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MODELING GAS DISTRIBUTION IN PROTOPLANETARY ACCRETION DISKS

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ABSTRACT

Protoplanetary accretion disks are disks of dust and gas which surround and feed material onto a forming star in the earliest stages of its evolution. One of the most useful methods for studying these disks is near infrared spectroscopy of rovibrational CO emission. This paper presents the methods in which synthetically generated spectra are modeled and fit to spectral data gathered from protoplanetary disks. This paper also discussed the methods in which this code can be improved by modifying the code to run a Monte Carlo analysis of best fit across the CONDOR cluster at Clemson University, thereby allowing for the creation of a catalog of protoplanetary disks with detailed information about them as gathered from the model.

Subject headings: Polarization — Stars: eclipsing binaries — Methods: observational — Techniques: photometric, polarimetry

1. INTRODUCTION

Protoplanetary disks are the result of a interstellar molecular cloud which has reached the critical Jeans mass and collapsed. Low mass versions of these systems (0.1-1.5$M_\odot$) are referred to as T Tauri stars and their higher mass analogs (2-10$M_\odot$) are referred to has Herbig Ae/Be stars. The focus of this paper is the study of Herbig Ae/Be stars. The material that does not initially form the protostar becomes gravitationally bound to it and forms into an orbiting disk consisting of gas and dust. This disk initially feeds additional material onto the pre-main sequence star and eventually will form the planets and asteroids of the the stellar system.

The existence of these protoplanetary disks has been long been established both through spectral energy distributions of young stars, kinematic evidence present in high resolution spectra, and direct imaging of a protoplanetary disk around stars such as HD 141569 (Weinberger et al. 1999). However the dynamics of these disks are still poorly understood, especially in relation to the formation of Jovian planets.

There are currently two main models of Jovian planetary formation: core accretion and gas instability. According to the core accretion model the formation of a Jovian planet begins with the aggregation of microscopic grains into a rocky core. Once this core forms, gas can then accrete out of the disk to form the planet. However there is a major drawback to modeling the formation of Jovian planets in this way: according to current observations, gas in the disk does not survive the $\sim 10^7$ yr needed to accrete enough gas to form a Jovian mass planet (Lissauer 1993). On the other hand, the gas instability model predicts that a Jovian planet can form through the gravitational collapse of an overdensity of gas and dust in the disk (Boss 2000). This model however requires an unusual gas distribution and thermal profile (e.g. Wuchterl et al. 2000).

While these two models provide two very different mechanisms for planetary formation, they share one important similarity; once the planet exceeds $\sim 1M_J$, it will open a gap in the disk (Lubow et al. 1999; Lubow & D'Angelo 2006). The gas and dust of the disk is gravitationally attracted towards the star at the center of the disk, however once a large planet forms all the material beyond its orbit is intercepted by the planet. The nature of these gaps as well as many other key aspects of the accretion disk can be understood through the study of gas emissions from the disk.

Since most, if not all, Jovian planets form within 50 AU of the star, this is the region of the disk that we are most interested in observing and modeling. CO in the entire range of the planetary formation region can be excited into the 4^{th} positive system (transitions between the ground electronic state, $X^1\Sigma^+$, and first excited electronic state, $A^1\Pi$) whose band origin is at 1545Å and whose transitions range from 1300-2700Å (Herzberg 1950). CO also has a wide range of energy transitions due to the rovibrational states caused by its dipole moment which emit a broad range of emission lines in the spectral energy distribution of the stellar system. These emission lines provide us with a vast amount of information about the system, making CO the perfect probe of warm gas in the accretion disk.

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TABLE 1
Parameter Dependencies

Feature	Parameter Dependence
Line Strength	UV temperature, $^{12}CO/^{13}CO$ ratio, $^{12}CO/^{18}CO$ ratio, density, power law of density, power law of rotational temperature, inner radius, outer radius
Line Broadening	Turbulence, stellar mass, inner radius, outer radius, power law of rotational temperature, density, power law of density, inclination
Flux Profile	Turbulence, inclination, stellar mass, distance to star

2. METHODS

Initially, spectral energy distributions (SEDs) are gathered from pre-main sequence star systems known to have protoplanetary disks, such as HD 100546 and HD 141569, in order to measure the distribution of dust in those systems. The IR emissions of ^{12}CO and ^{13}CO originating from the transitions between upper vibrational levels v=1 through v=8 are observed. The rotation speed of the inner edge of the gas can be determined from the half-width at zero intensity of the individual lines with a wider spread originating from a larger Doppler shift differential, which itself originates from a larger velocity differential. Since the gas is assumed to be in Keplerian orbit around its host star the radius of inner edge can then be determined (e.g. Brittain et al. 2007).

