Adaptive-Optics Integral-Field Spectroscopy of NGC 4388

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ADAPTIVE-OPTICS INTEGRAL-FIELD SPECTROSCOPY OF NGC 4388

Defended October 28, 2016

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Nature's most powerful objects are well-fed supermassive black holes at the centers of galaxies known as active galactic nuclei (AGN). Weighing up to billions of times the mass of our sun, they are the most luminous sources in the Universe. The discovery of a number of black hole-galaxy relations has shown that the growth of supermassive black holes is closely related to the evolution of galaxies. This evidence has opened a new debate in which the fundamental questions concern the interactions between the central black hole and the interstellar medium within the host galaxy and can be addressed by studying two crucial processes: feeding and feedback. Due to the nature of AGN, high spatial resolution observations are needed to study their properties in detail. We have acquired near infrared Keck/OSIRIS adaptive optics-assisted integral field spectroscopy data on 40 nearby AGN as part of a large program aimed at studying the relevant physical processes associated with AGN phenomenon. This program is called the Keck/OSIRIS nearby AGN survey (KONA). We present here the analysis of the spatial distribution and two-dimensional kinematics of the molecular and ionized gas in NGC 4388. This nearly edge-on galaxy harbors an active nucleus and exhibits signs of the feeding and feedback processes. NGC 4388 is located in the heart of the Virgo cluster and thus is subject to possible interactions with the intra-cluster medium and other galaxies. Outflows of ionized gas has been detected to the southwest and northeast of the active nucleus. The molecular gas has been pushed to the western part of the disk as a consequence of the outflow. Analysis of the kinematics of molecular gas provides evidence of a warped disk surrounding the inner black hole. These kinematics hint at a possible past minor merger event. Furthermore, the angle of the southwestern outflow conflicts with the current unified model for active galaxies, as it indicates a misalignment between the AGN and the galactic plane.
# Contents

Abstract 1

1 Introduction 4

1.1 Active Galactic Nuclei 4

1.2 NGC 4388 7

2 Observations 9

2.1 Integral Field Spectroscopy 9

2.2 Adaptive Optics 10

2.3 Observations 11

3 Data Reduction and Processing 12

3.1 OSIRIS Data Reduction Pipeline 12

3.2 Combining Datacubes 13

3.3 Visualizing Datacubes 13

3.4 Extraction of the Emission-line Gas Properties 14

3.5 Kinemetry 15

4 Results 16

4.1 Integrated Spectra at Different Regions 16

4.2 Kinematics of Emission Lines 18

  4.2.1 Molecular Hydrogen 18
4.2.2 Silicon-VI .................................................. 20
4.2.3 Brackett-γ .............................................. 20
4.2.4 Helium-I .................................................. 21
4.2.5 Calcium-VIII ............................................. 21

4.3 Kinematic Modeling of OSIRIS Data ...................... 21

5 Discussion ................................................... 23

5.1 Location of the AGN in NGC 4388 .......................... 23
5.2 Stellar Kinematics ......................................... 25
5.3 Extraplanar Gas .......................................... 26
  5.3.1 High Ionization Complexes ......................... 26
  5.3.2 The Very Extended Emission Line Region .......... 27
5.4 Interpretation of the Kinematics of the Ionized Gas in the OSIRIS Data ... 27
5.5 Interpretation of the Kinematics of the Molecular Gas in the OSIRIS Data 28
5.6 Comparison with Multi-wavelength Datasets .............. 30
  5.6.1 Comparison with Radio Data ....................... 30
  5.6.2 Comparison with X-ray Data ....................... 31
5.7 Explanation of Extraplanar Gas .......................... 33
  5.7.1 Nuclear Outflow .................................. 33
  5.7.2 Intra-Cluster Medium ............................. 35
  5.7.3 Starburst Driven Superwind ....................... 36
5.7.4 Tidal Debris from Galaxy Merger .......................... 36

6 Conclusion 37

7 References 40

Appendix 44
1 Introduction

1.1 Active Galactic Nuclei

Active galactic nuclei (AGN) are nuclear regions in galaxies that exhibit high emission levels of radiation in the electromagnetic spectrum. These high luminosity levels are usually attributed to the accretion of material onto a supermassive black hole (BH) in the nuclear region. AGN allow scientists to learn more about the mysteries of black holes as well as study the history of the universe. This is because AGN are steady sources of radiation that correspond to a particular instant in the evolution of the galaxy and thus serve as a means to discover the age of the universe. As we look further into the depths of the universe, we peer back in time. Knowing the distance to an AGN and its stage in evolution help put constraints on the age of our universe (Carroll and Ostile, 2006).

AGN come in many forms, all of which are distinguished by differences in their electromagnetic spectrum. Observation of broad and narrow emission lines, relative amounts of energy ranges, presence of relativistic jets, and variability are all elements used to categorize AGN. One main classification is known as Seyfert galaxies, which have very high surface brightness with high ionization emission lines in their spectra. Seyferts branch off into two classes based on their electromagnetic spectra. Seyfert 1 galaxies have very broad emission lines that include both allowed emission lines as well as forbidden, or highly improbable, lines. They also contain some narrow allowed emission lines, but these lines are usually broader than typical galaxies. Seyfert 2 galaxies only have narrow lines, both allowed and forbidden. Other differences arise between the Seyfert classifications as well. Seyfert 2 continuum is less luminous than that of Seyfert 1 galaxies; it is often difficult to separate the continuum of the AGN from stellar continuum in the host Seyfert 2 galaxy. Seyfert 2 galaxies also have more faint X-ray emission.

The unified model of AGN proposes that all classifications of AGN make up one intrinsically similar system and that the differences in spectra between the
classifications are due to the orientation of the central nucleus with respect to the observer's line of sight, as seen in Figure 2. The unified model suggests cold material falls towards a central black hole (BH) creating an accretion disk that surrounds the BH. In a process known as feeding, the material then descends onto the BH and causes the BH to grow. This accretion disk is responsible then for the X-ray through optical continuum emission as the mass converts to energy. Surrounding the accretion disk is an optically thick torus that obscures radiation as well as absorbs and re-emits energy in the infrared. There is also thought to be a broad line region (BLR) of dense clouds within the torus that accounts for the broad emission lines visible in Seyfert 1 galaxies. A narrow line region (NLR) of gas clouds residing outside of the torus and around the jet can explain the narrow lines of Seyfert 1 and 2 AGN spectra. Thus, the different classifications of AGN can be attributed to the angle at which the observer views the nucleus. Observers that view a Seyfert 1 AGN view from an angle in which the BLR can be seen, conversely, Seyfert 2 observers cannot directly view the BLR.

Figure 1: A model of an active galactic nuclei (AGN) labeling the different components. Courtesy of google. http://heasarc.gsfc.nasa.gov/docs/cgro/images/epo/gallery/agns/
The accretion disk heats and ionizes surrounding material then releases the energy into a relativistic jet that extends along the rotational axis of the disk. The jet then can interact with the dust, gas, and stars in the host galaxy in a process called feedback. Various feedback models (Di Matteo et al., 2005; Springel et al., 2005) propose that BH accretion supplies energy for outflows into the interstellar medium through jets, winds, and radiation. The energy discharge is large enough to quench star formation by depleting the surrounding area of gas and dust. It will also stop BH growth as mass is converted to energy. This particular process is known as negative feedback. Other models call for positive feedback in addition to negative in order to explain phenomena that occur in galaxies with AGN (Ishibashi and Fabian, 2012; Silk, 2013). An example
of positive feedback is increased star formation rates in a host galaxy due to outflows (Silk, 2013). However, due to our current technology prohibiting the ability to resolve the processes close to the black hole and in far away galaxies, the topic of feeding and feedback continues to be discussed and debated in extragalactic astronomy.

