Adaptive Optics-Assisted Integral Field Spectroscopy of NGC 5506

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Abstract

The physical structure of active galactic nuclei (AGN) is a topic of great importance for the understanding of galactic structure and evolution. Due to their nature, high spatial resolution observations are needed to study their properties in detail. We have acquired Keck/OSIRIS adaptive optics-assisted integral field spectroscopy of 40 nearby AGN. In this thesis, we have analyzed the spatial distribution and two-dimensional kinematics of the molecular and ionized gas in the Seyfert 2 galaxy NGC 5506. Since this is a nearly edge-on galaxy, the data allow us to study the motion of gas perpendicular to the galaxy disc and assess the impact of AGN-driven outflows in the evolution of the host galaxy. We show evidence of a dual outflow from the circumnuclear region of the galaxy. We observe redshifted outflows of H$_2$, [He I] and [Si VI] to the northeast, with outflows of Br$_\gamma$ blueshifted in the north and redshifted in the south. This evidence suggests that these two outflows consist of an AGN-driven outflow (H$_2$, [He I] and [Si VI]) and a starburst-driven outflow (Br$_\gamma$). This evidence supports a positive AGN feedback model. The northeastern outflow from the AGN suggests a misalignment between the galactic plane and the central torus proposed in the unified model of active galaxies.

1. Introduction

An active galactic nucleus is a compact region at the center of a galaxy that has a much higher-than-average luminosity. There are many different types of AGN, but we will focus on Seyfert galaxies. The spectra of Seyfert galaxies reveal strong, high-ionization emission lines. Seyfert galaxies were the first AGN to be classified as type 1 or type 2, characterized by which kinds of emission lines were present in their spectra. Type 1 Seyfert galaxies have both broad and narrow emission lines, while type 2 Seyferts show only narrow lines.

The unified model of AGN (see Lawrence 1987 for a review) suggests that these differences in spectra are not intrinsic to the host galaxy, but depend on the orientation of the central region of the galaxy with respect to the observer’s line of sight. However, this model is not without controversy. Some studies claim that Seyfert classification, for example, depends more on the intrinsic properties of the central region of a galaxy than its orientation (Ramos Almeida et al. 2011). These conclusions are in direct contradiction with the predictions given by the unified model. Another study (Villarroel et al. 2014) suggests that there may be an evolutionary link between the two types of AGN. These studies and many others challenge the unified model. Continuing to test this model is very important in this field of research.

In order to test the unified model, however, it is necessary to understand it. In this model, cold material close to the central black hole (BH) in a galaxy falls toward the BH to form an accretion disc around the BH, a process called feeding. This accretion disc is surrounded by a dense, opaque circumnuclear torus of gas and dust. It is theorized that each AGN contains a broad-line region (BLR) and a narrow-line region (NLR), and that a BLR obscured by the torus around the accretion disc will result in the measurement of only narrow lines at near-infrared and optical wavelengths, leading to a Seyfert 2 classification.
As this material in the accretion disc orbits, it heats up and some of the material becomes ionized. Some accretion discs produce highly-collimated radio jets and high-velocity outflows of ionized gas. It is possible for these outflows to interact with the rest of the dust, gas and stars in the host galaxy in a process called feedback. In the various proposed feedback models (e.g., di Matteo et al. 2005), once the AGN is triggered, it injects energy into the surrounding interstellar medium via jets, winds and radiation. This inhibits the build-up of massive galaxies and suppresses star formation—a process called negative feedback. Some models also require positive AGN feedback, to reproduce some of the observed black hole-galaxy relations (e.g., King 2005, Ishibashi & Fabian 2012, Silk 2013). Some examples of positive feedback have been observed to enhance star formation in the host galaxy (Croft et al. 2006, Silk 2013). However, the real impact of AGN feedback (positive or negative) in the evolution of galaxies is still one of the most-debated topics in extragalactic astronomy.

NGC 5506, the specific subject of this thesis, is a Seyfert 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. The main science goals of this survey are to explore the mechanisms for feeding and feedback, to discover how feedback affects the host galaxy, and to test the overarching unified model of AGN.

There has been much debate on whether to classify NGC 5506 as a Seyfert 1 or a Seyfert 2. Some studies suggest that NGC 5506 is a narrow-line Seyfert 1 galaxy. This is based on the ionized oxygen and iron lines ([O I] and [Fe II], respectively) that can be seen in its spectrum between 0.9 and 1.4 microns (Nagar et al. 2002), and the broad component in the iron Kα line of its X-ray spectrum (Guainazzi et al. 2010). It is argued that the [O I] and [Fe II] lines can only form in the optically-thick BLR (Nagar et al. 2002). Even still, there is not a clear consensus on the Seyfert classification of NGC 5506, as it is regularly referred to as a Seyfert 1.5, Seyfert 1.9 or even a Seyfert 2 galaxy. The high inclination of the galactic plane (76 degrees, Fischer et al. 2014) is likely part of the reason for the disputes involving its Seyfert classification, as the plane of the galaxy can help obscure the BLR. An image of NGC 5506 is shown in Figure 1 to illustrate its high inclination.

Although the high inclination makes it difficult to assign a Seyfert classification, it also provides other unique opportunities. In general, our results should be much easier to measure and interpret, since rotational kinematics of the disk will not interfere with the kinematics of any outflows perpendicular to the plane of the galaxy. The nearly edge-on orientation also allows us to more easily investigate the relationship between the rotational axis of the galaxy and that of its central torus. There is currently some dispute in the scientific community about whether or not the central torus and the rest of the galaxy can rotate about different axes, so studying high-inclination galaxies like NGC 5506 might help us answer this question.