In order to gather more detailed information about the temperature, excitation, and distribution of gas in the protoplanetary disk, we generate a synthetic spectra using code developed by Brittain et al. (2007, 2009) and fit the model to the observed CO spectra.

2.1. *Synthetic CO Spectra Generation*

The synthetic CO emission spectrum is based on the distribution of CO in the $v = 1$ through $v = 8$ rovibrational populations as a function of distance from the star. We take into account two main excitation mechanisms: UV florescence and collisional excitation.

UV florescence is the effect whereby CO which has been excited out of its ground state to the A electronic state then relaxes back to the ground state, cascading through its rovibrational states $v = 8$ through $v = 1$ and emitting photons of discrete energies for each transition. The relative strengths of each transition are determined by the color temperature of the UV radiation field. At larger radii the UV flux through the gas becomes weaker so that rovibrational emission "cools" the levels more efficiently (Krotkov et al. 1980).

The disk is dived into 1 AU annuli and the UV flux is calculated at each annuli, with no dust assumed to be along the line of sight between the star and annuli. Each annuli is then divided into layers, usually on the order of 300, and the UV flux through each layer is calculated using the turbulence of the gas and relative populations of ^{12}CO, ^{13}CO, and ^{18}CO isotopologues as parameters. It should be noted that the isotopolouge populations are used to determine the column density of dust within the disk and common interstellar medium ratios of each are assumed (Lewis et al. 2010).

After the initial florescence calculations are complete, the model applies a correction in order to include excitation due to collisions for each annuli, which is initially ignored. The collisions are assumed to be caused primarily by atomic hydrogen; the rate of which is dictated by the temperature and density of the gas per level. The temperature is determined by the UV flux passing through each layer. Density is determined by assuming a homogenous gas column whose density is radially described by a power law. The model also takes into consideration the overall shape and flux of the SED which is determined by the inclination of the disk and the distance to the star.

2.2. *Utilizing Synthetic CO Spectra*

The parameters fall into two groups, depending on how well predetermined they are. Distance, mass, inclination and UV temperature of the disk at 1 AU have been determined through other surveys to within some uncertainty. Inner and outer radius of the disk, turbulence, power law of rotational temperature, density, power law of density and the ratios of $^{12}CO/^{13}CO$ and $^{12}CO/^{18}CO$ are parameters which have not been as well established and have a wider range of possible values. The synthetic spectra are viewed as having three main components to its structure; intensity of individual lines, broadening of each line, and overall flux profile of the spectrum. The parameter dependence of these features can be seen in Table 1

Working within these initial boundaries the parameters are adjusted by hand until the synthetic spectra models the observed spectra most accurately. Goodness of fit is determined by overlaying the two spectra and minimizing the discrepancies between them by eye. This process has been used to acquire model fits to HD 100546 (Brittain et al. 2009) and HD 141569 (Brittain et al. 2007) as well as HD 98922, 97048, 37357, 142527 and GW Ori (Lewis et al. 2010).

Due to the many interdependent parameters, fitting the synthetic spectra by hand is difficult and inefficient. The subjective opinion of the researcher becomes very prevalent when encountering degeneracies in the code as well as in the fine-tuning of parameters. There is also no way for the researcher to determine the uncertainty of the fit based on this technique. This will limit the scope of this model fitting technique by reducing the number of spectra that can be fitted based on time constraints and well as limit the accuracy and uncertainty calculation of any given fit.

3. AUTOMATION

In order to increase the scope of this technique to be able to accommodate the creation of a protoplanetary disk catalog the process must be automated. In order to do this three steps are taken:

1. Conversation of the IDL code to MatLab.
2. Application of a Monte Carlo, χ^2 minimization technique to find the best fit.
3. Parsing the fitting jobs to the CONDOR computing cluster to increase speed.

