On OH Ro-Vibrational Lines in HD 100546: Symmetric or Asymmetric?

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On OH Ro-Vibrational Lines in HD 100546: Symmetric or Asymmetric?

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In Partial Fulfillment
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Master of Science
Physics

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Abstract

The study of planets has fascinated observers for millennia, from careful observers plotting the motions of the “wandering stars” to modern astronomers utilizing equipment to study planets within and beyond our Solar System. We have discovered, in recent decades, that planetary systems are found around a large fraction of stars of varying types. The study of the structure of these systems provides a way to study the initial conditions of planet formation and place constraints on models of planet formation and disk-planet interactions. To determine these constraints and identify indirect probes of ongoing planet formation, astronomers have turned to young stellar objects, such as Herbig Ae/Be stars or T Tauri stars, which are surrounded by a disks of gas and dust. By studying these disks, where planet formation takes its first steps, we can determine the signposts of planet formation in disks and complete the planet formation models.

This paper investigates one such disk around Herbig star HD 100546. Previous observations of the disk by Liskowsky et al. (2012) and Fedele et al. (2015) have found contradicting OH line profiles. These molecular lines are used to probe the dynamic structure of the inner rim of the outer disk. Liskowsky et al. (2012) present evidence that the asymmetry in the OH line is caused by disk interactions with a massive planetary companion. However, Fedele et al. (2015) show that a similar asymmetric effect can be caused by subsampling of the disk with a narrow slit. In
this thesis, the likelihood that a circular disk appears asymmetric is weighed against
the likelihood that an asymmetric disk appears symmetric by modeling synthetic
observations of both situations. Best practices for future observations of HD 100546
and other circumstellar disks are discussed.
Dedication

For Paul Jackson, without whom I would never have made it this far.
Acknowledgments

I would first like to thank my friends for putting up with my level of stress, general grouchiness, and inability to attend important events over the past few months. Your support through all of this has been a sizable contribution to my drive to follow through and finish this project. I could not have done this without you. I would also like to thank my parents who have entertained my interest in space from a young age and always supported me in my quest to follow my heart and my happiness. Thank you for your support and love through the years, especially when I was too stubborn to appreciate it.
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Chapter 1

Introduction

1.1 Protoplanetary Disks

The study of the early epochs of planet formation necessitates the study of young stellar objects (YSOs) and the circumstellar disks that surround them.

Disk formation is a natural consequence of angular momentum conservation during the formation of the protostar. As the molecular cloud collapses, there is a fraction of material with residual angular momentum values too high for it to collapse directly to stellar densities and the material orbits the forming star instead (Armitage, 2010; Bernath, 2005; Cieza, 2008; Cieza et al., 2010). The disk evolves to its final size and mass over the course of approximately 0.5 Myr as the protostar evolves through Class 0 and Class I. During this initial evolution, the mass of the disk does not increase as material is drawn in from the molecular cloud. This implies a rapid transport of material from the disk onto the star. This early disk is thought to be gravitationally unstable due to the high mass fraction between the disk and the protostar (Armitage, 2010; Williams & Cieza, 2011).

Once the star has entered Class II, disk formation is essentially over and the
disk becomes gravitationally stable. Neither the star nor the disk accrete an non-negligible amount of material from the molecular cloud, but the star continues to accrete material from the disk (Williams & Cieza, 2011). From this description, it is easy to conclude that the disk inherits its mass, size, and chemical composition from the star formation environment and that, initially, much of the evolution will be driven by ongoing accretion and the stellar radiation.

Protoplanetary disks are composed of dust and gas and the ratio of gas-to-dust is assumed to be consistent with the ISM value of 100. However, dust is the main carrier for opacity in the disk and much of our understanding of disks is based on measurements of that dust (Williams & Cieza, 2011).

Dust is mainly composed of microns sized silicate grains with an admixture of graphite grains and polycyclic aromatic hydrocarbons (PAHs). These small grains settle and agglomerate. At large radii or as the grains settle to the midplane, molecules can freeze out of the gas and form icy mantles around some grains. Other grains that are closer to the star are heavily processed via thermal annealing and therefore have a higher crystallinity fraction compared to the ISM (Williams & Cieza, 2011).

The gas is primarily $H_2$ but the chemical composition of the disk is rich in other molecular gases. The difficulty in detecting the gas lies in the opacity of the dust which causes emission or absorption features of the gas to disappear if the temperature of the gas does not differ from that of the surrounding dust (Williams & Cieza, 2011). Despite this difficulty, ro-vibrational lines of multiple gas species have been detected and certain abundant gases such as CO and OH can be used to trace features of the inner disk (Brittain et al., 2009; Dullemond & Monnier, 2010; Fedele et al., 2015; Liskowsky et al., 2012).
Figure 1.1: Disk Structure (Dullemond & Dominik, 2004b)
The disk has a flared structure which is indicated by the large far-IR excess (Dullemond & Dominik, 2004b,a; Dullemond & Monnier, 2010). The scale height depends upon the competition between the vertical component of stellar gravity and the thermal pressure within the disk (Armitage, 2010). There is also evidence for a puffed-up inner rim in disks where photoevaporation has sublimated the dust from the inner regions. This sublimation opens a hole in the inner disk which allows the stellar radiation to directly impact the inner rim. This causes the inner rim to become much hotter than the material behind it and develops a puffed-up structure that, depending on the height of the rim and the geometry of the outer disk, can shadow part or all of the outer regions (Dullemond & Dominik, 2004b,a; Meeus et al., 2001). These shadows can also be caused by instabilities in the disk which cause small ripples that shadow the region directly behind them. Disks can also become self-shadowed, where the height of the inner rim is large enough such that the entire disk is in shadow. Disks with this kind of structure are sometimes thought to be older than flared disks (Dullemond & Dominik, 2004b). Both types of structures are shown in Figure 1.1.

The temperature of the disk is highly dependent on the structure of the disk because the geometry affects the amount of stellar radiation that impacts the disk. The directly exposed surface layers absorb and reprocess the stellar radiation to heat the interior of the disk. Temperatures at the inner rim are on the order of $10^3$ K while the outer regions of the disk have temperatures of 10-30 K (Williams & Cieza, 2011). This temperature variation is why different sub millimeter and IR wavelengths are useful for probing different regions of the disk. The relevant wavelengths to study the different areas of the disk is shown in Figure 1.2.
Figure 1.2: Disk Wavelengths (Dullemond & Monnier, 2010)
The mass of the disk can be well estimated using sub millimeter measurements. These wavelengths are the best indicators of dust presence and abundance. However, because the dust begins to settle during the early stages of disk formation, there is a non-negligible fraction of mass that has agglomerated into larger grains that the sub millimeter probing misses. Fortunately, this underestimation of the mass is roughly balanced by the overestimation caused by assuming a gas-to-dust ratio equivalent to the ISM value of 100. The median mass of a Class II YSO disk is $5 \, M_{Jup}$ and the median ratio to stellar mass is 0.9% (Williams & Cieza, 2011).