The size scales on which models predict the central torus vary from an inner edge at 1 pc out to several tens of parsecs (Pier & Krolik 1992, Nenkova et al. 2002, Schartmann et al. 2005). One parsec is about 3.26 light-years (about 30 trillion km), which is the distance scale typically used in galactic astronomy. These crucial size scales of tens of parsecs are exactly those that can
be resolved with the OSIRIS instrument (detailed in the Integral Field Spectroscopy subsection) in the nearest AGN. NGC 5506, the topic of this research project, has a redshift of 0.006181, corresponding to a distance of 26.5 Mpc. This is close enough to get the detailed measurements we need to study AGN-driven outflows in nearly edge-on galaxies and to test the predictions of the unified model of active galaxies in NGC 5506.

![Optical image of NGC 5506](https://cgs.obs.carnegiescience.edu/CGS/object_html_pages/NGC5506.html)

**Figure 1.** Optical image of NGC 5506. At an inclination of 76 degrees, the galactic plane is seen as nearly edge-on. Source: https://cgs.obs.carnegiescience.edu/CGS/object_html_pages/NGC5506.html

2. Observations and Data Processing

2.1. Observations

The observations for this project were made at the Keck Observatory near the summit of Mauna Kea in Hawaii. Keck features two ten-meter telescopes, one of which was used with the OSIRIS instrument (Müller-Sánchez et al. 2011) and its Adaptive Optics System to record our data. The observed galaxy is NGC 5506, which is found in the constellation Virgo at a right ascension of 4h 13m 14.866s, and a declination of -03° 12’ 26.95”. Two observations of rectangular datacubes were made on two different nights at two different position angles. The first observation was made on March 15th, 2011, at 11:11:22 UTC at a position angle of 90 degrees, which is along the plane of rotation of the galaxy, or photometric major axis. The second observation was made on July 24th, 2012, at 6:15:52 UTC at a position angle of 0 degrees. Position angle is the angle measured counterclockwise relative to the north celestial pole. Having these two specific perpendicular position angles is important, as it allows us to make measurements along the photometric major axis (91 degrees east of north) and the photometric minor axis (1 degree east of north) of the galaxy. Each datacube contains spectral data from 1.965 to 2.381 microns, which lies in the K band.
2.1.1. Integral Field Spectroscopy

Some integral field spectrographs, such as OSIRIS, use an array of tiny lenslets across the focal plane of the telescope. These lenslets focus individual portions of the image into different slits. These slits, which typically measure just a few microns across, allow light into the spectrograph, and a spectrum is recorded for each slit. The data returned by an integral field spectrograph is in the form of a datacube, which is a file containing a two-dimensional image that has a spectrum corresponding to each pixel in the image. This process is diagrammed in Figure 2. When viewed as a two-dimensional image, the default value of each pixel displayed is the full integrated flux of the recorded spectrum for that given pixel.

![Diagram of the function of three different types of integral field spectrographs](http://ifs.wikidot.com/what-is-ifs)

Figure 2. Diagram of the function of three different types of integral field spectrographs. The lenslet system (top row) is the system used by OSIRIS in our measurements. Source: http://ifs.wikidot.com/what-is-if

The OSIRIS instrument is an integral field spectrograph on one of the Keck telescopes in Mauna Kea, Hawaii. OSIRIS measures wavelengths in the near-infrared and works with the Keck Adaptive Optics System, which is detailed in the following subsection. Using integral field spectroscopy, we can sample portions of the sky small enough that they approach the diffraction limit of the Keck telescope. OSIRIS provides a full broadband (z, J, H and K) spectral coverage at about 2.5 angstroms per pixel for our observations.
2.1.2. Adaptive Optics

The OSIRIS instrument is able to achieve resolutions that approach the diffraction limit to Keck’s ten-meter primary mirror. This is not common for a ground-based telescope, as perturbations in the Earth’s atmosphere are normally the limiting factor when attempting to achieve this kind of resolution. Adaptive optics (AO) correct for these atmospheric effects by deforming one of the mirrors every few milliseconds. Because galaxies are extended objects, the telescope needs to focus on a nearby point source, like a star, for the system to be able to accurately calculate how to deform the mirror to image the object in question. When nearby stars are not available, AO systems typically use high-powered laser beams as artificial guide stars. A diagram of a typical AO system in shown in Figure 3.

![Figure 3. Diagram of an adaptive optics system which deforms the adaptive mirror to correct for the distorted wavefront typically associated with atmospheric turbulence. Source: http://www.lyot.org/background/adaptive_optics.html](http://www.lyot.org/background/adaptive_optics.html)

The Keck Adaptive Optics System, coupled with the OSIRIS integral field spectrograph, have allowed us to record these datacubes at a resolution of less than 0.2 arcseconds, with pixel scale of 0.035 arcseconds per pixel. The method for determining our spatial resolution is outlined in the Spatial Resolution subsection. The field of view for our data is 72 pixels by 93 pixels (after combining our datacubes into a cross shape, which is described in the Combining Datacubes subsection), or 2.52 arcseconds by 3.25 arcseconds. At a distance of 26.5 Mpc, this field of view is roughly 320 pc by 420 pc, with each pixel spanning about 4.5 pc. Adaptive optics allows us to accurately probe the inner few tens of parsecs of nearby galaxies, which is ideal for studying AGN.
2.2. Data Processing

Reduction of the data for NGC 5506 was done in the same manner as in Müller-Sánchez et al. 2011. These reduction steps include trimming, bias and background subtraction, flat fielding, cosmic rays cleaning, correction for nonlinearity, alignment and interpolation of the data, extraction of the spectra, wavelength calibration, sky subtraction and co-addition of different exposures. After this reduction, some additional steps were taken to fully prepare the datacubes for analysis. A series of original programs were used to accomplish this, along with some that were already publicly available.

