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A STUDY OF THE DYNAMICAL SIGNATURES OF STAR FORMATION

by

Gopalakrishnan Narayanan

A Dissertation Submitted to the Faculty of the
DEPARTMENT OF ASTRONOMY
In Partial Fulfillment of the Requirements
For the Degree of
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1997
As members of the Final Examination Committee, we certify that we have read the dissertation prepared by Copalakrishnan Narayanan entitled A Study of the Dynamical Signatures of Star Formation and recommend that it be accepted as fulfilling the dissertation requirement for the Degree of Doctor of Philosophy.

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DEDICATION

Dedicated to my (future) children
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ABSTRACT

A multi-pronged study aimed at disentangling the kinematical signatures of the earliest stages of star formation is presented. Radiative transfer calculations of millimeter and submillimeter molecular line emission from fully three-dimensional models of protostars are reported. These models are compared with detailed submillimeter molecular line observations of dynamical motions towards seven Class 0 protostellar objects.

The radiative transfer calculations are performed for two classes of protostellar collapse solutions: (1) "self-consistent", nonspherical, hydrodynamic, collapsing, rotating protostellar systems (Boss 1993); (2) parameterized, semi-analytic, rotating collapse solutions of Terebey, Shu and Cassen (1984). The morphology of the gas and dust emission is found to be a strong function of collapse time and angular resolution. From model centroid velocity maps, a distinctive new infall signature called the "blue-bulge" infall signature is derived. The blue-bulge infall signature can be observed in the centroid velocity maps of protostellar objects when infall dominates over rotation. This infall signature can be detected under a wide variety of source conditions, and should be easily observable using single-dish submillimeter telescopes. At high angular resolutions, models with moderate to high rotational rates exhibit the "polar blue-bulge" - a centroid velocity signature of underlying Keplerian rotation in an embedded cloud core. Submillimeter transitions of HCO+ and CS are found to be better than millimeter transitions in detecting infall, especially at early collapse times.

Using new submillimeter observations in CS and HCO+ towards IRAS 16293-2422, the first detection of the "blue-bulge" signature towards a protostellar
object is presented. The mass accretion rate through the infall region appears consistent with an inside-out collapse model for the source. Using new submillimeter HCO+ and CO observations, a detailed study was performed of six other nearby Class 0 objects. The blue-bulge signature of infall is detected in five sources. Among these, SMM4 and B335 are known infall candidates. VLA1623, L483 and L1262 are new sources for which evidence for infall is derived in this work. SM1N, which does not exhibit a blue-bulge appears to be a pre-protostellar object. A low luminosity bipolar outflow was detected toward SM1N, suggesting that it may be in an extremely early stage of collapse. Of the six sources, only three, SMM4, B335 and L1262 exhibited the classic blue asymmetric line profile signature of infall, suggesting that the blue-bulge signature is more robust in detecting infall than traditional line profile techniques. Evolutionary trends are seen between observationally obtainable source parameters and model derived timescales for the Class 0 sources presented in this work. Such a study when extended to a larger sample of YSOs will help in the understanding of the evolution of YSOs from the embedded protostellar stage to revealed pre-main-sequence objects.
CHAPTER 1

INTRODUCTION

Due to their large accretion luminosities, and location in embedded dense cores, candidate protostellar objects are expected to be identified best using continuum observations at far-infrared and submillimeter wavelengths (Larson 1969). However, to unambiguously identify the kinematic motions of gas corresponding to infall, rotation or outflow in protostellar regions, one requires spectroscopic observations. Without observational constraints on the velocity, temperature and density laws in a collapsing protostar, critical tests of even the most rudimentary star formation theories are not possible. Despite the existence of a large number of candidate protostellar objects (see for e.g. Pollanen & Feldman 1995), direct observational evidence for protostellar infall exists only for a handful of candidates (Walker et al. 1986, Zhou et al. 1993, Zhou 1995, Velusamy et al. 1995, Narayanan et al. 1997). What are the reasons for the paucity of observational evidence of infall? One of the main reasons is probably the relatively short time scale of the main protostellar collapse phase ($10^4$ to $10^6$ years) compared to lifetimes of molecular clouds ($10^7$ to $10^9$ years). Secondly, astronomers are limited to viewing the three-dimensional sky in two-dimensional images. Consequently, it is difficult to separate different cloud
components along a line of sight. Thirdly, the small infall sizes that result from gravitational infall onto single stars prevent us from resolving the infall regions in all but the nearest star-forming regions. The most pressing problem in the detection of infall is the kinematic confusion from dynamical motions other than infall (such as rotation, outflow and turbulence) in the same protostellar object.

1.1. Protostellar Objects – The Kinematic Confusion Problem

Molecular emission from protostellar objects arise from various motions like infall, rotation, turbulence and outflow. It is extremely hard to disentangle these motions in the emitted molecular spectrum. There is a need to generate spectral profiles of molecular line emission from model protostellar cores that includes all these motions in a realistic manner. Such model calculations will help us derive observational diagnostics and procedures to disentangle the kinematics in real protostellar systems. In addition, such models can be used to constrain observations and derive useful physical information of the protostellar region under study.

Methods of detecting infall using molecular line observations have been discussed previously by several authors (Leung & Brown 1977, Walker et al. 1986, Adelson & Leung 1988, Walker 1988, Zhou 1992). In all of these discussions a spherical geometry is assumed and a careful study of high signal-to-noise asymmetric emission line profiles is required. If all phases of protostellar evolution involved spherically symmetric bodies of gas, and infall were the only source of systematic motions, then the task of detecting infall using these techniques would be difficult, but straightforward. However, the universe has not been so kind to us. Observations of candidate protostars in both the thermal dust continuum and in
molecular lines over the past decade have shown that the assumption of spherical symmetry is, in the vast majority of cases, incorrect. Many cloud cores are found to be elongated and rotating (e.g., Goldsmith & Arquilla 1985). It has also become increasingly apparent that a large number (if not all) young stars undergo a period of mass loss characterized by cold, energetic outflows of molecular gas (Lada 1985). Indeed, after the initial collapse phase, outflow may play an important, if not essential, role in the mass accretion process (Shu et al. 1987). Walker (1988) has shown that molecular outflows are capable of distorting line profiles in ways that mimic infall. Before one can be certain the infall interpretation of molecular data is unique, the effects of a nonspherical geometry, rotation, and molecular outflow on line formation must be understood and accounted for. A radiative transfer program which has the capability of including these effects is needed.

1.2. Spectroscopic Signatures of Infall: A Brief Review

1.2.1. Classic Blue-shifted Asymmetric Signature of Infall

When the infalling cloud core is not resolved in the radio beam, and when observing an optically thick transition, the "classic" asymmetric blue line profile signature of infall can be seen. A straightforward explanation of the origin of line asymmetry is presented in Figure 1.1. The spherically symmetric\(^1\) infalling cloud core is divided into layers numbered 1 through 8. As illustrated at the top of the figure, the

\(^1\)Spherical symmetry is considered only for ease of presentation of the idea. Asymmetric blue line profiles can also be obtained when symmetry considerations are not met, as long as there is a gradient in temperature, density and velocity in the infalling cloud core.
temperature and density within the cloud core decrease with radius. Infall velocities
increase with decreasing radius. Within a given layer, the density, temperature,
and velocity are constant. Emission from layers (1 through 4) on the near side of
the protostar appear redshifted to the observer. The emission from the layers (5
through 8) on the farside of the protostar appear blueshifted. The emergent line
from the collapsing core is shown at the bottom of the figure. The line is broken
up into velocity bins. The layer responsible for the majority of the emission in a
particular bin is indicated by its number. The emission from the inner layers on
the near (redshifted) side of the protostar will be partly absorbed by the cooler
foreground layers before reaching the observer. Emission from the far (blueshifted)
side of the protostar is not absorbed by foreground layers because 1) the foreground
layers are hotter than the layer where the emission originated or 2) the foreground
layer is at a substantially different velocity than the layer where the emission
originated. Therefore, the emergent line appears self-absorbed and asymmetric,
with the blueshifted (lower velocity) side of the line brighter than the redshifted
side. The degree of photon mixing between layers is determined by the turbulent
velocity field. Higher turbulent velocities act to blur the distinction between layers.

In general, for optically thick gas, the greater the temperature gradient through
the core, the greater will be the depth of the self-absorption feature. When the
optical depth is not very high, we get a “red-shoulder” in the asymmetric blue
profile (as shown for example in Figure 1.1). Similarly, the greater the velocity
gradient through the cloud core, the more asymmetric the emission lines will appear.
Both the depth of the self-absorption feature and the degree of the line asymmetry
are sensitive to the density law governing the cloud core. The infall line asymmetry
is not limited to line center velocities. The asymmetry can occur in the line wings
as long as the emission remains optically thick.
Figure 1.1 Classic Blue-shifted Asymmetric signature of Infall. A schematic view illustrating the formation of the asymmetric blue-shifted line profile towards an infalling cloud core. See text for details.

The “classic” asymmetric line profile signature has been the technique of choice for most studies of infall (Walker et al. 1986, Zhou 1992, Zhou et al. 1994, Myers et al. 1995, Gregersen et al. 1997). However, as we will discuss below, relying on this line profile alone to deduce infall is fraught with peril. Other motions like rotation and outflow can also produce blue asymmetric line profiles.

1.2.2. Inverse P-Cygni Profiles

When the infalling cloud core is partially resolved by the telescope beam there is the possibility of detecting the inverse P-Cygni profile signature of infall. Figure 1.2a shows the schematic appearance of the inverse P-Cygni profile. This profile is characterized by red-shifted absorption in the molecular line against the
continuum, and the presence of blue-shifted emission. The conditions under which the inverse P-Cygni profile occurs are somewhat restrictive. At the frequency of the line emission, the brightness temperature of the dust emission from the embedded protostellar source, averaged over the telescope beam, has to be higher than the excitation temperature of the molecular transition. In such a case, the cold, dense molecular material from the foreground falling into the hot dust core causes the redshifted absorption seen in Figure 1.2a. The origin of the asymmetric blue-shifted emission is as discussed in the previous section. While expansive motions like outflow can sometimes cause asymmetric blue line profiles (Walker 1988), expanding motions would tend to manifest themselves in P-Cygni profiles (blue-shifted absorption and red-shifted emission) when observed with high angular resolution. Only infall can produce the inverse P-Cygni line profile. The occurrence of the inverse P-Cygni line profiles requires an extended, uniform and infalling molecular envelope relative to the telescope beam, and hence a smaller telescope beam is better. The continuum brightness is also much higher in a smaller beam because of smaller beam dilution. Thus, we expect that the inverse P-Cygni signature of infall is best seen using molecular line observations made with interferometers.

![Figure 1.2 Red-shifted Absorption Signatures of Infall. (a) Inverse P-Cygni Line Profile Signature of Infall. (b) Pure red shifted Absorption Line Signature of Infall](image)
Inverse P-Cygni line profiles have been seen in the near-infrared in the rotation-vibration lines of CO toward the Becklin-Neugebauer (BN) object (Scoville et al. 1983). Using inverse P-Cygni line profiles of the HCO+ J=1→0 transition observed with the Hat Creek millimeter interferometer, Welch et al. (1987) deduce large scale collapse of the surrounding molecular cloud into a cluster of O-stars in the W-49A molecular cloud. Both of these instances are toward high mass star-forming regions. Despite the availability of several millimeter interferometers that have angular resolution < 5", there have been no reported instances to date, of the inverse P-Cygni line profiles toward isolated low-mass protostellar objects. One possibility is that at millimeter wavelengths, the brightness temperature of the continuum emission is not high enough to produce this effect towards low mass protostellar objects. Higher lying molecular transitions at submillimeter wavelengths might be a better choice because of the increased continuum brightness at submillimeter wavelengths. The detection of the inverse P-Cygni signature of collapse might have to await the commissioning of the Submillimeter Array (SMA).

1.2.3. Red-shifted Absorption Line

When the infalling cloud core and the continuum source onto which infall is occurring are completely resolved by the telescope beam, the blueshifted emission seen in Figure 1.2a completely disappears, and we should see only a redshifted absorption line against the background hot continuum (see Figure 1.2b), one of the most unambiguous signatures of infall. But this technique requires even higher angular resolution observations than the inverse P-Cygni line profile method. An accretion disk could possibly provide a strong continuum source against which we might see redshifted absorption due to infalling molecular material from the foreground gas. To resolve a 100 AU accretion disk at the distance of Rho-Ophiuchi
(160 pc) needs an angular resolution of 0.6". As in the inverse P-Cygni signature, high angular resolution submillimeter observations would be the best way of detecting the red-shifted absorption line signature of infall.

1.3. Past Observational Studies to Detect Infall

From the above discussion, it is clear that except for the "classic" blue-shifted asymmetric signature of infall, other existing techniques require very high angular resolution observations. It is no surprise that most of the reported detections of infall have relied on the "classic" asymmetric signature. There is growing acceptance to the theory that many low-mass stars form in isolated cores which are centrally condensed, after which dynamical collapse occurs from the inside out (Shu 1977, Shu et al. 1987). The inside-out collapse scenario suggests the use of molecular tracers which probe primarily the higher densities expected in the infalling gas. Using self-absorbed asymmetric line profiles of CS toward IRAS 16293-2422 (hereafter IRAS 16293), Walker et al (1986) provided the first detection of infall toward a protostellar object. Evidence for fast rotation in the source, however, raised questions about the infall interpretation (Menten et al. 1987). However, Zhou (1995) using radiative transfer models that included rotation with infall were able to reproduce the observations of Menten et al. (1987), thereby supporting the infall interpretation of Walker et al. (1986). This view of IRAS 16293 has recently been confirmed by Narayanan, Walker and Buckley (1997), using centroid velocity maps of multiple transitions of submillimeter CS and HCO⁺ emission. Another good candidate for infall is the isolated globule, B335. Zhou et al (1993) were well able to model the H₂CO and CS line profiles with an inside-out collapse model (Shu 1977). Using CCS observations, Velusamy et al. (1995)
provide evidence that the protostellar envelope of B335 is collapsing. More recently, using the appearance of line profiles, and using trends in line peaks and centroid velocities, Myers et al. (1995) presented strong evidence for gravitational infall in L1527 and L483. Ward-Thompson et al (1996) suggest protostellar infall in NGC 1333-IRAS2 using optically thick HCO+ J=4→3 and optically thin H$^{13}$CO+ J=4→3 line profiles towards the central position.

Wang et al (1995) performed a C$^{18}$O and H$_2$CO line survey toward 40 Bok globules to detect the asymmetric blue signature of infall. They identified three collapse candidates. CB 244, CB 54 and CB3. More recently, Gregersen et al. (1997; hereafter GEZC) performed an HCO+ survey of Class 0 sources for the “classic” asymmetric blue line profile signature of infall. Of the 23 class 0 sources they surveyed, only nine sources had the “correct” blue asymmetry in the line profiles obtained towards the central position of the protostellar objects. Most searches and surveys for infall have relied only on single line profiles towards the central object(s). Only by mapping the observed line asymmetry will we be able to distinguish infall from rotational motions.

1.4. Organization of This Work

In this thesis, we report on the development of theoretical radiative transfer models that yield new techniques for detecting, quantifying and disentangling the kinematic motions that accompany the birth of a star. Due to the relatively low temperatures and high densities expected in regions of infall, molecular line observations at submillimeter wavelengths offer the best opportunities for identifying such gas motions. We present new submillimeter and millimeter observations of infall, rotation and outflow towards a selection of protostellar objects. These observations
verify our model predictions and used in conjunction with our three-dimensional models help to constrain the infall parameters of the object under study. The purpose of this multi-pronged study is to better understand dynamical evolution in the earliest stages of star formation.

The organization of this work is as follows. In Chapter 2, we present the first radiative transfer calculations of millimeter and submillimeter molecular line emission from “self-consistent” models of nonspherical, collapsing, rotating protostellar systems. Using model centroid velocity maps of CS and HCO+ emission, we present a unique new signature, which we call the “blue-bulge” signature, to detect infall in protostellar systems. In Chapter 3, we present radiative transfer calculations of emergent spectra from the semi-analytic solution of rotating collapse by Terebey et al (1984; hereafter TSC). We explore the sensitivity of the “blue-bulge” infall signature to rotational rate, and abundance and temperature gradients. In Chapter 4, we present the first detection of the predicted “blue-bulge” signature in IRAS 16293. In Chapter 5, we present results of a preliminary survey for the detection and study of the “blue-bulge” signature of infall toward six other protostellar systems. Finally in Chapter 6, we present the conclusions and outline strategies to improve upon this present body of work.
CHAPTER 2

THEORETICAL RADIATIVE TRANSFER MODELS FOR THE DETECTION OF INFALL - SELF-CONSISTENT HYDRODYNAMIC MODELS

2.1. Introduction

An object can be identified as a candidate protostar from continuum observations in the far-infrared and submillimeter. Due to their large accretion luminosities and location in dense dust cores, the peak in the energy distribution of protostars occurs at these wavelengths (Larson 1973). When far-infrared and submillimeter observations are available, this property makes candidate protostars relatively easy to identify.

Despite the existence of many candidates, the true evolutionary status of
suspected protostars has never been certain. Both theoretical considerations and our intuition suggest that stars form as the result of the collapse of a portion of a molecular cloud. Therefore, definitive identification of a protostar requires the direct observation of collapsing or infalling molecular gas. Indeed, without observational constraints on the velocity, temperature, and density laws in a collapsing protostar, critical tests of even the most rudimentary star formation theories are not possible.

To directly detect infall motions around protostars requires spectroscopic observations. Clearly molecular line observations offer the best opportunities for identifying such gas motions. One major difficulty is in deciding which molecular line and what spatial resolution are needed to make such an observation possible. The spherically symmetric, isothermal collapse models of Shu (1977) have provided valuable insights into the conditions in an “ideal” protostellar system. These models suggest that the infall region around protostars is relatively small. For a typical case the collapse velocity exceeds 1 km s\(^{-1}\) within about 2000 AU of the protostellar core, about 15" at the distance of Ophiuchus or Taurus. The densities in such regions are expected to exceed \(10^6\) cm\(^{-3}\). To detect emission from such a region requires: 1) a spectral line formed at high density, 2) high spatial resolution, and 3) high spectral resolution.

These conclusions led Walker et al. (1986) to perform a systematic study of the CS emission toward IRAS 16293-2422 (hereafter IRAS 16293). Both the C\(^{32}\)S \(J=2\rightarrow1\) and \(J=5\rightarrow4\) line profiles appeared double-peaked and self-absorbed. The corresponding C\(^{34}\)S spectra were single peaked, with a central velocity corresponding to that of the self-absorption dip in the main line. The \(J=5\rightarrow4\) emission line is asymmetric, with the blueshifted side of the line brighter than the redshifted side. The presence of self-absorption implies the existence of a
temperature gradient. Asymmetries in the self-absorption feature like that observed toward IRAS 16293 are expected if the emission is optically thick and arises in a region of infall (Leung & Brown 1977, see discussion in Chapter 1).

As a first approximation, Walker et al. (1986) used a spherically symmetric microturbulent code to model the molecular line emission. The analysis showed the \( ^{32}S \) \( J=2\rightarrow1 \) line to be more sensitive to the outer regions of the cloud core where infall velocities are lower. The \( J=5\rightarrow4 \) line, being more sensitive to denser gas located deeper in the cloud core, was found to have a more pronounced self-absorption feature. As long as they remain optically thick, higher lying transitions will, in general, appear even more self-absorbed and asymmetric. A comparison between the model spectra and the observations suggested infall was still occurring in the vicinity of IRAS 16293. Higher angular resolution CS observations by Menten et al. (1987) suggested the object is rotating. Interferometric observations by Mundy et al. (1986) showed the molecular cloud core to be elongated. The presence of two VLA sources (Wootten 1989) and two molecular outflows (Walker et al. 1986, Walker et al. 1988) provided evidence that IRAS 16293 is in fact a protobinary system. This conclusion has been supported by further high resolution observations with millimeter-wave interferometers (Mundy et al. 1992, WCB 1993).

Clearly, a radiative transfer program capable of modeling the emission from non-spherical, rotating systems is needed to interpret the spectra obtained from protobinary systems like IRAS 16293. For single stars, spherical collapse models like those used by Walker et al. (1986), Zhou (1992), and Zhou et al. (1994) give a good first-look at conditions within the collapsing cores. However, since single stars form from rotating, nonspherical cloud cores, a flexible radiative transfer code is also required to more accurately probe their properties. Recent observations by
a number of workers have indicated multiple PMS star systems may be much more common than single PMS star systems (Simon 1992, Ghez et al. 1992, Zinnecker et al. 1992). The ubiquity of multiple PMS star systems further emphasizes the importance of determining the effects of non-spherical geometries and velocity fields on molecular line emission from protostars.

Walker, Narayanan and Boss (1994, hereafter WNB) used the results of non-spherical, self-consistent, three-dimensional hydrodynamic simulations to examine the spectral evolution of single and multiple star systems. In the course of their study they found 2-dimensional centroid velocity maps to be a sensitive probe of the evolutionary status of protostars. We recently updated the numerical code used in WNB to “digest” the protostellar nebula. Although the overall results of WNB are the same, many of the details are changed by this more accurate analysis. In this chapter, we present the corrected and updated results of WNB. The results provide insight into which molecules and transitions are best suited for probing the velocity fields of protostars at different free-fall times. Methods for detecting infall in single and multiple star systems are described.

2.2. Numerical Methods

In previous studies of molecular line emission from protostars, the velocity fields and temperature and density distributions were imposed on a spherically symmetric model in an effort to generate line profiles that match observational data. We have adopted a “self-consistent” approach in which we couple the results of the 3-D hydrodynamical models of Boss (1993) with a flexible radiative transfer code. The 3-D hydrodynamic code is based on finite-difference solutions of the equations of hydrodynamics, gravitation, and radiative transfer, written in spherical
coordinates. Viscous and magnetic effects are neglected; viscosity is unimportant during the collapse phase, and magnetic fields are not thought to be dynamically important once protostellar collapse begins (Boss 1993). The hydrodynamic code is discussed in full by Boss (1993) and Boss and Myhill (1992). The calculations are performed inside a spherical volume with a rigid boundary. This arrangement does not allow for mass flow across the boundary. The numerical resolution used in all the models is \(N_r = 51, N_\theta = 23\) for \(\pi/2 > \theta > 0\), and \(N_\phi = 64\). Models are typically evolved for at least \(\sim 10^4\) time steps, and yields 70,451 (center + rotational axis + main grid = 1 + 50 + 50 \times 22 \times 64) grid points. The model protostar is symmetric about the equatorial plane. Symmetry is not imposed across the rotational axis.