The radius of the disk has a median value of 75 AU, however a number of disks have outer radii closer to 1000 AU. The inner radius of the disk is more consistent from disk to disk, and roughly corresponds to the region where temperatures reach the dust sublimation temperatures, 1500-2000 K (Dullemond & Monnier, 2010). The inner radius is not a sharp cut off due to the different sizes of grains within the disk sublimating at different temperatures. Both molecular and atomic gas persist within the inner rim of the disk (Mulders et al., 2013; Tatulli et al., 2011; Panić et al., 2014).

The disk evolves through a combination of a number of processes including: accretion, dust settling, grain growth, photoevaporation, planet formation, and interactions with companions. The timeline of each processes is not divided into clearly defined epochs. Instead, the processes overlap and interact to mutually affect the evolution of the disk.

When the disk initially forms, the gas and dust are both distributed in the flared structure. The dust is small and well coupled to the motion of the gas. However, the $z$-component of the stellar potential causes the dust particles to settle vertically toward the midplane of the disk. This settling can be seen in the reduced mid-IR flux of the disk as the opacity decreases in the flared sections (Williams & Cieza, 2011).

As the dust settles, it collides with other grains and agglomerates to create
larger grains. When these grains reach a radius greater than 0.1 microns, the dust will decouple from the gas and experience Stokes’ drag (Armitage, 2010). This additional drag and mass causes further settling which, in turn, causes more collisions and agglomeration. At this small radius, the coagulation is assisted by the strong electromagnetic interaction between the grains. As more grains settle and grow, the density of the midplane is increased which further speeds up the grain growth. Even at the micron to centimeter size, not all collisions end in agglomeration. This can be seen through the persistence of small grains in the disk beyond their expected coagulation lifetime, which implies that the larger grains must occasionally collide and fracture (Williams & Cieza, 2011).

Photoevaporation is the main driving force through which disks lose mass and dissipate. The process is driven by the energetic photons from central star in the far ultraviolet (FUV; 6-13.6 eV), the energetic ultraviolet (EUV; 13.6-100 eV), or x-ray (> 100 eV) regimes (Williams & Cieza, 2011). The outer edges of the disk can be affected by energetic photons from nearby stars, however, the effect is generally small in comparison to that of the central star. These energetic photons interact with the gas and dust molecules and the molecule experiences an increase in energy expressed through faster velocities and higher temperatures. If the molecule is given enough energy, it can reach speeds high enough to escape the gravity of the central star and "evaporate" into space.

When accretion onto the star is ongoing during the early phases of stellar and disk evolution, the photoevaporation of the disk does not greatly effect the evolution. This is because the stellar radiation can only act upon the surface layers of the disk and the inner edge of the dusty disk caused by dust sublimation, causing a small evaporation rate in comparison to the accretion. However, when the stellar evolution begins to end and the accretion rate drops, the outer disk is no longer resupplying...
the inner regions with material. This allows for the evaporation rate to overtake the accretion rate and their coupled effects open a hole in the inner disk. Once this gap is opened in the inner disk, the edge is directly exposed to the energetic photons and the disk evaporates from the inside out on a timescale of 1 Myr (Dullemond & Monnier, 2010; Williams & Cieza, 2011).

The process of photoevaporation of the disk generally leaves behind what is known as a debris disk (Williams & Cieza, 2011). The process of disk evolution is shown in Figure 1.3. Debris disks are populated by rocky planetesimals (∼ 1 m-1 km) which did not complete the process of planet formation and were therefore not large enough to accrete gas from the disk to form an atmosphere. In the cases where the disk does develop a planetary companion or companions, these objects are left behind instead of the debris disk and continue their evolution.

1.2 Planet Formation

Planet formation occurs around many types of stars and creates many different kinds of planets and stellar systems (Williams & Cieza, 2011). The detection of exoplanets has become increasingly frequent thanks to Kepler. The results from Kepler are consistent with virtually every sun-like star harboring at least one exoplanet. Further, there is evidence of a positive correlation between stellar mass and the likelihood that the star has a massive companion (Johnson et al., 2010). However, it is always the finished product that is observed and not the process. The theory of planet formation was therefore initially tailored to reproduce our Solar System, and over time, has been reworked as different types of systems and planets are discovered (Lissauer, 1993).

The settling and growth from micron to centimeter sized bodies within disks is
the first step in the formation of objects called planetesimals. Planetesimals are bodies that have grown large enough that the aerodynamic coupling to the disk is no longer the dominant effect on the evolution of their orbit. Once formed, the planetesimals interact with one another through gravitational torque to form terrestrial and gas giant planets (Lissauer, 1993; Lissauer & Stewart, 1993).

There are some difficulties, however, in forming planetesimals. When the bodies are small, the electrostatic force between the grains is strong enough to hold the body together and allow for further growth. The objects are small enough that they remain roughly coupled to the gas and drag is limited. When the bodies reach sizes on the order of kilometers, the gravitational force between the components hold the body together as it grows and interacts with other large bodies. The kilometer sized bodies are not coupled to the gas, but are large enough that the drag experienced can be treated as a minor perturbation to the orbit instead of debilitating (Armitage, 2010; Lissauer, 1993).

However, in the in between stage where the objects are on the order of meters, neither force is sufficient to hold the body together well. This means that collisions often result in fracturing instead of agglomeration. Furthermore, meter sized bodies interact with approximately their own weight in gas over the course of a single orbit. This causes an enormous drag which causes the bodies to drift radially inwards at a rate of $\sim 10^6$ km/yr (Armitage, 2010; Johansen et al., 2007).

Initially, the so-called meter barrier was thought to be overcome with the help of turbulence. It was possible that turbulence within the disk created quiescent vorticies where the meter sized objects could survive and grow (Johansen et al., 2007; Lambrechts & Johansen, 2012; Youdin & Goodman, 2005). However, when applied to planet-formation models, the mechanism worked too slowly to form gas giant planets. The classical timeline for gas giant core formation through planetesimal accretion is
on the order of $10^7$ years, but the gas in the disk has a lifetime limit of roughly $10^6$ years (Kretke & Levison, 2014; Levison et al., 2015). This indicates that the cores must form through a different mechanism that is fast enough that the gaseous component of the disk has not been depleted.

The theory of pebble accretion serves as a work around for both the meter barrier and the timing issues with forming gas giant cores. The meter barrier is bypassed when turbulence in the disk concentrates millimeter to centimeter sized objects into dense clumps. These clumps then become gravitationally unstable and collapse into kilometer sized objects (Lambrechts & Johansen, 2012; Youdin & Goodman, 2005). This allows 100-1000 kilometer-sized planetesimals to form without having to grow through the difficult intermediate stages. Once the large planetesimal has formed, it accretes any remaining pebbles from its Hill Sphere rapidly (Armitage, 2010). This process is much faster than traditional pairwise collisions and agglomeration. This helps in fixing the timescale problem for the development of 10 Earth mass objects which are capable of accreting the surrounding gas (Lambrechts & Johansen, 2012).