2.2.1. Visualizing Datacubes

A program called QFitsView was used to visualize our datacubes. QFitsView is publicly available software, which is designed for visualizing these types of files (FITS files). This program allows the user to view a 2-dimensional image in which the value of each pixel is given by the total integrated flux of the recorded spectrum. Each pixel contains a spectrum, which can be seen by scrubbing over pixels in the main window. QFitsView was used not only to visualize these datacubes, but also to extract spectra at different regions of the image, to fit Gaussian functions to specific emission lines in the spectrum of a given region, and to determine the spatial resolution of our data.

2.2.2. Combining Datacubes

Because we are dealing with datacubes of two different position angles which have been sent to us in the same orientation, it is important to orient them at the angles at which they were originally measured and then combine them. In order to do this, we wrote PAStitcher, a Python program designed to take any two rectangular datacubes, orient them, stitch them together, and return a single datacube of the combined data. The overlapping regions of data between the individually stitched datacubes are averaged.

The original datacubes for NGC 5506 were of dimensions 19 pixels by 93 pixels and 19 pixels by 72 pixels. Because the position angles of our observations for NGC 5506 were perpendicular to each other, the resulting datacube is of dimensions 72 pixels by 93 pixels in a cross shape, with the leg of each cross spanning 19 pixels in width.

The PAStitcher program is automated to take position angles and image dimensions from a FITS header—a list of information included in each datacube. Writing this program was important for the KONA survey, because it automates the process of stitching datacubes of any orientation, so that any two datacubes can be stitched together, even if the observations were not made in simple perpendicular orientations.
2.2.3. **Orienting Datacubes**

Occasionally, some datacubes recorded at Keck are sent mirrored along one axis or the other. The NGC 5506 datacube was mirrored along the long axis of the datacube recorded at the 90-degree position angle. To remedy this, we wrote CubeFlipper, a Python program designed to mirror a datacube across a given axis. The program requires an axis be specified, so it is still required for the user to determine which axis is flipped. In order to do this for NGC 5506, we used spectral features from previous observations by Dr. Francisco Müller-Sánchez and found that the strong [Si VI] emission line was in the wrong location. After flipping the datacube at the 90-degree position angle, it was stitched with the 0-degree datacube to verify that the two lined up correctly.

2.2.4. **Flux Calibration**

Flux calibration is part of the reduction process for these types of datacubes. Flux calibration involves scaling the value of each pixel at each position in the spectral direction by a constant to reflect the proper units. Only one of the datacubes that we received at the start of this project was flux calibrated, so we wrote FitsAmplifier, a Python program designed to scale flux values for datacubes. In order to match the scaling for the two datacubes, the program takes a symmetric region of pixels around the pixel with the largest integrated flux and adds all of those values together. It then does the same thing with the uncalibrated datacube. The ratio of the sum of the calibrated region to the sum of the uncalibrated region is the scaling constant that is multiplied by the entire uncalibrated datacube array to scale it. After the scaling is complete, the datacubes are combined with PAStitcher and checked for smoothness. Properly scaled datacubes will look smooth and continuous, and if proper scaling is not achieved, the user is able to manually select different pixels to sum together before the scaling constant ratio is computed.

2.2.5. **Spatial Resolution**

Spatial resolution describes the ability of any image-forming device, such as a telescope or a camera, to distinguish small details of an object, thereby making it a major determinant of image resolution. It is important for us to determine our spatial resolution so that we can know to what detail we can trust our results. The spatial resolution for our observations is found by integrating the complete recorded spectrum for each pixel into an image, plotting the flux of this image across the three central rows of pixels, and finding the full width at half maximum (FWHM). This flux plot increases to a maximum at the AGN, and then decreases again, which is very much like the shape of a Gaussian function. Fitting this plot with a Gaussian function and finding the FWHM gives our resolution of 5 pixels ± 1 pixel. At a pixel scale of 0.035 arcseconds per pixel, this is 0.175 arcseconds ± 0.035 arcseconds.
2.2.6. Two-dimensional Flux, Velocity, and Dispersion Maps

Two IDL programs were used to determine the kinematics of our data, which are taken from Müller-Sánchez et al. 2009. These are an emission line Gaussian-fitting program (LineFit), and a velocity mapping program (PlotVel). These two programs are essential in determining flux, velocity and velocity dispersion of each species of gas in each region of the two-dimensional image of the galaxy.

LineFit works by fitting Gaussian functions to select emission lines in the spectra at each pixel. In order to use LineFit, a range of wavelengths must be given by the user for the program to consider when looking for the emission lines. Additionally, certain ranges for the surrounding continuum must be given, so that LineFit can subtract the continuum from the fit. QFitsView was used to find ranges for these lines, and for the continuum subtraction. Because this process contains a component of human error, the LineFit routine was run multiple times for each of the chosen emission lines, and the input resulting in the best Gaussian fits was kept.

The shifts and widths of the lines are important in determining the kinematics of specific elements in the observed galaxy. PlotVel determines the relative flux, velocity and velocity dispersion at each pixel, based on the shape and position of each Gaussian-fitted line. In order to do this, PlotVel uses the relative Doppler shifts and the FWHM values of the Gaussian fits from LineFit for each of the emission lines chosen.

Because there is a spectrum at each spatial pixel of the two-dimensional image, we can compare the location of specific emission lines from pixel to pixel to determine redshifts and blueshifts, and we can compare the shapes of these lines from pixel to pixel to determine the difference in FWHM. For all resulting maps, an inner arcsecond radius (corresponding to the inner 130 parsecs) is plotted. The four main emission lines chosen are molecular hydrogen (H$_2$), Brackett-gamma (Br$_\gamma$), helium-I ([He I]) and silicon-VI ([Si VI]). The rest wavelengths corresponding to the specific transitions of these elements are included in Table 3. All maps are oriented so that north is up and east is left.