3.1. *Conversion to MatLab*

The code was initially written in IDL, which is not well suited for cluster processing or parallelization of the code. IDL is not supported on the Clemson CONDOR cluster where the code will be run and there is no native support for multithreading of code. MatLab is supported on the CONDOR cluster and has excellent built-in support for multithreading. MatLab is also much more compatible with other scripting programs such as C and C++ which will allow it to integrate into any future projects.

While IDL and MatLab are both designed to work around matrices there are differences both in the structure and built in functions which must be dealt with when converting the code. Primarily the array index of IDL starts at 0 and lists the matrix column–by–row while the array index of MatLab starts at 1 and lists the matrix row–by–column. Primarily, it is necessary to convert the IDL convention into the MatLab convention. While this can be done by hand, a script called `idl2matlab`[2] can be utilized to automate this step. It should be noted that while the code works quite well in converting between the conventions it is not flawless and the code must be gone through to make sure all conversions were done correctly.

The IDL logical structure is different from MatLab in a few areas and must be readjusted when converting the code. Any `GOTO` commands in IDL must be replaced with an `if-then` structure since `GOTO` is not supported in MatLab. IDL has two different structures for "`for`" and "`if`" statements. The formal is structured as: `if/for (condition) then begin (operation) endif/endfor`, while the less formal is structured as: `if/for (condition) then (operation)`. The latter does not require a closing end statement but must be written on one line. MatLab only has the formal structure where `then begin` is assumed and "`if`" and "`for`" share the common `end` statement. This conversion is also handled in `idl2matlab` to some extent, but the code must be carefully checked for common errors and `GOTO` is not handled at all.

There are many routines in the IDL library which are not present in the default MatLab distribution. The IDL routine `SVSOL` uses "back-substitution" to solve a set of simultaneous linear equations by using the products of singular value decomposition of the matrix being used. MatLab does not have is this routine, but rather can solve systems of linear equations by using matrix division. If it becomes necessary to utilize the singular value decomposition method, or any other IDL exclusive routine, there are two methods of incorporating them into MatLab code. If the routine is relativity short, it may be most efficient to directly translate it into MatLab by finding the code in the IDL library. However if the routine is based on C code, as many of the routines are, it is more efficient to find the C routine and call it from the MatLab code. This is done by first creating a gateway routine which specifies and verifies the input and output parameters of the routine. Using this gateway routine it is then possible to compile the C routine into a MatLab executable, or MEX, file and call it directly. The same technique can also be used to incorporate Fortran code into MatLab.

[2] idl2matlab is open source freeware developed by Emmanuel Farhi and available through SourceForge

3.2. *Monte Carlo*

In order to increase the efficiency of fitting the synthetic CO spectra, the process of finding the best possible fit must be done through a best fit algorithm. Given the large number of degeneracies caused by interrelated parameters as well as the number of actual parameters, we will use a Monte Carlo χ^2 minimization. This algorithm will create a contour map with local minima being parameter combinations that give the best fit. From these local minima the algorithm will narrow the range of allowed parameter values and calculate a new contour map, repeating the process until the desired level of accuracy is reached. This algorithm will also be able to state the uncertainty in the fit parameters, a quantity which is impossible to acquire with the current methods.

3.3. *Cluster Computing*

Once the synthetic spectra can be fit automatically the process will be transferred to a computer cluster such as the CONDOR cluster at Clemson University or the University of Washington. With these clusters we will be able to utilize the extended processing power necessary to build a catalog of protoplanetary systems.

4. SUMMARY

The synthetic modeling of CO spectra holds excellent potential to become a powerful tool in understanding protoplanetary accretion disks and the planetary formation that happens there. It has already been used to map the gas distribution of a number of protoplanetary accretion disks. The scope of the code has been limited due to the inefficiency of manual fitting. Automating the process will allow the model fitting technique to be used in the creation of a protoplanetary system catalog complete with all of the parameters indicated by the model. From such a catalog we will be able to build a fuller picture of planetary formation as well as test our understanding of stellar evolution in the pre-main sequence stage. Future work will include finishing the port to MatLab, an optimization algorithm that will allow us to determine the uncertainty in our model parameters, and a port to a CONDOR system.

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