seek advice on using the planetarium theater.

Third, as was highlighted by PLUS, most of the learning that occurs in a typical undergraduate courses using a planetarium is spent in the classroom setting. As a consequence, an instructor's most practiced pedagogy likely hails from the classroom setting, and the pedagogy used in the planetarium is modified from this practiced one. The data collected in PLOBS suggest that this is indeed the case, with planetarium pedagogy being a more passive version of an otherwise "standard" classroom pedagogy. Thus it follows that if an instructor were desiring to increase the level of active-learning strategies in the planetarium, it might be of benefit to also focus on increasing active-learning in the classroom, rather than focusing all effort on a more active planetarium environment alone. By increasing the "standard" level of these reformed practices in the classroom, the planetarium's natural pacification might be less severe for a given class. Yes, it would still be likely that a planetarium lesson would be comparatively more passive than a classroom lesson, but the reduction in active-learning would be from an inherently higher percent-of-lesson amount. Accompanying this point, I might also recommend that planetarium instructors participate in planetarium lessons given by other instructors, especially during academic terms when they themselves are not instructing in the planetarium (where feasible). This participation could be of many forms (e.g., team teaching with the primary instructor, acting as an additional lesson facilitator like a TA, or acting as a temporary learner in the audience), but the purpose remains the same—instructors being involved in the planetarium might be more prone to reflect upon their own planetarium lessons. Moreover, seeing other instructors use the space might offer insights or ideas for planetarium instructors that they may not have considered in isolation.

Lastly, instructors may want to consider subjecting themselves to COPUS-like observations more often, especially if their host institution has the resources available to provide these observations as a part of professional development. Should an institution not be able to provide this service, a body of planetarium-using faculty might want to consider having one or two members trained in a COPUS-like protocol such that a local, familiar observer would be available to observe their peers. Why would I recommend this to instructors? In both the classroom and planetarium environments, instructors' own self-reflection of their lessons might not accurately capture the details of the pedagogical strategies *actually* used. An observation protocol offers a chance to reflect upon pedagogical practices with much of the subjective nature of self-reflection removed. Groups of instructors might use their own reflections and observational data to better strategize lesson pedagogies, and the availability of peer observers might relieve instructors of some of the anxiety associated with having their instruction observed. Finally, I would contend that the very act of being trained in an education-focused instrument like COPUS might raise instructors' awareness of their own pedagogical choices and strategies, possibly guiding their own advancement towards reformed practices by instilling the same identification and categorization skills used by education researchers.

6.2 Investigating the effects of the Martian obliquity cycle on heavy ion escape

Lastly, I conclude the findings of MOP and detail future simulation work that might follow. The Mars Obliquity Project (MOP) has been completed simulating the effects of a changing planetary obliquity on the loss of heavy ions from the planet Mars using a multifluid, MHD simulation campaign. The effects of a changing obliquity angle on Martian heavy ion loss are characterized as follows:

- Heavy ion loss from Mars is, in general, suppressed when a change in obliquity angle increases the magnetic obstacle along the day/night terminator.
- Species-dependent changes in loss rate favor the retention of heavy species (e.g., CO_2^+) compared to lighter ones (e.g., O^+).
- IMF-dependent escape behavior is exacerbated at high obliquity angles for heaviest ion species (O_2^+ and CO_2^+)
- Loss rates are not drastically altered by obliquity angle—crustal field position can only modify ion loss, but cannot stop it completely.
- Insensitivity to obliquity angle suggests that gravity, not magnetic field generation is most critical factor to atmospheric retention for partially magnetized planets
- Crustal field sources on the nightside may be prone to magnetic reconnection with the draped IMF as the obliquity angle raises them into the orbital plane.

6.2.1 Future Work: Combined Diurnal/Obliquity Effects

As was highlighted in chapter 4, the experimental setup of MOP used steady-state calculations with a “frozen” Mars to make the escape calculations. These benefits of this calculation style are most importantly counted in amounts of time—a steady-state simulation can converge to a solution in just a few hours, while the same time-dependent simulation might take upwards of an entire day to complete [34, 82]. However, time-dependent simulations are undoubtedly the more realistic simulation style, especially when the timescale of changes in the system are not negligibly long [82]. As intensive computing resources become more accessible, a reevaluation of this study as a time-dependent experiment may be warranted. Furthermore, MOP sampled only the obliquity regime characteristic of Mars’ most recent geological past, which may be only a subset of the entire Martian obliquity history [136].