Initially, the groups modeling the results of this theory assumed that the disk had an even distribution of preformed pebbles. However, they found that having preformed pebbles created a situation in which Earth sized objects were forming far more often and far more rapidly than expected. These results can be seen in Figure 1.4.a. When the models were changed to mimic the slower growth of pebble sized objects, a few Earth mass objects were created over the course of $10^6$ years, as seen in Figure 1.4.b. This puts the objects in the epoch of disk evolution where they could still develop into gas giants. The slowly growing pebbles allowed for the larger planetesimals that formed earlier to gravitationally interact with other planetesimals and launch them to high orbital inclinations. This left the larger planetesimal to accrete the remaining local pebbles while the smaller had very little local material to
accrete (Lambrechts & Johansen, 2012). The larger planetesimal therefore experiences something similar to runaway accretion since there is no object competing locally for the material.

Once the planetesimals have formed and accreted their local material, their gravitational interactions with one another become important. The planetesimals exert gravitational torques upon one another, causing orbital changes and radial drift. This brings them close enough together that further gravitational interactions can occur. This ultimately ends with a number of planetesimals colliding and accreting one another until planet sized objects or gas giant cores have been formed. For scale, it would take roughly 500 million Ceres sized planetesimals to form the Solar System’s terrestrial planets. The gas giant cores will accrete gas from the disk, forming their thick atmospheres. Terrestrial planets can accrete gas from the disk, but their atmosphere is typically formed by the evaporation of the icy mantles that covered the grains during formation. The chemical make up of the mantles determines the atmosphere, where gas giant atmospheres have similar chemical compositions to that of the star (Armitage, 2010).

1.3 Effects of Planets on Disks

The development and evolution of a planetary companion has a number of effects upon the disk. Planets accrete the local material in their orbits, opening up gaps in the disk. Very massive companions closer to the star can accrete the material spiraling in towards the star, halting the stellar accretion and opening up a dust-free, optically thin hole in the inner disk. While these effects can be seen, either through direct imaging of the disk or through the SED, then can also be produced by non-planetary objects or, in the case of the inner hole, occur naturally during
the evolution of the disk. However, through a type of resonance called Lindblad resonance, massive companions can cause the inner rim of the disk to become elliptical (Duffell & Chiang, 2015; Kley & Dirksen, 2006; Lubow, 1991; Papaloizou et al., 2001). This feature can occur with stellar companions as well as planetary companions, but the two are visually distinctive (Gor’kavyj & Fridman, 1994). Furthermore, due to the symmetric nature of the disk as it forms, any eccentricity within the disk is a non-natural phenomenon and is a very strong indicator of the presence of a massive planetary companion (Lubow, 1991).

Much like a simple harmonic oscillator, the material in the disk can be excited into density waves by the interaction with the gravitational potential of the companion. The gravitational interaction serves as a driving function and the density wave will only be excited if the driving force falls on an eigenfrequency or a simple multiple of the eigenfrequency such as 1:2, 2:3, 1:3, etc. (Gor’kavyj & Fridman, 1994).

There are three types of Lindblad resonance: corotational, inner, and outer. Each are defined below in which $m$ is the azimuthal number and $\Omega_s$ is the frequency of the companion’s driving force. The inner resonance drives a density wave from the inner resonance point to the planet, while the outer drives the wave from the planet outward into the disk (Gor’kavyj & Fridman, 1994).

$$\Omega(r_{cor}) = \Omega_s$$

$$\Omega(r_{in}) = \frac{m}{m-1} \Omega_s$$

$$\Omega(r_{out}) = \frac{m}{m+1} \Omega_s$$

Having the resonant driving force is a requirement to generate resonance, but it is not the only requirement to generating eccentricity through resonance. Both the
inner and outer Lindblad resonances help to drive eccentricity, but the corotational Lindblad resonance damps it. In order to excite the inner and outer resonances while damping the corotational, the planet must carve out a wide gap in the surrounding gas and dust (Duffell & Chiang, 2015; Gor’kavyj & Fridman, 1994; Kley & Dirksen, 2006; Lubow, 1991; Papaloizou et al., 2001). This reduces the number of particles left for the corotational resonance to interact with, and reduces its strength. The inner and outer Lindblad resonances must be larger than the corotational resonance by approximately a factor of three in order for eccentricity to develop (Duffell & Chiang, 2015).

There must also be a small initial eccentricity in the orbit of the planet. This is relatively easy to create given the number of interactions between large planetesimals that occurs and alter orbits during the course of planet formation. This small eccentricity generates, through the inner and outer resonances, eccentric density waves that propagate outwards into the disk. This change in the disk structure can back-react, through the density waves, on the planet and increase the eccentricity of its orbit (Kley & Dirksen, 2006). The density wave also removes angular momentum from the inner disk without removing any energy. This causes the eccentricity of the inner rim to increase because if energy is not removed with the angular momentum, the orbits of the gas and dust cannot remain circular.

The severity of the eccentricity depends strongly upon the mass of the companion. Strong eccentricity growth occurs in the companion to star mass ratio range of 0.02-0.03. Models run with companions of roughly 3 $M_{Jup}$ were capable of inducing eccentricities of roughly 0.1. Simulations run with larger mass companions (5 $M_{Jup}$) found induced eccentricities of up to 0.22 (Kley & Dirksen, 2006).
1.4 Spectroscopy

One way to study protoplanetary disks is through IR spectroscopy or interferometry. The IR wavelengths, as seen in Figure 1.2, probe the inner and planet forming regions of the disk. The focus of this work is OH molecules and transitions, this section will describe the excitation and nomenclature specific to OH observations. This section will also cover the formation of and shape of line profiles from inclined objects.

Molecular emission is the result of the change of an energy state in the molecule, either by gaining or losing energy. This change in energy causes the molecules to emit or absorb photons respectively.

There are two ways for excitation to occur: stimulated or collisional. However, there are three ways for deexcitation to occur: stimulated, spontaneous, or collisional. Stimulated emission or absorption occurs when the molecule interacts with a photon and this interaction causes an molecule in the molecule to fall to a lower energy state (emission) or rise to a higher state (absorption). The photon interacted with must have a wavelength that corresponds to a possible transition for the molecule as dictated by the discrete energy levels of the molecule. Emission can also occur spontaneously. Energy states that are not the ground state have certain lifetimes where the molecule stays in the higher state before emitting a photon at random and falling to a lower energy state. Finally, excitation to a higher state can also occur during collisions, in which the energy “lost” in the collision transfers an electron to a higher energy state (Bernath, 2005). The excitation of a molecule can occur through the electronic, rotational, vibrational, or translational modes. Electronic modes correspond to changes of the electron energy levels, where rotational, vibrational, and translational all correspond to changes in the bonds of the molecule.
The wavelengths of the emission is dictated by the discrete energy levels of the molecule which depends upon the sum of the rotational and vibrational energies. 

\[
\frac{E_v}{\hbar c} = (v + 1/2)w - (v + 1/2)^2\chi w + B_vJ(J + 1) - D_JJ^2(J + 1)
\]

\(J\) is the total angular momentum of the molecule, \(D_J\) is the rotational constant, \(v\) is the vibrational quantum number, \(B_v\) is the vibrational constant, and \(w\) is the angular velocity. In order for transitions between these levels to occur in the high energy molecule, the surrounding gas must be incredibly warm. This can be seen by looking at the equation for the relative populations of various energy levels 

\[
\frac{n_i}{n_o} = \frac{(2J_i + 1)}{(2J_o + 1)}e^{-(E_i-E_o)/kT}
\]

and noting that, in order for excitations to be visible, the exponent term \(E_i/kT\) must approach a value of one (Liskowsky, 2012).