The radiative transfer calculations are performed in two steps. First a program reads in the temperature, density, and velocity field at each of the 3-D model grid points. Figure 2.1a shows the spherical coordinate system of the model protostar. The rotational axis OC coincides with the Y-axis (see Figure 2.1a). A coordinate transformation is then performed in the protostellar frame to convert from spherical to rectangular coordinates. In Figure 2.1a, a point denoted R in the grid with coordinates \((r, \theta, \phi)\) is transformed into \((x, y, z)\). At each grid point, the velocity field \((v_r, v_\theta, v_\phi)\) is converted to \((v_x, v_y, v_z)\) by solving the following simultaneous equations:

\[
\begin{align*}
v_x \sin \theta \cos \phi + v_y \sin \theta \sin \phi + v_z \cos \theta &= v_r \\
v_x \cos \theta \cos \phi + v_y \cos \theta \sin \phi - v_z \sin \theta &= v_\theta \\
-v_x \sin \phi + v_z \cos \phi &= v_\phi
\end{align*}
\] (2.1)

The model protostar is then rotated to the desired viewing angle. As seen in
Figure 2.1 Coordinate Transformation From Protostellar to Sky Frame. (a) Spherical Coordinate System of the Model Protostar. $OC$ is the direction of the rotational axis. (b) The sky frame and the observer. The protostellar rotational axis $OC$ is shown rotated by an $\alpha$ from the plane of the sky, and by an angle $\psi$ from the $y$-axis on the plane of the sky.
Figure 2.1b, the rotational axis of the protostar (denoted by OC in Figure 2.1) is rotated by an angle $\psi$ in the plane of the sky, and by an angle $\alpha$ out of the plane of the sky towards the observer. Thus if $\psi = 0$ and $\alpha = 0$, the rotational axis of the protostar is in the plane of the sky, and our line-of-sight is perfectly edge-on to the equatorial plane of the protostar. Using $\alpha = 90^\circ$ gives a pole-on line-of sight. The rotational transformation from the protostellar frame to the sky frame can be shown to be

$$
\begin{align*}
\tilde{x} &= \cos \psi x - \sin \psi y \\
\tilde{y} &= \cos \alpha \sin \psi x - \cos \alpha \cos \psi y + \sin \alpha z \\
\tilde{z} &= -\sin \alpha y + \cos \alpha z,
\end{align*}
$$

(2.2)

where ($x, y, z$) are the coordinates of the sky frame.

Next, the average conditions at each point along a chosen line of sight (LOS) are determined. The number of points along a LOS is set by the desired spatial resolution. The greater the number of points, the greater the CPU time required to digest the model nebula. For the model results discussed in this chapter, a spatial resolution of $1.2 \times 10^{16}$ cm was chosen. This spatial resolution also matches the radial spacing of the input 3-d grid of density, temperature and velocity conditions. At the distance of the Rho Ophiuchi molecular cloud (160 pc), the resulting angular resolution is $\sim 5''$. Each LOS point in the sky frame is transformed back into the protostellar frame, and a gaussian weighting technique is used when computing the conditions at each LOS point. The sigma of the Gaussian function is set by the chosen spatial resolution. The projected line of sight velocity in the observer's frame can then derived from
\[
\nu_{\text{los}} = \sin \alpha \nu_0^y + \cos \alpha \nu_0^z
\]

where, \( \nu_0^y \) and \( \nu_0^z \) are the Gaussian weighted velocity components in the protostellar frame. The gaussian weighted temperature and density (being scalar quantities) do not undergo any transformations.

The conditions along each LOS are then stored. A second program reads in the Gaussian averaged conditions along each LOS and predicts the emergent spectrum for the desired molecular transition. The standard model spectrum is divided up into 300 frequency points. The equation of transfer is solved at each LOS point for each frequency. The calculated intensity at each velocity is then summed-up along the LOS. The effective spectral resolution in each model spectrum obtained corresponds to 0.05 km s\(^{-1}\). If \( z_{\text{min}} \) and \( z_{\text{max}} \) denote the near-side and far-side boundaries of the protostellar cloud core along a given LOS, the numerical solution to the equation of transfer used in the model has the form,

\[
I_\nu = \sum_{z_{\text{min}}}^{z_{\text{max}}} S_\nu(z) e^{-\tau_{\nu_{\text{tot}}}(z)} \Delta \tau_\nu(z)
\]

where \( S_\nu(z) \) is the source function at point \( z \), \( \tau_{\nu_{\text{tot}}}(z) \) is the total optical depth from the sample point at \( z \) to the observer, and \( \Delta \tau_\nu(z) \) is the incremental change in optical depth over a distance \( \Delta z \) between sample points along the LOS. The density of the cloud cores we will be modeling is quite high (typically \( \geq 10^6 \) cm\(^{-3}\)) (also see below). Many of the lower lying rotational transitions will be thermalized. Therefore, we will assume an LTE condition exists such that the populations of the rotational energy levels at a given point in the cloud core are characterized by a single temperature \( (T_{\text{ex}}) \) equal to the kinetic temperature \( (T_k) \) of the gas. In LTE the source function is the Planck function. The expressions for \( \Delta \tau_\nu(z) \) and \( \tau_{\nu_{\text{tot}}}(z) \)
are given by,
\[ \Delta \tau_{\nu}(z) = (\alpha^g_{\nu}(z) + \alpha^d_{\nu}(z))\Delta z, \tag{2.5} \]

and
\[ \tau^\text{tot}_{\nu}(z) = \sum_{z_{\text{min}}}^{z} \Delta \tau_{\nu}(z). \tag{2.6} \]

The quantity \( \alpha^g_{\nu} \) is the gas opacity at a sample point and \( \alpha^d_{\nu} \) is the dust opacity at the same point. The technique used to estimate the dust opacity as a function of frequency is the same as that outlined by Boss and Yorke (1990) and includes the effects of both refractory (i.e., graphite and silicates) and volatile (i.e., water, ammonia, and methane ices) dust components. For diatomic molecules, the gas opacity is given by

\[ \alpha^g_{\nu}(z) = \frac{n_l c^2 A_{ul} g_u}{8\pi\nu_o^2 g_l} \left( 1 - e^{-\frac{\nu_o}{T_{ex}}/\nu} \right) \phi_{\nu}(z) \tag{2.7} \]

where \( n_l \) is the number density of molecules in the lower state of the transition, \( A_{ul} \) is the Einstein spontaneous emission coefficient of the transition, \( \phi_{\nu} \) is the line profile function, \( \nu_o \) is the transition frequency, \( g_l \) and \( g_u \) are the statistical weights \((2u + 1 \text{ and } 2l + 1, \text{ respectively for } J = u \rightarrow l)\), and \( T_{ex} \) is the excitation temperature at the sample point. The \( \text{H}_2 \) density at each point is specified by the 3-D hydrodynamic model. To determine the number density \( n_{\text{tot}} \) of another molecule, we simply multiply \( n_{\text{H}_2} \) by the fractional abundance \( (X_{\text{mol}}) \) of the molecule of interest. For a diatomic molecule in LTE, \( n_{\text{tot}} \) can be related to \( n_l \) through the expression

\[ \frac{n_l}{n_{\text{tot}}} = (2l + 1)e^{-\frac{h\nu_{\text{trans}}}{kT_{ex}}} (Q_{r}(T))^{-1} \tag{2.8} \]

where, for a large number of states, \( Q_{r}(T) \) can be approximated by \( kT_{r}/hB_r \). The quantity \( B_r \) is the rotational constant for the chosen molecule.
The effect of the velocity fields enters the equation of transfer through the line profile function, \( \phi_v(z) \),

\[
\phi_v(z) = \frac{1}{\Delta \nu_D \sqrt{\pi}} \exp \left( - \left[ \frac{\nu - \nu_o}{\Delta \nu_D(z)} - \frac{(\nu_o/c)V(z)}{\Delta \nu_D(z)} \right]^2 \right) \quad (2.9)
\]

(Leung & Brown 1977). The quantity \( V(z) \) is the projected LOS velocity which is defined to be positive for motion away from the observer. The Doppler broadening function, \( \Delta \nu_D(z) \), includes the effects of both thermal and turbulent broadening;

\[
\Delta \nu_D(z) = \frac{\nu_o}{c} \left( \frac{2kT_k(z)}{m} + V_{\text{turb}}^2(z) \right)^{1/2} \quad (2.10)
\]

The velocity field given by the 3-D hydrodynamic code does not include a turbulent velocity term, i.e., \( V_{\text{turb}}(z) \), term. Therefore, we must introduce one. A mean turbulent velocity for a cloud core can be estimated from observational data by comparing observed line profiles to model line profiles generated using various values of \( V_{\text{turb}} \). In general, we do not find it necessary to use a radially dependent value for \( V_{\text{turb}} \); the assumption of a single, average value for \( V_{\text{turb}} \) fits the observations of IRAS 16293 and other young stellar systems quite well.

The resulting spectra obtained at 5" resolution is used to make integrated intensity and centroid velocity maps. To obtain model spectra and maps at lower angular resolution, the model mosaic is convolved with a gaussian beam with FWHM that matches the required angular resolution.

With the "self-consistent" 3-D hydrodynamic model as input, the only free parameters in the radiative transfer portion of the analysis are the values for the molecular abundance and turbulent velocity. The temperature, density, and velocity fields are all set by basic physical laws. With this approach, there are relatively few
"ad hoc" assumptions.

2.3. Model Results

2.3.1. Initial Conditions

The emergent spectra from three model protostellar systems were studied. Model A collapses to a single protostar. Model B evolves into a binary system with a separation of 14 AU. Model C also becomes a binary system, but with a separation of 200 AU. Each model starts with a moderately centrally condensed (20 times higher at the center than at the initial boundary), prolate cloud core possessing a Gaussian density profile. It is expected that the density profiles obey a power law of $\rho \propto r^{-2}$ in the outer isothermal regions not participating yet in the collapse, and a free-fall density profile of $\rho \propto r^{-1.5}$ in the central regions within the head of the expansion wave of collapse (Shu et al. 1987). Indeed power laws appear to fit observations of dense cores with and without dense cores (Fuller & Myers 1992). However, observations have been limited by finite beam sizes to map molecular cloud cores smaller than 0.02 pc in size. If the core has yet to undergo collapse, it would be expected that at some inner radius, the density profile should flatten out, and that the power law density profiles probably cannot be extrapolated indefinitely to the center (Boss 1993). For this reason, in his models, Boss (1993) uses an initial centrally condensed density profile that is Gaussian. This has the advantage that the density flattens out to a finite central value, and the density profile has smoothly varying profiles throughout, with the outermost regions being even steeper than $r^{-2}$.

The prolate axial ratio of the cloud core is 1.5:1 for models A and B, and 2:1 for model C, with $r_a = 0.87 R$ for 1.5:1 ($r_a = 1.16 R$ for 2:1) and $r_b = r_c = 0.58 R$. 


where \( R = 1.0 \times 10^{17} \text{ cm} \). Initially, the cores are rotating as solid bodies. The rotational axis is coincident with the minor axis of the core. All models start with a uniform temperature \( (T_i = 10 \text{ K}) \) gas of composition \( X = 0.769, Y = 0.214, \) and \( Z = 0.017 \). The specific angular momentum and mass of each model system is listed in Table 2.1. The table also lists the value of \( \alpha \) (ratio of thermal to gravitational energy) and \( \beta \) (ratio of rotational to gravitational energy) for each model core.

<table>
<thead>
<tr>
<th>Model</th>
<th>( \rho_0 ) (g cm(^{-3}))</th>
<th>( \Omega_0 ) (rad s(^{-1}))</th>
<th>( \alpha )</th>
<th>( \beta )</th>
<th>( M_i ) (M(_\odot))</th>
<th>( J/M ) (cm(^2)s(^{-1}))</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>A(^a)</td>
<td>( 2 \times 10^{-18} )</td>
<td>( 1.0 \times 10^{-13} )</td>
<td>0.43</td>
<td>0.012</td>
<td>1.3</td>
<td>( 3.1 \times 10^{20} )</td>
<td>Single Star</td>
</tr>
<tr>
<td>B(^b)</td>
<td>( 3 \times 10^{-18} )</td>
<td>( 1.0 \times 10^{-13} )</td>
<td>0.29</td>
<td>0.0083</td>
<td>2.0</td>
<td>( 3.1 \times 10^{20} )</td>
<td>14 AU Binary</td>
</tr>
<tr>
<td>C(^c)</td>
<td>( 2 \times 10^{-18} )</td>
<td>( 3.1 \times 10^{-12} )</td>
<td>0.39</td>
<td>0.012</td>
<td>1.5</td>
<td>( 1.0 \times 10^{21} )</td>
<td>200 AU Binary</td>
</tr>
</tbody>
</table>

\(^a\) Model N0; Boss 1993.

\(^b\) Model N1; Boss 1993.

\(^c\) Model 2N8; Boss 1993.

Figure 2.2 shows the evolution of the radial density profiles for five successive free-fall times of Model B (14 AU binary). The central density increases by six orders of magnitude from \( \sim 17,000 \) years to \( \sim 47,000 \) years since the onset of collapse. The intermediate regions show a density profile that is asymptotic with a \( r^{-2} \) power-law, and the outermost regions show an even steeper gradient. The radius at which the density profile turns over from the constant central value is seen to decrease to smaller radii with time.

Figure 2.3 shows a map of the equatorial density distribution of Model B at \( t = 1.225 \text{ t ff} \). It is seen that while the density falls off smoothly at the outer radii, the contours in the central regions show considerable ellipticity and indications that
Figure 2.2 Evolution of the radial number density profile towards Model B. The radial variation of number density with distance in cm is shown for five successive free-fall times. Here, $t_{ff} = 38,400$ yr.

There is more than one density maximum. Indeed, at this time (~47,000 years since the onset of collapse), the two density maxima are separated by 14 AU, a possible intermediate configuration to the formation of a close binary system.

As an example of the distribution of velocity fields, we show in Figure 2.4 contours of the velocity field $(v_r, v_\theta, v_\phi)$ in one quadrant of Model B at $t = 1.225 \ t_{ff}$. The velocities are shown in the $\bar{y}$-$\bar{z}$ quadrant with $\phi = 90^\circ$ (see also Figure 2.1). The resulting velocity components from the hydrodynamic solution do not obey any smooth power law, but it can be seen that towards the central regions, the radial infall velocity $v_r$ is greater than the rotational component, $v_\theta$ and the theta component $v_\phi$ by several factors.
Figure 2.3 Density contours in the equatorial plane for Model B at $t = 1.225 \, t_{\text{ff}}$. The map is shown in normalized units, with one map unit representing a linear distance of $2.4 \times 10^{15}$ cm.

Figure 2.4 Velocity fields for Model B at $t = 1.225 \, t_{\text{ff}}$ in the $y$-$z$ quadrant with $\phi = 90^\circ$ (also refer Figure 2.1). $v_r$ is shown in solid contours from 0 to 0.7 by 0.05 km s$^{-1}$. $v_\theta$ is shown in dashed contours from 0 to 0.1 by 0.0075 km s$^{-1}$, and $v_\phi$ is shown in dotted contours from 0 to 0.25 by 0.025 km s$^{-1}$. The contour limits are based on maximum velocities for each component. The map is shown in normalized units, with one map unit representing a linear distance of $2.4 \times 10^{15}$ cm.
The evolution of the temperature profile of Model B with time is shown in Figure 2.5. For the first four time steps, the temperature profile increases very slowly towards the center. However, at the latest free-fall time \((t = 1.225 \, \tau_f)\), the temperature gradient increases very sharply towards the center. The large central densities at this latter time probably results in increasing opacities for dust and molecular line emission. This in turn would prevent the easy escape of photons from the central regions. Without the cooling effects brought about by escaping radiation, the heat due to contraction would result in increasing temperatures towards the central regions.

![Temperature profile](source)

Figure 2.5 Evolution of the radial temperature profile towards Model B. The radial variation with distance in \(\text{cm}\) is shown for five successive free-fall times. Here, \(\tau_f = 38,400 \, \text{yr}\).

For the radiative transfer analysis we have assumed a CS to \(\text{H}_2\) abundance ratio of \(1 \times 10^{-9}\), \(\text{HCO}^+\) to \(\text{H}_2\) abundance ratio of \(3 \times 10^{-10}\), and a turbulent velocity...
of 0.5 km/s. In the earliest phases of collapse the density of the cloud cores is just sufficient \((n_0 \approx n_{\text{crit}})\) to thermalize the \(J=2\rightarrow1\) transition of CS. The \(J=5\rightarrow4\) transition of CS may not be fully thermalized. In the later stages of collapse, the ambient density is much greater than the critical density of either transition \((n_0 > n_{\text{crit}})\), justifying the assumption of LTE (see Figure 2.2).

2.3.2. Line Profiles

Due to their sensitivity to high density regions, the emission associated with millimeter/submillimeter rotational lines of CS were modeled. Figures 2.6 through 2.10 show mosaics of the CS \(J=5\rightarrow4\) (dashed line) and \(J=2\rightarrow1\) (solid line) emission at five different times during the collapse of Model B (binary with 14 AU separation). Each mosaic shows the appearance of an emission line over the central \(20''(\sim 5.0 \times 10^{16} \text{ cm})\) of the northern hemisphere of the protostellar system. The southern hemisphere is a mirror image of the northern hemisphere. In the mosaics the system is being observed edge-on. Figures 2.6 through 2.10 show the appearance of the emission lines after \(0.450 t_\text{ff}\), \(1.052 t_\text{ff}\), \(1.189 t_\text{ff}\), \(1.212 t_\text{ff}\), and \(1.225 t_\text{ff}\), respectively. For Model B, the free-fall time \(t_\text{ff}\) equals \(1.21 \times 10^{12} \text{ sec (38.343 yrs)}\). The distance between adjacent lines of sight is \(1.2 \times 10^{16} \text{ cm}\). The distance between sample points along each line of sight is \(1.2 \times 10^{16} \text{ cm (800 AU)}\). The spectra of Figures 2.6 through 2.10 are what would be observed with a \(\sim 5''\) telescope beam if the model protostellar system was at the distance of Rho Ophiuchi (160 pc). Such angular resolutions are possible with millimeter-wave interferometers.

In Figure 2.6 both the CS \(J=5\rightarrow4\) and \(J=2\rightarrow1\) lines appear Gaussian and have a uniform temperature across the map. There is no obvious sign of a central condensation, dust continuum, rotation, or infall in either line. In Figure 2.7, the
Figure 2.6 Spectral Evolution of Model B. \( t = 0.45 \, t_{\text{ff}} \). CS \( J=2\rightarrow1 \) emission lines are solid. The CS \( J=5\rightarrow4 \) emission lines are dashed. The model protostellar system is being viewed edge-on. Only northern hemisphere lines of sight are shown. The southern hemisphere spectra are a mirror image of the northern hemisphere spectra. Angular offsets from the center of the protostar are indicated. The mosaic corresponds to what would be observed with a 5'' angular resolution, at a collapse time of \( 0.45t_{\text{ff}} \), where \( t_{\text{ff}} = 38,400 \) yr.
Figure 2.7 Spectral Evolution of Model B. $t = 1.052 \, t_{ff}$. See Figure 2.6 for other details.
Figure 2.8 Spectral Evolution of Model B. $t = 1.189 \, t_{ff}$. See Figure 2.6 for other details.
Figure 2.9 Spectral Evolution of Model B. $t = 1.212\ t_{ff}$. See Figure 2.6 for other details.
Figure 2.10 Spectral Evolution of Model B. \( t = 1.225 \, t_{\text{ff}} \). See Figure 2.6 for other details.
CS J=2→1 lines start to become optically thick, and the tops of the lines become flattened. In the CS J=5→4 line the emission only starts to become optically thick along a line of sight through the center of the core (0,0). At this point in time (40,336 yrs. after the onset of collapse) there is still no significant dust continuum emission evident in the spectra. Figure 2.8 shows the situation just 5,242 yrs later. Over this brief period of time, the cloud core has evolved dramatically. The elevation in line temperatures and the continuum level toward the center of the cloud core indicate it has become much more centrally condensed. Small asymmetries in the CS J=2→1 and J=5→4 line profiles are present. Along the rotation axis (which runs down the middle of the figure) the blueshifted side of the line is brighter than the redshifted side of the line. This type of line asymmetry is the classic infall signature described in Figure 1.1. Figure 2.9 shows the cloud core 6,144 yrs later. The most noticeable difference between the appearance of this map and the previous map (Figure 2.8) is the elevated continuum level toward the map center due to the rapid accumulation of material in the center of the cloud core. The increase in the central density is also apparent from the increased depth in the self-absorption present in the line profiles. In Figure 2.10 (1365 yrs later) the concentration of matter at the center of the cloud core has increased to the point that emission lines seen at earlier epochs toward the central position are now in absorption. Indeed, the fact that the continuum level associated with the CS J=5→4 line is lower than the continuum level of the CS J=2→1 line indicates that even the dust emission at 1.22 mm is now optically thick. The absorption line is slightly redshifted indicating it arises in the infalling envelope of material between the observer and the embedded protostellar object(s).

Figure 2.11 show the spectral evolution of the CS J=2→1 line toward the central position of Model B as a function of free-fall time. The emission from the
Figure 2.11 Evolution of CS J=2→1 spectra toward the central position of Model B. The assumed distance to the model protostar is 160 pc. The spectra appear as they would in a 12" telescope beam. Part (a) shows the time evolution of the emission line as it would look if viewed through the equatorial plane. Part (b) is how the spectral evolution would appear if the system were being viewed pole-on.

The model protostar has been convolved with a telescope beam such that the resulting spectra are what would be observed with a 12" beam at the distance of Rho Ophiuchi. Figure 2.11a shows the spectral evolution as seen through the equatorial plane, and Figure 2.11b shows the same time sequences as seen from the pole. From both vantage points the effects of infall motions can be seen in the line profiles after 1.052 \( t_{\text{ff}} \). From 1.189 \( t_{\text{ff}} \) to 1.212 \( t_{\text{ff}} \) the line profiles show the classic infall induced asymmetric emission line profile. At 1.225 \( t_{\text{ff}} \) the line profiles are of the inverse P-Cygni type: the blueshifted side of the line is still seen in emission while
the redshifted side goes into absorption. The inverse P-Cygni profile is also a classic signature of infall and occurs because of the high level of continuum emission present at 1.225 $t_{\text{ff}}$. The dramatic change in the appearance of the line profiles between 1.212 $t_{\text{ff}}$ and 1.225 $t_{\text{ff}}$ illustrates how quickly the collapse phase proceeds. It is also interesting to note that infall motions have a slightly greater effect on line profiles for pole-on lines of sight. In the equatorial plane the effects of infall are less pronounced due to a slowing of the infall velocity field as a result of centrifugal support of material entering the accretion disk(s).