3. Results

3.1. Integrated Spectra at Different Regions

Nine specific regions were chosen for closer examination of their spectra. Each region corresponds to an integrated spectrum, consisting of data centered on a specific pixel, but enclosing an aperture of four pixels in radius. Integrating spectra in these regions is useful, as it increases the signal-to-noise ratio of the data and dampens the negative effect of bad pixels. For each spectrum, the continuum has been subtracted out. The plots for all nine of these regions is shown in Figure 4.

It can be seen in region 1 that all of the emission lines are very narrow, and that [He I] is very prominent, at ~2.07 microns. This [He I] line is also found in other regions, but not nearly as prominently. [Si VI] (not shown) is also very pronounced in this region, as is discussed in the
Spatial Distribution and Kinematics section. Brackett-gamma is very pronounced in every region, but is especially narrow in region 1.

Figure 4. Integrated spectra at different regions near the galactic nucleus. The encircled areas are enclosed by an aperture of eight pixels. Purple corresponds to a lower overall flux, and white, a higher overall flux. The three prominent emission lines in Region 1 correspond to (from left to right): [He I], H$_2$, Br$\gamma$. Regions 1, 2, 3, 7, 8 and 9 show strong H$_2$ and Br$\gamma$ lines, with Br$\gamma$ strong in all regions.

Molecular hydrogen lines (~2.13 microns) appear suppressed in regions 4, 5 and 6, compared to other regions, while [He I] lines appear slightly intensified. Both lines, however, exhibit a very low signal-to-noise ratio, and will be difficult to trust for any significant measurements. Brackett-gamma lines (~2.18 microns) are very broad in almost every region of the data, but are especially broad in regions 4, 5 and 6. There do not appear to be any double-peaked lines or asymmetric wings prominent enough to be trusted for any of the lines in any region.

There are two main areas of interest in this dataset. Region 1 contains narrow lines with large flux values for ionized gas, while regions 4, 5 and 6 contain broader lines with some signs
of ionized gas and lower H$_2$ flux. These regions are investigated in more detail in the Spatial Distribution and Kinematics section.

### 3.2. Continuum

From analyzing the raw spectra for the nine regions specified in Figure 4, we see that the northern, southern and central regions all show an increasing slope in the continuum. The other regions did not show this same slope to the same degree. A plot of all nine regions without the subtracted continua is given in Figure 5.

![Figure 5. Spectra of the nine regions shown in Figure 4 with region 1 at the top left, region 2 at the top center, and region 9 at the bottom right. The slope of the continuum is shown to be increasing in regions 4-6.](image)

The average slope of the continuum can tell us something about the average temperature of the region. We know this from the blackbody curve that results from a radiating object. Hotter objects peak at shorter wavelengths of the spectrum than cooler objects, which will peak at longer wavelengths. This wavelength-dependent flux is given by the Planck function, and the peak wavelength is found using the Wien’s Law approximation: $\lambda_{\text{max}} = b / T$, where $b = 2.8977729 \times 10^{-3}$ m K. Because the Planck function only peaks once for a given blackbody, we know that this increase in slope in regions 4, 5 and 6 must be due to some other sort of emission. This extra emission must not be stellar, as a peak wavelength longer than 2.4 microns would correspond to a temperature cooler than 1,200 K, by Wien’s Law.

Temperatures this low are less likely to be explained by stellar emission, and more likely to be explained by dust emission. While dust usually emits photons in the range of tens of Kelvins, high energy photons can excite dust enough for it to emit at a temperature of around
1,000 K. The emission of high energy photons in these regions would be consistent with what we see in the dispersion maps in Figure 6.

### 3.3. Spatial Distribution and Kinematics of Emission Lines

The flux, velocity and dispersion maps outlined in the Data Processing section are shown in Figure 6. For H$_2$, the flux map exhibits what we would expect to see from an edge-on disk, and the velocity map values along the photometric major axis is consistent with what we would expect for rotation. Each of the velocity maps have similar characteristics, corresponding to a line of sight velocity toward the observer in the eastern region.

![Figure 6.](image)

**Figure 6.** Flux, velocity and dispersion maps for the different emission lines near the galactic nucleus. Each flux map is overlaid with a contour map of the continuum, with each line in the contour corresponding to a ten percent change in flux. Velocity and dispersion values are in km/s, and flux values are relative to peak flux.
Both [He I] and [Si VI] show increased flux toward this same eastern region, compared to elsewhere in the field of view. These correspond with the prominent narrow lines seen in region 1 in Figure 4, and in Figure 7 under the Silicon-VI subsection.

The high dispersion values for Brγ along the photometric minor axis are consistent with what was found in the Integrated Spectra section for regions 4, 5 and 6, as the lines were much broader there. In these same regions, we see redshifted velocities in both H2 and [He I]. It is important to note that the data contained several bad pixels in these regions near the [Si VI] line, which are most obvious in the [Si VI] velocity and dispersion maps in gray. These pixels are to be ignored in these maps, and also in the [Si VI] flux map.

In this section, each of the four species is broken down into more detail. The H2 and Brγ emission lines used to make the maps in Figure 6 were fitted with Gaussians in QFitsView for each of the nine regions in Figure 4, and a table of the values for the centers of the Gaussian curves and the FWHM is given for each, with their respective errors. The emission lines for [He I] and [Si VI] did not exhibit a large enough signal-to-noise ratio in many of the regions, so this same analysis could not be performed.

3.3.1. Molecular Hydrogen

Because molecular hydrogen is usually the most abundant and stable species of gas in most galaxies, we expect to be able to use it as a standard for the rotational motion of the galaxy. We have already seen many of the typical characteristics that are common for H2 in other galaxies, and we will use these Gaussian fits as a sort of check for what we have already seen. The specific H2 line chosen here is H2 1–0 S(1).