6.2.2 Future Work: Expanded Experimental Parameter Space

Additional to the integration of time-dependent simulations, future investigations would benefit from the inclusion of some of the variables that were purposefully set aside for the execution of the MOP. Concurrent with their study of the Martian obliquity cycle, Laskar et al. (2004) were also able to make determinations of the Martian inclination and eccentricity over the same stable time period [136]—we set these aside for MOP, however the two do represent important parameter spaces for future studies of the planet. Moreover, the climatic changes that normally follow a change in planetary obliquity were similarly ignored in this work. Greater accuracy towards calculations of ion loss (and implied atmospheric loss) would benefit from ensuring that a simulated Mars has the most accurate obliquity-appropriate neutral atmosphere during other simulation runs. Such an atmosphere might itself be simulated using a global circulation model campaign which simulates Mars’ atmosphere for a particular obliquity angle (or combination of other planetary parameters) and reports the necessary density and velocity profiles for each species to a multifluid MHD simulator which then calculates the corresponding ion loss.

6.2.3 Future Work: Different Simulation Engines & Similar or Generalized Planets

Lastly, the choice of a multifluid, MHD simulator, while a sound one given past research efforts at Mars, did specifically omit particular physical processes that cannot be meaningfully described in the fluid representation (e.g., kinetic effects, individual particle motions, reconnection). The results of MOP suggest that during particular obliquity and IMF conditions, some of these processes (especially reconnection) may be more prone to occur; however, the choice of simulator made capturing these non-feasible. Future investigations with greater available calculation resources might benefit from a multispecies or hybrid style model that can accurately capture kinetic effects induced by obliquity change. Additionally, the planet Mars possesses a particularly unique magnetic environment, given the planet's asymmetric crustal field distribution [1, 53]. Future work into obliquity induced effects might challenge the results of MOP with a different crustal field distribution, perhaps one without a central strong region or a collection of moderate sources scattered around the planet.

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Appendix A

PLUS Supplemental Material: PLUS 2.0

A.1 Revised Planetarium Usage Survey, PLUS 2.0

Based upon analysis of the initial Planetarium Usage Survey (PLUS 1.0), we have refined this instrument for future study. PLUS 2.0 is targeted towards planetarium professionals (e.g., directors, education coordinators) to describe how their planetariums are used. PLUS 2.0 is constructed using the Qualtrics surveying platform and is estimated to take 10–15 minutes for a respondent to fully complete.

The revised survey items for PLUS 2.0 are provided below, divided into appropriate question sections. We present the question items in italics, with each question's response mechanism and response items following each question in standard font. The constructs sought by this instrument are: respondent characterization; learner populations and use frequency; subject-materials and projector-dependent variety; interactive strategies and perceived environmental traits; and the nature of presented content.

The opening salutation and human subjects consent information is omitted from the revised PLUS 2.0 instrument presented here.

A.1.1 Section 0: Introduction & Informed Consent

This section contains the opening salutation and the IRB approved consent information, necessary for collecting research data. No questions are contained in this section.

A.1.2 Section 1: Contact Information & Respondent Characterization

This section asks respondents to provide a point of contact, should follow-up communication be needed. Additionally, respondents describe their planetariums by answering a set of multiple choice questions.

Q1.2: Please specify which type of institution your planetarium's college/university is located upon.

Respondents are presented with a compressed list of Carnegie Classification descriptions [86], and select the single best description from:

- Doctoral
- Master's
- Baccalaureate
- Associate's.

Q1.3: Please select the best option describing the approximate population size of your planetarium's immediate surrounding area.

Respondents select an option from this list of numerical ranges:

- less than 10,000 people

- 10,001–50,000 people
- 50,001–100,000 people
- 101,000–500,000 people
- 501,000–1,000,000 people
- more than 1,000,000 people.

Q1.4: Please select the best description of your planetarium's projection system.

Respondents select a single option from: "fully analog," "hybrid analog/digital," "fully digital," or "portable." If a respondent planetarium is currently undergoing renovations or upgrades, respondents are prompted to answer this question as if those upgrades were complete.

A.1.3 Section 2: Usage by Learner Populations

This section asks respondents to describe the use of their planetarium by a pre-defined set of learner groups. These groups are defined for the respondent in the front matter of this section, and can be found in Table A.1 with the learner populations in the left-hand column and their definitions in the right-hand column.

Q2.1: During the last two calendar years, which learner population has been your single largest service user, based on the total number of learners coming to your planetarium.

Respondents select a single learner population from the list of possible populations shown in Table A.1.