2.3.3. Centroid Velocity Maps

Adelson and Leung (1988) investigated the use of centroid velocity maps in probing the dynamics of spherically symmetric cloud cores. They found that a velocity centroid map with concentric contours denotes pure radial motion. A velocity centroid map with contours consisting of parallel lines flanked by ovals with opposite velocity signs indicates rotation. They suggest that the two velocity components can be disentangled in a collapsing rotating system by observing along the rotational and equatorial axes of the system. The centroid velocities derived along the rotation axis will be dominated by the radial velocity component, while the centroid velocities found along the equatorial axis will be dominated by the rotational velocity field.

Figure 2.12a through 2.12e are centroid velocity maps of the CS $J=5\rightarrow4$ emission toward Model B at each of the collapse times shown in Figure 2.11. The angular resolution of the maps corresponds to a 14" beam at the distance of Rho Ophiuchi (160 pc). Solid contours indicate redshifted gas motions, dashed contours blueshifted gas motions. The axis of rotation runs from top to bottom through the center of the maps. If the projected rotational velocity components are much larger
than the projected infall velocity components, the maps would be divided down the middle, with redshifted emission on one side and blueshifted emission on the other. For the first two collapse times shown in Figure 2.12, this is indeed the case. However, due to the presence of infall, starting at 1.189 $t_{\text{ff}}$ (2.12d) the blueshifted velocity centroid contours cross the rotational axis into what would otherwise be the redshifted side of the protostar. Within this "blue-bulge", infall velocity motions dominate over rotational velocity motions. The blue-bulge is even more apparent at 1.225 $t_{\text{ff}}$ (Figure 2.12e).

![Figure 2.12 Evolution of centroid velocity plots.](image)

Figure 2.12 Evolution of centroid velocity plots. The maps were computed from the HCO$^+$ J=4$\rightarrow$3 emission lines of Model B. The assumed distance to the protostar is 160 pc. The offsets are in arcseconds. The effective angular resolution of the maps is 14". In the plots, blueshifted velocity contours are dashed and redshifted velocity contours are solid. The time ($t$) since the onset of collapse is indicated for each centroid plot. The contour limits and intervals for each plot are (in km/s); a) -0.07 to 0.06 by 0.01, b) -0.08 to 0.07 by 0.01, c) -0.08 to 0.08 by 0.01, d) -0.08 to 0.08 by 0.01, and e) -0.08 to 0.07 by 0.006.
In Figure 2.13 we present velocity centroid maps of Model B at three inclination: pole-on (2.13a), at 45° (2.13b), and edge-on (2.13c). All three correspond to the same collapse time, 1.225 $t_{\text{ff}}$. The velocity centroid maps were computed from HCO+ J=1→0 emission obtained with a 10" beam. At 45° the blue-bulge is more pronounced than in the edge-on case. When viewed pole-on (Figure 2.13a), only blueshifted velocities are observed, and the velocity centroid contours are concentric circles. The observed dependence of the velocity centroid contours on inclination to the equator ($i$) is consistent with the projected rotational velocity field going to zero as $i$ approaches 90°. In the absence of outflow, it is easier to detect infalling gas motions if the protostellar system is not viewed edge-on.

2.3.4. The Effect of Molecular Outflows on Infall Signatures

While our current models include the effects of nonspherical geometry, rotation, and infall, they do not include the effects of molecular outflow. In Chapter 7, we will discuss the incorporation of molecular outflows in our radiative transfer calculations. Previous studies (Walker 1988) have shown that molecular outflows can produce infall-type line asymmetries if the protostellar object is observed through a blueshifted outflow lobe. There are several ways to avoid the confusion between infall and outflow: 1) limit searches for infall to objects which are so young they have yet to develop molecular outflows, 2) limit searches to objects which have outflow lobes that appear spatially distinct from the protostellar core, and 3) choose molecular probes which are not excited within molecular outflows. Approaches 1) and 2) severely limit the number and variety of protostellar sources toward which infall can be observed. High lying transitions of density sensitive molecules (e.g., submillimeter-wave transitions of CS) may be able to fulfill the requirements of approach 3), but are not observable with the current generation of millimeter-wave
Figure 2.13 Effect of inclination on velocity centroid plots. The velocity centroids were computed from the HCO$^+$ $J=1\rightarrow0$ emission lines of Model B at $t = 1.225\, t_{\text{ff}}$. The assumed distance to the protostar is 160 pc. The offsets are in arcseconds. The effective angular resolution of the maps is 10". Bluesthifted velocity contours are dashed lines and redshifted contours are solid lines. The contour limits and intervals for the polar line of sight (top panel) are -0.04 to 0.01 by 0.006 km/s. For the 45° line of sight (center panel) the contours are from -0.06 to 0.06 by 0.01 km/s. The contours for the equatorial line of sight (bottom panel) are from -0.09 to 0.08 by 0.01 km/s.

interferometers. However, since molecular outflows are believed to be confined to the minor axis of a protostellar system, the blue-bulge infall signature (which occurs along the major axis) should, at least in some instances, be detectable in millimeter-wave transitions toward protostellar systems with molecular outflows.

2.3.5. Choice of Molecular Probe

In general, if two molecules have a transition at similar frequencies and the transitions have similar collision rates, the molecule with the larger dipole moment
will be a more sensitive probe of infall velocity fields. This effect occurs because the higher dipole moment molecule will have a greater Einstein spontaneous emission coefficient and therefore a greater critical density. If the molecule is collisionally excited, then the critical density gives an indication of the density regime to which a particular molecular transition is sensitive. In the dense cores we have modelled, collisional excitation is expected to dominate over other excitation mechanisms. Both the gas volume density and the magnitude of the infall velocity field increase toward the center of a collapsing cloud core. Therefore a molecule with a larger dipole moment (and higher critical density) should be more sensitive to high velocity infalling gas than a molecule with a smaller dipole moment. The higher the velocity of the gas to which a molecule is sensitive, the more asymmetric its line profile should appear. For example, HCO+ has a dipole moment approximately twice that of CS. As a result, at similar frequencies and for similar column densities, one would expect the HCO+ line asymmetries generated by infalling gas to be more pronounced than those observed in CS lines. The larger line asymmetries, if present, would produce greater velocity extremes in centroid velocity plots, making infall easier to detect.

As pointed out by Zhou (1992), other density-sensitive molecules such as H$_2$CO and NH$_3$ can be used to search for infall, but the greater complexity of their energy level structures make the required radiative transfer calculations more difficult to perform. How effective a molecule is at tracing infall also depends on the molecule's abundance and excitation temperature requirements. Since molecular abundances and temperature distributions are likely to vary from source to source, the detection of infall toward candidate protostars may require observations of several different molecular species and transitions.
The critical density of a molecular transition increases with frequency. Therefore, higher lying transitions of a molecule will be more sensitive to regions deep within a cloud core than lower lying transitions. As a result, higher lying transitions (due to their increased sensitivity to denser gas) sample regions with higher characteristic infall velocities. By performing a multitransitional study of line profiles of molecules such as CS and HCO+, one can, in principle, determine the velocity and density structure of an infall region. Such studies have been performed toward IRAS 16293 (Walker et al. 1986; 1994) and B335 (Zhou et al. 1993).

2.3.6. Effect of Angular Resolution on Results

The appearance of line profiles and the resulting velocity centroid maps is a strong function of the angular resolution used to perform the observations. In Figure 2.14 through 2.14e we present a series of spectra and centroid velocity maps which illustrate this effect. The observations are made in the CS J=5→4 line toward Model B at a collapse time of 1.225 \( t_{\text{ff}} \). The model protostellar system is assumed to be at a distance of 160 pc. Each panel shows a CS J=5→4 spectrum toward the center of the cloud core and a velocity centroid map at the same angular resolution. For angular resolutions \( \leq 10'' \) the CS line is in absorption, with a slight redshift. For resolutions \( \geq 20'' \) the CS line is observed in emission and has the classic infall line asymmetry. Since the region of infall is relatively small, larger beam sizes tend to wash-out the signature of infall. The presence of infall is clearly seen in all the velocity centroid maps, although details concerning the velocity structure are lost at larger angular resolutions. High angular resolution observations with interferometers have the added advantage that they have been spatially filtered. Observations with interferometers can be made to suppress structures that are
Figure 2.14 Effect of angular resolution on the appearance of CS J=5→4 spectra and velocity centroid maps. Both the velocity centroid maps and the central spectrum of Model B (t = 1.225 t_{ff}) are shown for angular resolutions of a) 5", b) 10", c) 20", d) 30", and e) 60". The assumed distance to the model protostellar system is 160 pc. The contour limits and interval for each centroid map are (in km/s) a) -0.09 to 0.09 by 0.01, b) -0.08 to 0.08 by 0.01, c) -0.06 to 0.05 by 0.01, d) -0.05 to 0.02 by 0.006, and e) -0.03 to 0 by 0.002.

extended relative to the synthesized beam size. Since features associated with molecular outflows and ambient cloud material are often extended, interferometers work to suppress them. By suppressing these features, interferometers make the task of detecting infall easier.
2.3.7. Effect of Binary Separation and Orbital Position on the Detection of Infall

As mentioned in the introduction, there is an ever increasing body of observational evidence that the majority of low mass stars form in multiple star systems. Therefore a study of the detection of infall toward protostars would not be complete unless the effect of binary separation on infall signatures is addressed.

In Figure 2.15 we present CS $J=5\rightarrow4$ spectra and velocity centroid maps toward a single protostar (Model A), a protobinary with a separation of 14 AU (Model B), and a binary with a separation of 200 AU (Model C). The spectra are taken toward the center of the cloud core. Both the spectra and velocity centroid maps are made at an angular resolution of 5" (assumed distance 160 pc). The spectra and velocity centroid maps toward the single star and close binary appear similar and clearly show infall signatures. Redshifted absorption lines are observed toward each source and a prominent blue-bulge is present in the velocity centroid maps. In the case of the wide binary the effect of infall on the model line profile and centroid velocity map are more subtle. The CS line is in emission and a blue-bulge is not as prominently seen in the velocity centroid map. The spectral line toward the geometric center of the binary also does not show the classic infall asymmetry prominently.

For both Models B and C, the axis of the binary (the imaginary line connecting the binary members) is rotated $\sim35^\circ$ out of the plane of the sky. To test the azimuthal dependence of infall signatures, model runs were made with the binary axis of each model parallel and perpendicular to the observer's line of sight. There was no significant change in the appearance of the spectra toward the geometric center of the models over the 90° swing in azimuth. The morphology of the central
Figure 2.15 Effect of binary separation on the appearance of CS \( J=5 \rightarrow 4 \) spectra and velocity centroid maps. Velocity centroid maps and the central spectrum of Model B (\( t = 1.225 \, t_H \)) are shown for a) single star, b) 14 AU binary, and c) 200 AU binary. The assumed distance to the model protostellar system is 160 pc, and the angular resolution of the model maps is 5\(^\circ\). The contour limits and interval for each centroid map are (in km/s) a) -0.1 to 0.1 by 0.01, b) -0.1 to 0.1 by 0.01, and c) -0.3 to 0.3 by 0.05.

Contours of the centroid velocity plots of Model B were also found to be insensitive to azimuth angle. Only the low-level structure of contours in the equatorial plane showed a sensitivity to azimuth angle. The total velocity gradient across the centroid velocity map was 30% greater when the binary axis was parallel to the observer's line of sight than when the axis was perpendicular to the observer's line of sight. In the case of Model C, the central contours on the redshifted side of the centroid velocity map showed a greater extension to the east when the binary axis was parallel to the observer's line of sight. The velocity gradient across the map was insensitive to azimuth angle. The rotational velocity field associated with
the most dense component of a binary system has a minimum projected velocity when the observer's line of sight is parallel to the binary axis. Therefore, the larger velocity gradient observed toward Model B and the greater elongation of redshifted contours in the velocity centroid map of Model C have a direct relationship to the structure of the infall velocity field.

These model results indicate the unambiguous detection of infall toward binary systems becomes more difficult as the separation between the members increases. The ability to detect infall is not significantly affected by the orbital position of the binary members.

2.3.8. Sensitivity of Infall Signatures to Molecular Abundance and Turbulent Velocity

The assumption of a constant molecular abundance throughout the protostellar core is probably unrealistic. For example, observations by Walker, Carlstrom, and Bieging (1991; 1993) suggest that toward IRAS 16293 the relative abundance of CS to H$_2$ ([CS]) may be a factor of 100 less in the protostellar core than in outflow material. Ammonia also appears to be underabundant in the core material (Mundy et al. 1986). In order to test the sensitivity of our results to variations in molecular abundance, we ran a suite of models with a radial abundance variation. The value of [CS] was allowed to decrease linearly from a value of $1 \times 10^{-9}$ at the core edge, to a value of $1 \times 10^{-11}$ at the core center. A CS J=2→1 spectral mosaic and centroid velocity plot were then generated. Due to lower line center optical depths, the CS J=2→1 spectra no longer look self-absorbed and asymmetric. The classic spectral infall signature of Figures 1.1 is not observed. However, the corresponding velocity centroid plot does possess the “blue-bulge” infall signature. These results suggest that for single stars and close binary systems, the “blue-bulge” in the velocity
centroid maps is a more robust infall signature than the classic line asymmetry.

The only other free parameter in our models is the turbulent velocity, $v_{turb}$. Observations of molecular cloud cores have yielded the power law correlation $\Delta v \propto \rho^{-1/2}$ for the nonthermal component of molecular line widths (Solomon & Sanders 1985, Dame et al. 1986, Myers 1987, Scoville et al. 1987). This correlation has been expressed by Lizano and Shu (1989) in the form $v_{turb} = (\kappa/\rho)^{1/2}$, where $\kappa$ is an observationally determined proportionality constant. Estimates of $\kappa$ in the literature are mean values for an entire cloud core. The radial dependence of $\kappa$ in a collapsing cloud core is unknown, but $\kappa$ is expected to be substantially less in collapsing cores than observationally derived mean values (Zhou 1992).

For simplicity, we have used a constant $v_{turb} = 0.5$ km/s in our models. This value of $v_{turb}$ provides a good match between our model line profiles and observations of IRAS 16293 and other young stellar systems. To test the sensitivity of our results to the value of $v_{turb}$, we made a series of model runs with $v_{turb} = 0.1$ km/s. The resulting line profiles, although much narrower, still show the classic infall line asymmetry as well as the blue-bulge in the velocity centroid maps. These results suggest that while the choice of $v_{turb}$ affects the line profiles, the spectroscopic signatures of infall are fairly insensitive to the value of $v_{turb}$.

2.4. Summary

We have combined the 3-D collapse models of Boss (1993) with a flexible LTE radiative transfer code and modeled the millimeter/submillimeter-wave CS, HCO$^+$ and dust emission from collapsing, rotating protostellar systems. The principal results of the study are:
1. The morphology of the molecular line and dust emission is a strong function of collapse time. Initially, CS and HCO+ lines appear Gaussian and uniform across the model map. Soon after the onset of collapse, the increased central density results in brighter CS and HCO+ and dust emission toward the center of the cloud core. As the line opacity increases, the line profiles become self-absorbed and asymmetric. The sense of the symmetry (i.e. which side of the line profile is brighter) varies with the line of sight through the core and is directly traceable to a combination of rotation and infall velocity fields.

2. Centroid velocity maps can be used to detect the presence of infall in the vicinity of protostellar sources. If only a rotational velocity field is present, then a centroid velocity map will show blueshifted emission on one side of the rotation axis and redshifted emission on the opposite side. However, if infall is occurring, blueshifted emission may be observed across the rotational axis on what would otherwise be the redshifted side of the map. This “blue-bulge” of emission becomes more prominent 1) towards the end of the initial collapse phase and 2) at disk inclinations > 0°. Indeed, if it were not for the presence of molecular outflows, the optimum orientation of a protostellar disk for the detection of infall motions would be pole-on. WNB (1994) suggested that the “blue-bulge” should be detectable toward 1 M☉ protostars with the current generation of millimeter-wave interferometers. With the corrected numerical code presented in this chapter, it appears that the “blue-bulge” should be detectable even by using the current generation of single-dish submillimeter telescopes. Since the blue-bulge occurs preferentially in the equatorial plane of a protostellar system, it may be observable even if the protostar under study possesses a molecular outflow.
3. The appearance of line profiles and the resulting centroid velocity maps is a strong function of the angular resolution used to perform the observations. Indeed, a rotational transition of CS and HCO+ may appear as an emission line in a large single dish beam and show little evidence for the presence of infall, while in the much smaller beam of an interferometer a redshifted absorption line (clearly indicating the presence of infalling gas) would be observed. These large variations in the line profile appearance are due to the small angular size of the infall region.

4. The unambiguous detection of infall toward binary systems becomes more difficult with increasing binary separation. The greater the separation between binary stars, the smaller becomes the blue-bulge in the velocity centroid contours. However, the blue-bulge is still more prominent than infall asymmetries in the line profiles. The ability to detect infall is not significantly affected by the orbital position of the binary members.

5. There is observational evidence that some molecular species, e.g. CS, may be underabundant in high density cloud cores. Due to this phenomenon, in some collapsing cloud cores the CS opacity may be too low for the classic self-absorbed, asymmetric infall line profile to be formed. However, in such instances, it may still be possible to detect collapse from the "blue-bulge" infall signature. The formation of both the line asymmetry and blue-bulge infall signatures appears to be fairly insensitive to the degree of turbulence present in a cloud core.

While it is possible to detect infall in nearby protostellar sources with an angular resolution of ~ 15 to 30 arcseconds, higher angular resolution data of the same objects make line asymmetries resulting from infall more pronounced and
are useful in differentiating between the effects of infall, outflow, and rotation. In general, the higher the angular and spectral resolution of the observations, the better the chances of detecting the presence of infall. For low mass, nearby objects like the ones discussed here (1 to 2 $M_\odot$), an angular resolution of $\leq 20''$ and a spectral resolutions of $\sim 0.1$ km/s are required to study the region of infall. These angular and spectral resolutions are achievable with the current generation of millimeter-wave interferometers and single-dish submillimeter telescopes.
CHAPTER 3

THEORETICAL RADIATIVE TRANSFER MODELS FOR THE DETECTION OF INFALL
- THE SEMI-ANALYTIC TSC MODELS

3.1. Introduction

Theoretical models of star formation depend critically on the rotation rate of an evolving core (Shu et al. 1987). The relative contribution of systematic mass motions from rotation, outflow, infall and turbulence will change as a molecular cloud core evolves to form a star. The identification of rotation and determining its velocity law in protostellar objects are important in testing various models of star formation. In the current paradigm of star formation, the star accretes most of its mass from the disk rather than directly from infall. Rotation naturally leads to the formation of accretion disks. Observations of interstellar molecular clouds have shown that dense cores, the precursors of protostars, are mostly slow rotators (Arquilla & Goldsmith 1985, Myers et al. 1991). Rotation thus seems to play a
rather unimportant role in the earliest stages of star formation. However, in the late stages of star formation, due to the spin-up accompanying protostellar collapse, it is expected that rotation will become dynamically important. Because rotation and collapse motions are coupled, it is necessary to study them together to understand their observational consequences.

Adelson and Leung (1988) studied the process of line formation in spherically symmetric clouds with rotation and radial motion (expansion or contraction). In the course of their study, they identify isovelocity centroid velocity maps as the best way to distinguish rotation from radial motion. There have been several studies of line formation in a spherically symmetric cloud core undergoing only infall motions (e.g. Walker et al. 1986, Zhou 1992, Choi et al 1995). More recently, Zhou (1995) presented radiative transfer models of collapsing clouds with rotation using the semianalytic formalism of the Terebey, Shu and Cassen (1984; hereafter TSC) model. WNB (1994) studied the line formation in nonspherical, three-dimensional, hydrodynamic models of rotating and collapsing clouds. They predicted a set of observational properties of such systems at different stages of evolution.

In Chapter 2, we extended the WNB analysis and presented line profiles and maps of submillimeter molecular emission for protostellar models that used the hydrodynamical collapse simulations of Boss (1993) as the starting point. While being completely “self-consistent”, this approach suffers one major drawback. The large number of time steps needed in the Boss models typically requires weeks of CPU time (Boss 1993). Thus, this approach is not ideal for fitting real observations because of the computational time requirements in obtaining better fits.

In this chapter, we lay the foundation for fitting the observations of protostellar collapse in later chapters. We present radiative transfer calculations of emergent
spectra from the semi-analytic solutions of TSC. The TSC solution of protostellar collapse has the advantage that it is computationally less expensive to obtain output line profiles. Using the precalculated curves of TSC, we are better able to explore a larger volume of parameter space and generate source specific models. We extended the flexible radiative transfer code presented in the Chapter 2 to study the TSC solution of infall as well. In addition, using our radiative transfer code, we derive model centroid velocity maps and explore the sensitivity of the “blue-bulge” infall signature to rotational rate, infall time, sound speed, and abundance gradients in the molecular tracer of choice.

3.2. Numerical Methods

The TSC model is a semianalytic perturbational solution for the collapse of a slowly rotating cloud core. The initial (unstable) equilibrium state is exact and corresponds to the uniformly rotating analog (constant rotational rate, $\Omega$) of the singular isothermal sphere (see Shu 1977). If we denote the sound speed by $a$, then TSC (1984) define the turnover radius, $r_c = a/\Omega$, where the sound speed is equal to the rotational speed. The equilibrium state has a density profile that is proportional to $1/r^2$ in its inner regions (for $r < r_c$) and attaches smoothly to a uniform background in the outer regions, a plausible approximation for a molecular cloud core and its surrounding envelope. The angular momentum increases outward, and rotational support is small compared to gas pressure support for $r < r_c$.