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<th>Fit Error</th>
<th>FWHM</th>
<th>Fit Error</th>
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Table 1. Gaussian fit data for the nine specified regions from Figure 4 for H2. Values in red are results from a very low signal-to-noise emission line. All values are in units of microns.

We see from Table 1 that the centers of these Gaussian fits are blueshifted in regions 1, 2 and 3, as compared to regions 7, 8 and 9. This is what we would expect to see from rotation, and is consistent with the H2 velocity map. The rotation, however, does seem to be slightly tilted with respect to the plane of the galaxy. There are possible explanations for this, as are presented in the Discussion section. The FWHM measurements are consistent with the dispersion map, as
they do not deviate much from region to region. Again, this reflects what we would expect for molecular hydrogen in most galaxies.

Along with the expected rotation behavior that we see in the plane of the galaxy, there appears to be a redshifted component toward the north. These kinematics are not explained by rotation, as the motion is not in the rotational plane. One explanation for this could be a molecular outflow. It appears that the direction of motion in the north is actually a bit east of north. We will also return to this is greater detail in the Discussion section.

3.3.2. Brackett-gamma

The Brackett-gamma line is not strongly affected by extinction like many other lines, so a strong signal is generally expected for this line. We would generally expect a broader line for Brγ near the galactic center for AGN. The dispersion map shows high dispersion not just at the center, but also north and south of the center.

As is shown in Table 2, regions 4 and 5 are more strongly redshifted than the other lines, which is consistent with the velocity map in Figure 6. Region 1 shows a particularly narrow FWHM, which we have seen in both Figure 4 and Figure 6. As noted previously, the high dispersion values in regions 4, 5 and 6 should result in larger values for FWHM in Table 2, which we do see. It appears that the FWHM is the largest in region 6, which we would expect. However, the uncertainties for these values do not allow us to make a definitive claim about this. Nevertheless, the high dispersion in regions 4, 5 and 6 compared to the other regions does seem to be reliable. This would be consistent with an outflow along the photometric minor axis of the galaxy. It is interesting to note, however, that this outflow would not be in the same direction as the suggested outflow of molecular hydrogen, as it does not appear to be tilted, and the directions of propagation for H₂ and Brγ are opposite in the northern and southern regions. It appears that there might actually be two different outflows present in NGC 5506. We will examine this further in the Discussion section.

### Table 2.

<table>
<thead>
<tr>
<th>Region</th>
<th>Center</th>
<th>Fit Error</th>
<th>FWHM</th>
<th>Fit Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.17945</td>
<td>3.76E-05</td>
<td>1.71E-03</td>
<td>9.45E-05</td>
</tr>
<tr>
<td>2</td>
<td>2.17972</td>
<td>1.12E-04</td>
<td>4.13E-03</td>
<td>3.99E-04</td>
</tr>
<tr>
<td>3</td>
<td>2.17945</td>
<td>8.08E-05</td>
<td>3.12E-03</td>
<td>2.28E-04</td>
</tr>
<tr>
<td>4</td>
<td>2.18029</td>
<td>1.87E-04</td>
<td>4.78E-03</td>
<td>6.34E-04</td>
</tr>
<tr>
<td>5</td>
<td>2.18016</td>
<td>2.30E-04</td>
<td>5.25E-03</td>
<td>7.78E-04</td>
</tr>
</tbody>
</table>

Table 2. Gaussian fit data for the nine specified regions from Figure 4 for Brγ. All values are in units of microns.
3.3.3. Helium-I

Helium-I is an ionized species of gas that shows interesting characteristics in one particular region (region 1 from Figure 4) of NGC 5506. The FWHM for this region was measured to be 1.33E-03 microns, with an error of 1.13E-04 microns, using the same Gaussian fitting in QFitsView used for the tables above. In Figure 7, the [He I] line is shown at ~2.07 microns.

The high value of flux and narrow line are consistent with the flux and dispersion maps in Figure 6. The velocity map for this region shows a value that is redshifted compared to other regions, which may tell us something about a possible outflow. It is difficult to properly analyze the dynamics of the [He I] line with these maps alone. Because of the effects that rotation imposes, the H$_2$ rotation data must be subtracted from the [He I] velocity data. Analyzing the [He I] residuals after the H$_2$ velocity map is subtracted is more insightful. This is performed in the Velocity Residuals section.

3.3.4. Silicon-VI

Silicon-VI is a highly-ionized species of gas that shows interesting characteristics in one particular region of NGC 5506. In Figure 7, the [Si VI] line is shown to be the most prominent of any spectral line in the near-infrared. The FWHM for this region was measured to be 1.06E-03, with an error of 6.02E-05.

![Region 1](image)

**Figure 7.** Full integrated spectrum for region 1 of Figure 4. [Si VI] is the most prominent line in the region (~1.98 microns). [He I] is also pronounced (~2.07 microns).
The high value of flux and the narrow [Si VI] emission line are consistent with the flux and dispersion maps in Figure 6. As is the case with [He I], the velocity map for this region shows a value for [Si VI] that is redshifted compared to other regions. This may be consistent with some sort of outflow of [Si VI], as was suggested for [He I]. However, it is difficult to properly analyze the dynamics of the [Si VI] line with these maps alone. The subtracted H$_2$ velocity map in the Velocity Residuals section better illustrates what is happening with silicon-VI.

3.4. Kinematic Analysis

Data for wavelength, flux and FWHM of specific wavelengths is given in Table 3. Integrated flux for each emission line was measured by summing the total flux in an aperture of 10 pixels about the central AGN. The pixel corresponding to the central AGN lies at the center of the datacube, where the flux value of the pixel is higher than any other, integrated over the entire continuum.

Because these values were measured for an aperture of 10 pixels, and since the pixel scale of our datacube is 0.035 arcseconds per pixel, this corresponds to an aperture of 0.35 arcseconds. At 0.35 arcseconds, we know we can trust these results, given that our spatial resolution with the instruments used in our observations is smaller than this (5 pixels).