### 1.2 NGC 4388

The main interest of this thesis, NGC 4388, is a Seyfert 2 galaxy in a larger survey of 40 nearby AGN. This survey, named the Keck/OSIRIS Nearby AGN survey (KONA survey, Müller-Sánchez et al. 2016, in preparation), uses adaptive optics-assisted integral field spectroscopy to study the kinematics of the central regions of Seyfert galaxies. All of the data was taken at the W. M. Keck observatory using the OH-Suppressing Infrared Imaging Spectrograph (OSIRIS). The galaxies surveyed are at distances less than 150 Mpc from Earth and are known to host bonafied AGN. By conducting this large survey, we have begun a process that will allow us to study the processes of many different AGN and compare them to test the overarching unified model of AGN. With adaptive-optic assisted integral field spectroscopy data, we will be able to extract the statistical meaning of results in the inner parsecs of AGN. This will aid us in exploring the mechanisms for feeding and feedback, discover how feedback affects the host galaxy, and understand the coevolution of AGN with their host galaxy. I reduced the data for over half of the galaxies in the survey employing the OSIRIS data reduction pipeline along with original IDL and python code. I also created a step by step manual for reducing OSIRIS data, which is included in the appendix.

The KONA survey has equal numbers of known Seyfert 1 and 2 galaxies. Three of the Seyfert 2 galaxies are nearly edge on, one of them being NGC 4388. Edge-on galaxies are defined as galaxies a that are situated at an inclination close to 90°. This specific galaxy sits at a position angle (PA) of 90 deg and has an inclination of 78° determined by large-scale kinematics according to Veilleux et al. (1999b) and Greene et al. (2014). PA is the angle measured counterclockwise relative to the north celestial pole. An optical wavelength image of NGC 4388 is shown in Figure 3 showcasing these
parameters. Blue indicates the [O III] narrow-band filter, green indicates the V filter, and red indicates H-alpha. NGC 4388 is also located near the center of the Virgo cluster.

The high inclination provides unique opportunities to study specific components of the galaxy. For example, the rotational kinematics of the disk will not interfere with the kinematics of outflows that are perpendicular to the plane of the disk. Furthermore, the inclination will allow us to analyze the relationship between the rotational axis of the galaxy and the central torus. There is debate over whether the rotational axes of the two are aligned or if the torus can rotate about a separate axis. NGC 4388 is a well-known galaxy with publications spanning various wavelengths. Upon the study of these different areas of the electromagnetic spectrum in relation to NGC 4388, a more

Figure 3: Optical wavelength image of NGC 4388 taken with the Suprime-Cam on Subaru Telescope. Blue indicates [O III] narrow-band filter, green indicates V filter, and red H-alpha. The image spans 11.6 arcmins x 5 arcmins with north up and east to the left. courtesy of NASA. http://www.nasa.gov/centers/goddard/news/topstory/2004/0720donutcloud.html, (Yoshida et al., 2002)
comprehensive interpretation of the galaxy can be realized. By thoroughly examining nearly edge on galaxies like NGC 4388, we will come closer to reaching an answer to the question of the angle of the torus as well as examine processes of feeding and feedback.

2 Observations

2.1 Integral Field Spectroscopy

Integral Field Spectrographs (IFS) equipped with an Integral Field Unit (IFU) are instruments used to gather three-dimensional spectral data of wavelength and the two spatial axes, right ascension (RA) and declination (Dec). IFS help resolve the issues with traditional long-slit spectroscopy as IFS are able to retrieve the 2-dimensional kinematics of the gas and stars in galaxies by comparing wavelengths of emission lines at each position. This makes these devices ideal for exploring spatially extended sources such as individual or clusters of galaxies. There are different ways to achieve IFS, one of which being the use of an array of tiny lenslets across the focal plane of the telescope. The OSIRIS instrument used for taking our data is an IFS that is designed to work with
the Keck Adaptive Optics System. This instrument uses the lenslet technique to create a datacube that is a two dimensional image of the object that has a spectrum pertaining to each pixel in the image. This process is described in the Figure 4.

2.2 Adaptive Optics

Adaptive Optics (AO) is a technology used to aid ground-based telescopes reach their diffraction limit, or the minimum angular separation of two objects that can be distinguished from one another. This provides spatial resolution that is superior in some cases to telescopes situated in space (Davies and Kasper, 2012). As light from distance objects reach earth, it is in the form a virtually flat plane called a wavefront. AO measures distortions in wavefronts due to atmospheric turbulence by finding deformities of a known bright point source, such as a star. Whenever a luminous star near the object to be observed is not available, the AO system will typically use a laser as an artificial guide star. A device, such as deformable mirrors, is then used to correct for the wavefront distortions. A diagram of a basic AO system is depicted below in Figure 5.

![Diagram of adaptive optics system](http://www.lyot.org/background/adaptive_optics.html)
The OSIRIS instrument works with the Keck adaptive optics system to achieve a resolution of 0.2 arcseconds in the K-band by deforming the mirrors every few milliseconds. The spectral resolution of $R \approx 3800$ along with a pixel scale of 0.05 arcsec per pixel allows us to accurately study the inner few tens of parsecs of the AGN in a nearby galaxy.

### 2.3 Observations

The observations for this project were made at the W. M. Keck Observatory located at the summit of Mauna Kea in Hawaii. We used the 10 meter telescope containing Keck's IFS, termed OH- Suppressing Infra-Red Imaging Spectrograph (OSIRIS) with adaptive optics to record our data. All observations of the galaxy NGC 4388 were completed on the night of March 5, 2013. NGC 4388 is located in the Virgo Cluster at a right ascension of 12h 25m 46.7s and a declination of +12° 39arcmin 44arcsec. Two observations of the galaxy at two different position angles were made using the Kbb filter, which contains spectral features from $1.965 – 2.381 \mu m$. For the first observation, the long axis of the IFS was set to a PA of 90° in order to observe the rotational axis of the galaxy, or the photometric major axis. The second position angle used corresponded to the findings of Schmitt et. al in 2003 stating that the PA of the peak of emission of [OIII] was found at 25° (Schmitt et al., 2003). Thus, we positioned the IFS to sit at an angle of 20° across the plane of the galaxy which could observe the emission to the north and south of the nucleus of the galaxy. Each individual integration time was 600 seconds in length that was combined to achieve a longer exposure time. Using an observing sequence object-sky-object, we obtained forty minutes of data at the PA of 90° and 40 minutes at the PA of 20°. In order to be certain the extended region of the cone was observed, we conducted an additional thirty minutes of observing time at the PA of 20° with the IFS offset.
3 Data Reduction and Processing

3.1 OSIRIS Data Reduction Pipeline

All data collected was reduced using the OSIRIS data reduction pipeline (DRP), which performs all necessary steps to reduce near-IR spectra with an added step of creating a datacube. The OSIRIS manual (v. 2.3) was followed closely to complete the reductions. An original python code named list_maker.py was used first to identify all of the necessary files to be used in the reduction process, such as the spectra of NGC 4388, the sky, and a standard A5 star that was observed close in time and airmass to the galaxy. The object files were inputted to the DRP graphical user interface (GUI), and using the astronomical reduction pipeline (ARP_SPEC) reduction type, a preliminary reduction was carried out on each object exposure. The reduction steps include bias and background subtraction, crosstalk removing, glitch identification, adjustment of channel levels, cosmic ray cleaning, extraction of the spectra, alignment and interpolation of the data, wavelength calibration, and sky subtraction.

Telluric correction and flux calibration were done using the standard A5 star. First, a basic datacube of the star was assembled with the GUI. Using the program QFitsView, a one-dimensional spectrum was extracted from the star's datacube. The bracket-gamma absorption line was then removed via a Gaussian subtraction routine within QFitsView. A one dimensional blackbody spectrum that corresponds to the same temperature as the star was created using the IRAF software, and the spectrum was divided out of the standard star's spectrum. Because the magnitude of the star is known, this provides a correction curve that can be applied to all further observed spectra to calibrate their fluxes. After the star’s spectrum was completed, it was divided out of the preliminary NGC 4388 datacubes with the DRP.

Each step in the reduction of the data for all galaxies is outlined in the appendix. I created a data reduction manual that thoroughly explains what to look for and use in reducing OSIRIS data.
3.2 Combining Datacubes

Each of the datacubes was studied in QFitsView to determine which cubes needed to be re-reduced and which were clean enough to complete the reduction. Finally, the datacubes of a similar PA yet different exposures were all assembled within the GUI with the mosaic frames module. In order to orient the two position angles at the angles at which they were originally measured, the python program PAStitcher, created by Brian Davis, was employed. This program was designed to take any two rectangular datacubes, orient them, stitch them together, and return a single datacube of the combined data. The program takes position information from the header of a FITS file in order to combine the data. Once combined, the overlapping regions of data between the individually stitched datacubes are averaged. This program aided not only the merging of NGC 4388 data, but other exposures in the KONA survey as well.