To motivate this discussion with a numerical example, let us use $a = 0.35 \, \text{km} \, \text{s}^{-1}$ and $\Omega = 1 \times 10^{-14} \, \text{s}^{-1}$, giving $r_c = a/\Omega = 3.5 \times 10^{18} \, \text{cm}$. For a singular isothermal sphere where pressure gradients balance self-gravity everywhere, the
density profile can be shown to be,

$$\rho(r) = \frac{a^2}{2\pi G r^2} \quad (3.1)$$

(Chandrasekhar 1939). The mass contained within a radius $R$, then would be given by

$$M(R) = \int_0^R \rho(r)4\pi r^2 dr = \frac{2a^2 R}{G}. \quad (3.2)$$

The radius $R$ containing $M(R) = 1M_\odot$ would be $R = 5.4 \times 10^{16}$ cm, which is smaller than $r_c$. The collapse of this mass of gas would try to produce a protostellar system, whose radial extent for centrifugal balance, in the absence of angular momentum distribution, would be $r_d = \Omega^2G^3M^3/16a^8 = 6.4 \times 10^{12}$ cm, where $r_d$ is denoted as the centrifugal radius, and sets a possible size scale for the protostellar accretion disk (TSC 1984). It can be seen that $r_d$ is much smaller than the dimensions of the initial molecular cloud. Thus, over a wide range of scales, $r_c \gg r \gg r_d$, rotation may be considered a small effect. For a clean separation of scales, $r_d \ll r_c$, giving

$$\Omega \ll \frac{(16)^{1/3}a^3}{GM} \approx 2.6 t_{acc}^{-1}, \quad (3.3)$$

where the accretion time $t_{acc}$ to build up the central mass is given by $M/\dot{M}$, with $\dot{M} = 0.975a^3/G$ for the collapse of a singular isothermal sphere (Shu 1977). In other words, the cloud envelope should rotate only by a small fraction of a full turn in the time that the collapse of the cloud occurs. For the specific numerical case we considered, the rotational period is $\sim 20$ million years, while the accretion time scale is just $\sim 1 \times 10^5$ years, justifying the assumption that rotation is not significant for $r_d \ll r \ll r_c$.

This initial equilibrium state is unstable to core collapse, and hence, star (and disk) formation starts taking place. To zeroth order, the collapse can be described by the non-rotating solution found by Shu (1977). In this solution, the collapse
begins at the center of the cloud and moves outward as successive spherical layers of gas lose pressure support from below. The TSC solution follows the evolution of collapse in time as a perturbative analysis of the non-rotating similarity solution. The TSC solution has inner limiting forms that attach smoothly to existing solutions for the buildup of protostars (Stahler et al. 1980) and protostellar disks (Cassen & Moosman 1981). Their calculations thus provide a self-consistent description of the dynamical collapse of a rotating molecular cloud core, and a framework for the study of the formation of stars and nebular disks.

The TSC model has the three free parameters: the sound speed $a$, the rotational rate $\Omega$, and the infall time $t$ (or infall radius $r_{in} = at$). In the TSC formalism, collapse proceeds in the same way as the inside-out collapse of Shu (1977), except for a rotational perturbation of the order of $\tau^2$ ($\tau = \Omega t$). Once rotation is added as a perturbation, it modifies the spherical collapse in many ways, because the expansion wave travels into a moving medium. If we use a spherical coordinate system $(r,\theta,\phi)$ as shown in Figure 2.1a, the rotational perturbation on top of spherical collapse has the following effects: (1) It distorts the spherical expansion wave; (2) it modifies the density distribution; (3) it modifies the radial infall velocity; (4) it induces a velocity in the $\theta$ direction and (5) it adds a rotational component to the velocity field. Below we examine each of these terms in more detail, and then outline a recipe for generating a three-dimensional grid populated with TSC solution parameters. The following treatment closely follows the TSC approach used by Zhou (1995).

1. Rotation has a negligible effect on the distortion of the expansion wave front of spherical collapse. The relative distortion is given by TSC as the term, $\tau^2 \Delta Q$, where $\Delta Q = -3.52 \times 10^{-4}$. Here $\Delta Q$ is the aspherical distortion term of the expansion wave front due to the effects of rotation, and was obtained
by numerical integration of ordinary differential equations describing collapse in the presence of a rotational perturbation (TSC 1984). Hence for $r < 1$, the shape of the infall region differs by less than $10^{-3}$ from a perfect sphere. Shu (1977) introduces the similarity variable of radial collapse, $x = \frac{r}{\alpha}$, where $x$ is the size of the infall region. In the TSC model, the effect of rotation is to stretch this into a new similarity variable,

$$y = x \left[1 + \tau^2 \Delta Q P_2(\cos \theta)\right], \quad (3.4)$$

where $P_2$ is the second-order Legendre polynomial. For most combinations of $\Omega$ and infall time, $t$, we can consider the size of the infall region in similarity variable $y \approx x$.

2. The density in the TSC model is given by

$$\rho = \frac{1}{4\pi G t^2} \left\{\alpha_0(y) + \tau^2 [\alpha_M(y) + \alpha_Q(y)P_2(\cos \theta)]\right\}. \quad (3.5)$$

The first term, $\alpha_0$ is the same as the density solution of Shu 1977. The second term is the correction to the Shu collapse. All three $\alpha$'s are plotted in Figure 3 of TSC. In Figure 3.1, we show the evolution of radial number density profile with time of a sample TSC cloud core. The number density profile for five successive time steps are shown. The density profile is asymptotic to a power-law variation of $r^{-1.5}$ for $r < r_{\text{inf}}$, and steepens to a $r^{-2}$ power-law for $r > r_{\text{inf}}$. Furthermore, we see that the density reduces with time evolution, as successive layers of gaseous mass are added to the central protostar.

This picture is in marked contrast to the evolution of density in the Boss (1993) numerical models (see Figure 2.2), that treated the accumulation of a pre-protostellar clump by collapse. In the Boss hydrodynamical model, the central density was seen to increase with time. The difference arises because
the two solutions treat two different regimes of the problem of collapse of a molecular cloud core to a protostar. The Boss models are a solution for the accumulation of a cloud core with envelope from a molecular cloud clump. The TSC solution starts with this accumulated cloud core and envelope and using realistic assumptions, treats the collapse to a protostar surrounded by an accretion disk.

![Graph showing the evolution of the radial number density profile towards a TSC cloud core.](image)

Figure 3.1 Evolution of the radial number density profile towards a TSC cloud core. The radial variation of number density with distance in cm is shown for five successive time steps. The assumed parameters were $a = 0.5 \text{ km s}^{-1}$, $\Omega = 1 \times 10^{-13} \text{s}^{-1}$. The times corresponding to the infall radii of 0.01, 0.02, 0.03, 0.04 and 0.05 pc are $1.96 \times 10^4$, $3.93 \times 10^4$, $5.89 \times 10^4$, $7.86 \times 10^4$, and $9.82 \times 10^4$ years respectively.

3. The radial velocity in the TSC collapse model is

$$u_r = a \left\{ V_0(y) + \tau^2 \left[ V_M(y) + V_Q(y) P_2(\cos \theta) \right] \right\},$$

(3.6)

where the term $V_0(y)$ is the solution of Shu 1977. All three $V$'s are plotted in
Figure 4 of TSC. Over the range of $0.01 < y < 10$, the velocity perturbation is less than 10% of the sound speed (for $\tau < 0.1$), so its effect on the line profiles should be small, except in extreme cases of large $\tau$ and small $y$.

4. The velocity in the $\theta$ direction is given by

$$u_\theta = a r^2 W_Q(y) \frac{d}{d\theta} [P_2(\cos \theta)],$$

(3.7)

where $W_Q(y)$ is plotted in Figure 4 of TSC. The $u_\theta$ term is similar in magnitude to the perturbation term of the radial velocity.

5. The rotational component of the velocity ($u_\phi$) appears in the form of specific angular momentum, $\Gamma$ in the TSC solution:

$$\Gamma = (\Omega/a^2)(r \sin \theta) u_\phi = \tau^2 [0.5 m_0(y) \sin \theta]^2,$$

(3.8)

from which we can derive,

$$u_\phi = \frac{a \tau}{x} [0.5 m_0(y)]^2 \sin \theta.$$  (3.9)

In the above, $m_0(y)$ is the reduced mass interior to $y$, with $m_0(0) = 0.975$ being the reduced mass that has already fallen onto the core at the onset of collapse (Shu 1977).

To illustrate the variation of the TSC velocity fields with radius, we show the velocity profiles of a sample TSC cloud core in the equatorial plane in Figure 3.2. The radial infall velocity $u_r$ is seen to be almost 2 orders of magnitude larger than the rotational velocities in the inner radii. It can also be seen that the $\theta$ component of velocity is negligible in the equatorial plane. The rotational component, $u_\phi$, decreases with radii for most radii. For $r > r_c$, $u_\phi$ increases due to the solid body rotation of the cloud envelope. Figure 3.3 shows the spatial distribution of velocity...
fields \((u_r, u_\theta, u_\phi)\) in one quadrant of the same TSC model as shown in Figure 3.2. As was seen in the numerical Boss models (Figure 2.4), the radial infall velocities dominate other velocity components through most regions of the infalling core.

![Figure 3.2 Velocity Profiles in the equatorial plane for a TSC cloud core. The assumed parameters are \(a = 0.5 \, \text{km s}^{-1}, \, \Omega = 1 \times 10^{-13} \, \text{s}^{-1}\), and \(r_{in} = 0.03 \, \text{pc}\). (a) Variation of radial infall velocity, \(u_r\) is shown in solid lines, and rotational velocity, \(u_\phi\) is shown in dashed lines. (b) Variation of \(u_\theta\).](image)

In our radiative transfer calculations, the three free parameters that are input to the code are \(a\), \(\Omega\), \(r_{in}\) (which in turn sets the time since onset of collapse, \(t = t_{in}/a\)). The numerical resolution used in all our TSC models is \(N_r = 50\), \(N_\theta = 22\) for \(\pi/2 \geq \theta \geq 0\), and \(N_\phi = 64\) for \(0 \leq \phi \leq 2\pi\). At each of the grid points \((r, \theta, \phi)\) we generate the velocity field \((u_r, u_\theta, u_\phi)\), the temperature \(T\) and the density \(\rho\) as described below. At each grid point, we calculate \(x\) for every \(r\), and \(y\) for every \(r\) and \(\theta\). We use a look-up table (kindly provided to us by Susan Terebey from their TSC results). The lookup table contains the value of the coefficients, \(\alpha_0, \alpha_M, \alpha_Q, V_0, V_M, V_Q, W_Q\) and \(m_0\) as a function of the similarity variable \(x\) (for \(0 \leq x \leq 1.8\)). We calculate \(\rho\), \(u_r\), \(u_\theta\), and \(u_\phi\) for every grid point using the value of \(x\), the interpolated values of the coefficients from the look-up table, and equations (3.5) through (3.9). The temperature distribution is setup as a radial power law, \(T(r) = T_1 (r/0.01 \, \text{pc})^{-\beta}\). Different values of \(T_1\) and \(\beta\) were explored in our analysis.
Figure 3.3 Spatial distribution of TSC Velocity fields. Velocity fields for a model TSC core with the following parameters: $a = 0.5 \, \text{km s}^{-1}$, $\Omega = 1 \times 10^{-13} \, \text{s}^{-1}$, and $r_{inj} = 0.03 \, \text{pc}$. The $\hat{y}$-$\hat{z}$ quadrant with $\phi = 90^\circ$ is shown (also refer Figure 2.1). $u_r$ is shown in solid contours from 0 to 3.3 by 0.2 $\, \text{km s}^{-1}$, $u_\theta$ is shown in dashed contours from 0 to 0.03 by 0.005 $\, \text{km s}^{-1}$, and $u_\phi$ is shown in dotted contours from 0 to 0.45 by 0.025 $\, \text{km s}^{-1}$. The contour limits are based on maximum velocities for each component. The map is shown in normalized units, with one map unit representing a linear distance of $2.4 \times 10^{15}$ cm.

of line profiles and maps from the TSC solution.

Once we generate the physical conditions in our protostellar grid for a given model run, the problem of deriving line profiles and maps becomes the same as that described in Chapter 2. The effect or orientation to our LOS is treated by rotating the model protostar by an angle $\psi$ in the plane of the sky, and an angle $\alpha$ out of the plane of the sky (see Figure 2.1). Several different lines of sight are taken, and the protostar is “digested” and line of sight conditions recorded. A separate LTE radiative transfer code (for details see Chapter 2) then uses the LOS information to derive molecular and dust continuum emission toward the model TSC core.

The TSC models were run on the University of Arizona SGI Origin2000 system.
Each model run typically takes ~ 2 hours for 360 lines of sight (a 60" × 60" region centered on the protostar).

3.3. Model Results

3.3.1. Assumptions and Initial Conditions

The emergent spectra from 80 different model TSC protostellar systems were studied. For the model results discussed in this chapter, a fixed spatial resolution of $1.2 \times 10^{16}$ cm was chosen. At the distance of the Rho Ophiuchi molecular cloud (160 pc), the resulting angular resolution is ~ 5". The effect of varying the input parameters such as $\Omega$, $a$, $r_{inf}$, the temperature gradient, molecular abundance were studied in detail, and results are summarized below. For the radiative transfer analysis we have assumed a CS to H$_2$ abundance ratio of $1 \times 10^{-9}$, HCO+ to H$_2$ abundance ratio of $3 \times 10^{-10}$, and a turbulent velocity of 0.5 km/s. Leung (1978) showed that in the presence of systematic and turbulent velocities, the crucial parameter defining the emergent line profile is the ratio $\gamma = |V_{los}/v_{turb}|$, where $V_{los}$ is the projection of the systematic velocity along a line-of-sight. For $\gamma > 3$, the effect of turbulent velocity is small in line formation, and geometrical effects determined by the form of the velocity law play a major role in line formation.

For most regions in the TSC solution for a collapsing core, systematic velocities in the form of collapse and rotation velocities dominate over turbulent velocities, and hence the choice of $v_{turb}$ is not crucial. The effective spectral resolution in the radiative transfer code is taken to be 0.05 km s$^{-1}$. In the earliest phases of collapse the density of the cloud cores is just sufficient ($n_0 \approx n_{crit}$) to thermalize the lowest transitions of CS and HCO+. In the later stages of collapse, the ambient density is much greater than the critical density of most of the chosen transitions ($n_0 > n_{crit}$).
justifying the assumption of LTE.

### 3.3.2. Line Profiles

The dipole moment of HCO+ is more than twice that of CS (Monteiro 1985). As a result, one would expect the HCO+ line asymmetries generated by collapsing gas to be more pronounced than those observed in CS lines. We modeled HCO+ line emission to study the effect of evolution in the protostellar core on the emergent line profiles. In an effort to aid in the selection of the best molecular transitions for the detection of infall, we choose one millimeter HCO+ transition (J=1\rightarrow 0) and one submillimeter HCO+ transition (J=4\rightarrow 3). Figures 3.4 to 3.7 contain mosaics of the HCO+ J=4\rightarrow 3 (solid line) and J=1\rightarrow 0 (dashed lines) emission at four different times during the collapse of a protostellar system. For a cloud core at a temperature of 40 K, the appropriate speed of sound, \(a\) is \(\sim 0.4 \text{ km s}^{-1}\). However, if we include the effects of turbulence and magnetic pressure, it could drive up the value of \(a\) (Shu et al. 1987). In most of our simulations, we use \(a = 0.5 \text{ km s}^{-1}\). We take \(\Omega = 3 \times 10^{-13} \text{s}^{-1}\), or \(10 \text{ km s}^{-1} \text{pc}^{-1}\). The temperature gradient is assumed to be \(T \sim 30(r/0.01 \text{pc})^{-1.0}\). Figures 3.4 through to 3.7 are for infall radii of 0.0025, 0.015, 0.03 and 0.06 pc (or for times of 5000, 30000, 59000, and 118000 yrs since the onset of collapse) respectively.

In Figure 3.4, the HCO+ J=1\rightarrow 0 spectra in the center appear gaussian and symmetric. However, even at this early time (5000 yrs), the submillimeter HCO+ J=4\rightarrow 3 line profiles have already started showing some structure. Both lines are centrally peaked. Towards the central positions, the HCO+ J=4\rightarrow 3 lines are starting to get self-absorbed. However, the self-absorbed J=4\rightarrow 3 line profiles are still symmetric, showing no obvious sign of infall or rotation. From Figure 3.5 we see that in another 25,000 yrs, the "classic" asymmetric blue profile of signature
Figure 3.4 Spectral Evolution of a TSC Cloud Core, $r_{\text{in}} = 0.0025$ pc. HCO+ $J=4\rightarrow3$ emission lines are solid. The HCO+ $J=1\rightarrow0$ lines are shown dashed. The model protostellar system is being viewed edge-on. Only northern hemisphere lines of sight are shown. The southern hemisphere spectra are a mirror image of the northern hemisphere spectra. Angular offsets from the center of the protostar are indicated. The infall parameters for this model are $a = 0.5$ km s$^{-1}$, $\Omega = 3 \times 10^{-13}$ s$^{-1}$, with a temperature gradient of $T = 30(r/0.01\text{pc})^{-1.0}$. The equivalent angular resolution of the spectra is $5''$. The mosaic corresponds to an infall radius of 0.0025 pc, i.e., to a time $\sim 5000$ yrs since the onset of collapse.

Figure 3.5 Spectral Evolution of a TSC Cloud Core, $r_{\text{in}} = 0.015$ pc. The mosaic corresponds to a time $\sim 30,000$ yrs since the onset of collapse. See Figure 3.4 for other details.
Figure 3.6 Spectral Evolution of a TSC Cloud Core, $r_{in} = 0.03$ pc. The mosaic corresponds to a time $\sim 59,000$ yrs since the onset of collapse. See Figure 3.4 for other details.

Figure 3.7 Spectral Evolution of a TSC Cloud Core, $r_{in} = 0.06$ pc. The mosaic corresponds to a time $\sim 118,000$ yrs since the onset of collapse. See Figure 3.4 for other details.
has started to manifest itself in the $J=4\rightarrow3$ lines. We also see evidence for rotation in that the blue asymmetry in the $J=4\rightarrow3$ lines is more pronounced on the western half. The $J=1\rightarrow0$ lines are still symmetric. The Einstein A coefficient, $A_u$, goes as $\nu^3$, where $\nu$ is the frequency of the line. Hence, submillimeter lines will have higher Einstein A coefficient, and hence higher opacity than millimeter lines. Thus, at early evolutionary stages, submillimeter observations are more effective in detecting infall than millimeter observations. By 60,000 yrs (see Figure 3.6), even the $J=1\rightarrow0$ lines start becoming asymmetric. By this time, the evidence of infall and rotation are clearly seen in the HCO+ $J=4\rightarrow3$ mosaic. At late stages (see Figure 3.7), the $J=4\rightarrow3$ lines actually exhibit a red asymmetry in the eastern half as rotation becomes more and more significant due to rapid spin-up in the central regions.

Figure 3.8a and 3.8b show the spectral evolution of the CS $J=7\rightarrow6$ line toward the central position of a model with lower initial rotational rate than shown in Figures 3.4 to 3.7. We use $\Omega = 1 \times 10^{-13} \text{s}^{-1}$. Even with this lower rotational rate, the effect of infall is not seen in the CS lines till 0.03 pc ($t = 5.89 \times 10^4$ yrs). Figure 3.8a shows the spectral evolution as seen through the equatorial plane, and 3.8b shows the same time sequence as seen from the pole. At each time step, it is seen that the infall signature is more prominent in a pole-on view. The rotational velocity field is cancelled out in the pole-on line-of-sight.

The central densities achieved in the Boss (1993) models presented in Chapter 2, tend to be several orders of magnitude higher than those in the TSC models. Because of the lower central densities in the TSC model, the dust opacity is not high enough to cause a significant increase in the continuum level towards the central positions. This in turn prevents the formation of the inverse P-cygni profiles seen quite commonly in our model results in Chapter 2 (see for e.g. Figure 2.11).
address this weakness in the TSC models, we ran a few models, with a power law density profile which resulted in higher central densities. The velocity fields were derived from the TSC formalism. For such models, we do get red-shifted absorption and inverse P-cygni profiles in the emergent emission.
3.3.3. Centroid Velocity Maps

Figure 3.9a through 3.9e show the centroid velocity maps of HCO+ J=4→3 emission toward a model TSC core at five different collapse times. The angular resolution of the maps corresponds to 14″ at the distance of Rho Ophiuchi. This angular resolution can be matched by observations made with the 15 m diameter JCMT submillimeter telescope. The “blue-bulge” signature of infall presented in WNB and Chapter 2 is clearly seen in the centroid velocity maps. It is seen that with increasing time, the “blue-bulge” become less prominent, as rotational support in the equatorial regions becomes more and more important. Referring to Figure 2.12 in Chapter 2, and Figure 3.9, we can see a continuum of the centroid velocity morphology from the Boss models to the TSC models. The Boss (1993) models start as pre-protostellar clumps with very high central densities. The earliest Boss models (see Figure 2.12a) show pure rotation only in the centroid velocity maps. They then evolve into a rotating collapsing protostar, which exhibit the “blue-bulge” signature. In the earliest TSC models, we see the “blue-bulge” signature. In the TSC models, in the latest stages of evolution, as a result of centrifugal support of material entering the accretion disk, the effects of infall are slowed down by rotation. With high angular resolution observations, it may be possible to see this centrifugal deceleration of infalling material in the embedded accretion disk.

As in Chapter 2 (see Figure 2.13), we present centroid velocity maps as a function of inclination: pole-on (Figure 3.10a), at 45°(Figure 3.10b), and edge-on (Figure 3.10c). At 45° the blue-bulge is more pronounced than in the edge-on case. As seen before, the pole-on line of sight gives concentric blue-shifted contours in the centroid velocity map (owing to the projected rotational velocity going to zero).
Figure 3.9 Evolution of centroid velocity plots. The maps were computed from the \text{HCO}^+ J=4\rightarrow3 \text{ emission lines of a model TSC cloud core. The assumed distance to the protostar is 160 pc. The offsets are in arcseconds. The effective angular resolution of the maps is 14". In the plots, blueshifted velocity contours are dashed and redshifted velocity contours are solid. The infall parameters for this TSC solution are } a = 0.5 \text{ km s}^{-1}, \Omega = 1 \times 10^{-13} \text{s}^{-1}, \text{ with a temperature gradient of } T' = 30(r/0.01\text{pc})^{-1.0}. \text{ The infall radius } (r_{\text{in}}) \text{ is indicated for each centroid plot, and correspond to times of: a) } 1.96 \times 10^4 \text{ yrs b) } 3.93 \times 10^4 \text{ yrs c) } 5.89 \times 10^4 \text{ yrs d) } 7.86 \times 10^4 \text{ yrs and e) } 9.82 \times 10^4 \text{ yrs since the onset of collapse. The contour limits and intervals for each plot are (in km/s); a) -0.04 to 0.04 by 0.005, b) -0.08 to 0.06 by 0.01, c) -0.12 to 0.06 by 0.02, d) -0.17 to 0.08 by 0.02, and e) -0.2 to 0.1 by 0.025.}

3.3.4. Position Velocity Maps

Plotting the line profile as a function of position (in a "cut" or strip) in the form of a contour map gives a position velocity map or the so-called strip map. Position velocity maps are frequently used in outflow literature to demonstrate the bipolar nature of many outflows (e.g. Bally & Lada 1983). Ohashi et al. (1997) use position velocity maps to infer the presence of rotation and infall in interferometric maps of CO emission toward L1527. Theoretical models have shown that one can distinguish between expansion and rotation using position velocity maps (Adelson
Figure 3.10 Effect of inclination on velocity centroid plots. The velocity centroids were computed from the HCO+ J=4→3 emission lines of the model presented in Figure 3.9 at $r_{inj} = 0.03$ pc ($t = 5.89 \times 10^4$ yrs). The central $30'' \times 30''$ is shown. The effective angular resolution of the maps is $14''$. Blueshifted velocity contours are dashed lines and redshifted contours are solid lines. The contour limits and intervals for the polar line of sight (top panel) are -0.1 to 0 by 0.01 km/s. For the 45° line of sight (center panel) the contours are from -0.12 to 0.05 by 0.015 km/s. The contours for the equatorial line of sight (bottom panel) are from -0.12 to 0.06 by 0.015 km/s.