### Measured Values of Emission Lines

<table>
<thead>
<tr>
<th>Species</th>
<th>$\lambda_{measured}$ (µm)</th>
<th>$\lambda_{rest}$ (µm)</th>
<th>Flux (W m$^{-2}$)</th>
<th>FWHM (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$_2$</td>
<td>2.135</td>
<td>2.121</td>
<td>5.92E-17</td>
<td>1.48E-03</td>
</tr>
<tr>
<td>Br$\gamma$</td>
<td>2.180</td>
<td>2.166</td>
<td>5.58E-16</td>
<td>5.42E-03</td>
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<tr>
<td>[He I]</td>
<td>2.072</td>
<td>2.058</td>
<td>4.43E-17</td>
<td>6.79E-04</td>
</tr>
<tr>
<td>[Si VI]</td>
<td>1.976</td>
<td>1.963</td>
<td>3.08E-17</td>
<td>1.10E-04</td>
</tr>
</tbody>
</table>

Table 3. Values of flux and FWHM corresponding to specific emission lines in the spectrum of NGC 5506. These values are for an aperture of 0.35 arcseconds about the central AGN. Errors are roughly ten percent of the tabulated values.

From Table 3, we can see that the brightest emission in this region comes from Br$\gamma$. We would expect this, since Br$\gamma$ is produced by both AGN and stars, and since extinction does not affect this line as much as it does others. This Br$\gamma$ flux is significantly higher than that of [Si VI], which is also produced by AGN, but not by stars. Also, the Br$\gamma$ line has a wider FWHM, consistent with the results presented in the Results section, and also consistent with a higher overall flux when compared to the other emission lines.
3.5. Velocity Residuals

In order to better understand the kinematics of Br$_{\gamma}$, [He I] and [Si VI], it is useful to remove the kinematics imposed by rotation of the galactic disk. We assume that the kinematics of the H$_2$ line in the plane of the galaxy (along the horizontal axis) are explained entirely by rotation. This is a safe assumption, as molecular hydrogen is not ionized, so it is not as susceptible to kinematic effects imposed by the AGN. By subtracting the rotational velocities of H$_2$ at each pixel in the [He I] and [Si VI] velocity maps, we can see what residuals are left over. These residuals are presented in Figure 8.

We should note that it is only useful to examine the residuals in the plane of the galaxy. This is because we have subtracted the H$_2$ velocities from the other velocity maps at each pixel, but the H$_2$ velocities that are not in the plane of the galaxy would not be a result of rotation. In order to analyze the kinematics in the vertical axis for each of these species, we will have to refer back to Figure 6.

![Figure 8. Residuals of velocity maps for the different atomic species near the galactic nucleus after the subtraction of the H$_2$ velocities. All velocity values are in km/s. The horizontal axis is offset of right ascension (from the center of the AGN), and the vertical axis is offset of declination. Both offsets are in units of arcseconds.](image)

We can see in Figure 8 that the Br$_{\gamma}$ residuals appear to be virtually zero velocity in the plane of the galaxy. This is what we would expect when eliminating the rotational kinematics, so it gives us more confidence in our other two residual velocity maps. In both [He I] and [Si VI] we see a redshifted velocity component to the east, and no clearly defined structure anywhere else. This is in agreement with our results to this point, but a comparison with data for ionized oxygen from other sources reveals more about a potential outflow of ionized gas.

Observations of oxygen-III ([O III]) were found via the NASA/IPAC Extragalactic Database (NED) to further understand the kinematics of ionized gas in NGC 5506. These observations were performed by the Hubble Space Telescope in 1995, using the Faint Object Camera (FOC) instrument, which utilizes a 501 nm wavelength narrow filter. A plot of the [O
III] image from this observation is shown in Figure 9. The morphology of [O III] in NGC 5506 suggests an outflow to the northeast.

In Figure 10, the HST [O III] image is superimposed above the residual maps as well as beneath them, so that the images can be compared, especially for the ionized species of [He I], [Si VI] and [O III]. We would expect all three of these species of gas to exhibit outflows in the same general direction, and that is indeed what is suggested by these data.

The emission of [O III] coincides with the suggested outflows of [He I] and [Si VI]. It is perhaps most apparent in the bottom three plots that the [O III] emission is not symmetric about the vertical axis, but is instead tilted slightly toward the east. This is examined in more detail in the Discussion section.

![Figure 9. Images of [O III] in NGC 5506. The horizontal axis is offset of right ascension (from the center of the AGN), and the vertical axis is offset of declination. Both offsets are in units of arcseconds.](image-url)
3.6. Error Analysis

The PlotVel program used to create the velocity maps does so by fitting Gaussians to the data. In doing so, it also quantifies the error in its ability to properly fit a given line. Each emission line considered at each pixel is assigned an uncertainty based on the goodness of fit. The spectral shift of each emission line in wavelength corresponds to a velocity in km/s, and the deviation of these fits in km/s gives the uncertainties in units of velocity. Maps for those uncertainties are given in Figure 11.
The average uncertainties in the velocities given in Figure 11 are about 20 km/s, although some regions have much higher than average uncertainties. The vertical axis has systematically higher uncertainty values, and the eastern region had the lowest uncertainties. This is satisfactory for our purposes, as the regions in which we are most interested are associated with very small values of uncertainty. To further illustrate this, we have plotted in Figure 12 only the values in residual velocity maps that correspond to pixels where the uncertainties are smaller than 30 km/s.