3.3 Visualizing Datacubes

![Figure 6: The GUI of the FITS file viewer, QFitsView.](image)

In order to visualize our datacubes, we used a program called QFitsView. This
program is designed to view FITS files and is available to the general public. It can display one, two, and three dimensional FITS data. In viewing three dimensional data, such as datacubes, it presents the spatial data in x and y coordinates and the third dimension in a variety of ways. Our third dimension of spectral data is portrayed through different colors on the spatial layout as well as in a x-y plot at the bottom of the page. Each pixel contains its own spectral information that can be looked at in this way. QFitsView can also extract spectra from different regions, fit Gaussian functions to specific spectral lines in the spectrum of a given region, and determine the spatial resolution of data. The main display of QFitsView is showcased in Figure 6.

### 3.4 Extraction of the Emission-line Gas Properties

Two IDL programs created by Müller-Sánchez were used to determine the kinematics of our OSIRIS data, an emission line Gaussian-fitting routine (LineFit) and a velocity-mapping program (PlotVel). Through these two programs, we were able to determine the flux, velocity, and velocity dispersion of each species of emission in each region of the image of the galaxy.

LineFit, described in Davies et al. (2007) fits a Gaussian function to specific emission lines in the spectra at each pixel (Davies et al., 2007). To use Linefit, a range of wavelengths must be specified so that the program can look for a particular emission line to fit the Gaussian to. Furthermore, a range of wavelengths defining the continuum must also be given, so that LineFit can subtract the continuum from the fit. QFitsView was used to determine the ranges for the emission and continuum wavelengths. We estimate that the uncertainty in the continuum subtraction is on the order of 5 per cent (Müller-Sánchez et al., 2016).

The IDL program PlotVel is essential in determining the flux, velocity and velocity dispersion at each pixel of each species of gas based on the shape and position of each Gaussian-fitted line. In order to do this, PlotVel uses relative Doppler shifts for each of the lines chosen. Because there is a spectrum at each spatial pixel of the
galaxy’s datacube, we are able to compare the location of specific emission lines from pixel to pixel to derive redshifts and blueshifts. The main emission lines looked at for the velocity maps are \([\text{Si VI}], \text{Br}_\gamma, \text{H}_2, \text{[He-I]}, \text{and [Ca-VIII]}\). All maps are oriented so that north is Up and east is left.

Errors were estimated using Monte-Carlo techniques, assuming that the noise is uncorrelated and the intrinsic profile is well represented by a Gaussian. The method involves adding a Gaussian with the derived properties to a spectral segment that exhibits the same noise statistics as the data and refitting the result to yield a new set of Gaussian parameters. After repeating this 100 times, the standard deviation of the center and dispersion were used as the uncertainties for the velocity and line width.

<table>
<thead>
<tr>
<th>Emission Line</th>
<th>(\lambda_{\text{rest}} , (\mu\text{m}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>H(_2) 1-0S(1)</td>
<td>2.121</td>
</tr>
<tr>
<td>Br(_\gamma)</td>
<td>2.166</td>
</tr>
<tr>
<td>[Si VI]</td>
<td>1.963</td>
</tr>
<tr>
<td>[He I]</td>
<td>2.058</td>
</tr>
<tr>
<td>[Ca VIII]</td>
<td>2.322</td>
</tr>
</tbody>
</table>

**Figure 7:** Table of rest wavelengths of emission lines studied using LineFit and PlotVel.

### 3.5 Kinemetry

In order to determine the parameters of the rotating disk, we used the program Kinemetry developed and described in detail by Krajnović et al. (2006) (). Kinemetry is a generalization of surface photometry to the higher-order moments of the velocity distribution. The program operates by fitting the data with a series of concentric ellipses of increasing major axis length, defined by the system center, PA, and inclination. The center of the system is the only parameter determined prior to running the program. The PA and inclination can either be determined a priori and used as inputs or be measured functions of the semi-major axis length. The program finds inclination via the axial ratio, \(q\) of the major and minor axes of the concentric rings. This ratio is
related to the inclination, \( i \), through the equation

\[ \cos(i) = q \]

thus Kinemetry finds the axial ratio that in turn gives the inclination of the galaxy. At each radius, a small number of harmonic terms in a Fourier expansion is needed to determine the best-fitting ellipse

\[ K(\phi) = A_0 + \sum_{n=1}^{N} A_n \sin(n\phi) + B_n \cos(n\phi) \]

where \( K \) is the best-fitting ellipse at a given radius, \( N \) is the maximum fit order used, and \( \phi \) is the azimuthal angle in the case of disks. The best-fitting parameters are given by minimizing the coefficients \( A_1, B_1, A_2, \) and \( B_2 \) of the harmonic expression. Certain errors will produce non-zero coefficients. For example, an incorrect kinematic center will give a non-zero \( A_0, A_2, B_2 \) and to a lower level \( A_1, A_3, \) and \( B_3 \) coefficients.

4 Results

4.1 Integrated Spectra at Different Regions

The top image of Figure 8 showcases the combined datacubes at their respective position angles. The color purple corresponds to a lower overall flux and white to a higher overall flux. Circles indicate an aperture of eight pixels that was used to integrate the different regions of spectra that are displayed in Figure 8. Certain characteristic emission lines were looked for in all regions considered, the main being Brackett-gamma (Br\( _\gamma \)), helium-I ([He-I]), molecular hydrogen (H\(_2\)), and silicon-VI ([Si VI]). Each of these lines provides information on the kinematics of the planar and co-planar movements of NGC 4388.
Figure 8: *Top Image:* Encircled regions correspond to integrated spectra indicated below in the graphs. The regions are enclosed by an aperture of 8 pixels. The color purple is consistent with a lower overall flux and white to a higher overall flux. *Bottom Plots:* Integrated spectra at multiple regions near the galactic nucleus.
All regions show narrow emission lines, consistent with the Seyfert 2 classifica-
tion of NGC 4388. The spectrum of region 1, encasing the central region, has relatively
high values of [Si VI], H$_2$, [He-I], Br$_\gamma$, and calcium-VIII ([Ca VIII]) emission lines. Region
2 has [Si VI], H$_2$, [He-I], however the flux of the [Si VI] line is lower than that of region 1,
but the Br$_\gamma$ flux is higher. In region 3 and 4 to the south of the central region, the flux of
[Si VI] is greater than that in northwest, yet again less than the nucleus of output.

In region 6 we observe an interesting switch in the relative abundance of the
different species. Here, molecular emission increases drastically and the high-energy
line of [Si VI] diminishes in comparison to other regions. Furthermore the emission
line of H$_2$ 1-0S(0) appears in region 6, and it either not present or very weak in all other
regions. This indicates the presence of shocks.

Region 7 has relatively low fluxes of H$_2$, [Si VI], and Br$_\gamma$. To the north in region
8 there is H$_2$, [Si VI], and Br$_\gamma$ emission, and region in the southern portion of the cube
the molecular hydrogen lines lessen and [Si VI], Br$_\gamma$, and [He I] become the predominate
lines.

4.2 Kinematics of Emission Lines

Using the PlotVel program, we were able to create two-dimensional flux,
dispersion, and velocity maps. These maps are shown below in Figure 9 and discussed
in the following sections.

4.2.1 Molecular Hydrogen

Molecular Hydrogen is usually the most abundant and stable species of gas
in galaxies and is often used as a standard means to determine the rotational motion
of the galaxy. From the flux map, it is easy to see that H$_2$ resides mostly at the PA of
90° along the disk of the galaxy. This is to be expected as molecular hydrogen usually
indicates dust and gas within the disk. There is an obvious blueshift in the western
region of the data, and a redshift in the east. However, the kinematic major axis angle is difficult to determine from this particular plot due to an unclear division between
the red and blue shifted regions. Thus, other means must be used to determine the kinematic major axis. Relatively high levels of molecular hydrogen are seen extending to the northeast and southeast from the center of the galaxy. The specific emission of H2 2-1S(1) appears only in region 6, but other forms of molecular hydrogen are heightened in this region.