Any transition must obey the selection rules for the particular type of transition. For rotational transitions, the transition must correspond to \(\Delta J = -1, 0, +1\) which are labeled as the \(P\), \(Q\) and \(R\) branches respectively. For vibrational transitions, the selection rule is \(\Delta v = \pm 1, \pm 2, \pm 3...\). Rotational and vibrational transitions can occur in conjunction with each other and the resulting transition is called a ro-vibrational transition and both selection rules must be obeyed. In the case of OH, and all diatomic molecules, transitions with \(\Delta J = 0\), or the \(Q\) branch transitions, are forbidden.

The full structure of the first two electronic states of OH is shown in Figure 1.5. The nomenclature uses X as the ground state and labels the excited states as A,
B, C, and so on. The rest of the nomenclature takes the form

\[ \frac{2S+1}{\Lambda^{+/-}}J(g/u) \]

where \( \Lambda \) is the orbital angular momentum as is represented by \( \Sigma, \Pi, \Delta, \) etc, \( S \) is the spin quantum number, \( +/- \) is the reflection symmetry, and \( J(g/u) \) is the parity of the molecule. (Schleicher & Ahearn, 1982)

The observational line profiles observed from inclined disks rotating with approximately Keplerian velocities are distinctly double peaked. The double peaked structure can be seen in Figure 1.6 and has been shown to be a consequence on both the disk’s geometry and the Keplerian motion of the gas. The location of these peaks on a velocity diagram will correspond with roughly the rotational velocity of the disk at the outer rim, or \( V_d \sin i \) where \( i \) is the inclination of the disk. The visibility of the peaks can be affected by the resolution of the instrument, where an decrease in instrument resolution leads to the distance between the peaks broadening and the central depression becoming less obvious. (Smak, 1981).

In order to understand how to read velocity plots of line profiles, Figure 1.6 breaks the disk down into multiple iso-velocity contours and indicates where the observation of the color coded sections falls on the plots. We see that the iso-velocity contours closest to the star have the highest velocities but, due to their small size, emit a relatively small amount of flux. These sections build the wings of the velocity plot. The velocities are equal but opposite due to the way in which we view the disk. If, in the case of these figures, the disk is rotating clockwise, then the material in the purple contour is moving away relative to the observer while the material in the red contour is moving closer relative to the observer. The dark blue and orange contours contain the next highest velocity bin and emit more flux than the previous sections.
due to their larger size. The double peaks come from the material at the edges of
the disk that is moving slower but is again, larger in area and flared to catch and
re-emit more flux than the previous sections. Finally, the green contour indicates
the material moving perpendicular to the line of sight, giving it a relative velocity
of 0 m/s. This section is rather large, but due to the flaring disk, some of the flux
emitted is obscured and the plot dips slightly in this region. Typically, the disk is
actually broken down into multiple iso-velocity contours, depending upon the velocity
resolution necessary for the observations. This ensures that the data is smooth and
that there is less space between points where the data is extrapolated.
Figure 1.3: Disk Evolution (Williams & Cieza, 2011)
Figure 1.4: Pebble Accretion (Lambrechts & Johansen, 2012)
Figure 1.5: Energy Level Diagram of OH (Schleicher & Ahearn, 1982)
Figure 1.6: Building Line Profiles of Rotating Disks (see Smak 1981)
Chapter 2

Observations of HD 100546

HD 100546 is a close \((d = 103^{+7}_{-6} \text{ pc})\) Herbig Be star with a relatively massive disk \((M_{\text{disk}} = 0.072 \, M_{\odot})\) (Henning et al., 1998). Both modeling (Bouwman et al., 2001) and observations with \textit{Hubble Space Telescope} (Grady et al., 2005) have indicated the presence of an inner hole in the disk at 12-16 AU (Avenhaus et al., 2014). This inner hole would correspond to a width of 0.\textquoteright\textquoteright 2 – 0.\textquoteright\textquoteright 3 given uncertainties. Observations of both CO indicates that the molecular gas is truncated at 13 ± 6 AU and observations of [O I] indicates that some gas extends inwards of this. The presence of an inner hole is commonly interpreted as an indication that the disk is undergoing planet formation. However, there are a number of processes that can open an inner hole and create similar SEDs.

The following papers have made observations of HD 100546 and found contradicting observational data. One data set, taken with PHOENIX, indicates that the disk is not symmetric while the other data set indicates that it is. What follows is a summary of each paper’s observations, observational parameters, data, and conclusions drawn from that data.
2.1 PHOENIX Observations

Using PHOENIX at the Gemini South telescope, Liskowsky et al. (2012) observed HD 100546 in December of 2010. The group was focused on the ro-vibrational OH emission and how it compared to the ro-vibrational CO emission and the [O I] $\lambda 6300$ emission line. They focused on these lines to explore the properties and structure of the inner regions from which the features arise.

Three observations were taken with corresponding standard stars to remove problematic telluric lines. The spectra were centered at 3145 $cm^{-1}$, 2844 $cm^{-1}$, and 2032 $cm^{-1}$. The position angle of the 0.34" slit was 90° east of north for all observations and the point-spread function (PSF) of the continuum was 0.7". Figures 2.1, 2.2, and 2.3 have been reproduced from Liskowsky et al. and show the CO M-band spectra and two ranges of the OH L-band spectra. The OH lines $P_{10.5_{1-1}}$, $P_{10.5_{1+1}}$, $P_{9.5_{2-}}$, and $P_{9.5_{2+}}$ were used to construct the average OH line profile. This step is necessary because the individual OH lines have low signal to noise due to their small equivalent widths. A similar process was done to the CO lines $v = 3 - 2 \ P15$, $v = 6 - 5 \ R5$, $v = 4 - 3 \ P8$, $v = 1 - 0 \ P16^{13}\text{CO}$, and $v = 3 - 2 \ P14$. A representation of these lines and the average profiles are shown in Figures 2.4 and 2.5.

Inspecting Figure 2.4, Liskowsky et al. (2012) found that the average OH line profile is resolved and asymmetric. The blue to red flux ratio of the line is 4, indicating high asymmetry. In comparison, Figure 2.5 and the inspection of the average CO line profile indicates that CO is only slightly asymmetric with the line peaking just red of center.

