Modeling the Collapse of Star-Forming Regions using Hydrogen Cyanide

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ABSTRACT

Studying cold, dense molecular clouds can help scientists better understand gravitational collapse in star-forming regions. While these clouds are invisible to infrared and visible wavelengths of light, lower energy rotational transitions allow us to observe these regions using radio telescopes. Hydrogen cyanide is a bright tracer of dense gas in molecular clouds, but there can be hyperfine anomalies in its spectra. By using a combination of RADEX calculations and a HILL spectral model, we are able to create a simpler and more efficient method of modeling HCN anomalies. While we are able to accurately model the line height ratios of these anomalies in HCN spectra, line overlap is needed to model all of the possible hyperfine anomalies.

Keywords: stars: formation — ISM: clouds — ISM: molecules — HCN: hyperfine — HCN: anomalies

1. INTRODUCTION

Cold dark clouds, or molecular clouds, were first discovered by William Herschel in 1784 when he observed a strong absence of light coming from the direction of the Scorpius constellation, in Ophiuchus (Bergin & Tafalla 2007). At the time of his first discovery, it was clear to Herschel that these were regions where light from background sources was being blocked by something in the foreground. Today, scientists know that these regions are made of dust and gas, and these cold regions are able to absorb light from other sources, preventing this visible light from reaching our instruments on Earth.

Dark clouds are associated with star-forming regions, as new stars will form from the gravitational collapse of this gas and dust within the molecular cloud. These clouds are a part of the interstellar medium (ISM), which consists of the gases and dust between stars, within a galaxy. Roughly 90% of the medium is made of hydrogen, or H₂, with one atom per cubic centimeter. Dust is much less common, with only one thousand particles found in every cubic kilometer of the medium. The ISM is studied in order to learn information about star formation within galaxies. During star formation, the accretion disk of a protostar will gravitationally accrete into asteroids of different sizes. If these asteroids become large enough then they are considered planetesimals, or the building blocks of planets. Understanding star formation can provide information on this planetary formation, which can help scientists to determine how and why our Solar System, as well as others, formed in the wake of the formation of our Sun.

A star-forming region is divided up into multiple different layers. The region as a whole is called a cloud, which can be on the order of 10³-10⁴ solar masses (Mₜ), have a size of 2-15 parsecs (pc) across, and can be as dense as 50-500 particles/cm⁻³. Within a cloud there is a denser clump, which is where star clusters are formed. Clumps range in mass from 50-500Mₜ, they can be 0.3-3pc in diameter, and have a mean density between 10³-10⁴ particles/cm⁻³. Within clumps are even denser cores, and this is where individual protostars will form. Cores have masses ranging from just 0.5-5Mₜ, sizes around 0.03-0.2pc, and a mean density ranging from 10⁴-10⁵ particles/cm⁻³ (Bergin & Tafalla 2007). Individual cores can also be surrounded by a larger, less dense envelope, which can be on the order of 0.001-0.014pc (Rosen et al. 2020). Properties of the core such as mass, temperature, and density will determine the initial conditions of the protostar formed within the core.

Molecular clouds are cold (T ~ 10 K) and have relatively low density. Because of this, these clouds are able to absorb higher energies of light, such as visible and infrared. These clouds can only be observed by using the rotational transitions of molecules inside the clouds, which emit photons of very low energy. In order to observe this low energy emission, highly sensitive radio telescopes must be used. These transitions are observed by the telescopes using molecular spectroscopy, or the measurement of the excitation of atoms and molecules by photons (Meier 2020). Spectroscopy takes data in the form of a spectra, which provides information on kinematics of the dust and gas molecules within the star forming region.
The spectrum for hydrogen cyanide, or HCN, consists of three hyperfine transitions. These transitions are created when the spin angular momentum of a nucleus couples with the orbital angular momentum of an electron within the HCN molecule. Each transition is located at a different optical depth within the core. Looking at different optical depths allows scientists to trace the different regions of the core, which in turn provides an overall idea of the infall or expansion motion of the core. These spectral lines can be Doppler shifted as well, and this shift can be seen in the spectral data. A blue-shift means that the front of the core is moving toward the observer, suggesting that the core is expanding. A red-shift means that the front of the core is moving away from the observer, suggesting that the core is infalling or collapsing. HCN has multiple different quantum spin states, typically denoted with a capital F, and each of which denote a specific and quantized amount of spin angular momentum. Within each spin state there are three hyperfine transitions, denoted with a capital F. For the J=1-0 spin state, each hyperfine transition appears as a single peak in the spectrum of HCN. Through a process called line overlap, higher J spin states can have spectral lines which are the result of multiple different F transitions all combining to form a single spectral line (see figure from Goicoechea et al. (2021)). In an idealized HCN spectra for the J=1-0 transition, the line heights for each spectral line appear in a 5-3-1 ratio, with the 2-1 transition having the highest peak, and the 0-1 transition having the lowest peak. This 5-3-1 ratio assumes local thermal equilibrium, and an optically thin core or envelope.