4.2.2 Silicon-VI

Silicon VI is a highly ionized species of gas that is used to indicate regions of outflows. When looking at the spectra of the different regions, the flux [Si VI] is high compared to molecular hydrogen emission in all regions except 2, 6 and 7. The flux map indicates a higher flux of this species outside the nucleus to the southwest. The velocity map also indicates a blueshift in that same area and the dispersion map displays a higher dispersion there as well. There is an interesting redshift presented just south of the nucleus for the [Si VI] line.

4.2.3 Brackett-γ

The Brackett-gamma (Brγ) emission line of Hydrogen is fairly unaffected by interstellar extinction, so it is easily detected. Besides showing flux near the nucleus, Brγ emission is seen in regions 3, 4, and 6 as well, aligning somewhat with what [Si VI] has shown. The velocity map indicates a blue shift to the northeast. There is also small blue shift to the immediate southwest of the nucleus, but further away from the nucleus in that direction the velocity becomes more redshifted. Again, the redshift is seen south of the nucleus as it is portrayed in the [Si VI] velocity map. High dispersion is seen scattered throughout the southwest, and in the southeastern region.
4.2.4 Helium-I

Helium I is an ionized species of gas that showcases interesting features in NGC 4388. Its flux is seen in regions 3 and 4, like Br\textgamma and [Si VI], however it seems to have an even higher flux to the northeast in region 6. The velocity map shows similar features to that of Br\textgamma, with the southwest being blueshifted close to the nucleus, then more redshifted further away. The northeastern region is more redshifted as is the region south of the nucleus. The dispersion map indicates higher levels of dispersion in the southwest, and low levels in the northeast.

4.2.5 Calcium-VIII

Calcium VIII is also a highly ionized species of gas that we used to better understand the other ionized species. It is an indicator of an outflow. The only [Ca VIII] flux seen outside the nucleus was in region 3. The velocity in that region was blue-shifted and had a high dispersion, possible evidence of an outflow.

4.3 Kinematic Modeling of OSIRIS Data

We ran Kinemetry on our data following the assumption that the center of the active nucleus matched the peak of our K-band data; we input the right ascension and declination into the program as a priori knowledge. Using the full data from H2 1-0S(1), the first run of Kinemetry showed many errors. The emission to the north and the South of the galactic disk was skewing the kinemetric parameters of the rotational disk. Thus we eliminated these pixels to focus on the rotation of the disk by applying a flux mask. In removing all data points that had a flux below 11.4 per cent of the maximum flux of the image, we were able to limit the data to the disk. We then ran Kinemetry with the PA and inclination parameters free and the flux map in place. Upon analysis we saw that the PA ranged from 85° to 100° and the axial ratio ranged from 0.2 to 0.3, or synonymously an inclination of 78° to 72°.
The instability of the calculated parameters can be described by a warped disk, which Kinemetry cannot accurately model. However, we decided to continue using Kinemetry with the best possible parameters in order to attempt to understand the kinematics of the disk and the residuals. In order to find these parameters, we performed a multidimensional minimization of the function $\chi^2$ with a variety of PAs and inclinations. We also studied the Fourier coefficients corresponding to the PAs and inclinations. The values that give the lowest $\chi^2$ with coefficients closest to zero were considered to be the best-fit values. Furthermore, we made sure to review the better values so that we did not lose data in the modeling that was crucial for interpretation. Upon inspection of all aspects of the best fit, we found that a PA of 190 and an inclination ratio of 0.25 led to the best results for our data. The results of running Kinemetry with these parameters can be seen in Figure 10. The residuals in the bottom image represent the error in calculating the best fit model.
Figure 11: A table depicting the input parameters used to create the best rotational model of NGC 4388 with Kinemetry. The first column depicts the axial ratio, $q$, of the major and minor axes of the galaxy. The second column is the chosen position angle (PA). The third and fourth columns are the resulting Chi Squared error and values. The last columns represent the mean, median, and standard deviation of the first two Fourier coefficients. Values closer to zero for the Chi Squared and coefficients represent better data. However, the plots also were manually looked at to insure the best quality of data.

5 Discussion

5.1 Location of the AGN in NGC 4388

In order to determine the physical location of the AGN, we needed photometric data involving the coordinates of the galaxy. Using the NASA/IPAC Extragalactic Database (NED) we were able to obtain Hubble Space Telescope (HST) images in the optical and infrared spectrum of NGC 4388. Viewing the data from the WFC3 camera in the F160W, F438W, F665N, and FQ508N filters we were able to obtain information about the infrared, optical, H-alpha and [O III] emission of the galaxy respectively. It became apparent after first looking at the optical emission that the exact location of the AGN was obscured by gas and dust in the plane of the galaxy. Thus we employed other means to pinpoint the location. Infrared light can pass through gas and dust without being scattered and is therefore a good means to study objects hidden in other wavelengths by intergalactic materials. By assuming that the peak of emission in the infrared filter
F160W matched the peak of infrared emission in the K-band of our OSIRIS data, we found the RA and Declination of the nucleus to be at RA (J2000.0) = 12hr 25m 46.781s, Dec (J2000.0) = +12° 39 arcmin 43.51 arcsec, which is in agreement with Irwin and Saikia (2000), and Falcke, Wilson, and Simpson (1998). The position of the AGN is not in the direct center of the galaxy as is usual, but lies north-northeast of the optical [O III] nucleus (Irwin et al., 2000).

**Figure 12:** Contour plot of Hubble Space Telescope (HST) WFC3 data with the FQ508N filter to display [O III] emission. The cross indicates the location of the AGN, determined by HST infrared data using the WFC3 instrument and F160W filter.

This obscuration has implications for the unified model of AGN, as the plane of the galaxy can hide emission lines from our line of sight. The unified model as of now relies on only the torus of the AGN obscuring emission. However, with these findings we can begin to understand how the galaxy as a whole can affect the way an AGN is viewed from Earth.
5.2 Stellar Kinematics

It is well known that the disk of the galaxy NGC 4388 has a photometric PA of 90° on kiloparsec scales. The stellar kinematics at smaller scales surrounding the AGN were more difficult to identify as the stellar velocities exhibit an S-shaped form in the galactic disk seen in Figure 13a (I. Stoklasová and et al., 2009). Greene et al. used a best-fit method and Voronoi binning to achieve the best signal to noise ratio (S/N) and acquire information on stellar rotation (2014). Using these techniques, Greene found that within an aperture corresponding to the inner 100 pc, comparable to the OSIRIS data of NGC 4388, the stellar components rotate at a PA of 75°. The best explanation for this phenomenon is that there is a nuclear stellar disk component imbedded within and offset to the main bar of the galaxy. The maximum velocity of the stars according to Green was Vmax = 60 km/s, which agreed with data at scales of about 400pc (I. Stoklasová and et al., 2009).

Figure 13: Left Image (a): Stoklasová Stellar Velocities (2009). Right Image (b): Greene et al. Stellar Velocities (2014). Note that north is up and east is to the left.
5.3 Extraplanar Gas

5.3.1 High Ionization Complexes

To the northeast of the nucleus at a PA of 35° there resides a high ionization plume extending from the AGN up to 4 kpc above the plane of the galaxy in a direction that is roughly away from us (Pogge, 1988). This northeast plume (NE plume) is opposed to the southwest by a high ionization emission cone that appears to emanate from the nucleus along a PA of 35° (Veilleux et al., 1999b). This cone (SW cone) is in front of the galaxy and thus encounters less obscuration to our line of sight (Pogge, 1988; Yoshida et al., 2002). In terms of length, the NE plume stretches two times further than the SW cone (Corbin et al., 1988).

Figure 14: Velocity field of emission in NGC 4388, from Veilleux et al. (1999b). *Upper panel*: Hα, *lower panel*: [O III] λ5007. North is up and east is to the left. The optical continuum nucleus is indicated by a cross.
5.3.2 The Very Extended Emission Line Region

To the northeast of the nucleus there resides a very extended emission line region or VEELR as termed by Yoshida et al. (2002). This VEELR is seen as far as 35 kpc northeast of the nucleus between a PA of 30° to 65° (Yoshida et al., 2002). The filaments of the inner VEELR show high ionization, an indicator that the nucleus is exciting this area. Further supporting this idea is the fact that ionization levels decrease in the VEELR the as it moves further from the nucleus.