In the previous section, we showed the effectiveness of centroid velocity maps in probing and distinguishing the kinematic motions associated with rotation and infall. Here we derive position velocity maps of submillimeter emission from the TSC models. In Figures 3.11 and 3.12, we show the position velocity maps obtained with a cut along the equatorial axis and the rotational axis of the models presented in Figure 3.9. The maps are obtained for HCO+ J=4→3 emission with an effective angular resolution of 14''. It is seen that as time proceeds, the peak emission shifts to negative velocities in both cuts of the position velocity maps. We do not see the
Figure 3.11 Evolution of position velocity plots: Equatorial Cut. The position velocity maps were computed from the HCO$^+$ J=4→3 emission lines of the model TSC cloud core shown in Figure 3.9 by taking a cut perpendicular to the rotational axis (p.a. of 90°). The effective angular resolution of the maps is 14". The infall parameters for this TSC solution are $a = 0.5$ kms$^{-1}$, $\Omega = 1 \times 10^{-13}$ s$^{-1}$, with a temperature gradient of $T = 30(r/0.01pc)^{-1.0}$. The infall radius ($r_{inf}$) is indicated for each position velocity plot, and correspond to times of: a) $1.96 \times 10^4$ yrs b) $3.93 \times 10^4$ yrs c) $5.89 \times 10^4$ yrs d) $7.86 \times 10^4$ yrs and e) $9.82 \times 10^4$ yrs since the onset of collapse. The contour limits and intervals for each plot are (in K); a) 5 to 40 by 4, b) 5 to 35 by 4, c) 5 to 35 by 4, d) 5 to 35 by 4, and e) 5 to 30 by 4.

Figure 3.12 Evolution of position velocity plots: Rotational Axis Cut. The position velocity maps were computed from the HCO$^+$ J=4→3 emission lines of the model TSC cloud core shown in 3.9 by taking a cut along the rotational axis (p.a. of 0°). All other details and contour limits are similar to that shown in Figure 3.11.
skewing we expect from rotational velocities in the equatorial cut. The rotational rate, \( \Omega = 1 \times 10^{-13} \text{s}^{-1} \) is possibly too small to show the effect of rotation in the position velocity maps of Figures 3.11 and 3.12. In Figures 3.13 and 3.14, we show the equatorial and rotational axis cuts for models with a higher rotational rate, \( \Omega = 3 \times 10^{-13} \text{s}^{-1} \). Here, the effect of rotation is clearly seen in the skewing of the contours in the equatorial cut. In the polar cut (see Figure 3.14), the effect of rotation is cancelled out. The position velocity maps also show the effect of evolution on the morphology of the position velocity maps. Thus, using two cuts in orthogonal directions, it is possible to see the effect of rotation and infall. However, we see that centroid velocity maps in providing complete information in two spatial dimension and one velocity dimension are a more effective way of disentangling the combined motions of infall and rotation. In cases, where the rotational axis and position of the protostar is well known, position velocity maps obtained by performing strip maps can provide a good first look.

### 3.3.5. Effect of Rotational Rate

Surveys have found evidence that dense clouds have prolate shapes and appreciable rotation (Myers et al. 1991, Goodman et al. 1992). Prolate cores with rotation could lead to fragmentation that leads to the formation of binaries and multiple stellar systems (Boss 1993). What is the effect of the rotational rate on the emergent emission from protostellar systems? To answer this question, we ran a suite of models by varying \( \Omega \). Figure 3.15 shows the centroid velocity maps and central spectra towards four different model cores. All models are at the same epoch of collapse \((t = 5.89 \times 10^4 \text{ yrs})\), have the same temperature gradient and effective velocity of sound, \( a \). While the central spectrum shows no dramatic change with \( \Omega \), the centroid velocity maps show considerable variation. When \( \Omega \) is very small,
Figure 3.13 Evolution of position velocity plots. Higher Rotation: Equatorial Cut. The position velocity maps were computed from the HCO+ J=4→3 emission lines of a model TSC cloud core by taking a cut perpendicular to the rotational axis (p.a. of 90°). The effective angular resolution of the maps is 14". The infall parameters for this TSC solution are $a = 0.5 \text{ km s}^{-1}$, $\Omega = 3 \times 10^{-13} \text{s}^{-1}$, with a temperature gradient of $T = 30(r/0.01\text{pc})^{-1}$. The infall radius ($r_{inf}$) is indicated for each position velocity plot, and correspond to times of: a) $4.9 \times 10^5$ yrs b) $1.96 \times 10^4$ yrs c) $5.89 \times 10^4$ yrs d) $9.82 \times 10^4$ yrs and e) $1.18 \times 10^5$ yrs since the onset of collapse. The contour limits and intervals for each plot are (in K): a) 5 to 60 by 5, b) 0 to 40 by 0, c) 5 to 35 by 4, d) 5 to 30 by 3, and e) 5 to 30 by 3.

Figure 3.14 Evolution of position velocity plots. Higher Rotation: Rotational Axis Cut. The position velocity maps were computed from the HCO+ J=4→3 emission lines of the model TSC cloud core shown in 3.13 by taking a cut along the rotational axis (p.a. of 0°). All other details and contour limits are similar to that shown in Figure 3.13.
blueshifted velocities due to infall completely dominate the centroid velocity map (see Figure 3.15a). At high rotational rates, the “blue-bulge” signature is no longer evident (see 3.15d). Figure 3.15 thus shows the importance of mapping in constraining the combined effects of rotation and infall.

A corollary point from our analysis is that the classic, asymmetric blue line profile towards the center of the object remains a robust indicator of infall, independent of the rotational rate in the cloud. Walker et al. (1986) suggested an infall interpretation towards IRAS 16293, based on the asymmetric blue line profiles towards the driving source. This interpretation was later brought into question by Menten et al. (1987), who showed evidence for rotation in the core. Does the presence of rotation in a cloud core make the interpretation of infall questionable based on the classic asymmetric line profile? Figure 3.15 suggests that it does not. Towards the center of the object, the effects of rotation are seen to approximately cancel out in the line profile, and the classic, blue asymmetric line profile signature of infall is seen to remain unaffected by the presence of rotation. The effects of rotation can best be seen only in the centroid velocity maps.

3.3.6. The “Polar Blue-Bulge” Signature

In Figure 3.16a, we present the variation of radial velocity of collapse and rotational velocity (denoted $u_{r,E}$ and $u_{\phi,E}$ respectively) in the equatorial plane as a function of distance from the rotational axis for a TSC protostellar core with the following infall parameters: $a = 0.5 \text{ km s}^{-1}$, $\Omega = 1 \times 10^{-13} \text{s}^{-1}$, $r_{inf} = 0.05 \text{ pc}$. Also shown in the same plot is the variation of radial velocity and rotational velocity (denoted $u_{r,H}$ and $u_{\phi,H}$ respectively) in a cutout plane parallel to the equatorial plane, and at a height of 32" from the equatorial plane. The height of 32" of this plane (henceforth referred to as the “half-plane”) corresponds to 0.025 pc at a distance of 160 pc.
Figure 3.15 Effect of Rotational Rate. The velocity centroid maps were computed from the HCO$^+ \ J=4\rightarrow3$ emission at $r_{\text{inj}} = 0.03$ pc ($t = 5.89 \times 10^4$ yrs). The sound speed was set to $a = 0.5$ km s$^{-1}$. The rotational rate, $\Omega$ for each model run is shown. Also shown below each centroid velocity map is the spectrum towards the central position. The effective angular resolution of the model runs is 14". Blueshifted velocity contours are dashed lines and redshifted contours are solid lines. The contour limits and intervals (in km s$^{-1}$) are: a) -0.04 to 0.01 by 0.005, b) -0.1 to 0.05 by 0.01, c) -0.24 to 0.2 by 0.03, and d) -0.46 to 0.42 by 0.05.
This is the half height of the assumed edge of our model run. It is seen that in the equatorial plane, the radial velocity of infall is an order of magnitude greater than the rotational velocity over the inner radii of the protostellar core. The rotational velocity becomes supersonic at small radii. The radius at which the rotational velocity is equal to the infall velocity is called the centrifugal radius and sets the size scale for the accretion disk. It can be shown that this radius is \( R_c = r_d = \frac{\Omega_c r^3}{16} \).

With the parameters given above, we derive \( r_d \approx 60 \) AU. For \( r \gg r_d \), the rotational velocity takes on the characteristics of rigid body rotation of the parent molecular cloud. For \( r < r_d \), the rotational velocity is Keplerian. However in the "half-plane", it can be seen that the rotational velocity decreases by several orders of magnitude for small axial distances when compared to the rotational velocity in the equatorial plane. In addition, the rotational velocity component in the "half-plane" shows no Keplerian component. Also, the radial infall velocity in this high latitude plane is seen to be reduced somewhat, but not as drastically as the decrease in the rotational velocity component. Thus, in the polar regions, the radial infall velocity dominates rotational velocities by a much larger extent than in the equatorial regions.

A consequence of this velocity structure can be seen in the centroid velocity maps made with our radiative transfer program. In Figure 3.16b, we present a model centroid velocity map made with CS J=7→6 emission toward the protostellar core with the parameters outlined above. Also, shown in gray scale is the integrated intensity map. While the integrated intensity map shows no pronounced flattening, the morphology of the centroid velocity map shows considerable structure. The blueshifted velocities appear to encroach, to a small extent, eastward of the north-south rotational axis into a region which would be expected to be only redshifted in a pure rotation scenario. This encroachment is an expected signature of infall (see WNB and Chapter 2). However, the extent of encroachment is
Figure 3.16 TSC Velocity Fields and the "Polar Blue-Bulge" Centroid Velocity Signature. (a) Model TSC Velocity fields. The assumed infall parameters for the model cloud core are $a = 0.5 \text{ km s}^{-1}$, $\Omega = 1 \times 10^{-13} \text{ s}^{-1}$, and $r_{in} = 0.05 \text{ pc}$. The variation of radial infall velocity, $u_{r,E}$ with radial distance in the equatorial plane is shown in heavy dashed lines. The corresponding rotational velocity in the equatorial plane, $u_{\phi,E}$, is shown in heavy solid lines. Also shown is the variation of $u_{r,H}$ (shown in dashed lines) and $u_{\phi,H}$ (shown in solid lines) in the half-plane. All quantities are shown in similarity coordinates. (b) Model Integrated intensity and centroid velocity maps made with CS $J=7\rightarrow 6$ emission toward a collapsing cloud with parameters shown in a. The integrated intensity is shown in grayscale and is plotted from 5 to 52 by 4 K-$\text{km s}^{-1}$. The centroid velocity plot is shown in the dashed and solid line contour map. Blueshifted emission is shown with dotted lines and redshifted emission is shown with solid lines. The rotational axis is North-South through the center of the map. The contours for the centroid velocities extend from $-0.25$ to 0.11 by 0.025 $\text{km s}^{-1}$. The effective angular resolution of the model run is 5"
somewhat more in the polar region than in the equatorial region. We call this new morphological signature, the "polar blue-bulge".

A qualitative explanation for the "polar blue-bulge" can be derived from the velocity structure of the protostellar cloud presented in Figure 3.16a. The ratio of radial infall velocity to rotational velocity increases with increasing height above the equatorial plane. In addition, because of Keplerian rotation and centrifugal braking, close to the equatorial plane, the ratio of infall velocity to rotational velocity gets smaller with decreasing axial distances. The combination of these two factors produces a blue bulge on either side of the equatorial plane. The angular resolution of the model maps shown in Figure 3.16b (5") can be achieved with the current generation of interferometers and the planned SMA submillimeter array. The centrifugal radius of ~60 AU derived above for this model corresponds to ~0.4" at the distance of Rho Ophiuchi. Our modeling indicates that with smaller values of $r_d$, and inclinations of the rotational axis away from the most favorable angle of 90° to the line of sight assumed in this particular model, the "polar blue-bulge" does get less prominent. However, the "polar blue-bulge" signature appears more pronounced with increasing angular resolution. Although not sufficient proof for Keplerian rotation, we suggest that the presence of the "polar blue-bulge" morphology in centroid velocity maps of protostellar objects can be used as evidence for rotational support in the inner regions of the infalling cloud core. Recently, using other lines of evidence, Ohashi et al. (1997) have shown observational evidence for dynamically infalling envelopes with small rotation. We suggest that the "polar blue-bulge" signature is a powerful new technique to detect underlying structures with Keplerian rotation in an embedded cloud core. A more detailed study of the "polar blue-bulge" signature will be presented in a future paper (Narayanan and Walker 1997).
3.3.7. Effect of Molecular Abundance on the Infall Signature

The sensitivity of the infall signature to abundance of the molecular species was examined by varying its abundance. Figure 3.17 shows CS J=7→6 centroid velocity maps and central spectra for 5 different values of CS abundance towards the same model protostellar system. With increasing abundance, we see that the “classic” self-absorbed asymmetric blue line profile signature of infall gets more prominent. The morphology of the “blue-bulge” signature also appears to be a function of the value of molecular abundance. We see that for low values of CS abundance (see Figure 3.17a), the centroid velocity maps are tracing the “polar blue-bulge” signature much better than for higher values of CS abundance (see for e.g. Figure 3.17e). Lower CS abundances gives lower optical depth for a given line-of-sight. Hence the molecular emission traces material closer towards the center of the system. At an abundance of [CS/H₂] = 1.0 × 10⁻⁷ (see Figure 3.17e), the CS lines get optically thick much quicker in the outer layers of the cloud core. Hence, the centroid velocity maps are not very sensitive to the high rotational velocities in the inner regions. By mapping in two isotopic transitions (one optically thick and the other optically thin), we can effectively probe both the inner and outer regions of the cloud core (Zhou 1995).

We also examined the effect of radial variation in molecular abundance. Models where the abundance increases from inside-out in a linear fashion, show deep self-absorbed asymmetric line profiles, but the “polar blue-bulge” signature appears washed out. Models that have decreasing abundance from inside-out show a strong “polar blue-bulge” signature, but the line profiles have a less pronounced self-absorption dip, and frequently show the “red-shoulder” asymmetric line profile (see Myers et al. 1995 for observational examples of the asymmetric “red-shoulder
Figure 3.17 Effect of Molecular Abundance on the appearance of CS J=7→6 spectra and velocity centroid maps. Both the velocity centroid maps and the central spectrum are for TSC models with $\Omega = 1 \times 10^{-13} \text{s}^{-1}$, $r_{\text{inf}} = 0.05 \text{pc}$ ($t = 9.82 \times 10^4 \text{yrs}$), $a = 0.5 \text{km s}^{-1}$, temperature gradient of $T = 30(r/0.01 \text{pc})^{-0.4}$, and the CS abundances shown in each panel. The angular resolution of the model runs is 5″. The contour limits and interval for each centroid map are (in km s$^{-1}$) a) -0.2 to 0.12 by 0.025, b) -0.21 to 0.15 by 0.025, c) -0.3 to 0.1 by 0.025, d) -0.35 to 0.08 by 0.025, and e) -0.51 to 0.08 by 0.025.

3.3.8. Effect of Sound Speed

The parameter $a$ in the TSC model is the "characteristic" velocity of infall. In the inside-out model of collapse, $a$ sets the speed at which the head of the self-similar wave of collapse propagates outward (Shu et al. 1987). This in turn sets the speed at which the protostellar system evolves. To test the effect of the effective speed
of sound in the evolution of cloud core, we performed three model runs with three different values of $a$, 0.1, 0.5 and 0.75 km s$^{-1}$. The runs were performed for the same time since the onset of collapse ($t = 5.89 \times 10^4$ yrs). The cloud with $a = 0.1$ km s$^{-1}$ (see Figure 3.18a) shows almost no evolution. The line profiles are gaussian and symmetric. The centroid velocity maps show a "counter-rotation" in that redshifted emission is more on the western side (see Figure 3.18a). This was also seen by Zhou (1995) in models at very early times. It is simply an optical depth effect and arises predominantly from the outer envelope. For larger $a$, we see that the cloud has evolved considerably and shows both the "blue-bulge" in the centroid velocity maps and the "classic" asymmetric blue line profile signature (see Figures 3.18b and 3.18c).

3.4. Summary

We have extended the three-dimensional LTE radiative transfer code presented in Chapter 2 to predicting millimeter and submillimeter molecular line emission from the semi-analytic TSC model for collapse with rotation. Such models can be useful in constraining the infall parameters of real protostellar systems from the observed millimeter and submillimeter molecular emission. Our principal results for this study are the following:

1. The morphology of the molecular line emission is a strong function of collapse time. Submillimeter transitions are better than millimeter transitions in detecting infall at early collapse times.

2. Centroid velocity maps can be used to disentangle the kinematic motions associated with infall and rotation. The "blue-bulge" signature of infall was shown to be much more robust, with changes in infall parameters, than the
Figure 3.18 Effect of Sound Speed, \( a \) on the evolution of CS \( J=7 \rightarrow 6 \) spectra and velocity centroid maps. Velocity centroid maps and the central spectrum are for TSC models with \( \Omega = 1 \times 10^{-13} \text{s}^{-1} \), temperature gradient of \( T = 30(r/0.01 \text{pc})^{-1.0} \). The time since the onset of infall is fixed at \( 5.89 \times 10^4 \) yrs and the sound speed was set to \( a = 0.1 \text{ km s}^{-1} \) (a), \( a = 0.5 \text{ km s}^{-1} \) (b), and \( a = 0.75 \text{ km s}^{-1} \) (c). The angular resolution of the model runs is \( 5'' \). The contour limits and interval for each centroid map are (in \( \text{km s}^{-1} \)) (a) \(-0.06 \) to \(0.06\) by \(0.005\), (b) \(-0.1 \) to \(0.06\) by \(0.01\), and (c) \(-0.2 \) to \(0.1\) by \(0.025\).

"classic" asymmetric blue profile signature of infall. In observed cases, where only orthogonal "strips" of spectra were obtained, position velocity maps can provide a good first look at disentangling rotation and infall.

3. Using model centroid velocity maps obtained with high angular resolution, we presented the "polar blue-bulge" - a powerful new morphological signature for detecting underlying structures with Keplerian rotation in an embedded cloud core. For clouds with lower rotational rate, or for lower angular resolution observations, the normal "blue-bulge" signature is seen.
4. The appearance of the line profiles and resulting centroid velocity maps is a strong function of the abundance of the molecule under consideration. By mapping in two transitions, one optically thick and the other optically thin, we can constrain the kinematic properties of both the protostellar core and the outer envelope.

5. The effective speed of sound has considerable effect in the evolution of the protostellar cloud core and in the resulting appearance and morphology of molecular emission.

From our results in this chapter, we propose that single-dish submillimeter observations can be used to survey for the “blue-bulge” signature of infall. Recent surveys based on the asymmetric blue line profile signature of infall (Gregersen et al. 1997, Mardones et al. 1997) might have missed many prospective candidates for infall. In addition, by constraining the observed mapping data with the TSC models presented in this chapter, we will be able to obtain the infall parameters of real protostellar systems. Higher angular resolution observations can be used to probe for the “polar blue-bulge” signature of Keplerian rotation. In the next two chapters, we will present observational identification of the predicted “blue-bulge” and “polar blue-bulge” signature towards real protostellar systems.
CHAPTER 4

THE 'BLUE-BULGE' INFALL SIGNATURE TOWARD IRAS 16293-2422

4.1. Introduction

Over the past decade IRAS 16293-2422 (hereafter, IRAS 16293) has been the subject of intense observational scrutiny. It is located in the eastern streamer region of the Rho Ophiuchus molecular cloud complex, is enshrouded in a cold, dense dust and molecular gas core, and possesses an unusual quadrupolar outflow (Walker et al. 1986, Mundy et al. 1986, Wootten and Loren 1987, Walker et al. 1988). The extremely high column densities observed toward IRAS 16293 and the ellipticity of the high resolution 2.7 mm maps of Mundy et al. (1992) and Walker, Carlstrom & Bieging (1993, hereafter WCB) suggest IRAS 16293 is being viewed through an edge-on disk. The interferometric observations of Wootten (1989), Mundy et al. (1992), and Walker et al. (1993) indicate IRAS 16293 may be a protobinary system. The first observational study of this source by Walker et al. (1986) provided spectroscopic evidence that IRAS 16293 is still in the infall phase of evolution.
From a microturbulent analysis of CS emission profiles and the spectral energy distribution of the object, they derived an infall radius of $10^{16}$ cm, an accretion rate of $5 \times 10^{-6} M_\odot$ yr$^{-1}$, and a central object mass of $0.24 M_\odot$. The mass of the infall region was estimated to be $\sim 0.1 M_\odot$. Subsequent observations of the source by Menten et al. (1987) using the IRAM 30 m showed the object was undergoing rotation. They suggested that the presence of rotation would make the detection of infall toward the object difficult. However, papers by Adelson and Leung (1988), Walker, Narayanan, and Boss (1994, hereafter WNB) and Zhou (1995) have shown that even in the presence of rotation, infall is detectable along the central line of sight toward protostars.

In an optically thick transition, an infalling core is expected to exhibit the "classic" self-absorbed, double-peaked, asymmetric line profile with the blue peak stronger than the red peak (see §1.2.1 for a qualitative explanation). The amount of blue asymmetry would depend on the optical depth of the transition and the infall velocity field. In the optically thin limit, the line profile would be expected to be symmetric about the rest velocity of the cloud. With increasing optical depth, the blue asymmetry would become more pronounced. In the past, this "classic" asymmetric blue profile has been used to deduce infall towards IRAS 16293 and other sources (Walker et al. 1986, Zhou et al. 1993, Zhou 1995, Myers et al. 1995, Ward-Thompson et al. 1996). By observing the line profiles towards the central positions in dense cores of at least two isotopic species, one optically thick and the other optically thin, we can identify promising candidates using this technique.