Liskowsky et al. (2012) identified and discussed a few origins of the asymmetry. The group considered winds, transonic turbulence, a localized hot spot, and a gas giant companion.
Figure 2.1: High-resolution near-IR spectra of HD 100546. The top panel shows the M-band spectra containing the ro-vibrational CO transmissions after the ratio has been taken with the standard. Positions of features are marked by vertical dashed lines and labeled. The bottom panel shows the observed spectrum and the telluric standard spectrum, shown in red.
Figure 2.2: High-resolution near-IR spectra of HD 100546. The top panel shows the L-band spectra containing the ro-vibrational OH transmissions after the ratio has been taken with the standard. Positions of features are marked by vertical dashed lines and labeled. The bottom panel shows the observed spectrum and the telluric standard spectrum, shown in red.
Figure 2.3: High-resolution near-IR spectra of HD 100546. The top panel shows the L-band spectra containing the ro-vibrational OH transmissions after the ratio has been taken with the standard. Positions of features are marked by vertical dashed lines and labeled. The bottom panel shows the observed spectrum and the telluric standard spectrum, shown in red.
Figure 2.4: The individual lines used to construct the average OH line profile shown at the top. The offset in normalized flux is to visually separate the lines and is not indicative of true normalized flux. The lines were also shifted to the blue or red such that the residuals between the lines corresponded to the noise along the continuum.
Figure 2.5: The individual unblended lines used to construct the average CO line profile shown at the top. The offset in normalized flux is to visually separate the lines and is not indicative of true normalized flux. The lines were also shifted to the blue or red such that the residuals between the lines corresponded to the noise along the continuum.
Stellar winds have been known to generate asymmetries. The outflows from the star alter the motion of the surrounding gas and therefore alter the shape of the gas emission lines. However, winds were considered an unlikely source of the OH asymmetry in HD 100546 because the winds are typically well traced through the [Ne II] emission line and the asymmetry between the OH and [Ne II] lines varies dramatically. Since these lines probe similar regions, if the asymmetry was caused by a wind, the resulting shift in the lines should be the same.

Transonic turbulence was considered because it can produce spatial inhomogeneities in both the temperature and density of the disk. However, the turbulence driven by the magnetorotational instability has not been shown, through simulations, to be capable of generating a large enough turbulence to recreate the line profiles observed. Furthermore, the observed CO and OH lines have vastly different shifts and Liskowsky et al. (2012) considered it unlikely that both lines would be generated by the same turbulent disk.

A localized hot spot in the disk or disk wall could create non-axisymmetric emission. This hot spot would likely be due to the interactions between the disk and a massive companion and should therefore vary with respect to orbital phase. However, the data used in this paper were from a single observation and so it can neither confirm nor deny the variance with respect to period.

A final origin put forward is the presence of a gas giant planet. Hydrodynamic models of interactions between giant planets and disks has shown that they are capable of inducing an eccentricity through Lindblad resonances in the inner rim as high as 0.25 which falls of as $r^{-2}$. The models also predict that the semimajor axis of the eccentric inner rim would precess at $10^\circ/1000$ orbits. This indicates that the asymmetry of the OH lines would show minimal variation over the course of the planet’s orbit. Liskowsky et al. (2012) employed a model to test this possibility using
Figure 2.6: The synthesized spectrum of OH emitting from the inner wall of HD 100546 is plotted in red over the average OH line profile. The lower panel shows the difference between the two lines as a residual. To create this profile, Liskowsky et al. (2012) assumed the ratio of the luminosity of the wall to the disk was approximately 3:1.
Figure 2.7: The synthesized spectrum of CO emitting from the inner wall of HD 100546 is plotted in red over the average line profile of the unblended CO lines. The lower panel shows the difference between the two lines as a residual. To create this profile, Liskowsky et al. (2012) assumed the ratio of the luminosity of the wall to the disk was approximately 1:3.
the geometry described in Brittain et al. (2009) in conjunction with an eccentric inner rim and circular outer disk. The synthesized spectra compared well to the observed data, as shown in Figures 2.6 and 2.7, with minimum reduced chi-squared values of 1.0 and 1.1 for OH and CO respectively.

Based on the strong agreement of their models and the data, Liskowsky et al. (2012) conclude that a massive planetary companion is the source of the eccentric inner rim and that the eccentricity of the inner rim is $e = 0.18(0.07 - 0.30)$. The transitional nature of the SED helps support this claim, as does the observation that the star is not centered in the inner hole of the disk. This conclusion can be confirmed by further observations of the disk, as the line profile of a disk sculpted by a massive companion should remain constant with respect to orbital period.

2.2 CRIRES Observations

Using the CRIRES instrument on the Very Large Telescope (VLT), Fedele et al. (2015) used observations of HD 100546 in the L band during three different years: 2012, 2013, and 2014. The spectra were centered on 2911.5 nm, 2947.0 nm, and 2950.0 nm respectively. The 2012 and 2014 observations were taken with the 0.′′2 slit and the 2013 with the 0.′′4 slit. The continuums have PSFs of 0.′′16 and 0.′′7 respectively. The observations were also taken at various position angles: 26° in 2012, 90° in 2012, and 10° in 2014.

Fedele et al. (2015) identified the OH doublet $^2\Pi_{3/2}$ P4.5 in each observation of the disk. The normalized spectra are shown in Figure 2.8. The group identified the 2012 line as symmetric and the 2013 and 2014 lines as asymmetric. They also noted that the second and third observations suffered from diminished equivalent width. The group also compared the CRIRES observations to the PHOENIX data reduced
by Liskowsky et al. (2012), and found that the peak to peak asymmetry is more pronounced in the PHOENIX data as seen through the consistently lower redshifted component of the PHOENIX data. This comparison is reproduced in Figure 2.9.

The difference in equivalent width between the three observations is explained by the group as slit losses from slit offsets. Hein Bertelsen et al. (2014) found that slight offsets in the slit positioning can lead to losses in the CO ro-vibrational lines extreme enough to create asymmetric lines profiles. Fedele et al. (2015) reason that, due to the similar size and extent of the OH ro-vibrational lines, they may be affected similarly by slit offsets. If this were the case, then the 2012 observation would be the one least affected by the losses.

To test this hypothesis, Fedele et al. (2015) generated synthetic line profiles for both the 10° and 90° position angle at varying levels of slit offset. As seen in Figure 2.10, the group found that the asymmetric line profiles at a 10° PA can be explained by a slit offset of $-0.0.04$ to $-0.0.06$ and that for the 90° PA the offset must be as high as $-0.0.18$ to $-0.0.2$. This offset could be explained by the non-homogeneous illumination caused by the presence of both the star and the disk wall in the slit. This could cause the telescope, which automatically adjusts to point at the center of light, to include the bright rim, rather than centering on the star. Bright companions could also cause the offset, so long as the companion was within 0.2 of the central star. One challenge to this interpretation is that virtually all of the near-IR light arises from a compact annulus extending from 0.25-0.30 AU. (Tatulli et al., 2011; Mulders et al., 2013; Panić et al., 2014)

Fedele et al. (2015) conclude that the asymmetry seen in the OH ro-vibrational line profiles of HD 100546 is caused by slit losses due to slit offset. Due to the lack of conclusive detections of a companion within 0.2 of the central star, the group concludes that the offset is caused by the flux of the partially visible disk wall skews
the center of light and therefore the pointing of the telescopes.
Figure 2.8: CRIRES spectra of the $^{2}\Pi_{3/2}$ P4.5 OH doublet at three different epochs and positions angles.
Figure 2.9: Comparison of PHOENIX (red) and CRIRES spectra of HD 100546 at P.A. = 90°. The PHOENIX data is the average of the four lines detected by Liskowsky et al. (2012), while the CRIRES data is the average of the two P4.5 transitions.
Figure 2.10: Synthetic line profiles (dotted lines) plotted in comparison to the CRIRES OH spectra at P.A. = 10° (left) and P.A. = 90° (right). The offset along the right of each image indicates the difference between the slit position and the central star.
Chapter 3

Modeling and Results

3.1 Original Model

The model used in this experiment to simulate slit offsets is based on the work in Brittain et al. (2015). The model was originally designed to replicate an symmetric disk and create a synthesized line profile based on the provided disk and telescope parameters.