Q2.2: During the last two calendar years, how often was your planetarium used by any group from the following learner populations?

Table A.1: Learner populations explored in PLUS 2.0. Populations are defined for respondents to consider before answering survey items Q2.1, Q2.2, and Q2.3 described in Section 2 of the survey instrument.

Learner Population	**PLUS Definition**
Pre-K	Children enrolled in a pre-school, daycare, or similar institution before elementary school.
Elementary (K-8)	Children enrolled in elementary, middle, or junior high school.
High School (9-12)	Young adults enrolled in high school, vocational/technical school, or similar institution granting a high school diploma or GED upon completion.
Community College	Adults enrolled in a community college, junior college, or similar institution usually granting at least an Associate's degree upon completion.
Four-year College	Adults enrolled in a four-year college or university usually granting at least a Bachelor's degree upon completion.
Graduate Student	Adults already possessing a college degree seeking an advanced degree like a Master's or PhD.
General Public	Persons who might encounter or interact with the planetarium outside the experience of an enrolled student. These persons are usually attending a public lecture, video-screening, laser show, or other event that requires some form of general admission process.

For every learner population, respondents select a corresponding use frequency from:

- Daily
- Weekly
- Monthly
- Yearly
- Never.

This question includes the following example to help respondents guide their selection: *for example, if your planetarium is used every week by some class of elementary learners (but not necessarily the exact same class) you would select "Weekly" in the second row..*

Q2.3: During the last two calendar years, how often was your planetarium used by a given group from the following learner populations, on average? If a learner population could be described with two frequencies, please select the most frequent.

For every learner population, respondents select a corresponding use frequency as in Q2.2. This question includes the following example to help respondents guide their selection: *for example, consider a four-year college with two sections of an "ASTRO 101" class. The first section visits your planetarium once a month ("Monthly"), and the second section visits your planetarium only once every semester (best described with "Yearly"). On average, a given group of ASTRO 101 students would be best described as "Monthly," so the appropriate selection would be "Monthly" in the fifth row.*

Q2.4: During the last two calendar years, what kind of learning environments have you been asked to provide for visiting learners?

Respondents select learning environments from a pre-defined list (Table A.2) for each of the

Table A.2: Learning environments explored in PLUS 2.0. Environments are defined for respondents to consider before matching them to served learner populations items in Q2.4 of Section 2 of the survey instrument.

Learning Environment	**PLUS Definition**
Formal	Structured, well-defined lesson or presentation with a clearly defined learning goal like a lecture or recitation. More instructor-driven and topically driven by a class curriculum.
Informal	Partially structured, self-guided lesson or presentation without a clearly defined learning goal like a field trip, student club, or open house. More student-driven and topically driven by students' personal interests.
Entertainment	Structured, well-defined presentation expressly for diversion or distraction, with no true learning goal like movie screenings or laser shows. Neither instructor-driven nor student-driven.

learner populations (Table A.1 in a tabular, check-box format question. Respondents may also select a “None” option for learner populations that are not served by their planetariums.

The learning environments defined in Table A.2 have been defined by considering the traits of formal and informal learning environments [264, 270, 193], as well as considerations of planetariums as entertainment venues [11, 267].

Q2.5: If there are particular uses of your planetarium that you would like to describe in more detail, please include them in the space below.

Respondents are given an option to provide free-response feedback on the use of their planetarium after answering Q2.4, however respondents do not need to provide any free-response feedback. This question is the only free-response question item on PLUS 2.0, and respondents are not forced to answer before continuing the survey.

A.1.4 Section 3: Collegiate Use of the Planetarium

This section focuses the respondent specifically to collegiate use of their planetariums, the previous two sections collecting collegiate-specific information in addition to other learner populations.

This section periodically prompts the respondent to consider the characteristics of “typical” collegiate learners in their planetariums. Respondents are prompted to “disregard any novel, exceedingly rare, or one-of-a-kind uses of your planetarium unless those uses have actually become regular or usual practice for your collegiate-level learners within the last two calendar years” when considering typical uses of their planetariums.

Q3.1: During the past two calendar years, what kind of typical collegiate-level learners visited your planetarium?

Respondents are prompted to select all descriptions that apply to their planetariums from:

- freshmen (1st year)
- sophomore (2nd year)
- junior (3rd year)
- senior (4th year or higher)
- graduate students
- STEM major
- non-STEM major.

"STEM" is the commonplace shorthand for "science, technology, engineering, and mathematics."