However other motions like outflow and rotation could also produce an asymmetric blue profile. To unambiguously identify infall it is not sufficient
to obtain spectra in the central positions alone. Adelson and Leung (1988) demonstrated the usefulness of isovelocity centroid maps in disentangling the effects of rotation and infall. In Chapters 2 and 3, we found the ‘blue-bulge’ infall signature, seen in centroid velocity maps, to be more robust than the classic asymmetric line profile signature used by earlier authors. As long as the emission line remained optically thick, the ‘blue-bulge’ infall signature was found to be relatively insensitive to both variations in molecular abundance and the assumed source inclination. Most importantly, the blue-bulge occurs along the protostar’s equatorial axis, perpendicular to the rotation axis and the direction of molecular outflow. The anti-correlation in the directions of the blue-bulge and the outflow may increase the detectability of infall in sources simultaneously experiencing outflow and infall.

In this chapter, we perform a centroid velocity analysis on new, high quality CS and HCO+ maps of IRAS 16293. We report the detection of the “blue-bulge” infall signature in new CSO CS $J=5\rightarrow4$, $J=7\rightarrow6$ and HCO+ $J=4\rightarrow3$ transitions towards IRAS 16293. To confirm this detection and to study the dependence of the infall signature on angular resolution, we performed follow-up observations in the CS $J=7\rightarrow6$ and HCO+ $J=4\rightarrow3$ transitions using the JCMT, and in the HCO+ $J=3\rightarrow2$ transition using the HHT. In §4.2, we describe the observations. In §4.3, we present the results with some analysis. In §4.4, we discuss results of 3-d radiative transfer models based on the rotating, collapse solution of Terebey, Shu and Cassen (1984; hereafter TSC). We present the model results for IRAS 16293 and constrain the infall parameters. Finally, in §4.5, we summarize the results.
4.2. Observations

4.2.1. CSO Observations

We present a summary of all our observations in Table 4.1. Our CS observations were made using the Caltech Submillimeter Observatory (CSO)\(^1\) in June 1995. We mapped a 70\" x 70\" region centered on IRAS 16293 in the CS J=5→4 and CS J=7→6 transitions. The mapping was performed using the On-The-Fly (OTF) mapping technique, where the antenna was scanned in a rectangular grid centered on the source. Systematic errors such as pointing are considerably reduced by the use of the OTF mapping technique. The center of our maps is at \( \alpha (1950) = 16^h 29^m 20.9^s \), \( \delta (1950) = -24^\circ 22' 13'' \). The OTF map data was then gridded into 49 positions with a spacing of 10\". Seventeen OTF maps were made in the CS J=5→4 transition and averaged to get to \( \sim 0.12 \) K rms noise level in the resulting spectra. Thirty one OTF maps were made in the CS J=7→6 transition and averaged to get to \( \sim 0.20 \) K rms noise level in the resulting spectra. Pointing was verified between maps. Overall pointing uncertainty was estimated to be less than 3\". Position-switched observations were also made in the isotopic \(^{34}\)S CS J=5→4 transition towards the central position to perform column density calculations.

Towards the central position of IRAS 16293, CSO HCO+ J=4→3 observations were carried out in May 1996. In addition, observations were made in the isotopic \(^{13}\)CO+ J=4→3 transition. We also present new spectra in the \(^{32}\)S CS J=10→9 transition towards the central position of IRAS 16293. The J=10→9 observations were carried out in April, 1992. All observations were made with low-noise SIS

\(^1\)The CSO is operated by the California Institute of Technology under funding from the National Science Foundation, Contract No. AST-93-13929.
waveguide receivers (Kooi et al 1992, Ellison et al. 1989, Walker et al 1992) and a 1000 channel, 50 MHz wide acousto-optical spectrometer. The main beam efficiency at 230 GHz is ~ 0.76, at 345 GHz ~ 0.65 and at 490 GHz ~ 0.5. Calibration of observations was done by the chopper wheel technique. All spectra and maps are presented in terms of $T_A^*$. 

Table 4.1. Observations.

<table>
<thead>
<tr>
<th>Telescope</th>
<th>Transition</th>
<th>Frequency (GHz)</th>
<th>Beam Size (&quot;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSO</td>
<td>C^32S J=5→4</td>
<td>244.935606</td>
<td>30</td>
</tr>
<tr>
<td>CSO</td>
<td>C^34S J=5→4</td>
<td>241.016176</td>
<td>30</td>
</tr>
<tr>
<td>CSO</td>
<td>C^32S J=7→6</td>
<td>342.882949</td>
<td>22</td>
</tr>
<tr>
<td>CSO</td>
<td>C^34S J=7→6</td>
<td>337.396602</td>
<td>22</td>
</tr>
<tr>
<td>CSO</td>
<td>C^32S J=10→9</td>
<td>489.751125</td>
<td>15</td>
</tr>
<tr>
<td>CSO</td>
<td>H^{13}CO+ J=4→3</td>
<td>356.734256</td>
<td>21</td>
</tr>
<tr>
<td>CSO</td>
<td>H^{13}CO+ J=4→3</td>
<td>346.998540</td>
<td>22</td>
</tr>
<tr>
<td>JCMT</td>
<td>C^32S J=7→6</td>
<td>342.882949</td>
<td>15</td>
</tr>
<tr>
<td>JCMT</td>
<td>H^{12}CO+ J=4→3</td>
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<td>14</td>
</tr>
<tr>
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<td>15</td>
</tr>
<tr>
<td>HHT</td>
<td>H^{13}CO+ J=3→2</td>
<td>267.557625</td>
<td>28</td>
</tr>
</tbody>
</table>

4.2.2. JCMT Observations

HCO+ J=4→3 observations were also carried out at the James Clerk Maxwell Telescope (JCMT)\(^2\) in March 1996. Two OTF maps were made, centered on the

\(^2\)The James Clerk Maxwell Telescope is operated by the Royal Observatories on behalf of the United Kingdom Particle Physics and Astronomy Research Council.
same position as the CSO observations. The two maps were averaged together to yield an rms noise level of ~ 0.6 K. The JCMT HCO+ J=4→3 maps were gridded into 169 positions with a spacing of 5". Position-switched observations towards the central position of IRAS 16293 were made in the H^{13}CO+ J=4→3 transition. The rms uncertainty in the resultant H^{13}CO+ J=4→3 spectrum is ~ 0.25 K. In addition, one OTF map was made in the CS J=7→6 transition with a resulting rms uncertainty of ~ 0.8 K in the spectra. Position switched observations of CS J=7→6 with a resulting rms of 0.3 K were also obtained. For the CS observations, the local oscillator frequency was chosen to put the CS J=7→6 line in the lower sideband, and the CO J=3→2 transition in the upper sideband. The CO observations are not presented in this paper. All JCMT observations were carried out with the facility B3i single channel lead-alloy SIS receiver (Cunningham et al. 1992). The spectrometer backend used was the Dutch Autocorrelation Spectrometer (DAS) configured to operate with an effective resolution of 95 kHz and total bandwidth of 125 MHz. The main beam efficiency of the JCMT was measured to be 0.56 at 345 GHz. Calibration of observations was done by the chopper wheel technique. All spectra and maps are presented in terms of T^*_A.

4.2.3. HHT Observations

HCO+ J=3→2 observations were carried out at the 10 m Heinrich Hertz Telescope (HHT)^3 in March, 1997. Forty-eight high signal-to-noise spectra were obtained in a 30" × 30" region of IRAS 16293 with a 10" angular separation on the sky. The the Netherlands Organization for Scientific Research and the Canadian National Research Council.

^3The HHT is operated by the Submillimeter Telescope Observatory (SMTO), and is a joint facility for the University of Arizona's Steward Observatory and the
system temperature during the observations was \( \sim 400 \) K. The rms noise level of the resulting spectra is \( \sim 0.05 \) K. Observations were carried out using the facility 245 GHz receiver (Walker et al. 1996), and a 2048 channel 1 GHz AOS from MPIfR with an effective resolution of 1 MHz per channel. The main beam efficiency of the HHT was measured to be 0.74 at 245 GHz. Calibration of observations was done by using hot-sky-cold chopper measurements. All spectra and maps are presented in terms of \( T^*_A \).

4.3. Results

4.3.1. Mapping Results

*Spectral Mosaics*

In Figures 4.1 and 4.2, we present spectral mosaics of the CS \( J=5\rightarrow4 \) and \( J=7\rightarrow6 \) observations made at the CSO. The JCMT HCO+ \( J=4\rightarrow3 \) observations are shown in Figure 4.3. HHT HCO+ \( J=3\rightarrow2 \) observations are shown in Figure 4.4. The positional offsets from the IR source position are shown in the outer box. Only the central square arcminute of the OTF data are presented in the spectral mosaics. As in previous observations made in lower transitions of CS, the CS \( J=5\rightarrow4 \) and \( J=7\rightarrow6 \) emission is seen to be peaking toward the IRAS position. The HCO+ emission is also seen to be centrally peaked.

The CS \( J=5\rightarrow4 \) spectra in Figure 4.1 show a self-absorption feature that is spatially extended. A careful analysis shows the velocity at which the self-absorption occurs has very little systematic variation across the emission region.

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Figure 4.1 Mosaic of the CSO CS $J=5\rightarrow 4$ spectra. Angular offsets in RA and Dec from the central IR source of IRAS 16293 are shown in the outer box. For each spectrum, the displayed velocity extent is $-2$ to $10$ km s$^{-1}$, and the temperature range is $-0.5$ to $3$ K.

Figure 4.2 Mosaic of the CSO CS $J=7\rightarrow 6$ spectra. Angular offsets in RA and Dec from the central IR source of IRAS 16293 are shown in the outer box. For each spectrum, the displayed velocity extent is $-2$ to $10$ km s$^{-1}$, and the temperature range is $-0.5$ to $6$ K.
Figure 4.3 Mosaic of the JCMT HCO+ J=4→3 spectra. Angular offsets in RA and Dec from the central IR source of IRAS 16293 are shown in the outer box. For each spectrum, the displayed velocity extent is $-2$ to $10$ km s$^{-1}$, and the temperature range is $-4$ to $25$ K.

Figure 4.4 Mosaic of the HHT HCO+ J=3→2 spectra. Angular offsets in RA and Dec from the central IR source of IRAS 16293 are shown in the outer box. For each spectrum, the displayed velocity extent is $-2$ to $10$ km s$^{-1}$, and the temperature range is $-1.5$ to $12$ K.
The self-absorption feature has a constant velocity of $4.2 \pm 0.1 \text{ km s}^{-1}$ with a FWHM linewidth of $\sim 0.6 \text{ km s}^{-1}$. A similar self-absorption feature is seen in CS $J=3\rightarrow2$ and $J=2\rightarrow1$ emission (Menten et al. 1987, WCB 1993). The above result suggests that the self-absorption in the $J=5\rightarrow4$ transition is occurring in a cold, spatially extended, outer envelope surrounding a hot compact cloud core (see below). The asymmetry of the $J=5\rightarrow4$ line profiles exhibits considerable variation across the source. Blue asymmetry in the line profile dominates most of the emission region. The spectra in the north and west of the IRAS position show stronger blue asymmetry than in the south and east. A few spectra in the southeast show symmetric profiles. The CS $J=3\rightarrow2$ and $J=2\rightarrow1$ spectral profiles toward IRAS 16293 change the sign of asymmetry from blue to red across the source (Menten et al. 1987, WCB 1993). Rotation can account for the change in the sense of asymmetry across the position of the central object. In a pure rotation model, however, the emission toward the central position should be symmetric, and the sense of asymmetry in the line profile would flip across the rotational axis. In a pure infall model, all spectra would possess blue asymmetry. In a real protostar, one expects to see a combination of rotation and infall velocity fields. In such an instance, one expects the blue asymmetry in the line profile to dominate along lines of sight to the protostar, and rotation to dominate elsewhere (see for e.g. Zhou 1995, WNB).

The CS $J=7\rightarrow6$ emission seen in Figure 4.2 is more centrally concentrated than the $J=5\rightarrow4$ emission. Most of the central CS $J=7\rightarrow6$ spectra exhibit a blue peak with a red shoulder, consistent with the infall interpretation discussed above. The lack of significant self-absorption in the $J=7\rightarrow6$ emission indicates that the outlying gaseous layers responsible for the absorption in lower $J$ transitions are not sufficiently warm and dense enough to populate the $J = 6$ level to a density where
significant photon trapping can occur.

The HCO+ J=4→3 spectra in Figure 4.3 show deep self-absorption features and considerable blue asymmetry throughout the region. The ubiquity of the self-absorbed, blue asymmetry suggests that at low velocities, the HCO+ J=4→3 and CS J=5→4 transitions are primarily sensitive to cold, infalling gas. A careful analysis of the velocity of the self-absorption in each line shows no gradients across the region. Both the HCO+ J=4→3 and CS J=5→4 spectral mosaics show a decrease of blue asymmetry from north to south. The velocity and FWHM of the self-absorption dips are similar in both transitions. However, we see that the HCO+ J=4→3 lines exhibit much deeper self-absorption than the CS J=5→4 lines. The self-absorption dip in HCO+ J=4→3 almost reaches the zero level at most places in the region.

The HHT HCO+ J=3→2 spectra in Figure 4.4 also show deep self-absorption features. However, we see that while the spectra in the northwest show considerable blue asymmetry, the J=3→2 lines in southeastern quarter of the nebula appear to be symmetric or in many cases show red asymmetry. In this respect, the HCO+ J=3→2 observations seem to be more similar to the CS J=2→1 and CS J=3→2 observations toward IRAS 16293 where the asymmetry flips across the rotational axis (Menten et al. 1987, WCB 1993). Along the line of sight to the cloud core, lower transitions of CS and HCO+ will become optically thick much faster at the outer edges of the cloud core, and are thus expected to be less sensitive to the region of infall. In these lines, the infall induced blue asymmetry will be less pronounced and less spatially extended.

To summarize this subsection, the appearance of the CS J=5→4, J=7→6, and HCO+ J=4→3, J=3→2 spectral mosaics are consistent with the interpretation that
the IRAS 16293 cloud core is experiencing both infall and rotational motions. This interpretation will be tested using a 3-dimensional radiative transfer code in §4.

*Integrated Intensity Maps*

In Figure 4.5, we present the integrated intensity maps in CS $J=5\rightarrow4$, HCO+ $J=3\rightarrow2$, CS $J=7\rightarrow6$, and HCO+ $J=4\rightarrow3$ emission based on the spectra of Figures 4.1 – 4.4. For each transition, we present integrated intensity maps in three velocity bins (blueshifted wing: $-2$ to $2 \, \text{km} \, \text{s}^{-1}$; line core: $2$ to $6 \, \text{km} \, \text{s}^{-1}$; redshifted wing: $6$ to $10 \, \text{km} \, \text{s}^{-1}$). The line core map is shown in grayscale, the blueshifted emission is shown in heavy dashed contours, and the redshifted emission is shown in solid contours. The positions of the two VLA sources detected by Wootten (1989) are marked with two stars in all the maps presented in Figure 4.5. One VLA source (1629a) lies southeast of the IRAS position. The other source (1629b) lies to the northwest of this position.

From Figure 4.5a, we see that the emission in the line core of the CS $J=5\rightarrow4$ shows a small ellipticity with the major axis oriented with a position angle of $\sim 140^\circ$. The elongation of the line core emission is similar in orientation to the elongated, flattened structure traced by the 3 mm dust continuum maps made toward IRAS 16293 (Mundy et al. 1986, Mundy, Wootten, and Wilking 1990, WCB 1993). The peak of the low velocity CS emission is displaced toward 1629b as was the case in the dust continuum maps. The appearance of the line core emission of density sensitive tracers reported in this paper (also see below) is consistent with an origin from dense gas that is coexistent with the dust traced by continuum emission. Emission from the line wings of CS $J=5\rightarrow4$ has a more complicated morphology. The centroid of the blueshifted and redshifted line wing emission is coincident with
the line core emission region. In addition, Figure 4.5a shows a multilobed structure for the line wing emission further away from the IRAS position.

Observations of CO $J=1\rightarrow0$ and $J=2\rightarrow1$ toward IRAS 16293 have revealed a molecular outflow structure that breaks up into four lobes (Walker et al. 1988, Mizuno et al. 1990). Two redshifted lobes designated northeastern red ("NER") and western red ("WR"), and two blueshifted lobes designated southwestern blue ("SWB") and eastern blue ("EB") were observed in CO emission. In addition, combined interferometric and single-dish observations in CS $J=2\rightarrow1$ revealed that the CS was tracing clumpy, shell-like structures that appear to be limb-brightened emission from the dense gas at the perimeter of the CO outflow (Walker et al. 1990). The appearance of the $J=5\rightarrow4$ emission suggests that the line wings in this transition may be tracing some of the dense, shell-like clumpy gas at the perimeter of the outflow detected in CS $J=2\rightarrow1$ by Walker et al. (1990).

The line core emission of HCO$^+$ $J=3\rightarrow2$ is more extended than in the case of CS $J=5\rightarrow4$ (see Figure 4.5b). As in CS $J=5\rightarrow4$, the peak of the line core emission is displace toward 1629b. While there is some evidence for an elongation orthogonal to the outflow outflow axis, the line core emission in HCO$^+$ $J=3\rightarrow2$ also appears to be somewhat extended in the direction of outflow. As in CS $J=5\rightarrow4$, the line wings of HCO$^+$ $J=3\rightarrow2$ seem to trace the multiple outflow lobes of the IRAS 16293 system. The appearance of the $J=3\rightarrow2$ emission suggests that the line wings and to a smaller extent, the line core of HCO$^+$ $J=3\rightarrow2$ is affected by outflow. Another drawback of our HCO$^+$ $J=3\rightarrow2$ observations is the relatively coarse velocity resolution we obtain with the HHT backend spectrometer ($\sim 1$ km s$^{-1}$). Hence, in later sections, we will not use the HCO$^+$ $J=3\rightarrow2$ observations in detailed modeling of the IRAS 16293 system.
Figure 4.5 Integrated Intensity Maps toward IRAS 16293. Blueshifted wing emission (−2 to 2 km s$^{-1}$) is shown in heavy dashed contours, line core emission (2 to 6 km s$^{-1}$) is shown in grayscale, and redshifted emission (6 to 10 km s$^{-1}$) is shown in solid contours. The central square arcminute is shown for each transition. In all four panels, the positions of the two VLA sources detected by Wootten (1989) are marked in the maps with stars. The southeastern source, 1629a, is marked A, while the northwestern source, 1629b, is marked B. (a) Integrated intensity maps of the CSO CS J=5→4 emission. The contour levels are 0.2 to 0.4 by 0.05 K·km s$^{-1}$ for the blueshifted emission, 2 to 6 by 0.5 K·km s$^{-1}$ for line core emission, and 0.3 to 0.6 by 0.05 K·km s$^{-1}$ for redshifted emission. (b) Integrated intensity maps of the HHT HCO+ J=3→2 emission. The contour levels are 1 to 2.5 by 0.2 K·km s$^{-1}$ for the blueshifted emission, 10 to 25 by 4 K·km s$^{-1}$ for line core emission, and 3 to 5 by 0.4 K·km s$^{-1}$ for redshifted emission. (c) Integrated intensity maps of the CSO CS J=7→6 emission. The contour levels are 0.5 to 2 by 0.25 K·km s$^{-1}$ for the blueshifted emission, 5 to 14 by 2.5 K·km s$^{-1}$ for line core emission, and 0.5 to 2.25 by 0.25 K·km s$^{-1}$ for redshifted emission. (d) Integrated intensity maps of the JCMT HCO+ J=4→3 emission. The contour levels are 5 to 20 by 2 K·km s$^{-1}$ for the blueshifted emission, 10 to 40 by 5 K·km s$^{-1}$ for line core emission, and 4 to 15 by 2 K·km s$^{-1}$ for redshifted emission.
Figure 4.5c shows the integrated intensity maps of CS J=7→6 emission toward IRAS 16293. The line core emission has a small ellipticity, with a similar position angle as that observed in the J=5→4 transition. The J=7→6 line core emission appears more compact than the corresponding J=5→4 emission. The blueshifted and redshifted emission peaks occur within 5" of the IRAS position and the two VLA positions. In addition, we see that the blueshifted lobe and redshifted lobe of emission are displaced along the major axis of the elongated cloud core. A similar displacement was observed in the optically thick line emission of 13CO J=1→0 and interpreted as rotation (Mundy et al. 1986). We also note that the CS J=7→6 line wings do not seem to be coincident with the outflow lobes traced by the CS J=5→4 or HCO+ J=3→2 line wings. The appearance of the line wing emission in J=7→6 is consistent with it arising primarily from a disk-like, rotating flattened structure.

Although having a similar elongation, the line core emission in the JCMT HCO+ J=4→3 observations (see Figure 4.5d) is more extended than the corresponding CSO J=7→6 emission. In addition, the positional displacement of the blueshifted and redshifted lobes along the major axis of the flattened structure is more pronounced in HCO+ J=4→3 than in CS J=7→6. Similar to CS J=7→6, the HCO+ line wing emission appear to be unaffected by the presence of the outflow.

Figure 4.5 shows that blueshifted line wing emission is displaced to the north in both CS J=7→6 and HCO+ J=4→3 with respect to redshifted line wing emission. This situation is reversed in the case of CS J=5→4 and HCO+ J=3→2 emission with blueshifted line wing emission appearing stronger in the south. In addition, the lobes of the blueshifted and redshifted line wing emission of HCO+ J=4→3 and CS J=7→6 are seen to be displaced along the major axis of the flattened, elliptical cloud core. The lower transitions of CS and HCO+ have a lower critical density.
and hence seem to trace the dense shell features of outflow in line wing emission. On the other hand, the morphology of the maps (Figure 4.5c and d) suggests that submillimeter transitions of CS and HCO+ seem to be unaffected by outflow even in the line wings. This suggests that while CS $J=5\rightarrow4$ and HCO+ $J=3\rightarrow2$ line wing emission primarily traces the dense clumps of outflow lobes, the CS $J=7\rightarrow6$ and HCO+ $J=4\rightarrow3$ line wing emission arises primarily from a rotating, circumbinary, disk-like structure (Mundy, Wootten, and Wilking 1990) that is orthogonal to the outflows. In any case, the emission from the low velocity material in the line core of three transitions (CS $J=5\rightarrow4$, $J=7\rightarrow6$, and HCO+ $J=4\rightarrow3$) appear to originate in the circumbinary disk, and to be relatively unaffected by outflow.