5.4 Interpretation of the Kinematics of the Ionized Gas in the OSIRIS Data

In the OSIRIS data, to the southwest and northeast of the active nucleus there is [Si VI] emission. The morphology of the southwestern emission is conical and the flux, blueshifted velocities, and dispersion increases, as seen in the [Si VI] kinematic maps of Figure 9. This reveals the presence of a high-energy outflow in the region thought to harbor the SW cone. The northeastern area harbors blueshifted ionized gas, which is most likely a result of the same outflow in the SW cone.

Furthermore, the velocity map of [Si VI] is blueshifted to the southwest of the nucleus, but is redshifted directly to the south of the nucleus. This is within the SW cone region, and attests to the idea proposed by Corbin et al. that the material of the cone is rotating like the stellar disk, shown in Figure 15 (1988). This could be caused by interactions with material that has been tidally stripped from a less massive galaxy. As the transferred gas settles into the galaxy, it could orbit parallel to the disk itself. It could also be the result of an outflow from the nucleus, or the infall to the nucleus after a previous ejection (Corbin et al., 1988). However, the way in which the velocities change sign on the opposite side of the cone suggest that the material is following the rotating pattern of the galactic disk.
Figure 15: Velocity map of [O III] from Corbin et al. (1988). Circle diameters are proportional to the magnitude of the velocity relative to the systemic velocity of 2529 km/s found by Corbin et al. Filled circles represent blueshifted gas, open circles redshifted gas. You can see that to the southwest the velocities are blueshifted. However, to the southeast of the central region of the galaxy, the galaxies are redshifted. North is up and east is to the left.

Figure 16: [Si VI] velocity map of NGC 4388. To the southwest, the emission is blueshifted on the western side of the "ionization cone." The eastern side of the cone is redshifted. This implies a rotation of the ionization cone material in a way that is similar to the rotation of the galactic disk (Corbin et al., 1988).

5.5 Interpretation of the Kinematics of the Molecular Gas in the OSIRIS Data

The analysis of the OSIRIS molecular data indicates shifting position angles in the data. Running Kinemetry on the H$_2$ data using free parameters, we observed
three different regions with corresponding position angles. The central region of the map showed a PA of $0^\circ$, that was redshifted to the north, and blueshifted to the south. This is seen in both the Br$_\gamma$ and H$_2$ data. However, this area is marginally resolved and better spectral resolution will be necessary to determine the true kinematics. Extending from -1 to 1 arcsec we observe a PA of $75^\circ$; beyond that the PA is $100^\circ$. This presents evidence of a warped disk, as previously suggested by Yoshida et al. (2002).

The zero velocity line is inclined from the vertical at a PA of $30^\circ$ as seen in the H$_2$ map in Figure ???. However, a bulge can be seen to the southwest of the active center that corresponds with relatively high levels of dispersion. The tilt of the zero velocity line and bulge could possibly be caused by an outflow in this region pushing molecular gas to the southwest.

Flux maps of H$_2$ show bright clouds within the disk of the galaxy. The brighter emission to the east of the nucleus show large redshifted velocities. Further study will be necessary to find the cause of these clouds. If the low flux to the west of the nucleus is standard to NGC 4388, then the bright clouds to the east would most likely indicate an inflow. A minor merger may be the culprit then as gas settles into the galaxy in an asymmetric way. However, if the bright clouds to the east are normal, then there is material suppressing the flux to the west of the active nucleus. This could be due to the outflow pushing material away from the nucleus.
5.6 Comparison with Multi-wavelength Datasets

5.6.1 Comparison with Radio Data

The optical core of NGC 4388 is blended with a prominent radio jet that exists 1.5 arcsec south-southwest of the AGN (Irwin et al., 2000) (Irwin and Saikia 2000). Upon research of the radio qualities of NGC 4388, it was found that the radio jet occurs at a total PA of 8° extending in both the north and south direction from the core (Hummel and Saikia, 1991). However this total PA is not consistent between the north and south; the northern half extends at a PA of 5° and the southern section at a PA of 23° (Hummel and Saikia, 1991). With the major axis at the PA of 90° both sections of the radio jet bend towards the minor axis of the galaxy but on opposite sides of the galaxy (Hummel and Saikia, 1991). There are also discrepancies in the morphology of the two sections. As seen in Figure 18 below, the north consists of an extended diffuse blob whereas a compact blob resides in the south.

![Figure 18: Left Image (a): VLA image of NGC 4388 from Irwin and Saikia (2000). The gray scale ranges from rms noise level up to maximum. The asterisk denotes the optical center. Notice the bending of the jet to the north. Right Image (b): VLA map of NGC 4388 at 4.86 GHz at an angular resolution of 0.4" courtesy of Hummel and Saikia (1991). Right ascension is along the horizontal axis and declination is indicated along the vertical axis.](image)
The bending of the jet could be caused by many different incidents. Galactic winds from the galaxy itself could bend the jet towards the minor axis. Buoyancy and the refractive bending of the jet can also describe the bending action. The movement of radio plasma along curved magnetic field lines cannot be ruled out either as a possible explanation. What is unlikely to have induced the bend is ram pressure stripping due to the intracluster medium from the Virgo cluster that NGC 4388 is moving through. This is due to the fact that the radio jet bends towards opposite sides of the minor axis in the north and south.

We overlayed the radio map from Hummel and Saikia (1991) onto our OSIRIS images in order to better understand the morphology of the material. We assumed that the nucleus of the radio image and the nucleus of our data were spatially coincident, based on the positioning of radio nucleus given by Falcke et al. (1998).

![Image](image.png)

**Figure 19:** [Si VI] and H2 1-0S(1) OSIRIS images overlayed with the VLA radio map from (Hummel and Saikia, 1991). The [Si VI] flux follows the structure of the radio data. The molecular gas H2 1-0S(1) does not align with the radio map and instead the flux is spread to the west and east along a PA of 90°.

### 5.6.2 Comparison with X-ray Data

Study of NGC 4388 in X-ray wavelengths supports the Seyfert 2 classification of the active nucleus (Elvis et al., 2004; Fedorova et al., 2011). However, the absorption level of X-rays is highly variable. Using the Rossi X-Ray Timing Explorer (RXTE) Proportional
Counter Array (PCA) in the 1.5-3 keV energy range, Elvis et al. found a rapid decrease in the column density of NGC 4388 that was a factor of 100 lower than normal (2004). This decrease in absorption indicates that the obscuring materials around the nucleus are in a highly dynamic state. This can be produced by clouds of material in keplerian motion around the central source. Using information from INTEGRAL and Swift, a maximum variability by a factor of 2 was found in the 20-60 keV band on a timescale of 3-6 months (Fedorova et al., 2011). Fedorova et al. also found variations of the spectral shape in the 20-300 keV energy range that are uncorrelated with the flux level (2011). This could be caused by instabilities in the accretion flow (Fedorova et al., 2011).

A Chandra X-Ray Observatory study was conducted on NGC 4388 in the 0.3-7 keV energy band. The Hard X-ray peak from 4-7 keV indicated the position of the active nucleus coincided with that suggested by optical and radio observations of Falcke et al. (1998). This peak is located at RA 12h 25m 46.77sec and Dec +12° 39' 44.0" (J2000) Iwasawa et al. (2003). Below the 4 keV energy mark, the AGN is faint. This is due to obscuration from gas and dust in the stellar disc of the galaxy.

**Figure 20:** Composite X-ray image from Chandra of the central region of NGC 4388. The image is 45x43 arcsec$^2$ or 3.6x3.5 kpc$^2$. It is produced by three X-ray energy bands; red indicates 0.3-1 keV, green 1-3 keV, and blue 4-7 keV. The AGN is located at the position of the hard X-ray peak in the center of the image, shown in blue.
Extended soft X-ray emission, shown in Figure 21 on the left, shows a well-defined conical region to the southwest of the nucleus. The western side of this region is outlined by a sharp boundary at a PA 220°. The opening angle of the cone in the 0.3-1 keV range is determined to be 55° with the apex of the cone slightly displaced from the nuclear position (0.5 arcsec to east, 2.5 arcsec to north) (Iwasawa et al., 2003). Iwasawa et al. indicates that low ionization photoionized gas appears to be the cause of the prominent soft X-ray spectral features (2003). Highly ionized gas is also necessary to describe the features; however, the origin of this gas is unclear Iwasawa et al. (2003).

