# PHYS239 Final Project: Radiative Transfer for Collapsing Molecular Clouds

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## Introduction:

In the earliest stage of star formation, the molecular and dust clouds collapse due to gravitational forces with other kinematic motions such as rotation and turbulence. When gravitational forces outweighs rotation and turbulence, infall motions can be detected. However, it is not fully understood for the mechanisms of these stages, and observations of infall motions can provide us with more details and test the current theories. Infalling motions are observed in several earlier stages of star formation, including Class 0, I protostars. For exmaple, they are observed in the collapsing clouds (i.e. no protostars form in this stage), and collapsing clouds toward one or several central protostar(s). Several theories and models have been proposed, but now we do not have a consensus of a correct theory. If we can measure the velocity of the infalling motions of these clouds with spatial and spectral observations, it is possible to test those theories and models.

## Radiative Process:

There are two different scenarios for the radiative processes: one is for collapsing molecular clouds with no protostar in the center, the other is for collapsing clouds toward one or multiple central protostars. The corresponding spectral profiles are blue-skewed assymmetry profiles and the inverse P-Cygni profiles. The details are described below:

One spectral profile is blue-skewed assymmetry profile, which corresponds to collapsing clouds without protostars in the center. Assume the central region of the cloud is optically thick. We can view it as two different parts. From the front part, the collapsing is moving away from the observer, so the spectra is redshifted. The central part is warmer than the ambient collapsing clouds, and therefore the radiation from the central clouds are absorbed by the collapsing clouds, resulting in the lower peak of intensity in the redshifted region. On the other hand, the rear part of the collapsing, is now moving toward the observer, resulting in a blueshifted spectral profile, and the intensity is enhanced due to the radiation from the colder cloud to a hotter region of the central cloud. Combing these two effect together, the spectral profile that we observe is a two-peaked spectral profile, with a dip in the central spectral line, and the blue-shifted peak is higher than the redshifted peak (see Figure 1).

The other spectral profile is the inverse P-Cygni profile, which is often interpreted as the collapsing clouds toward to central protostar(s). The physical condition is very similar to that of blue-skewed profile, but now we consider a or multiple central protostars in the center. Now we have a optically thick hotter source in the cloud, and the absorption effect is stronger than the case of the previous one. If the redshifted peak is now an absorption in the spectral profiles, with a blueshifted peak, it is called the inverse P-Cygni profiles (see Figure 2).

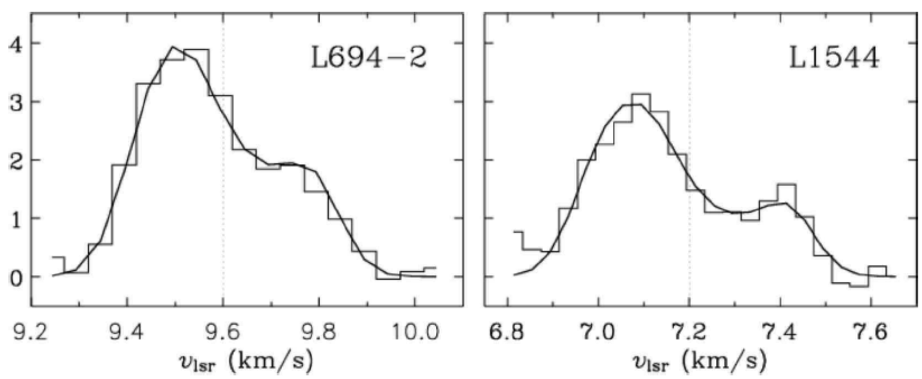


Figure 1: The blue-skewed profiles(William et al. 2006). The spectra are fitted with the model by Myers et al. 1996

## Observations:

In order to measure these spectral profiles, it is important to observe sources with good resolution and sensitivity. The spectral resolution must be good enough, with good sensitivity, to sample the redshifted peak or absorption, which are important to model the infall velocity. Spatial resolution is also important for analyzing the spatial distribution of the infall motions. For example, if observations of the infall motions is generally higher near the center than around the outer clouds, then the observations with the spin-up motions support the rotationally support disk.