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4. Discussion

4.1. Rotation

As was discussed in the Velocity Residuals section, we assumed that subtracting the H\textsubscript{2} velocity map from the other velocity maps would give reliable residuals in the plane of the galaxy. In order to verify that the velocity gradient that we see in the plane of the galaxy for H\textsubscript{2}
is a result of rotation, we need to check other rotational velocity measurements that have been performed for NGC 5506. A measurement from Rubin 1978 is given in Figure 13.

![Velocity curve for NGC 5506. From Rubin, V. C. 1978.](image)

**Figure 13.** Velocity curve for NGC 5506. From Rubin, V. C. 1978.

From Figure 13, we can see that the $H_2$ velocities measured in our data are consistent with other rotational velocity measurements. Considering only the data points within 2 or 3 arcseconds of the center, we have what looks like an infinite slope, so we cannot make any determinations about the how the velocity changes with distance from the center in this region. While the figure lacks precise velocities for the inner arcsecond that we are observing with OSIRIS, we can see that the eastern half of the galaxy shows radial velocities toward the observer, while the western half shows radial velocities away from the observer. This is consistent with the blueshifted eastern velocities that we measure, as well as the gradient toward more redshifted velocities in the west.

### 4.2. AGN-Driven Outflow

In order to be more quantitative with the HST $[O III]$ data, we have made some measurements for the position angle and opening angle of the emission. Other studies on this emission of $[O III]$ in NGC 5506 yield similar results. One of these in particular includes a kinematic model of $[O III]$, performed by Fischer et al. 2013, so we have provided these results along with ours in Figure 14.
The position angle that we see for the [O III] emission in Figure 14 is consistent with the suggested outflows of other highly-ionized gas that we observe in the eastern region of NGC 5506 (and most notably region 1 from Figure 4). This opening angle of the magenta lines in Figure 14 is measured to be 67 degrees. These lines were fit to the [O III] image based on a conical outflow model that would enclose the majority of the flux in the outflow. From these magenta lines, the position angle was calculated, which is 19 degrees east of north. Because this suggested outflow tends eastward, more of this outflow would interact with the eastern part of the disk, and less with the western part of the disk. These interactions would result in more ionizing of other species of gas in this part of the disk. This is consistent with what we have measured for [He I] and [Si VI].

The kinematic model from Fischer et al. 2013 gives largely the same result, but with an added inclination angle that could not be determined from the HST image alone. The modeling was done using slitless spectra via the Space Telescope Imaging Spectrograph on the Hubble Space Telescope (Ruiz et al. 2005). The position angle given by this model is 22 degrees with an inclination of 10 degrees (shown by the yellow line). The red and green lines show the photometric major axis and the photometric minor axis, respectively. The model shows that the line-of-sight component of the outflow is pointed away from the observer, which corresponds to a redshifted velocity component. This is exactly what we see in our velocity residuals for the other ionized species of [He I] and [Si VI] as well as molecular hydrogen.

As was mentioned in the Results section, the rotation of molecular hydrogen that we measure appears to be slightly tilted with respect to the plane of the galaxy. One explanation for this is a radial expansion of the gas in the galactic plane. As explained in Arribas et al. 2008, outward radial motion can cause our measurement of rotational velocities to be offset by a phase.
angle which depends on the rate of the expansion. This kind of expansion is commonly associated with outflows.

4.3. Starburst-Driven Outflow

It is worth noting that this same tilted gradient of rotational velocities is not seen in Brγ. The high dispersion and Doppler-shifted velocities are aligned at a position angle closer to zero than for H2. While the H2 velocities in the north seem to follow the same position angle as the [O III] emission, Brγ does not. The data also shows that Brγ is blueshifted in the north and redshifted in the south, while H2 exhibits the opposite behavior, and that Brγ is commonly produced by stars. This provides evidence for a different kinematic component. The fact that this is perpendicular to the plane of the galaxy, and that there is high dispersion in this region suggests that there are two different outflows—an AGN-driven outflow (H2, [He I] and [Si VI]) and a starburst-driven outflow (Brγ). Additionally, we calculate the star formation rate for the inner 300 parsecs to be more than 500 solar masses per year (M☉ yr⁻¹), which is unusually high for a circumnuclear region of a galaxy, further supporting the starburst-driven-outflow model. This calculation is based on a result from Maiolino et al. 1994 which finds the circumnuclear star formation rate density to be 0.002 M☉ yr⁻¹ pc⁻² at about 300 to 400 pc from the nucleus. Multiplying this star formation rate density by the area of a disk with radius 300 parsecs (the lower limit) gives us our estimate for the circumnuclear star formation rate.

4.3. Comparison with Radio and X-Ray Data

Analyzing our data in the K band, along with the HST and other visible band data, has allowed us more insight into what is happening along the photometric minor axis of NGC 5506. In this section, we will consider more data from previously published studies. These studies present images of extended emission around NGC 5506 in the X-ray and radio regions of the spectrum. It is important to consider other portions of the spectrum to see how these correlate with the emission that we have already measured in the northeast and in the north-south direction. Figure 15 shows data in radio frequencies.

Figure 15. Radio contours at 4.9 GHz in NGC 5506 at two different resolutions. From Colbert et al. 1996.
From this data, we can see diffuse structures extending out into the northwest and southeast directions. This is interesting, because this extended region is not aligned at the ~20 degree position angle measured using the [O III] HST image or using the results of the kinematic conical modeling by Fischer et al. In fact, the position angle of this radio emission seems to be tilted west of north. It is suggested that this strange radio emission might be a bubble of hot plasma rising from the nucleus or a magnetically dominated coronal arch (Wehrle & Morris 1987). There seems to be no connection between either of the suggested outflows (Br$\gamma$ or the other three species) and the radio jet.

In addition to visible and radio data, it is also useful to examine X-ray data. Included in Figure 16 are plots from Colbert et al. 1998, which used data from the ROSAT X-ray satellite.