To the north of the active nucleus there is a faint emission extending to 1 kpc in the soft X-ray energy band. However, in the 1-2 keV range, the northern and southern extensions are comparable, as shown in the rightmost image of Figure 21. In this figure, narrow, bright filaments emanate from the nucleus to the north at a PA of 35°. This filament bends northward at 3 arcsec from the nucleus, at which point it opens, similar to the radio plume observed in Falcke et al. (1998). The stellar disc is tilted upwards by about 12° thus the southwest cone is clearly visible to the observer. The northern emission, on the opposite side, is obstructed from view by the material in the disk. The difference of luminosity of the soft X-rays may be due to the obscuration toward the northern extension and nucleus because of the inclination to our line of sight. It is possible that in the absence of absorbing materials, the nebulae to the north and south would be similar in brightness and ionization conditions (Iwasawa et al., 2003). There is also a portion of the soft X-ray emission that reaches up to 16 kpc to the north of the galaxy (Iwasawa et al., 2003).

5.7 **Explanation of Extraplanar Gas**

5.7.1 **Nuclear Outflow**

There have been many different explanations for these instances of extraplanar gas, one of which is due to outflow from the nucleus or inflow to the nucleus after material has already been ejected. This could account for the opposite velocity signs to
Figure 21: X-ray contours from the Chandra X-Ray Observatory (?) Left Image: 0.3-1 keV image of NGC 4388 depicting the central 2x1.65 arcmin² or 9.7x8.0 kpc². Contours drawn at 10 logarithmic intervals in the range of 0.5 - 50 per cent of the peak flux which occurs at the inner part of the southern cone. The apex of the cone is slightly displaced from the nuclear position determined by the hard X-rays. Right Image: 1-2 keV image of NGC 4388. The active nucleus is located at the central peak. Contours denote nine logarithmic intervals in the range of 0.15-80 per cent of peak brightness.

the north and south, however the nature of the SW cone does not coincide with this interpretation. Corbin, Baldwin, and Wilson found that the velocities change signs on opposite sides of the SW cone, which indicates rotation of the cone material similar to the disk rotation (1988) (1988). Furthermore, emission to the north moves faster when it is further from the nucleus (Corbin et al., 1988). Another difficulty with this scenario is that the radio outflow does not correlate with optical and infrared extraplanar gas. The NE plume is three times larger than the radio jet (Veilleux et al., 1999b). Whereas the radio jet to the northeast is at a PA of 5 deg, the optical gas of the NE plume and SW cone extend at a PA of 35 deg, thus offset from the outflow. This misalignment does not rule out entirely the possibility of the ionization being due to nuclear outflow. Density differences between the radio cloud and halo gas as well as the galactic gravitational gradient are able to cause a buoyancy force to bend a radio structure (Stone et al., 1988). Such a process may have decoupled the radio and optical emission from the AGN.

As for the VEELR, it is also unlikely that this gas is due only to the radio jet outflow. Like the opposing complexes, the VEELR is misaligned from the jet by 35-55 degrees. This large discrepancy makes it difficult to explain the full presence of the
extended gas. Second, the size of the VEELR is 35 kpc compared to the 1kpc size of the radio jet (Yoshida et al., 2002). This gives the VEELR an age of roughly $10^8$ years, which is an order of magnitude greater than the jet (Yoshida et al., 2002).

5.7.2 Intra-Cluster Medium

Interaction with the intra-cluster medium (ICM) yields another interpretation of the cause of the two emission areas. Because NGC 4388 is moving edge-wise through the center Virgo cluster at a velocity of -1500 km/s, it is a prime candidate for ram pressure stripping due to the ICM (Veilleux et al., 1999b). The edge on movement could account for the gas being seen on both the north and south sides of the galaxy. The extraplanar gas may have arisen from gas that has cooled and condensed from the ICM itself after interacting with the galaxy, or gas that has been pulled from the disk of NGC 4388 as it moves through the ICM. The first scenario however seems unlikely as the cooling time exceeds Hubble time for the Virgo cluster conditions (Veilleux et al., 1999b). The density of this gas could be increased through other processes such as nuclear outflow or disk ejection (e.g. supernova). The possible rotation of the cone may also be explained as gas from the disk retains some of its angular momentum as it interacts with the ICM and leaves the galactic plane (Corbin et al., 1988). However, it is difficult to explain the opposite directions of the gas directly to the north and south. The dynamical timescale of the gas is $t_{dyn} = 2 \times 10^7$, but the evaporation time of the heated ICM is determined to be 104 years (Veilleux et al., 1999b). Shock waves could continue to heat the gas, however not long enough to coincide with the dynamical time (Veilleux et al., 1999b). Another argument against ICM interaction is that the velocity predicted for extraplanar material at 2-4 kpc exceeds what is seen with NGC 4388 (Veilleux et al., 1999b).
5.7.3 Starburst Driven Superwind

A supernova driven event may also be the reason for the extraplanar gas. This explanation seems highly unlikely as the NE plume morphology does not show any signs of filaments or loops that are usual with star forming events in the disk of the galaxy. [O III] high emission optical data suggests that the NE plume and SW cone are being transferred mass from the nucleus as opposed to the disk. Furthermore the long orbital period of the disk implies that we should still be able to see morphological or kinematic traces of supernova disturbances. The VEELR too is asymmetrical, as it is only seen to the northeast of the galactic plane. If a superwind from starburst were to occur, we would expect to see remnants of the wind on both sides of the disk if it is powerful enough to extend to VEELR lengths (Yoshida et al., 2002).

5.7.4 Tidal Debris from Galaxy Merger

NGC 4388 lies near the core of the Virgo cluster where interactions between galaxies may be comparatively frequent. The extraplanar material may represent tidal debris from a recent dwarf galaxy merger that has interacted with NGC 4388 and is being accreted onto the disk (Pogge, 1988). If the tidal gas extends along the major axis, it could account for the rotation of the SW cone as the gas has settled into the orbit of the galaxy. However, Veilleux et al. reject this idea, as they do not observe damage to the disk’s inner regions as expected in a merger. They also dismiss this possibility because the velocity field of the debris from a recent merger should continue to reflect the orbital motion of the original dwarf galaxy (Veilleux et al., 1999b).

However, the presence of the VEELR makes the merger a good explanation for the extraplanar gas and perhaps even the existence of the AGN. Yoshida et al. found that in fact the disk of NGC 4388 is asymmetrical at low surface brightness with respect to the nucleus. A faint hump and tail are noticed to the west-southwest and west of the galaxy respectively as seen in Figure 22 below (Yoshida et al., 2002). The bulge of the galaxy is also boxy as opposed to spherical (Veilleux et al., 1999a). Research on
the modeling of the origin of box shaped bulges have led to a general conclusion that they are in consequence of mergers (Mihos et al.; Walker et al., 1996). Because of this Yoshida et al. conclude that NGC 4388 is a minor merger remnant and the VEELR is due to dense gas clouds of debris from that merger. The gas is heated by nuclear power law radiation. A minor merger can even concentrate gas in the nucleus of NGC 4388 and fuel nuclear activity. Minor-merger driven fueling has been studied and is found to be consistent with what is observed in Seyfert galaxies (Taniguchi, 1999).

Figure 22: Low surface brightness $R_c$ band image of NGC 4388. The shape of the bulge is boxy and a faint hump and tail are seen to the west-southwest and west of the galaxy respectively. Courtesy of Yoshida et al. (2002)

6 Conclusion

NGC 4388 is a complex galaxy with many components. The nearly edge-on angle of the galaxy has allowed for a thorough analysis of extraplanar phenomena. To the southwest of the central active nucleus resides an ionization cone at a PA of about
35° that our OSIRIS data indicates has a 90 km/s outflow. This outflow also exhibits signs of rotation similar to that of the galaxy, as it is blueshifted on the western edge of the cone and redshifted on the eastern edge. This cone is tilted compared to the plane of the galaxy, suggesting that outflows need not be perpendicular to the host galaxy. This also puts forth the idea that the AGN itself could possibly be tilted relative to the galaxy’s disk. On the opposite side of the galactic plane to the northeast, there is also evidence of outflow. Blueshifted ionized material is observed at 70 km/s. However, the material is obscured in optical wavelengths due to the inclination of NGC 4388. The ionized gas here is most likely due to the same outflow in the southwest. What we see in this region is the back side of the SW cone. Also, the lack of molecular gas in the western portion of the galaxy leads us to believe that the outflow is pushing such material away from the nucleus.