Once the user parameters are loaded, the model then proceeds by generating the symmetric disk face on according to the supplied parameters. This disk is fit to a Cartesian grid where each pixel corresponds to 0.15 AU which corresponds to, in the case of HD 100546, 0."0015. The intensity profile of the desire molecule is then calculated using a power law with respect to radius and those values are assigned to the corresponding grid coordinates. The disk is then inclined to the given angle and the inner hole is swept out. Using a rough power law of the intensity of the inner rim, the sections of the rim now visible due to inclination are assigned their intensity values. The disk is also convolved with a Kepelerian velocity profile, and broken up into isovelocity contours. Once this is complete, synthetic observations of the disk
can be taken using the desired telescope parameters.

3.2 Changes to the Model

While the original model is effective for symmetric disks, to test whether or not the observations found by Fedele et al. could have come from an asymmetric disk the final portion of the code needed to be reworked. In order to create an asymmetric disk, the user supplied parameters was expanded to include the eccentricity and semiminor axis of the disk. The eccentricity was varied with respect to radius \( r^{-2} \) to make the inner edge of the disk have the desired eccentricity while the outer regions remained circular.

The disk was then built out of 1000 annuli where each annulus contained 2000 points. The even spacing of the points did create some low point density areas in the outer annuli, but they were considered well outside of the range of the telescope offsets to be tested and therefore negligible. The disk was then tilted to the desired inclination, and then approximated onto the Cartesian grid from the original model. Using the original grid rather than staying with the polar coordinates allowed for as little of the code to be modified as possible. This prevents errors and ensures that the model still runs with the same accuracy as before. This accuracy was confirmed by running the modified model with a zero-eccentricity disk and comparing the results to the original model. The final code is reproduced in Appendix A.

For all tests, the model was run at all three position angles used in the Fedele et al. observations. The model was iterated over 40 even steps, beginning a full slit width off center to the left and ending a full slit width off center to the right, in order to investigate the possibility of slit losses due to slit offset. In order to simplify the faux observation technique, the slit was always held vertical while the disk was
rotated to the correct position angle and then observed.

3.3 PHOENIX Results

Fedele et al. concluded that the data shown in Liskowsky et al. could have come from a slit offset in the observations of a symmetric disk. To test this, the model was set to run with an eccentricity of zero, inner rim of 13 AU, a slit width of 0.′′34, and a PSF of 0.′′7.

Since the only comparative observations available were taken at a P.A. of 90°, only the synthetic line profiles for that P.A. will be shown in this section. The synthetic observations within the pointing error are shown in Figure 3.1. Intermediate synthetic observations have been removed for clarity.

Visual inspection of the data indicates that PHOENIX will produce roughly symmetric line profiles within its pointing error, given a symmetric disk.

3.4 CRIRES Results

To investigate the possibility that the lines seen by Fedele et. al came from an asymmetric disk but appeared symmetric due to slit losses, the model was set to run with an eccentricity of 0.17 and a semiminor axis of 13 AU. For all three position angles, the model was run with both the 0.′′2 and 0.′′4 slits with PSFs of 0.′′17 and 0.′′65 respectively.

Since Fedele et al. believed that the observation with a P.A. of 26° and 0.′′2 slit was the only observation not affected by slit losses, the synthetic line profiles for that position angle and slit width are the only ones that will be shown in this section. Figure 3.2 shows the synthetic profiles that correspond to data that could occur given
Figure 3.1: Synthetic PHOENIX Line Profiles within Pointing Error
the CRIRES pointing error.

Visual inspection of the data, especially the $-0.03$ line, suggests that observing a symmetric line with an asymmetric disk is possible well within the pointing error of CRIRES’s $0.2$ slit.
Figure 3.2: Synthetic CRIRES Line Profiles within Pointing Error
Chapter 4

Conclusions & Discussion

4.1 Conclusions

When observing a disk with a narrow slit, portions of the disk will be occulted which can result in asymmetric lines (e.g. Hein Bertelsen et al. 2014). However, the PHOENIX and 2013 CRIRES observations were taken without adaptive optics and relatively wide slits (0.′′34 and 0.′′4 respectively) and the symmetric hot band CO lines have been reproducible over a span of 10 years using two different instruments. Since these M-band lines probe where the outer disk begins to contribute, we find it unlikely that the disk wall results in systematic pointing errors as suggested by Fedele et al. (2015).

To reproduce the asymmetry seen in the PHOENIX data, the slit must be offset from the stellar continuum by nearly a full slit width from the center of the slit. Given that this pointing far exceeds the PHOENIX pointing error, it is highly unlikely that this offset would be reproducible. However, the observation taken with the 0.″2 CRIRES slit and PSF of 0.″17 aligned with the semiminor axis does show a symmetric line within the CRIRES pointing error. This suggests that is it plausible
that subsampling of the inner rim could result in a symmetric line from an asymmetric disk. Furthermore, if the pointing error of CRIRES is treated as a normal distribution as seen in Figure 4.1, we find that this symmetry could reasonably occur in 11.3% of observations.

4.2 Future Work & Notes

The next step in this work is to run a Monte Carlo $\chi^2$-squared minimization model fit to the data and determine the range of parameters that can reproduce the observed lines.

Further observations of HD 100546 at varying position angles would be able to resolve the discrepancy in the interpretation of OH emission. If the disk is truly eccentric, observations at multiple P.A.s will result in a constant line profile, provided that the slit is wide enough to sample the full inner disk. If the asymmetry is due to subsampling, as suggested by the models, then the line profile would vary with respect to position angle.