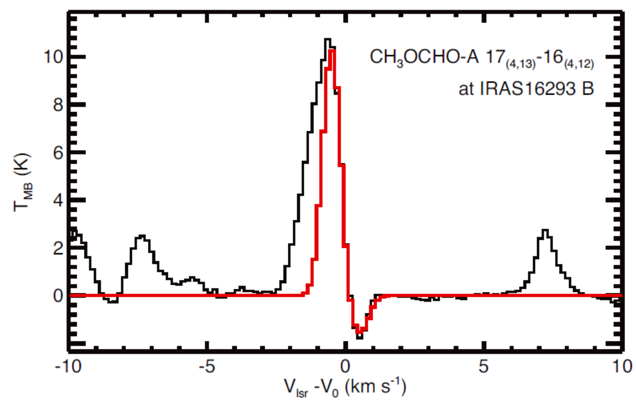


Figure 2: The inverse P-Cygni profiles (Pineda et al. 2012). The spectra are fitted with the model by Myers et al. 1996

Source velocity and infall velocity can be derived with different spectral lines. Optically thin lines are used to measure the source velocity, and optically thick lines are used to detect blue-skewed assymmetry or the inverse P-Cygni profiles. Models, such as Myers et al. 1996, can have a good estimate of the infall velocity.

We use several molecular line transitions in the spectra to analyze different physical conditions in different sources. For example, HCN, $CH_3CN$, $CH_3OH$ are often observed toward high-mass protostars because these molecules are formed in a higher temperature (several hundred or a thousand Kelvin) around massive protostars. For low-mass protostars, some organic molecules are also used to detect infall motions. For instance, $CH_3CHO$-A is found with the inverse P-Cygni profile (Pineda et al. 2012, Figure 2).

There are some differences for massive and low-mass protostar observations. The optical depths and central temperature are different. For low-mass protostars, usually the turbulence is not a main problem to account for the observations, but the luminosity is much lower than the observations in high-mass protostars. For the high-mass protostars, usually a large mass (M $> 8$ $M_{sun}$) protostar is formed with other protostars, with more turbulence and high luminosities.

We can use several telescopes to observe these features. In the infrared band, we have Herschel telescope; in radio band, Submillimeter Array (SMA), NOrthern Extended Millimeter Array (NOEMA), and Atacama Large Millimeter/submillimeter Array (ALMA) are great interferometers to achieve the science goal.

With these observation techniques, we can further derive the velocity, column density, and opacity with modeling. Using these derived parameters, we can test some of the models. For example, we can use infall velocity to derive mass accretion rate.

## Current Models:

One of the most widely used models is the model from Myers et al. 1996, which is based on the theoretical model from inside-out collapse model from Shu et al. 1977. The central continuum source introduced by Di Francesco et al. 2002 can model the inverse P-Cygni profiles better. This model is great for a quick estimation of the infall velocity in comparison to some time-consuming modeling. The model assumes that there are two isothermal layers accounting for the infalling clouds, the front and the rear part, and the central continuum source is optically thick, emitting as a blackbody with a peak temperature. Although this model is simple, it can fit various sources, including a dense starless core, an isolated protostar, and a small group of stars. Starless cores L694 and L1544 (Figure 1) is one of the examples to fit the blue-skewed profiles successfully.

The weakness of the model is that it assumes two isothermal clouds (i.e. two-layers), we cannot know more about the inner temperature of the region, and of course it is unphysical for this assumption. Therefore, it some model fitting, the fitting result is not ideal enough for the blueshifted emission part (Figure 2, Pineda et al. 2012).

There are other models used now, based on different assumptions for the sources:

For example, De Vries and Myer 2005 introduced the Hill model, which is more realistic. The assumption of the temperature profile of the clouds are flat in the outer parts of clouds and linearly increased toward the central source. This account for the observations that it is in general hotter in temperature of collapsing molecular clouds.

There are also some models with full radiative transfer solutions. For example, Keto et al. 2004. The model can be used to model hyperfine emission, fitting velocity, column density, temperature, and the molecular abundance.

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