From analysis of the kinematics of the molecular gas in the galaxy, we observed three different position angles of the central region surrounding the AGN. The very center showed a PA of 0°. From -1 to 1 arcsec offset from the center, the PA switched to 75°. Further out, the PA is closer to 100°. This is evidence for a warped disk around the AGN, again a possible effect of a merger. Another explanation is the possibility of a bar in the galaxy warping the AGN region.

In order to fully comprehend all components of NGC 4388, the inner region of the AGN must be further resolved. Only then will we be able to analyze the central area’s rotational axis. We can also learn more about this galaxy if we take integral field data with an instrument with a larger field of view to study the VEELR. This could be done with the Atacama Large Millimeter Array (ALMA) telescope. This will help us determine if the galaxy has been subject to a minor merger by analyzing the kinematics of the VEELR.

In the future, we hope to compare this galaxy to other edge-on galaxies in the KONA survey. By studying these galaxies simultaneously, we will be able to determine relationships between the extraplanar gas and the rotating stellar disk. Upon completion of this comparison and the analysis of the other galaxies, we will widen
our inspection to include all galaxies in the KONA survey. This will allow us to better understand the total impact of feeding and feedback of a super massive BH, as well as the physical occurrences within the central 200 pc of AGN.
7 References


S. Ciroi, M. Contini, P. Rafanelli, and G.M. Richter. 2-D Spectroscopy and modeling of the biconical ionized gas in NGC 4388. SAO/NASA ADS.


Müller-Sánchez et al. The nature of active galactic nuclei with velocity offset emission lines. 2016.


Appendix A: OSIRIS Data Reduction Manual

The next few pages is the OSIRIS data reduction manual created in 2016. It outlines the necessary programs and steps needed to complete a clean datacube. This method was used to reduce the data of over 20 galaxies in the KONA survey including NGC 4388.
1 Identifying Necessary Files

The first step to reducing your data to a datacube is to identify the files you need to use through this process. A python code called list_maker.py creates a table of all the files and keywords; however, python and astropy are both necessary to run the code. In order to create your own code for this, you will need to find the following keywords in the header of your data files:

- **itime** Integration time. Science times usually 600 sec or more.
- **pa_spec** Position Angle
- **sscale** Pixel Scale
- **sfilter** Spectrum Filter
- **dataset** Name of the object
- **object** Name of the object
- **issky** Object (0) or Sky (1) image.
- **filename** filename of your data

All of these keywords, except the filename, can be found in the raw data headers. It is imperative to keep your data organized as you go through the reduction process.

2 Beginning the Reduction Process

Now we will start to reduce the raw data using the OSIRIS GUI. Be sure to familiarize yourself with the interface and modules. You can click on the available modules to read a description. The full OSIRIS manual can be found on their website at [https://www2.keck.hawaii.edu/inst/osiris/OSIRIS_Manual_v2.3.pdf](https://www2.keck.hawaii.edu/inst/osiris/OSIRIS_Manual_v2.3.pdf)

2.1 Starting Up the OSIRIS GUI

Access the OSIRIS GUI on Calculon using the following pathname:

```
• /usr/local/osiris-3.2/odrfgui/
```

To start up the GUI, use the command:

```
• ./odrfgui.bat &
```

2.2 Downloading Rectification Matrices

The first step will be downloading the correct rectification matrix for your data off of the OSIRIS website. [http://tkserver.keck.hawaii.edu/osiris/](http://tkserver.keck.hawaii.edu/osiris/)

Criteria for the correct rectification matrix include the following:

- Time Period. The time period should cover the date of your science data.
- Filter. Our group often works with Kbb.
- Pixel Scale.

You can store these matrices in `/usr/local/Osiris-3.2/drs/calib/SPEC/rectification/`. However, you will need to ask for permission to access and write to this folder.
Figure 1: The OSIRIS Data Reduction GUI
2.3 Preliminary Datacubes

After you have your rectification matrix and data information, we can begin reducing the data.

1. You will need to specify the **Output** and **Log Paths** into a directory you have created. You will not be able to access a directory someone else has created in Calculon.

2. The **Reduction Type** needs to be set to **ARP_SPEC**

3. The **Reduction Templates** needs to be set to **basicARP_drfTemplate.xml**

4. **Add Files** to the GUI. You will want to do one cycle of objects at a time. Often there is an Object-Sky-Object sequence to the data. Following this example, add only the two Object data sets to the GUI. Control-click to add multiple files at once.

5. Click on the **Specify a File** in the **Subtract Frame** module. Here, you will add the Sky data set out of the Object-Sky-Object sequence to be subtracted from the science data.

6. Click on the **Specify a File** in the **Extract Spectra** module. Add the correct rectification matrix, as specified in section 2.2.

7. Once you have finished the above steps, click on the **Drop DRF in Queue** button at the bottom. The script is now ready to run. You can have as many scripts as you would like in the queue; therefore, you can go back through all of steps 1-6 with your other Object sequences.

2.4 Run the DRF Files

After you are created DRF files using the steps outlined in section 2.3, you are ready to run the pipeline and create the preliminary datacubes.

- Return to your terminal within Calculon
- Enter the command "run_odrp" anywhere in Calculon. The program will run from any directory.
- An external window with the program will appear and begin to work its magic.
- **NOTE:** if the window is left open, any DRF files dropped in the GUI will automatically run.

As stated above, you can run one sequence at a time or you can complete all object sequences as outlined in 2.3.

3 Telluric Correction

Now we will create a star datacube to use on our science data in order to correct for telluric contamination. We will also be using the program **QFitsView** in order to complete this portion of the data reduction.

3.1 Creating a Star Datacube

Going back to the GUI (see section 2.1 to open GUI), we will create a star datacube using the following steps:

1. Again specify the **Output** and **Log Paths** to a directory you have created.

2. Set **Reduction Type** to **ARP_SPEC**

3. Set **Reduction Templates** to **telluricARP_drfTemplate.xml**

4. **Add Files** to the GUI. You are adding the science image of your star here.
5. Click on *Specify a File* in the **Subtract Frame** module. Add the Sky image to be subtracted from the image of the star. The Sky image is usually the second file of the star.

6. Click on *Specify a File* in the **Extract Spectra** module. Add the correct rectification matrix, as specified in section 2.2.

7. Remove the **Extract Star** module. This can be done by double clicking on the name of the module, or by checking the *skip* button.

8. Remove the **Remove Hydrogen Lines** module.

9. Remove the **Divide Blackbody** module.

10. Once above steps are completed, **Drop DRF in Queue** by clicking the button.

11. In your terminal, run the pipeline using the command `run_odrp`.

---

**Figure 2:** The preliminary star data cube visualized in QFitsView

### 3.2 Using QFitsView To Remove Brackett-Gamma Absorption

QFitsView is a FITS file viewer. It allows us to view 3-dimensional datacubes with the spectra in a cube spectral plot window. The spectrum in QFitsView is given in terms of micrometers. In order to learn more or download the program visit [http://www.mpe.mpg.de/~ott/dpuser/qfitsview.html](http://www.mpe.mpg.de/~ott/dpuser/qfitsview.html)

1. Secure copy the star’s datacube onto your own computer in order to open it in QFitsView. It is best to scp from outside Calculon on your own computer.

2. Open the datacube in QFitsView. You will notice that there is a positive and negative image of your star in the datacube.

3. Using the drop down menu currently portraying **Single Pixel** above the spectral window, choose instead the option for **Circular**.

4. Increase the size of the radius of the circle until it encompasses the whole of your star. It only needs to cover the positive image of the star. Usually a radius of 3 pixels will work.