Given that the 0.2 CRIRES slit is smaller than the inner rim of the disk, it is possible that this contributed to the slit losses that caused the line profile of an asymmetric to look symmetric (Massey & Hanson, 2013). This author believes that future observations should take care to use a slit with a width larger than the inner rim of the disk to help prevent these complications.
Figure 4.1: CRIRES Pointing Error as a Normal Distribution \((\sigma = 0.0167)\)
Appendices
Appendix A  Disk Model Code

A.1 User Parameters

; Set user defined variables
; First Load the Variables

layers=300 ; number of layers in disk (75 for b=2)
rel_lum=20. ; UV luminosity relative to HD141569
disk_in=13 ; inner edge of disk
dist=1.496e13*disk_in ; convert inner edge of disk to cm
disk_out=100.0
Mstar=2.4 ; Stellar mass in solar units
Grav=6.7E-11
v_turb=3.e5 ; Turbulent Velocity

ecc=0.17
semiminor=13
c_test=semiminor*SQRT(1-ecc^2)
semimajor=c_test/(1-ecc^2)
staroffset=semimajor*ecc
focus=semimajor-staroffset

T_rot0_fl=2.5e3 ; Fiducial temp at 1AU
T_rot_alpha_fl=0.25 ; Power law of rotational temp

T_rot0_cl=2.5e3 ; Fiducial temp at 1AU
T_rot_alpha_cl=0.25
H_den0=2.5e10 ; Fiducial density at 1AU
H_den_alpha=.15;0.05 ; Power law of density

X12CO_13CO_fl =65./30. ; C-12/13 ratio
X12CO_C18O_fl =550./16.25 ; O-16/18 ratio

X12CO_13CO_cl =65. ; C-12/13 ratio
X12CO_C18O_cl =560.

inc=40.*!pi/180. ; Disk inclination
f_i=2027.0 ; Frequency range in wavenumbers
f_f=2039.0

d=double(103.d*3.0856d18); Distance to star in cm
inst_res=6.0 ; Resolution of instrument
END

A.2 Disk Building

; Create a cartesian grid xy where each point contains v, A, I, etc...
; inc, Mstar, rdisk, and iten_line5 (integrated intensity of P26 line
; as function of radius) are predefined.

; goto, skip_aloops
angles=[-16,0,64]
offsets=FLTARR(40)
specsave1=FLTARR(3,40,121)
specsavel2 = specsavel1
centsave1 = specsavel1
centsave2 = specsavel1

FOR i=0.,39. DO BEGIN
    offsets(i) = i * (532/40)
ENDFOR

FOR twist=0.,2. DO BEGIN
    FOR oset=0.,39. DO BEGIN
        rotang = angles(twist)
        slit_o = offsets(oset)
    ;skip_aloops:

    disk_wall_scale = 1.0 ; scaling of disk wall.
    cont_line_rat = 2500. ; ratio of continuum to line emission
    disk_power_law = -2.4
    wall_power_law = -4.8

    rgrid = FLTARR(1001)
    epsilon = FLTARR(1001)
    rpolar = FLTARR(1001,2001)
    xcom = rpol
    ycom = rpol
    phase = FLTARR(2001)
    ifinerot = FLTARR(1001,2001)
    rtilt = FLTARR(1001,2001)
rphi=FLTARR(1001,2001,2)
xx=FLTARR(2001)
yy=FLTARR(2001)
xy=FLTARR(2001,2001,2)

;Determine scaling eccentricity
FOR i=0.,1000. DO BEGIN
  rgrid(i)=i*.15 ;Each pixel corresponds to 0.15AU = 0.0015''

  226.666pix=.3400''

IF rgrid(i) LT focus THEN BEGIN
  epsilon(i)=ecc*(rgrid(i)/focus)^2
ENDIF ELSE BEGIN
  epsilon(i)=ecc*(rgrid(i)/focus)^(-2)
ENDELSE
ENDFOR

;Define r as a function of annulus (i) and phi (j)
FOR i=0.,1000. DO BEGIN
  FOR j=0.,2000. DO BEGIN
    xx(j)=j*0.15-150
    yy(j)=xx(j)
    phase(j)=j*0.001*!pi
    rpolar(i,j)=((rgrid(i)*(1+epsilon(i)))*(1-epsilon(i)^2))/(1+
      epsilon(i)*COS(phase(j)))
    xcom(i,j)=rpolar(i,j)*COS(phase(j))
  END
END
\[
y_{com}(i,j) = r_{polar}(i,j) \times \sin(\text{phase}(j))
\]
\[
r_{tilt}(i,j) = \sqrt{(x_{com}(i,j)^2 + (y_{com}(i,j)/\cos(\text{inc}))^2)}
\]
ENDFOR
ENDFOR

; Define disk intensity, removing all negative values
FOR \(i=0.,1000.\) DO BEGIN
FOR \(j=0.,2000.\) DO BEGIN
\[\text{innerrim} = \frac{\text{c testim}}{1 + \text{ecc} \times \cos(\text{phase}(j))}\]
\[\text{ifinerot}(i,j) = \frac{\text{iten line 5}(1) \times (r_{polar}(i,j)/\text{disk in})^{\text{disk power law}}}{10}\]
; Remove cleared inner region
IF \(r_{polar}(i,j) < \text{innerrim}\) THEN \(\text{ifinerot}(i,j) = 0\)
; Define and place wall intensity
IF \(r_{polar}(i,j) > \text{innerrim} - 0.1\) THEN BEGIN
IF \(r_{polar}(i,j) < \text{innerrim} + 0.1\) THEN BEGIN
\[\text{ifinerot}(i,j) = \frac{\text{iten line 5}(0) \times (r_{polar}(i,j)/\text{disk in})^{\text{wall power law}}}{10}\]
ENDIF
ENDIF
IF \(\text{ifinerot}(i,j) < 0\) THEN \(\text{ifinerot}(i,j) = 0\)
ENDFOR
ENDFOR

; Tilt the disk and create \(r\phi(1001,2001,2)\)
FOR i=0.,1000. DO BEGIN
    FOR j=0.,2000. DO BEGIN
        innerrim=ctest/(1+ecc*COS(phase(j)))
        rtest=rpolar(i,j)
        tilt=rtilt(*,j)
        rfine=SQRT(xcom(*,j)^2+ycom(*,j)^2)
        IF rpolar(i,j) LT 100 THEN BEGIN
            aind=WHERE(tilt GE rtest-.21218/2. AND tilt LE rtest
                +.21218/2.,count)
            IF count NE 0 THEN BEGIN
                IF count GT 1 THEN aind=aind(0)
                rphi(aind,j,0)=SQRT(887.*Mstar/ABS(rpolar(i,j)))*COS(phase(j))*SIN(inc)
            ENDIF
        ENDIF
        ind=where(rfine LE rtest+.21218/2. AND rfine GT rtest
            -0.21218/2., count)
        IF count NE 0 THEN BEGIN
            IF N_ELEMENTS(ind) GT 1 THEN ind=ind(0)
            aind=WHERE(tilt GE rtest-.21218/2. AND tilt LE rtest
                +.21218/2.,count)
            IF count NE 0 THEN BEGIN
                IF count GT 1 THEN aind=aind(0)
                rphi(aind,j,1)=finerot(ind,j)/SIN(inc)
            ENDIF
            IF rpolar(i,j) LE innerrim+0.2 AND ycom(i,j) LE 0 THEN