### Centroid Velocity Maps

The centroid velocity of a line profile is that velocity at which the integrated intensity (the area under the line profile) is equal on either side. Centroid velocity maps have been shown to be a better tool in the detailed study of complicated velocity fields than integrated intensity plots (Adelson & Leung 1988, WNB 1994, Narayanan and Walker 1996). In Figure 4.6, we present centroid velocity maps obtained using our CS $J=5\rightarrow4$, HCO+ $J=3\rightarrow2$, CS $J=7\rightarrow6$ and HCO+ $J=4\rightarrow3$ data. The centroid velocities are expressed with respect to the $v_{LSR}$ of the source, i.e., we have subtracted the $v_{LSR}$ (4 km s$^{-1}$) from the centroid velocities, making negative velocities (shown with dashed lines) blueshifted, and positive velocities (shown with solid lines) redshifted. In an effort to separate out the effect of outflow velocity fields from the dynamics of the cloud core, the velocity centroids were computed over line core velocities. As was shown in the previous section, the line core velocities largely exclude the outflow components in all four transitions.
The centroid velocity maps are shown blanked in the outer 10", where there is no line emission. As in Figure 4.5, the position of 1629a and 1629b are marked in the maps of Figure 4.6.

All four centroid velocity maps shown in Figure 4.6 show an increasing gradient in centroid velocity from the northwest to the southeast. The contours are seen to be more or less orthogonal to the major axis of emission detected in dust continuum and in the integrated intensity maps of the line core (Figure 4.5). Figure 4.7 shows centroid velocity cuts along the equatorial and polar axis obtained from CS J=5→4, J=7→6 and HCO+ J=4→3 emission. The HHT HCO+ J=3→2 observations show similar results, but are omitted here for reasons mentioned above. The polar cut was made with a position angle of 60° (East of North) at the position of 1629a: the equatorial cut is orthogonal to the polar cut. The error bars show the error in the determination of the centroid velocity. The gradient in centroid velocity is consistent with a cloud core that is rotating on an axis at a position angle of \( \sim 60° \). This position angle is consistent with the outflow maps of WCB, the interferometric maps of Mundy et al. (1990), and the direction of the ambient magnetic field deduced from the work of Vrba, Strom and Strom (1976).

The blueshifted emission in all four centroid velocity maps shown in Figure 4.6 are seen to encroach well south of the rotational axis. The morphology of the CSO CS J=5→4, the HHT HCO+ J=3→2, and the JCMT HCO+ J=4→3 centroid velocity maps have a resemblance to the predicted morphologies of the "washed out" blue-bulge signature of infall (see Figure 2.14). In Chapters 2 and 3, we predicted that the centroid velocity of optically thick molecular tracers in a rotating, infalling cloud core would have a distinctive blue-bulge in velocity centroid maps made with high angular resolution. At lower angular resolutions, the bulge
becomes less pronounced, but the blue velocities still encroach well into what would otherwise have been the redshifted half of the centroid map. The centroid velocity maps of Figure 4.6 are consistent with the predicted blue-bulge infall signature occurring towards IRAS 16293. This blue-bulge is seen in the polar cut of HCO+ J=4→3, and to a lesser extent in the polar cut of CS J=5→4 (see Figure 4.7).

The centroid velocity map of CS J=7→6 has a slightly different morphology than that of the other three transitions (see Figure 4.6). The morphology of the J=7→6 centroid velocity map differs in some respects from the blue-bulge infall signature described by WNB. In the blue-bulge signature of infall, the degree to which the blueshifted velocities encroach across the rotational axis increases closer to the equatorial plane. The appearance of the CS J=7→6 centroid velocity map shows a somewhat different effect. Close to the equatorial plane of the flattened core, the blueshifted contours do not encroach across the rotational axis as deeply as seen in CS J=5→4 or HCO+ J=4→3. However, blueshifted velocities appear to encroach deeper across the rotational axis further away from the equatorial plane. This effect is also seen in the polar cut of CS J=7→6 data in Figure 4.7. The morphology of the CS J=7→6 centroid velocity map is similar to the “polar blue-bulge” we predicted in Chapter 3 (see Figure 3.16). We postpone a discussion of the blue-bulge and “polar blue-bulge” signatures in IRAS 16293 to a later section, where we present results of our 3d radiative transfer models.

To summarize this subsection, we have presented observational evidence for the detection of the blue-bulge signature of infall in IRAS 16293 using centroid velocity maps of CS J=5→4, J=7→6, HCO+ J=3→2 and J=4→3 data.
Figure 4.6 Centroid Velocity Maps. In all four panels, the centroid velocities only in the line core (2 to 6 km s\(^{-1}\)) are shown. The central 40'' × 40'' is shown. In all four panels, the positions of the two VLA sources detected by Wootten (1989) are marked in the maps with stars. The velocity of the ambient cloud (4 km s\(^{-1}\)) has been subtracted in the maps. Blueshifted velocities are shown in dashed contours, and redshifted velocities are shown in solid contours (a) Contour map of the centroid velocities in the line core of the CSO CS J=5→4 emission toward IRAS 16293. Contour levels are −0.5 to 0.5 km s\(^{-1}\), in steps of 0.08 km s\(^{-1}\). (b) Contour map of the centroid velocities in the line core of the HHT HCO+ J=3→2 emission. Contour levels are −0.8 to 1 km s\(^{-1}\), in steps of 0.07 km s\(^{-1}\). (c) Contour map of the centroid velocities in the line core of the CSO CS J=7→6 emission toward IRAS 16293. Contour levels are −0.6 to 0.6 km s\(^{-1}\), in steps of 0.1 km s\(^{-1}\). (d) Contour map of the centroid velocities in the line core of the JCMT HCO+ J=4→3 emission toward IRAS 16293. Contour levels are −0.7 to 0.7 km s\(^{-1}\), in steps of 0.1 km s\(^{-1}\).
4.3.2. Molecular Line Observations Towards the Central Position of IRAS 16293

*Line Profiles*

In Figure 4.8, we present the line profiles of several different molecular transitions observed towards the central position of IRAS 16293. As will be discussed below, the appearance of the line profiles are consistent with the detection of the "classic" asymmetric line profile infall signature. Where available, the spectra from both the CSO and the JCMT are shown. The $v_{LSR}$ of IRAS 16293 ($\sim 4$ km s$^{-1}$) is shown in the figure with dotted lines. The choice of the $v_{LSR}$ toward IRAS 16293 was based on the centroid velocity of the optically thin C$^{17}$O $J=3\rightarrow 2$
transition from this work and Blake et al. (1994).

The HCO+ J=4→3 spectra are seen to be self-absorbed, with the blue peak stronger than the red. The deep self-absorption trough that is seen to absorb the line profile almost to 0 K is at a slightly redshifted velocity of ~ 4.2 km s$^{-1}$. The isotopic H$^{13}$CO+ J=4→3 emission has a slight blue asymmetry in the line profile. But the isotopic transition does not have the deep self-absorption present in the main line. The presence of the blue asymmetry in the H$^{13}$CO+ spectra indicates that even the isotopic transition is moderately optically thick. The detection of line emission in the HC$^{18}$O+ transition by van Dishoeck et al. (1995) toward IRAS 16293, also indicates that the H$^{13}$CO+ emission should be somewhat optically thick.

The CSO and JCMT CS J=7→6 spectra also show blue asymmetry, but lack a pronounced self-absorption dip. The CSO isotopic C$^{34}$S J=7→6 spectrum is not self-absorbed, but does possess blue asymmetry. The CSO CS J=5→4 spectrum shows both self-absorption and blue asymmetry, whereas the isotopic, optically thin C$^{34}$S J=5→4 line is approximately symmetric with respect to the $v_{LSR}$. Finally, the CSO CS J=10→9 and the C$^{17}$O J=3→2 transitions exhibit symmetric line profiles, with no self-absorption evident.

Centroid Velocities

Figure 4.8 shows that nearly all of the observed transitions have blueshifted asymmetry, with or without a well defined self-absorption dip. Using systematic trends of line peaks and centroid velocity of observed line profiles with respect to optical depth, Myers et al. (1995) show that there is a good case for gravitational infall in L1527 and L483.
Figure 4.8 Observed Line Profiles toward the Central IR position of IRAS 16293. The velocity extent of the displayed spectra is $-10$ to $15 \text{ km s}^{-1}$. The scaling applied to the observed spectra for displaying on the same panel is shown on the right hand side. The velocity of the ambient cloud ($4 \text{ km s}^{-1}$) is shown as a vertical line (dotted line).
Table 4.2. Observed Centroid Velocities.

<table>
<thead>
<tr>
<th>Telescope</th>
<th>Transition</th>
<th>Beam Size (&quot;)</th>
<th>$v_c$ (km s$^{-1}$)</th>
<th>$\sigma$ (km s$^{-1}$)</th>
<th>Average $\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSO</td>
<td>$^{32}$S $J=5\rightarrow 4$</td>
<td>31</td>
<td>3.92</td>
<td>0.02</td>
<td>8.00</td>
</tr>
<tr>
<td>CSO</td>
<td>$^{34}$S $J=5\rightarrow 4$</td>
<td>31</td>
<td>3.97</td>
<td>0.08</td>
<td>0.32</td>
</tr>
<tr>
<td>CSO</td>
<td>$^{32}$S $J=7\rightarrow 6$</td>
<td>22</td>
<td>3.98</td>
<td>0.01</td>
<td>3.25</td>
</tr>
<tr>
<td>CSO</td>
<td>$^{34}$S $J=7\rightarrow 6$</td>
<td>22</td>
<td>3.84</td>
<td>0.05</td>
<td>0.13</td>
</tr>
<tr>
<td>CSO</td>
<td>$^{32}$S $J=10\rightarrow 9$</td>
<td>15</td>
<td>3.96</td>
<td>0.03</td>
<td>-</td>
</tr>
<tr>
<td>CSO</td>
<td>H$^{13}$CO+ $J=4\rightarrow 3$</td>
<td>21</td>
<td>3.68</td>
<td>0.06</td>
<td>11.57</td>
</tr>
<tr>
<td>CSO</td>
<td>H$^{13}$CO+ $J=4\rightarrow 3$</td>
<td>22</td>
<td>4.06</td>
<td>0.04</td>
<td>0.13</td>
</tr>
<tr>
<td>JCMT</td>
<td>$^{32}$S $J=7\rightarrow 6$</td>
<td>15</td>
<td>3.74</td>
<td>0.02</td>
<td>-</td>
</tr>
<tr>
<td>JCMT</td>
<td>H$^{13}$CO+ $J=4\rightarrow 3$</td>
<td>14</td>
<td>3.67</td>
<td>0.16</td>
<td>14.24</td>
</tr>
<tr>
<td>JCMT</td>
<td>H$^{13}$CO+ $J=4\rightarrow 3$</td>
<td>15</td>
<td>4.00</td>
<td>0.02</td>
<td>0.16</td>
</tr>
</tbody>
</table>
In Table 4.2, we present calculated centroid velocities of observed line profiles towards the central position of IRAS 16293. Because of the low spectral resolution of the HCO+ J=3→2 data, we do not include it in the results of Table 4.2. In order to reduce the possible contamination of the line profile from outflows, the centroid velocities were computed only in the line core (2 to 6 km s\(^{-1}\)). The centroid velocities were computed using \( v_c = \sum_i v_i T_i / \sum_i T_i \). A derivation of the uncertainty in the calculation of centroid velocities is presented in Section 4.6. In addition to the centroid velocities, the beamwidth of the telescope at the frequency of the transition are also presented in Table 4.2.

Opacity calculations were performed at the central position when both main line and isotopic transitions were available. The average opacities in the velocity interval of 2 to 6 km s\(^{-1}\) are presented in the last column of Table 4.2. In all opacity calculations we assumed that the isotopic line is optically thin. We assumed isotopic ratios that are approximately terrestrial \((^{12}\text{C}/^{13}\text{C} = 89; ^{32}\text{S}/^{34}\text{S} = 25)\).

From Table 4.2, we see the following systematic trends in centroid velocity. We consider the variation of the centroid velocity with beamwidth, opacity and dipole moment of the molecule under consideration.

1. For observations of the same transition with a smaller beamwidth, the centroid velocity is expected to be lower or bluer. For example, the centroid velocity of the CS J=7→6 line observed at the JCMT with a 15" beam is 0.24 km s\(^{-1}\) lower than the CSO CS J=7→6 line observed with a 22" beam. Based on their 3-d models, WNB predicted that the appearance of line profiles and the resulting centroid velocity maps is a strong function of the angular resolution used to perform the observations. With a smaller beam, we are more sensitive to regions with higher densities and infall velocities and larger line opacities.
Hence, in regions of infall, the centroid velocities are expected to be bluer as the angular resolution of the observations is increased. However, the CSO and JCMT HCO+ J=4→3 centroid velocities are identical within their respective uncertainties. The HCO+ J=4→3 transition which is mostly sensitive to the outer envelope (as will be shown below), does not show the expected decrease of centroid velocity with increasing angular resolution.

2. For observations at similar angular resolution, the centroid velocity is lower or bluer for transitions with larger optical depth. This effect is seen for all pairs of observations of the same molecular transition with different isotopic constituency. The molecule with the more abundant isotope has a higher optical depth, and a centroid velocity that is lower or bluer than its less abundant isotopic counterpart. This trend with opacity can be seen to extend even outside different molecular species. Due to the greater dipole moment of HCO+ (3.9 D; Dickel and Auer 1994, Botschwina 1989), as opposed to CS (1.98 D; Lang 1986), the HCO+ J=4→3 lines are more opaque than the CS J=7→6 lines. As a result, the HCO+ J=4→3 line is seen to have a lower (bluer) centroid velocity than the CS J=7→6 line in both the CSO and JCMT datasets. See §2.3.5 for a more detailed discussion of the choice of molecular probe in detecting infall.

These results are consistent with an infall model for IRAS 16293, where infalling, redshifted material is so optically thick that it becomes self-absorbed.
Optical Depths

The HCO+ spectra in Figure 4.8 seem to exhibit the self-absorbed asymmetric blue infall signature. The classic infall signature is also seen in the CS J=5→4 spectra. However, the CS J=7→6 spectra do not have the deep self-absorption. Is the CS J=7→6 emission tracing the same volume of molecular material as the CS J=5→4 emission? In order to answer this question we computed optical depth profiles for the observed HCO+ J=4→3, CS J=7→6, and CS J=5→4 transitions. The results are shown in Figure 4.9. For reference, the line profile of the main line is also shown in each case. The opacities were calculated for the more abundant isotope, assuming that the less abundant isotopic transition is optically thin. The CS optical depth profiles are derived from the CSO data. The HCO+ J=4→3 optical depth profile shown in Figure 4.9 is derived from JCMT data, but is consistent with the CSO HCO+ J=4→3 data. It can be seen that at higher velocities from the $v_{LSR}$, the blueshifted sides of the CS J=7→6 transition has larger optical depth than the redshifted side. However the HCO+ J=4→3 optical depth profile looks exactly opposite from the CS J=7→6 optical depth profile. Redshifted HCO+ J=4→3 gas has, on average, twice as much optical depth as blueshifted gas. The appearance of the CS J=5→4 optical depth profile is intermediate between the above two cases, showing similar opacities in blue and redshifted gas.

For the asymmetric blue spectral line infall signature to occur, both the emergent line intensity and the emergent optical depth profiles must be asymmetric; the line intensity is greater at blueshifted velocities, and correspondingly, the line optical depth is greater at redshifted velocities. These criteria are met across the HCO+ J=4→3 line, and in the line core region of the CS J=5→4 line (see Figure 4.9). However, in the CS J=7→6 transition, at higher velocities away from the
line center, blueshifted optical depth is higher than its redshifted counterpart. In addition, we see that the CS J=7→6 opacity profile does not show the enhanced optical depth at ~ 4.2 km s\(^{-1}\) seen in both the CS J=5→4 and HCO+ J=4→3 transitions. If the 4.2 km s\(^{-1}\) opacity feature is due to a large gaseous envelope surrounding the embedded cloud core, the CS J=7→6 emission does not seem to be affected by its presence.

The curious nature of the optical depth profile in CS has been touched upon by other authors (Menten et al. 1987, hereafter MSGW; WCB 1993). In their CS J=3→2 data, MSGW derive that the optical depth in the blue wing is much larger than in the red wing. WCB derive similar results from their CS J=7→6 data, and suggest that the higher opacity in the blue wings may be either due to asymmetric infall dominated from the far side of the cloud, or due to an unresolved, optically thick outflow. In addition, MSGW find a broad “pedestal” feature with Δv ∼ 5 – 7 km s\(^{-1}\) that is unresolved in their 17” beam. Our CS J=7→6 observations arise from a region only 13”.7 in size (see below). This result suggests another possibility for the greater opacity in the blueshifted wings of the CS J=7→6 line profile. The high resolution 3 mm dust continuum maps of WCB (1993) show that the size of the dust continuum emission is ∼ 15”. From the centroid velocity maps of Figure 5, we see that 1629b lies in the northern blueshifted half of the rotational axis. Is it possible the higher opacity blueshifted side of the CS J=7→6 line profile is tracing the material associated with larger column densities toward 1629b? Indeed, the interferometric observations of WCB (1993) indicate that the dust column density is twice as high toward 1629b than 1629a. In this scenario, beam dilution effects would result in the blueshifted side of the optical depth profile of CS to possess greater opacity than the redshifted side. The HCO+ emission, however, arising mostly from an extended envelope, would thus show the classic red asymmetric
Figure 4.9 Optical Depth Profiles toward the Central IR position of IRAS 16293. The velocity extent of the displayed profiles is 1 to 7 km s\(^{-1}\). The line profile of the main isotopic transition is shown in heavy solid histograms, while the optical depth of the main isotopic transition is shown in light dashed histograms. The temperature scale of the line profile is shown on the left-hand side Y axis, while the opacity scale is shown on the right-hand side Y axis. The velocity of the ambient cloud (4 km s\(^{-1}\)) is shown as a vertical line (dash-dot line) in each panel. (a) JCMT HCO+ J=4→3 line profile and optical depth profile. The computation of the optical depth in the vicinity of the self-absorption dip (\(\sim 4.2\) km s\(^{-1}\)) breaks down because the H\(^{13}\)CO+ J=4→3 line is brighter than the main line (the assumption of identical excitation temperature for both isotopes breaks down). In this instance, the H\(^{13}\)CO+ (being optically less thick) probes deeper, hotter regions. (b) CSO J=7→6 line profile and optical depth profile. Note the absence of the 4.2 km s\(^{-1}\) optical depth feature seen in a and c. (c) CSO J=5→4 line profile and optical depth profile.
signature of infall in the optical depth profile. Since CS J=5→4 emission arises both from the inner circumbinary core and the extended envelope, its optical depth profile is intermediate in appearance between the CS J=7→6 and HCO+ J=4→3 transitions, showing approximately equal opacities in blue and redshifted gas.

Source Size

We have CS J=7→6 and HCO+ J=4→3 spectra towards the central position made with two independent telescopes with different angular resolutions. Using these two sets of data, it is possible to estimate source sizes for the emitting region of the CS J=7→6 and HCO+ J=4→3 transitions. The beam dilution factor in observing a gaussian source of FWHM size, θ*, with a telescope that has a FWHM beam of θb can be shown to be \( f_f = \theta_b^2 / (\theta_b^2 + \theta_\ast^2) \) (Turner and Ziurys 1988). For a uniform source of diameter θ*, the beam dilution factor would reduce to \( f_f = \theta_b^2 / \theta_\ast^2 \).

The appearance of the CS J=2→1 maps (WCB 1993) suggests a gaussian source distribution rather than a uniform distribution. In the following analysis, we will assume that the emission regions for CS and HCO+ have a gaussian distribution.

The assumption of gaussian source distribution allows us to estimate the source size, given the ratio of main beam temperatures between the JCMT and CSO data. We can write \( \frac{\theta_b^2 + \theta_\ast^2}{\theta_b^2 + \theta_\ast^2} = \frac{T_{mb,J}}{T_{mb,C}} \), where θJ and θC are the FWHM of the JCMT and CSO beams respectively, and \( T_{mb,J} \) and \( T_{mb,C} \) are the peak main beam temperatures of the JCMT and CSO spectra respectively. Using the telescope main beam efficiencies and beamwidths listed in §2 and Table 1, we derive the ratio, \( \frac{T_{mb,J}}{T_{mb,C}} = 1.75 \) for CS J=7→6 which gives \( \theta_\ast = 13''7 \). In comparison, for HCO+ J=4→3, \( \frac{T_{mb,J}}{T_{mb,C}} = 1.18 \)
The HCO+ $J=4\rightarrow3$ emission arises from a region which is almost three times bigger than that emitting CS $J=7\rightarrow6$. At the distance of 160 pc to the $\rho$ Oph cloud complex, the HCO+ $J=4\rightarrow3$ region has a size of $\sim 6000$ AU. The CS $J=7\rightarrow6$ region is $\sim 2000$ AU in size. The size of the CS emission corresponds to the size of the circumbinary envelope traced by van Dishoeck et al. (1995) and Blake et al. (1994). The HCO+ $J=4\rightarrow3$ region encompasses a considerable portion of the cooler, lower density outer envelope which fades into the ambient cloud material. The much smaller source size for the CS emission might explain why the CS $J=7\rightarrow6$ line profile has very little self-absorption compared to the HCO+ emission. The cooler, overlying layers of gas are responsible for the deep self-absorption seen in the HCO+ $J=4\rightarrow3$ line profiles.

**Column Densities**

In Table 4.3, we present opacity, column density and mass estimates derived in three different velocity bins (blueshifted wing: $-2$ to $2$ km s$^{-1}$; line core: $2$ to $6$ km s$^{-1}$; redshifted wing: $6$ to $10$ km s$^{-1}$) using our data in CS $J=5\rightarrow4$, $J=7\rightarrow6$, and in HCO+ $J=4\rightarrow3$ main line and isotopic transitions. These calculations were carried out using the line profiles towards the central position of IRAS 16293. The average opacity of the less abundant isotope in each velocity bin is presented in column 3 of Table 4.3. Column density of H$_2$ is determined by fixing either the

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$^4$We use the peak brightness temperature for calculation of line ratios. Since the peak brightness occurs on the blueshifted side, which predominantly arises in the inner part of the infalling envelope, the size estimates we derive here should be considered lower limits to the size of the emitting region.
filling factor, \( f_F \), or the excitation temperature, \( T_{ex} \). The fixed quantity is indicated by an asterisk. The filling factor of low velocity material in CS \( J=7\rightarrow6 \) and HCO+ \( J=4\rightarrow3 \) can be derived from the source sizes derived in the previous section. From the half-power contour of the integrated intensity map (made in the velocity range \((-2, 2) \text{ km s}^{-1}\)) of CS \( J=5\rightarrow4 \), we estimate \( \theta \), for the \( J=5\rightarrow4 \) emission to be 20\".