There can be anomalies in the spectra for HCN, which will change the ratio of the spectral line heights. These anomalies can result from infall or expansion motion as well as line overlap. Anomalies due to motion of the core or envelope will primarily affect the F=0-1 transition in the spectra. This line will appear to be taller than the F=2-1 or F=1-1 hyperfine lines adjacent to it, however upon closer inspection it can be seen that the two other transitions are actually losing intensity in relation to the F=0-1 line, which remains at a relatively constant intensity. Another anomaly that can be seen in spectra is when the F=1-1 transition is more intense than the two hyperfine lines adjacent to it. This anomaly is due to line overlap effects, however any time the hyperfine lines are out of their 5-3-1 line height ratio then the spectra is considered "anomalous".

2. MOTIVATION

When studying star-forming regions, scientists use spectral analysis to collect information on the region of interest. Since these regions absorb many higher energy wavelengths of light, low energy photons from molecular transitions are collected by radio telescopes such as the Green Bank Telescope in West Virginia, the Very Large Array in New Mexico, the Very Long Baseline Array spread across the United States, as well as many others. Tracers of dense gas are studied in the molecular cloud to determine the properties of the star-forming core. A tracer such as HCN is bright and easy to observe at low frequencies, making this a good molecule to use for research.

The problem with HCN is that any anomalous spectra collected by the telescopes become very difficult to use for research. Data that shows a 5-3-1 ratio in line heights can automatically provide scientists with information on the different properties of the core. If a spectra has anomalies, then these anomalies can be difficult to account for and do not necessarily make sense under simple assumptions. While there are models which can account for these anomalous effects in the spectra, they are often very complicated. Models that use complicated radiative transfer techniques can be very time consuming and require lots of data storage, which can make it inconvenient to use such models. Using a simpler model could allow scientists to still account for the anomalies in their HCN spectral data, however they could run the model in a relatively short amount of time, and the model would not use as much data as the more complicated techniques. The purpose of this research was to create a simple model, using numerical and analytic code, in order to account for anomalies in the spectra of HCN so these anomalous data can still be used for scientific research.

3. METHODS

The initial conditions for the model were set with a program called RADEX\(^1\). This program was originally created as a Fortran code, however there is a version available online. RADEX is a radiative transfer code which is used to determine the properties of molecular clouds. The code uses statistical equilibrium to determine various physical conditions of a cloud, given some initial parameters. We rewrote the RADEX code in the Julia programming language, and the new name for the code is JADEX\(^2\). This Julia version of the code takes parameters such as kinetic temperature, column density, volume density, and turbulence velocity of the core or envelope gas. All of these values were found using the Gonzalez-Alfonso & Cernicharo (1993) paper. JADEX was used to get the excitation temperature and optical depth for the core or envelope, given the code’s initial parameters. The values obtained from JADEX were then used in the HILL model.

The HILL model is an analytic model which was used to model spectra during our research. The model uses various physics equations of a star-forming core in order to create a model spectrum for a tracer within the core, such as hydrogen cyanide. The HILL model assumes that excitation temperature is a linear function of optical depth (De Vries & Myers 2005). This means that the temperature is equal to the cosmic microwave background temperature until the observer begins to look into the front of the core. At this point the temperature will linearly increase until the center of the core, then it will linearly decrease on the way out the back. The version of the HILL model we used to make spectra was the HILL8 model, or an eight parameter HILL model. This model uses the following equations:

\(^1\) http://var.sron.nl/radex/radex.php
\(^2\) https://github.com/autocorr/Jadex.jl
between these two. Based on the initial comparison of these spectra, it seems that the higher the column density, the more anomalous the spectra become in terms of the F=0-1 hyperfine anomaly.

5. DISCUSSION

Over the course of this project, we showed that we were able to use the JADEX calculations to get values for the HILL model. Although we needed to add more parameters to the HILL model than previous papers, our model was still simple and quick to run, which was the goal we set for the project. Using this model, we were able to measure different infall using each of the hyperfine components of our spectra. The HILL model allowed us to clearly see when the core or envelope was infalling, due to the Doppler shift of the spectral lines. When the core was infalling then the spectrum was red-shifted, since the front of the core was moving away from us. Although it was not able to be very accurately represented in terms of the anomalies, our model was also able to show expansion of the core or envelope. In order to get expansion we used a negative infall velocity, which would create a blue-shift in the spectra, but the ratio would not change between infall or expansion, assuming all other parameters remained constant. In order to get a changing ratio between infall and expansion conditions, a model with line overlap effects would need to be used.