        ENDIF
    ENDIF
ENDIF

53
rphi(aind,j,1)=0

IF rpolar(i,j) LT innerrim-0.1 THEN rphi(aind,j,1)=0

IF rpolar(i,j) GE innerrim-0.1 AND rpolar(i,j) LT

innerrim+0.1 AND ycom(i,j) GT 0 THEN rphi(aind,j,1)=

rphi(aind,j,1)*7.*disk_wall_scale

ENDIF

ENDIF

ENDIF

IF rphi(i,j,0) GT 20000 THEN rphi(i,j,0)=0

IF rphi(i,j,1) GT 20000 THEN rphi(i,j,0)=0

ENDFOR

ENDFOR

FOR i=0.,1000. DO BEGIN

FOR j=0.,2000. DO BEGIN

xtest=xcom(i,j)
ytest=ycom(i,j)
xind=WHERE(xx GE xtest-0.0575 AND xx LE xtest+0.0575, xcount)

IF xcount NE 0 THEN BEGIN

IF xcount GT 1 THEN xind=xind(0)
yind=WHERE(yy GE ytest-0.0575 AND yy LE ytest+0.0575, ycount)

IF ycount NE 0 THEN BEGIN

IF ycount GT 1 THEN yind=yind(0)

xy(xind,yind,*)=rphi(i,j,*)

ENDIF

ENDIF

ENDFOR

ENDFOR
xy(0,*,1)=0.0
xy(2000,*,1)=0.0

;SET FOLLOWING TO GET SLIT PA CORRECT
FOR i=0,1 DO xy(*,*,i)=ROT(xy(*,*,i),rotang) ;,CUBIC=-0.5,/PIVOT)

ind_plt=WHERE(xy(*,*,1) LT 0)
vel=FINDGEN(121)-60.

xy_vel=FLTARR(2001,2001,121)

tmp1=xy(*,*,1)
tmp2=tmp1
tmp2(*,*)=0.0
xy_fft=xy_vel

xygauss=xy(*,*,0)
xygauss(*,*)=0.0

;PHOENIX PSF
;sigx=70./2.35482 ;This is the FWHM in AU divided by 2.354
;sigy=70./2.35482

;CRIRIES PSF
;sigx=17./2.35482
;sigy=17./2.35482
sigx=65./2.35482
sigy=65./2.35482

;Now define seeing function
FOR i=0,2000 DO BEGIN
  FOR j=0,2000 DO BEGIN
    xygauss(i,j)=exp(-(((xx(i))^2/(2.*sigx^2)) + (yy(j)^2/(2.*sigy^2)))) ;max = 1
  ENDFOR
ENDFOR

xygauss=ROT(xygauss,45)
xygauss=SHIFT(xygauss,1000,1000)

xygauss=xygauss*5.*1120./total(xygauss) ;The integrated line/continuum ratio is .2

;The integrated intensity per .1AU^2 pixel is 1120. The integrated intensity of the star over the same wavelength region spread over a .1AU box is 5x this value; for the P26 line. This is now the image of the star.
FOR k=0,120 DO BEGIN
    tmp2(*,*)=0.0
    ind=WHERE(xy(*,*,0) LE k-59.5 AND xy(*,*,0) GT k-60.5,count)
    IF count NE 0 THEN BEGIN
        tmp2(ind)=tmp1(ind)
    ENDIF
ENDIF
xy_vel(*,*,k)=tmp2
;FOR i=0.,2000. DO BEGIN
;FOR j=0.,2000. DO BEGIN
;IF i LT 1000 THEN q = 1000 - i
;IF i GT 1000 THEN q = i -1000
;xy_vel(i,j,k)=(Grav*Mstar*(1+epsilon(q)^2+2*epsilon(q)*(xx(i)/SQRT(xx(i)^2+yy(j)^2))))/(rgrid(q)*(1+epsilon(q)))
;ENDFOR
;ENDFOR
xy_vel(1000,1000,k)=cont_line_rat ;the ratio of the stellar flux to line flux is 3.21735. Assume flat over the spectral line
; so continuum=TOTAL(xy_vel)*3.21735/27.
; IF k EQ 3 THEN xy_vel
(1036:1037,1048:1049,3)=720.

xy_fft(*,*,k)= FFT( FFT(xy_vel(*,*,k)) * FFT(xygauss) , 1)
ENDFOR

xy_fft=xy_fft*TOTAL(xy_vel)/TOTAL(xy_fft) ;Conserve the intensity
slit_c=1000.-266.+slit_o
slit_i=slit_c-133
slit_f=slit_c+133

;Now create spectral images over 81km/s. Can be made broader if necessary, but be careful about undefined velocity elements.
slice=FLTARR(121,2001)
slice2=slice
FOR k=0,120 DO BEGIN
   slice(k,*)=TOTAL(xy_fft(slit_i:slit_f,*,k),1) ; .15AU=.0015" -> slit is 226 pixels (0.34") - 966:1034
   slice2(k,*)=TOTAL(xy_vel(slit_i:slit_f,*,k),1)
ENDFOR

slice_conv=slice
vel=FINDGEN(121)-60
inst_prof2=EXP(-(vel)^2/(2.*(6.6/2.35482)^2.))/(SQRT(2.*!pi)*6.6/2.35482)

FOR i=0,2000 DO slice_conv(*,i)=CONVOL(slice(*,i),inst_prof2,/CENTER,/EDGE_ZERO,/NORMALIZE)

cent1=FLTARR(121)
cent2=FLTARR(121)
FOR i=0,120 DO BEGIN
    FOR j=0,2000 DO cent1(i)=cent1(i)+slice_conv(i,j)*yy(j)/TOTAL(slice_conv(i,*))
    FOR j=0,2000 DO cent2(i)=cent2(i)+slice2(i,j)*yy(j)/TOTAL(slice2(i,*))
ENDFOR

spec1=FLTARR(121)
spec2=spec1

FOR i=0,120 DO BEGIN
    spec1=spec1+(exp(-(vel-vel(i))^2/(3./1.665)^2)/(SQRT(2.*!pi*(3./1.665)))) *(TOTAL(xy_fft(slit_i:slit_f,*,i))+xy_fft(slit_i:slit_f,*,0)) *(.15*1.5e13)^2
    spec2=spec2+(exp(-(vel-vel(i))^2/(3./1.665)^2)/(SQRT(2.*!pi*(3./1.665)))) *(TOTAL(xy_vel(slit_i:slit_f,*,i))+xy_vel(slit_i:slit_f,*,0)) *(.15*1.5e13)^2
ENDFOR

spec1_conv=CONVOL(spec1,inst_prof2,/CENTER,/EDGE_ZERO,/NORMALIZE)
cent1_conv=CONVOL(cent1,inst_prof2,/CENTER,/EDGE_ZERO,/NORMALIZE)
spec2_conv=CONVOL(spec2,inst_prof2,/CENTER,/EDGE_ZERO,/NORMALIZE)
cent2_conv=CONVOL(cent2,inst_prof2,/CENTER,/EDGE_ZERO,/NORMALIZE)
;goto, skip_runsave
    specsave1(twist, oset, *) = spec1_conv
    specsave2(twist, oset, *) = spec2_conv
    centsave1(twist, oset, *) = cent1_conv
    centsave2(twist, oset, *) = cent2_conv
    ENDFOR
ENDFOR
;skip_runsave:

BEEP

END
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