5. While covering the star, right click and copy spectrum to new buffer.
Figure 3: The preliminary star data cube with aperture to extract 1-dimensional spectra

Figure 4: 1-dimensional star spectrum with Brackett-Gamma absorption line

6. Now remove Hydrogen lines, specifically the Brackett Gamma absorption feature. Occurs around 2.165 $\mu m$.
   - click "d" on left-most point of absorption line
   - click "d" on right-most point of absorption line
   - click "g" then find the best fit by pulling the line down to the bottom of the absorption line. Trial and error.
   - click "f" to fit the line when you have the best possible fit.
   - click "−" (minus sign twice) to remove the absorption line

7. File\textbullet;Save as FITS and save the 2D spectra.

We will return to QFitsView and this spectra after creating a blackbody spectrum in IRAF.
3.3 Blackbody Spectrum in IRAF

Using IRAF, we will now create a 1D blackbody spectrum to divide out of our star's spectrum. In order to do this, we will need to return to Calculon enter IRAF. If you would like to learn more about IRAF, see http://iraf.noao.edu/

1. Return to Calculon in your terminal and cd into a directory where you want to save your blackbody spectra.

2. Type in "cl" to start IRAF.

3. NOTE: if you would like to work outside IRAF in your terminal while the program is running, hit "!" then type your usual command

4. Type "noao" to get into that package

5. Type "artdata" to get into the artificial data package

6. Type "epar mk1dspec" to edit the parameters of the 1D spectrum task
   (a) Set **Input** to the name you would like for the file. Be sure that the name is NOT previously used, otherwise it will grab and use that file.
   (b) **Output** should be the exact same as input
   (c) Set **ap** equal to 1
   (d) Set **rv** equal to 0
   (e) Set **z** equal to no
   (f) Set **title** to the title of the spectra
   (g) Set **ncols** equal to the spectral range index. This can be found using QFitsView. If the spectrum has not been cut, it is usually 1665. This is essentially the end wavelength index of the star.
   (h) Set **naps** equal to 1
   (i) Set **header** to artdata$stdheader.dat
   (j) Set **wstart** equal to the starting wavelength. See QFitsView for exact number. In Angstroms.
   (k) Set **wend** equal to the ending wavelength of your star. See QFitsView for exact number. In Angstroms.
(l) Set continu to the continuum of your star. It is best to use a point after the ugly beginning of the star spectrum, when the spectrum begins to have "clean" small slope.

(m) Set slope equal to 0

(n) Set tempera to the star's temperature. See Figure from Osiris manual.

(o) Set fnu to no

7. After you have set all of the parameters, now run the program using the command ":go"

8. If you would just like to exit epar, use the command ":q"

9. To exit IRAF, type "logout"

You now have a blackbody spectrum that should line up with your star's spectrum. However, finding the correct blackbody spectrum takes trial and error, as you will find in the next section.

### 3.4 Dividing Star Spectrum by Blackbody Spectrum using QFitsView

Here you will see that creating a blackbody spectrum and dividing it out of the star's spectrum takes time with trial and error. We will divide the black body spectrum created in section 3.3 out of the star spectrum so we have absorption features from the sky that we can remove from our science data cubes.

1. Copy the blackbody spectrum from Calculon to your computer and open in QFitsView.

2. Also open the star's spectrum from section 3.2 in another buffer, and make sure you are in that buffer.

3. From the top bar, choose ImRed arithmetic (Image)

4. Set the operation to divide.

5. Using the drop down menu, divide the star by the blackbody spectrum. Select blackbody buffer in menu.

6. Select Store result in new buffer

7. Inspect the new spectrum with the blackbody divided out. The "clean" part of the spectrum should lie at about 1.

8. If the spectrum is not at 1, return to section 3.3 and create a new blackbody spectrum.

   (a) Make sure the new spectrum has a different input and output name

   (b) It is best to try different values for the continuum to move the divide spectrum towards 1.

   (c) Higher continuum values will lower the overall divided spectrum.

9. After you get the best spectrum, closest to 1, rename and save the new spectrum as a FITS file.

### 3.5 Telluric Correction of the Datacubes Using the OSIRIS GUI

Using the newly created 1D spectrum with the blackbody spectrum divided out, we will correct the science datacubes for telluric contamination.

1. Copy the spectrum from 3.4 into Calculon.

2. Return to the OSIRIS GUI using steps in section 2.1.

3. Set Reduction Type to ARP_SPEC

4. The Reduction Template should be set to cubes_telluric_correct_drfTemplate.xml

5. Add Files of all the datacubes from the night or specific time when the star can be used.
6. Specify **Input** and **Output Paths** to a directory you have created.

7. Click on **Specify a File** for the **Divide by Star Spectrum** module and choose your blackbody corrected spectrum from section 3.4.

8. Once above steps are completed, **Drop DRF in Queue** by clicking the button.

9. In your terminal, run the pipeline using the command `run_odrp`

The corrected datacubes will now be saved with the extension of `_tlc_` in the filename.

### 4 Combining Datacubes

Using the GUI we will mosaic the datacubes together. It is important to first view each cube individually to be sure that only the best datacubes are combined into a final result.

#### 4.1 Inspect Datacubes Using QFitsView

First, you will need to open each science datacube in QFitsView and use the circular spectrum view to evaluate the spectrum of all parts of the cube (section 3.2 step 3). If it is a clean spectrum with genuine emission lines, we will use the cube in the combination. Otherwise the cube will be scrapped.

#### 4.2 Combining the Datacubes in the GUI

Using the OSIRIS GUI and the satisfactory datacubes from 4.1, we will combine cubes of specific galaxies of similar position angle.

1. Specify the **Output** and **Log Paths** to a directory you have created.

2. Set **Reduction Type** to **ARP_SPEC**

3. Set **Reduction Templates** to **cubes_mosaic_drfTemplate.xml**

4. **Add Files** of the telluric corrected galaxies to the GUI. Only do the same galaxy’s cubes of the same position angle into the combination cube.

5. Click on **Mosaic Frames** under Module_Name

6. A box with the header **Argument** and **Value** will pop up.

7. In the **Combine_Method** Argument, click on **AVERAGE** and a dropdown menu will appear

8. Choose the best combination method. Usually **MEANCLIP** is used to combine. The OSIRIS manual gives a description of the other methods to choose from:

   (a) "The **Combine_Method** determines whether to combine the frames with either a median (MEDIAN), average (AVERAGE), or sigma-clipping average routine (MEANCLIP). The MEANCLIP method is generally preferred because it has good statistical properties and handles bad pixels and other deviants. But if the observations are meant to tile a large field of view, without significant overlap between each frame, then the best option is to combine with AVERAGE so frames where a simple DC offset has occurred doesn’t bias output values. The MEDIAN option should be used with caution and typically only when there are more than 10 strongly overlapping frames. Please note that the MEDIAN option does not honor bad pixels marked in the quality frame, and it may do strange things if the PSF or morphology change between frames.”
9. Once above steps are completed, **Drop DRF in Queue** by clicking the button.

10. In your terminal, run the pipeline using the command `run_odrp`

11. The extension of `_mosaic_` will be added to the filename

### 4.3 Flipping Your Datacube

In order to view the finished datacube, the x, y, and z axes will have to be arranged in the usual order that most FITS view programs such as QFitsView use.

1. Obtain the IDL program oflip.pro and oflip_list.pro from Dr. Francisco Muller-Sanchez.
   - oflip.pro only does one cube at a time
   - oflip_list.pro will flip multiple datacubes

2. To use oflip_list.pro you will have to create a text file will all of the pathnames/filenames to each datacube. Only `pathname/filename` per line in the txt file. Place txt file in same directory as oflip_list.pro.

3. Run IDL in Calculon in the directory where oflip_list.pro and the text file are located.
   
   (a) Type "idl" to start the program
   (b) Type ".com oflip_list.pro" to compile the program
   (c) Type "oflip_list, name_of_txt_file, number_of_datacubes_to_flip" to run the program.

   **Example:** oflip_list, datacube_names.txt, 33

4. An "f" will be added to the end of the filenames of the datacubes that are flipped

### 5 Final Inspection of Combined Datacubes with QFitsView

The datacubes are now completed and need inspection. There are certain signs of a bad cube to watch for that are seen often. It will take trial and error to get the cubes perfected. Some examples of good and bad datacubes are pictured below.
Figure 6: This datacube is not clean enough to be added with the others. OH lines are still present and the broad bump in the left part of the spectrum is most likely due to telluric overcorrection.

Figure 7: This datacube shows clean emission lines in its spectrum. However, there is still evidence of telluric overcorrection in the left-most part of the spectrum.