Q3.2: During the past two calendar years, how have typical collegiate-level learners experienced lessons or presentations in your planetarium?

Respondents are prompted to select as many applicable instructional archetypes that apply to their typical collegiate learners. These archetypes are:

- During the regularly-scheduled class period
- Outside the regularly-scheduled class period
- Presented content integral to class' curricular goals
- Presented content not integral or extraneous to class' curricular goals
- As a part of a lab, studio, or workshop style class

- As an entire class period, staying in the dome learning environment during the lesson
- As a partial class period, transitioning to another learning environment during the lesson
- As an active audience, discussing amongst themselves and/or guiding the course of the lesson
- As a passive audience, primarily listening to the course instructor, other presenter, or narrator

Q3.3: Consider the subject material presented in your planetarium during the last two calendar years. Please select which materials were presented to classes of undergraduate or graduate learners, and where possible, please include the number of students in a typical class learning that material.

Respondents are presented with definitions for each subject material. These definitions are defined through description, with each subject material given topical examples to guide respondents. These definitions are found in Table A.3. In addition, respondents are offered a numerical entry box to provide an approximate class size when able.

A.1.5 Section 4: Tools & Technologies

This section focuses on the available tools and technologies available for use in the collegiate planetarium setting. This section maintains use of the description "typical" explained above.

Q4.1: How often are the following tools or technologies used during a typical collegiate-level class period in your planetarium?

For each tool or technology, respondents select a single usage frequency from the following list: "frequently," "rarely," "never, but available," or "None available." The list of possible tools or technologies included in this question is:

- Electronic ARS (iClicker, cell-phone app, or similar)
- Analog ARS (voting cards, hand-raises, or similar)
- Online forms for answer submissions (e.g., GoogleDocs)
- Small, personal whiteboards for learners
- Augmented or virtual reality (AR or VR) devices
- Auditory support devices (headphones, closed captioning)
- 360-degree, full dome projections
- 2D slide projections
- Large whiteboards for presenters
- Interactive demos (e.g., lobby installations, experiment carts, etc.)

"ARS" stands for "Audience Response System(s)." These tools or technologies are used to gather immediate feedback from the audience, usually without direct verbal discourse, and are often used as supports for "ABCD" or "True / False" format questions.

Q4.2: For a typical collegiate-level class held in your planetarium, which of these options best describes the division of responsibilities in your planetarium during a lesson with regards to planetarium operation and lesson presentation?

Respondents may select a single option from the following list of archetypes describing how the division of responsibilities occurs:

- Planetarium staff operates planetarium and presents lesson material.

- Planetarium staff operates planetarium, but class instructor presents lesson material.
- Class instructor operates planetarium and presents lesson material.
- Class instructor operates planetarium, but planetarium staff presents lesson material.
- No distinction possible—planetarium staff and class instructors are not separate entities.

A.1.6 Section 5: Closing Comments

Respondents are finally allowed the opportunity to provide any comments about the survey or their responses to it. This open-ended, non-compulsory question is meant to allow respondents to provide unfettered feedback. Once a respondent has completed this question (or chosen not to) the survey ends and responses are recorded.

Table A.3: Subject materials explored in PLUS 2.0. Materials are defined by a descriptive list of topics or disciplines to guide the respondent when answering Q3.3.

Subject Material	**PLUS Definition**
Astronomical Sciences	Space-centered material like sky motions, seasons, ancient astronomies, solar system structure, planetary geology, orbital/stellar/galactic dynamics, scale/structure of the Universe, solar/stellar structure.
Earth Sciences	Earth-specific material like geology, rheology, seismology, geography, oceanic sciences, atmospheric or meteorological sciences.
Physical Sciences	Physical or chemical material like mechanics, electromagnetism, relativity, physical/organic chemistry, stoichiometry, or redox reactions.
Engineering & Mathematics	Materials like engineering structures, practices, design principles, trigonometry, algebra, calculus, or other mathematical methods.
Life & Medical Sciences	Materials like biology, ecology, botany, zoology, anatomy/physiology, mental or physical therapy, or medicine.
Humanities & Social Sciences	Materials like history, English, classics, literature, foreign language, political science, religious studies, anthropology, psychology, sociology, or behavioral studies.
Fine & Performing Arts	Materials like photography, visual arts, musical or orchestral arts, poetic or literary arts, comedy, dance, or theatrical arts.
Pedagogical & Instructional Techniques	Materials like best practices, practice instruction, student teaching, or instructor preparation for any grade level.