![Figure 16. Left: NGC 5506. ROSAT PSPC contours over gray-scale plot of B-band image. Middle: ROSAT HRI contours over gray-scale plot of B-band image. Right: Extended radio and X-ray emission. Contours are soft X-ray emission from the ROSAT HRI image, and gray scale is from a 4.9 GHz radio continuum image. The gray-scale image is displayed on a logarithmic scale to bring out the structure of the extended radio emission. From Colbert et al. 1998.](image)

We see that the position angle of the extended X-ray emission is perpendicular to the plane of the galaxy, and at such large scales, it is hard to tell whether this is related to the suggested outflow of molecular hydrogen and ionized gas, or with the kinematics we see in Br$\gamma$, which seem to be almost perfectly perpendicular to the plane of the galaxy. At these scales, this X-ray emission is consistent with either of these, so while it does not give us any extra insight, it does show activity that would have to be absent if there were no outflow at all.

5. Conclusions

In this work we have used adaptive optics and integral field spectroscopy to study in detail the spatial distribution and kinematics of the molecular and ionized gas in NGC 5506. We have seen the kinematics of several different species of gas in our data, and compiled evidence about the kinematics of other species of gas from other sources. Our main results and conclusions can be summarized as follows:
• H$_2$ and Br$_\gamma$ are rotating in the galactic plane, and both exhibit motion perpendicular to the galactic plane.

• H$_2$ and ionized species of gas ([He I], [Si VI] and [O III]) have redshifted components of motion toward the northeast. None of these species show any kinematics in the southwest.

• Br$_\gamma$ exhibits redshifted velocities to the south and blueshifted velocities to the north.

• These observed kinematics suggest the existence of two separate outflows in NGC 5506. This proposed dual outflow model is shown in Figure 17.

1. An AGN-driven outflow is present in the northeast, which is responsible for the emission of H$_2$, [He I], [Si VI] and [O III] in this region. This emission is directed to the northeast with line-of-sight velocities on the order of 100 km/s.

2. A starburst-driven outflow is present in the north-south direction, which is responsible for the emission of Br$_\gamma$ in this direction. The opposite line-of-sight components of motion of H$_2$ and Br$_\gamma$ and their differing position angles suggest that these two outflows are separate. Because increased emission of Br$_\gamma$ is often measured in regions of increased star birth, and because we have determined the inner 300 pc of this galaxy to have increased star birth, we conclude that this is a starburst-driven outflow. This is responsible for the non-rotational kinematics of Br$_\gamma$ that we measure above and below the galactic plane, with line-of-sight velocities on the order of 100 km/s.

• The AGN-driven outflow that we see is aligned along a different position angle (~20 degrees from north) than the rotation axis of the galaxy (~0 degrees from north). Because the unified model requires that the direction of an AGN-driven outflow be perpendicular to the plane of the circumnuclear torus, we know that the plane of the circumnuclear torus does not lie in the plane of the galaxy. Whether or not this type of orientation of the torus could occur within the unified model is still very much in debate in the scientific community. This evidence is important in our test of the unified model, as it supports the idea that AGN-driven outflows can, in fact, be out of alignment with the galactic rotation axis.

• The increased rate of star formation is likely a direct result of the AGN-driven outflow, suggesting positive AGN feedback. One of the main science goals of the KONA survey is to determine how feedback from AGN-driven outflows might affect star formation. In the case of NGC 5506, we see an AGN-driven outflow occurring simultaneously alongside an outflow from an unusually high rate of circumnuclear star formation. It has been proposed that radial expansion of the molecular hydrogen near the BH can force pockets of high density to form in the surrounding few hundred parsecs, as the gas closer to the center is being pushed toward the gas farther from the center in a radially-expanding ring. As we have calculated, the inner 300 parsecs of NGC 5506 is experiencing a higher-than-normal rate of star formation during this outflow. We conclude that the enhanced star formation in the inner 300 parsecs is likely caused by the AGN-driven outflow creating these high-density circumnuclear regions, and thus the AGN feedback is leading to increased star birth.
Seeing the outflows in the northern and southern regions of the galaxy independently of the motion of the disk is one of the benefits of studying outflows in a nearly edge-on galaxy, as was initially posited as part of the motivation of this research. Had NGC 5506 not been inclined at such an angle, it might have been very difficult to parse out the kinematics in these regions, given the three different kinematic components present for molecular hydrogen, for example (see Table 4). Because we were able to see the galactic disk almost entirely independently of either outflow, it was easier to identify the radial expansion component of the motion, and it was easier to piece together a clearer picture of the two outflows. A complete summary of the kinematics of the emission lines from our OSIRIS measurements is given in Table 4.

The next step for the KONA survey is to continue our work with two other galaxies of nearly edge-on inclination in the hopes of finding clear results like those demonstrated in this thesis. We hope to find interesting and enlightening results with these other galaxies, in order to further test the unified model.
Summary of Kinematics of Emission Lines

<table>
<thead>
<tr>
<th>Emission Line</th>
<th>Kinematic Components</th>
</tr>
</thead>
</table>
| $H_2$         | 1) Rotation (position angle $\sim$90 degrees)  
                2) Expansion (radial motion, changing apparent position angle measured)  
                3) AGN-driven outflow |
| $Br_{\gamma}$ | 1) Rotation (position angle $\sim$90 degrees)  
                2) Starburst-driven outflow |
| [He I]        | 1) Rotation (position angle $\sim$90 degrees)  
                2) AGN-driven outflow |
| [Si VI]       | 1) AGN-driven outflow |

Table 4. Summary of the kinematics of each emission line.

Figure 17. Proposed dual-outflow model, consisting of an AGN-driven outflow (purple) and a starburst-driven outflow (green). The red arrows show redshifted kinematic components and the blue arrows show blueshifted kinematic components.
6. References

Villarroel B., Korn A. J., 2014, NatPh, 10, 417