Our model was able to accurately recreate Figure 2 from Gonzalez-Alfonso & Cernicharo (1993) for most of their more advanced models. Although some of the models we ran required line overlap to produce the exact line height ratios found in Figure 2, our models matched many of the hyperfine anomalies shown in this figure. It is possible that our model could be used as a diagnostic for real data when looking at star-formation spectra. If our model can work on simulated data, then we would be able to use this model for real core data. It is possible that we could look at an observed spectra for a core, then find a model spectra that looks very similar in line heights to the real data. If these two spectra match, then we could determine the physical properties of the observed core based on the parameters we used to create the matching model. Similarly, we could take known properties of a star-forming core and put them into the HILL8 model. This model will then produce a spectrum, and if the model is accurate enough then this spectrum should very closely match the core’s real spectrum upon telescopic observation of the region.

6. CONCLUSION

The purpose of our project this summer was to better reproduce the hyperfine anomalies present in many hydrogen cyanide spectra. Using a RADEX (van der Tak et al. 2007) calculation recreated in Julia code, as well as version of the HILL model (De Vries & Myers 2005) rewritten to support
eight parameters, we were able to accurately and efficiently reproduce HCN anomalous spectra. These spectra would show the F=0-1 hyperfine transition as taller than the other two transitions in the same spectrum, which was the anomaly we set out to reproduce. This anomaly occurs when there is an envelope with a thick optical depth present around the core. This envelope will obscure or absorb light of specific frequencies, significantly limiting the amount of light which can reach our instruments at these frequencies. This can be seen in Figure 4 since the F=1-1 and F=2-1 hyperfine lines are absorbed and therefore become less intense than the F=0-1, which causes an anomalous spectrum. Further work on this project would be required to test the accuracy of our model in relation to real or even simulated spectral data. Along with this, some sort of line overlap effects could be incorporated into the model to improve the reproduction of all hyperfine anomalies for HCN. While this would add some complexity to the model, it would better enable scientists to use HCN data with all types of anomalies for their research. The overall goal of this summer project was to help the scientific community better understand gravitational collapse in pre-stellar cores, and our work with model HCN spectra was able to provide insight into the different anomalies which could prevent us from achieving this goal.

7. ACKNOWLEDGMENTS

Mitchell Hernandez would like to thank Dr. Brian Svoboda, Dr. Yancy Shirley, the National Radio Astronomy Observatory, and the National Astronomy Consortium for the opportunity to complete this summer research.

Software: This research has made use of the following software projects: Astropy (The Astropy Collaboration et al. 2018), Matplotlib (Hunter 2007), NumPy and SciPy (Oliphant 2007), Pandas (McKinney 2010), IPython (Pérez & Granger 2007), and Julia (Bezanson 2015).

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Figure 1. A 3x3 grid of plots using values from JADEX calculations. The y-axis for each row shows the volume density in units of \( \text{cm}^{-3} \). The \( F = 0 - 1 \) transition is shown on the top row, the middle row shows the \( F = 1 - 1 \) transition, and the bottom row shows the \( F = 2 - 1 \) hyperfine transition. The x-axis for each column is also different, with the column on the left showing kinetic temperature in units of K, the middle column shows column density in units of \( \text{cm}^{-2} \), and the right column shows line width on the x-axis. The colorbar shows different \( \tau \) optical depths at each of the given points on the graph.
Figure 2. This grid of plots is shown in Gonzalez-Alfonso & Cernicharo (1993). To create this figure, the authors used a full radiative transfer technique. Each of the subplots is labeled with the models used to create the specific spectral lines shown. All plots are representing the HCN J=1-0 spin state, and all hyperfine transitions are shown with the F=0-1 on the left, F=1-1 in the center, and F=2-1 on the right. All spectra are centered with the F=2-1 line at a velocity of zero, but this is arbitrary and picked for convenience.
Figure 3. A 3x3 grid of plots using values from JADEX calculations. The y-axis for each plot shows temperature in units of K. The x-axis for each plot shows velocity in units of km/s. The model numbers used for each plot are shown in the top right of the plot, in the form $M_{ijk}$, where $i$ is the core model number, $j$ is the envelope model number, and $k$ gives the set of collision coefficients (Gonzalez-Alfonso & Cernicharo 1993).
Figure 4. A plot showing three models all plotted on the same spectral axes. These models all consider an infalling core inside of a static envelope, and each envelope has the same volume density, temperature, and line width. The only thing varying between envelopes is the column density, and each envelope’s column density is labeled in the key in the top left corner of the plot.