The filling factors calculated from source sizes for the CSO CS \( J=7\rightarrow6 \) and \( J=5\rightarrow4 \) transitions and JCMT HCO+ \( J=4\rightarrow3 \) are 0.29, 0.31 and 0.88 respectively.

In Table 4.3, for each transition and each velocity bin, we present estimates of \( N_{H_2} \) and mass using three different methods. In method 1, we calculate the excitation temperature by assuming a \( f_F \) of 1. This will yield a lower limit to the excitation temperature. In general, a \( f_F \) of 1 is seen to give the largest column densities and mass estimates. In method 2, the excitation temperature and \( N_{H_2} \) are derived using the gas filling factors calculated above. In method 3, we fix the excitation temperature to be constant for both CS and HCO+ in all transitions, and derive filling factors and column densities. In the third method, the gas excitation temperature for CS is assumed to be the same as the dust temperature of the inner core (\( \sim 40 \text{ K} \)) derived by Walker et al. (1986); the HCO+ excitation temperature is assumed to be the same as the dust temperature of the extended envelope region (\( \sim 20 \text{ K} \)), derived by MSGW (1987). In Section 4.7, we present a short discussion on the estimation of excitation temperature and temperature power law coefficient toward IRAS 16293.

From our \( ^{17}\text{CO} \) \( J=3\rightarrow2 \) data presented in Figure 4.8, we can derive beam averaged LTE column densities assuming that the \( ^{17}\text{CO} \) emission is optically thin. We find that \( N(^{17}\text{CO}) = (5.0 - 6.8) \times 10^{15} \text{ cm}^{-2} \) for \( T_{ex} = 40 - 80 \text{ K} \). This \( ^{17}\text{CO} \) column density yields a total column density of \( N(H_2) = (1.3 - 1.8) \times 10^{23} \text{ cm}^{-2} \).
(assuming a terrestrial isotopic ratio of $^{12}\text{C}/^{17}\text{O} = 2674$, and a CO abundance of $\text{CO}/\text{H}_2 = 10^{-4}$; Blake et al. 1994). The total mass in a 22'' beam is 0.24-0.32 \( M_\odot \). Our derived value of $^{17}\text{O}$ column density is consistent with those derived by Blake et al. (1994). We also see that the line core column densities presented in Table 4.3 are consistent to an order of magnitude to those derived by our $^{17}\text{O}$ observations. Using dust continuum observations, Mezger et al. (1990) derive a hydrogen column density in the central 10'' core to be $5.1 \times 10^{25}$ cm$^{-2}$. Our column densities are lower by 1 to 2 orders of magnitude. The lower column densities derived by molecular transitions may possibly be because of the freezing out of gas molecules to form ice mantles around refractory grain cores (MCGW 1987, WCB 1993). The large densities ($n_H = 5 \times 10^3$ cm$^{-3}$) and low temperatures (20-40 K) derived in the IRAS 16293 cloud core (Mezger et al 1990) may be conducive for molecular depletions to occur in the cloud core (for examples in NGC 1333 and other sources see Blake et al. 1995, Mundy, McMullin and Blake 1995).

Our column density estimates for line core CS $J=7\rightarrow6$ are a factor of 50 - 100 times larger than the corresponding ones obtained by WCB. The spectra presented in this work have higher signal-to-noise ratio than that presented in WCB. A small pointing offset could also have resulted in lower column densities in the observations of WCB.
Table 4.3. Cloud Core Properties

<table>
<thead>
<tr>
<th>Transition</th>
<th>Velocity Range (kms$^{-1}$)</th>
<th>( r^a )</th>
<th>( \lambda )</th>
<th>( N_{H_2}^b ) (cm$^{-2}$)</th>
<th>( \text{Mass}^c ) (M$_\odot$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(-2, 2)</td>
<td>0.32</td>
<td>1.0*</td>
<td>6.6</td>
<td>6.5 \times 10^{23}</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>0.31*</td>
<td></td>
<td></td>
<td>12.3</td>
<td>0.49</td>
</tr>
<tr>
<td></td>
<td>0.07</td>
<td></td>
<td></td>
<td>6.8 \times 10^{23}</td>
<td>1.04</td>
</tr>
<tr>
<td>CSO (2, 6)</td>
<td>0.28</td>
<td>1.0*</td>
<td>3.4</td>
<td>6.4 \times 10^{24}</td>
<td>9.73</td>
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<tr>
<td></td>
<td>0.31*</td>
<td></td>
<td></td>
<td>1.7 \times 10^{24}</td>
<td>2.65</td>
</tr>
<tr>
<td></td>
<td>0.01</td>
<td></td>
<td></td>
<td>6.0 \times 10^{23}</td>
<td>0.92</td>
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<tr>
<td>CSJ = 5→4$^d$</td>
<td>(-2, 2)</td>
<td>0.42</td>
<td>9.1</td>
<td>5.1 \times 10^{24}</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td>0.29*</td>
<td></td>
<td></td>
<td>1.0 \times 10^{24}</td>
<td>0.76</td>
</tr>
<tr>
<td></td>
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<td></td>
<td>9.2 \times 10^{23}</td>
<td>0.64</td>
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<tr>
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<td>2.7 \times 10^{23}</td>
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<td></td>
<td>102.6</td>
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<tr>
<td></td>
<td>0.84</td>
<td></td>
<td></td>
<td>2.9 \times 10^{23}</td>
<td>0.22</td>
</tr>
<tr>
<td>(6, 10)</td>
<td>0.12</td>
<td>1.0*</td>
<td>10.4</td>
<td>9.3 \times 10^{23}</td>
<td>0.69</td>
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<tr>
<td></td>
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<td></td>
<td></td>
<td>5.1 \times 10^{23}</td>
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<tr>
<td></td>
<td>0.13</td>
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<td></td>
<td>2.7 \times 10^{23}</td>
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<tr>
<td>(-2, 2)</td>
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<td>1.0 \times 10^{22}</td>
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<tr>
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<td></td>
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<tr>
<td>JCMT (2, 6)</td>
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<td>1.0*</td>
<td>22.2</td>
<td>9.8 \times 10^{22}</td>
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<td>HCO+ J = 4→3$^f$</td>
<td>0.88*</td>
<td>24.0</td>
<td>1.0 \times 10^{23}</td>
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<tr>
<td></td>
<td>1.0</td>
<td></td>
<td></td>
<td>2.0 \times 10^{23}</td>
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</tr>
<tr>
<td>(6, 10)</td>
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<td>1.0*</td>
<td>9.7</td>
<td>5.5 \times 10^{21}</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>0.88*</td>
<td></td>
<td></td>
<td>1.0 \times 10^{21}</td>
<td>0.02</td>
</tr>
<tr>
<td>Transition</td>
<td>Velocity Range (kms$^{-1}$)</td>
<td>$T_{ex}$ (K)</td>
<td>$N_{H_2}$ (cm$^{-2}$)</td>
<td>Mass (M$_\odot$)</td>
<td></td>
</tr>
<tr>
<td>------------</td>
<td>-----------------------------</td>
<td>-------------</td>
<td>------------------</td>
<td>-----------------</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.28</td>
<td>20.0$^a$</td>
<td>7.8 $\times$ 10$^{21}$</td>
<td>0.04</td>
<td></td>
</tr>
</tbody>
</table>

$^a$Optical depth of the rare isotope

$^b$Derived from main line column densities. $N_X = N_{IX} \times$ ISO, where $N_X$ is the main line column density, $N_{IX}$ is the isotopic column density and ISO is the isotopic ratio. The following isotopic ratios were assumed: $^{32}$S/$^{34}$S = 25; $^{12}$C/$^{13}$C = 89. $N_{H_2} = N_X / ABD$, where $N_{H_2}$ is the molecular hydrogen column density, and ABD is the abundance of X relative to H$_2$. The CS and HCO+ abundances were assumed to be $5 \times 10^{-9}$.

$^c$Mass is derived by multiplying the $N_{H_2}$ by the mass of the hydrogen molecule and the source size of emission in cm$^2$. The source size, $\theta$, is used to calculate the area projected on the sky.

$^d$ff of 0.31 in calculations is derived from assuming a CS $J=5\rightarrow 4$ source size of 20''; CSO beamwidth = 30''

$^e$ff of 0.29 in calculations is derived from assuming a CS $J=7\rightarrow 6$ source size of 13.7''; CSO beamwidth = 22'' (see §3.1.3)

$^f$ff of 0.88 in calculations is derived from assuming a HCO+ $J=4\rightarrow 3$ source size of 37.5''; JCMT beamwidth = 14''
4.4. Discussion

4.4.1. Three-dimensional Collapse models

One of the thorniest problems in the unambiguous detection of infall is the kinematic confusion that exists in protostellar regions. The velocity fields associated with protostars include infall, rotation, turbulence and outflow motions. To disentangle these motions, one needs an accurate physical model for the protostar and a flexible radiative transfer code to predict the appearance of emergent spectra. Such model calculations will help us derive observational diagnostics and procedures to disentangle the kinematics in real protostellar systems. In addition, such models can be used to constrain observations and derive useful physical information of the protostellar region under study. In Chapters 2 and 3, we presented results of three-dimensional calculations of rotating and collapsing protostellar systems. More particularly, in Chapter 3, we studied the process of line formation in submillimeter molecules when applied to the semi-analytic TSC (1984) solution for rotating collapse. The study was done with a view to fitting real observations of protostellar systems and constraining the infall parameters of such systems with model results.

In reality, cloud collapse is often accompanied by an outflow along the rotational axis. Outflows occur at extremely early stages of star formation (e.g., see André, Ward-Thompson, & Barsony 1993). Collapsing clouds without outflows may be too rare to find. Recently we have presented the results of line formation from a three-dimensional LTE outflow model (Narayanan and Walker 1996). In a future paper we will incorporate the effect of molecular outflows, rotation and infall in our radiative transfer models. However, there are some ways to avoid the problem of confusion of infall and outflow: (1) limit the search for infall in objects that are too young to develop an outflow (2) limit the study to objects that have
outflow lobes that appear to be spatially distinct from the protostellar core (3) choose molecular probes that are not excited within molecular outflows. While approaches (1) and (2) severely limit the number and variety of objects that can be studied, approach (3) may be a more viable option. Emission from high lying submillimeter transitions of density sensitive molecules like CS and HCO+ is often seen to be absent from outflow lobes. As shown in §4.3.1, the CS $J=7\rightarrow6$ and HCO+ $J=4\rightarrow3$ transitions do not seem to be tracing the outflow lobes in IRAS 16293. The blue-bulge infall signature, which occurs along the major axis of a protostellar system is expected to be relatively insensitive to molecular outflows which occur along the minor axis. For the above reasons, and in an effort to reduce the complexity of our models, we have adopted the third approach.

The radiative transfer models presented in Chapter 2 have only two free parameters, the molecular abundance and turbulent velocity. The temperature, density and velocity fields are all set by basic physical laws in the Boss (1993) models. However, the resulting fragmented cloud core models in the Boss models depend on the initial conditions imposed on the pre-protostellar clouds. The radiative transfer code presented in Chapter 3 adopts the TSC model and has three free parameters: the sound speed $a$, the rotational rate $\Omega$, and the infall time $t$ (or infall radius $r_{inf} = at$). In addition, the temperature distribution, the molecular abundance and turbulent velocity are input parameters in the radiative transfer code.

The TSC solution of protostellar collapse has the advantage that it is computationally less expensive to obtain output line profiles. Using the precalculated curves of TSC, we are better able to explore a larger volume of parameter space and generate source specific models. Zhou (1995) did perform
similar modeling for IRAS 16293. However, this was done using a limited data set. Using our new data set, we are able to obtain better constraints on the infall parameters of the IRAS 16293 system. Our model derived values for the infall parameters are consistent with those of Zhou (1995) and provide new constraints on the abundance distribution of dense molecular tracers in the IRAS 16293 cloud core. In addition, using our radiative transfer code, we derive model centroid velocity maps which well reproduce the blue-bulge infall signature seen towards the object.

**Model Results for IRAS 16293**

IRAS 16293 is known to be a binary system with a projected separation of 5″, and is known to possess a circumbinary disk (Wooten 1989, Mundy et al. 1992, WCB 1993). The angular resolution of the observations presented in this work is not sufficient to resolve the individual components of the IRAS 16293 protobinary system. Indeed, the integrated intensity and centroid velocity plots of Figures 4.5 and 4.6 suggest that our observations toward IRAS 16293 are dominated by emission from the circumbinary disk and a lower density outer envelope of gas and dust. The TSC solution is an idealized solution for the evolution of a protostellar system resulting in a single star. In the outer envelope, the rotation timescale of a TSC system is $\sim 20 \times 10^6$ years (for $\Omega = 1 \times 10^{-14}$ s$^{-1}$), whereas the accretion timescale is typically of the order of $\sim 10^4$ years. Given that the angular momentum transport times are no faster than rotation time, appreciable redistribution of angular momentum (that may result in multiple stellar systems) is likely to occur only in the innermost parts (e.g. in a disk), where the rotation time is much shorter than the accretion time (TSC 1984). Since our observations are not sensitive to the inner parts of the IRAS 16293 protobinary, there is some justification in using the
TSC solution to fit the outer envelope. In this subsection we will attempt to use the TSC solution to model these regions.

Zhou (1995) modeled the emission from lower transitions of CS and CO toward IRAS 16293 cloud core using his radiative transfer code based on the TSC solution. Here, we use new submillimeter data on higher transitions of CS and the HCO+ together with lower frequency transitions to constrain our models. We ran 40 different models, each time varying one or more parameters. Our best fit model results are listed in Table 4.4. The rotational axis was assumed to be in the plane of the sky and oriented to be 50° east of North (p.a. of 50°). The best fit parameters are similar to those obtained by Zhou (1995) in his model fits. The best fit model was determined by a visual comparison of the model spectra with the data in all observed transitions.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>0.5 km s$^{-1}$</td>
</tr>
<tr>
<td>$\Omega$</td>
<td>$5 \times 10^{-13}$ s$^{-1}$</td>
</tr>
<tr>
<td>$r_{inf}$</td>
<td>0.03 pc</td>
</tr>
<tr>
<td>$T(r)$</td>
<td>$30(r/0.01\text{pc})^{-1.5}$ K</td>
</tr>
<tr>
<td>$v_{turb}$</td>
<td>0.75 km s$^{-1}$</td>
</tr>
</tbody>
</table>

Figure 4.10 shows a panel of the observed main line and isotopic transitions of CS $J=5\rightarrow4$, CS $J=7\rightarrow6$, and HCO+ $J=4\rightarrow3$ transitions toward IRAS 16293, along with best-fit model spectra. The model spectra were obtained by convolving with Gaussian beams of FWHM 30", 22", and 14" respectively corresponding to the
observed telescope beamwidths. Only the central positions are shown, but the fits are good at all mapped locations. The observed spectra are shown in histograms, while the model spectra are shown in heavy solid lines.

Figure 4.10 Best Fit Model Spectral Profiles. Observed transitions are shown in solid histograms, while best fit model spectra are shown in heavy solid lines. See text for details of model. (a) CSO C$^{32}$S $J=5\rightarrow4$ data and model fit (b) CSO C$^{32}$S $J=7\rightarrow6$ data and model fit (c) JCMT H$^{12}$CO$^+$ $J=4\rightarrow3$ data and model fit (d) CSO C$^{34}$S $J=5\rightarrow4$ data and model fit (e) CSO C$^{34}$S $J=7\rightarrow6$ data and model fit (f) JCMT H$^{13}$CO$^+$ $J=4\rightarrow3$ data and model fit.

As we have discussed before, the CS $J=7\rightarrow6$ and HCO$^+$ $J=4\rightarrow3$ data presented in this work appear to reflect a chemical differentiation between CS and HCO$^+$ in the protostellar core and extended envelope. The CS $J=7\rightarrow6$ line profiles do not exhibit the deep self-absorption seen in the HCO$^+$ $J=4\rightarrow3$ lines. In our best fit model, we assumed a radial variation of abundance for both CS
and HCO+. Assuming a constant abundance for CS and HCO+ throughout the core and envelope fails to reproduce the observed line profiles. Assuming very large abundances \((X > 1 \times 10^{-9})\) for HCO+ results in self-absorbed HCO+ lines, but the depth of the self-absorption is hard to reproduce with just a constant abundance throughout the core. A low (constant) value of HCO+ does a poor job reproducing observations because it tends to make the HCO+ lines more symmetric. A low (constant) value for the CS abundance gives CS \(J=7 \rightarrow 6\) lines that are not self-absorbed, but at the same time results in almost symmetric line profiles. The observed CS \(J=7 \rightarrow 6\) line profiles, however, exhibit considerable asymmetry. A larger (constant) value of CS abundance \((X > 1 \times 10^{-8})\), however, results in self-absorbed CS \(J=7 \rightarrow 6\) line profiles, which again is not seen in our observations. Our best fit model uses a CS abundance that decreases linearly from \(1 \times 10^{-8}\) at the center to \(\sim 3 \times 10^{-9}\) at the edge of the envelope. To reproduce the deep self-absorption in the HCO+ \(J=4 \rightarrow 3\) line profiles, we use a HCO+ abundance that increases linearly from \(1 \times 10^{-10}\) at the center to \(5 \times 10^{-9}\) at the edge of the envelope. The beam averaged CS and HCO+ abundances derived toward IRAS 16293 \((X_{CS} = 1.1 \times 10^{-9}, \text{Blake et al. 1994}; X_{HCO+} = 1.8 \times 10^{-9}, \text{van Dishoeck et al. 1995})\) lie within the lower and upper limits of our assumed abundance range.

The chemistry in the circumstellar environments of deeply embedded, young stellar systems is quite complex. The complex chemistry is expected to be driven by several factors such as depletions of gas phase molecules, grain mantle evaporation, interaction with shocks generated from protostellar winds, and photon heating from the nascent protostar. The combination of all these factors make chemistry in protostellar regions dependent on both time and position within the nebula (Mundy, McMullin and Blake 1995). In the chemical evolution model outlined by Mundy et al. (1995), the onset of strong wind activity in protostellar regions
starts liberating gas phase molecules from the grain molecules, thereby causing rising abundances at the center of protostellar regions. Recent high resolution interferometric observations do show evidence for enhanced abundances of several gas tracers including CS, in the immediate region of IRAS 05338-0624 (McMullin, Mundy and Blake 1994). The enhanced CS abundance that we have to apply in the central protostellar core of our models to fit the data in IRAS 16293 suggest that IRAS 16293 is in a similar evolutionary state as IRAS 05338-0624. However, in IRAS 05338-0624, McMullin et al (1994) find that the HCO+ fractional abundance is also enhanced in the central regions, whereas our best fit model for IRAS 16293 requires an underabundance of HCO+ in the central regions. Recent chemical evolution models suggest that CO and HCO+ can show larger depletions in regions dominated by water grain mantles rather than CO grain mantles (Bergin and Langer 1997). Depletion (by adsorption) of CS on the other hand is not very sensitive to the composition of the grain mantles. The suggested depletion of HCO+ in the inner regions of IRAS 16293 might indicate that gas-grain chemistry in the inner regions of the IRAS 16293 cloud core might be dominated by H2O grain mantles.

Another interesting result can be derived from the model fits of Figure 4.10. While the velocity width of the model profiles are similar to the observed velocity width in the main transition, the observational line profiles for the isotopic transitions appear to be broader than the model fits. In the fitting process, the model parameters were chosen to obtain a good fit for the main isotope. For such model parameters, the model fits for the isotopic transitions appear narrower than observations. If we optimize the fits for the rare isotopic transitions, then the line profiles of the main isotopic transitions appear broader than the corresponding observational profiles. A possible explanation for this is that the rare isotopic transitions, because of their lower opacity trace inner regions in the protostellar
core that have large systematic motions over and above the prescribed systematic velocities in the TSC model. This suggests that there are large velocity dispersions within the circumbinary disk associated with IRAS 16293.

Figure 4.11 Best Fit Model Centroid Velocity Maps. Model Centroid velocity maps are shown on the right and the observed centroid velocity maps from Figure 4.6 are reproduced on the left. (a) CS $J=5\rightarrow4$ emission (contours $-0.5$ to $0.5$ by $0.06$ km s$^{-1}$) (b) CS $J=7\rightarrow6$ emission (contours $-0.6$ to $0.6$ by $0.1$ km s$^{-1}$) and (c) HCO$^+ J=4\rightarrow3$ emission (contours $-0.7$ to $0.7$ by $0.1$ km s$^{-1}$) toward the best fit TSC model. Blueshifted emission is shown in dashed contours, while redshifted emission is shown in solid contours. See text for details on the model.

In Figure 4.11, we show the centroid velocity maps made with the model spectral mosaics in the CS $J=5\rightarrow4$, $J=7\rightarrow6$, and HCO$^+ J=4\rightarrow3$ transitions. It can be seen from Figure 4.11 that the model centroid velocity maps appear to be morphologically similar to the observed centroid velocity maps. The CS $J=5\rightarrow4$
and HCO+ J=4→3 model centroid maps show the signature of the "washed out" blue-bulge signature. Because the CS J=7→6 emission is preferentially arising from the inner core where rotational velocities in the equatorial direction provide support, blueshifted emission dominated by infall is most apparent only in the polar regions. This effect produces a bowing of the blueshifted velocity contours around the disk. When such a "polar blue-bulge" is observed, it may indicate the presence of an underlying rotationally supported disk.

The lack of self-absorption and the smaller source size in the observed CS J=7→6 emission suggest that it arises from the hotter, more compact circumbinary region, while HCO+ J=4→3 emission arises primarily from the extended outer envelope region. CS J=5→4 emission arises both in the inner circumbinary region and, because of the lower critical density of the J=5→4 transition, also in the outer envelope. This picture is consistent with the abundance variation of CS and HCO+ in our best fit model for IRAS 16293.

We have thus presented one infall model for IRAS 16293 that can reproduce the "classic" line profile signatures of infall for all the observed transitions reported in this work. The same model also reproduces the blue-bulge signature of infall in the CS J=5→4 and HCO+ J=4→3 emission, and the "polar blue-bulge" signature seen in CS J=7→6 emission. Figure 4.12 (updated from the cartoon picture of WCB 1993) schematically illustrates our current understanding of the IRAS 16293 system. The figure depicts the appearance of the protobinary with 800 AU separation and two separate bipolar outflows. The protostars are shown surrounded by a common circumbinary disk traced by the CS J=7→6 and J=10→9 observations of this work. The outer infalling envelope (~ 6000 AU in size) is shown with arrows depicting the infall velocity field, and is traced predominantly by the HCO+ J=4→3 and CS
$J=5\rightarrow 4$ observations.

Figure 4.12 Schematic Illustration of the IRAS 16293 Protobinary System.

**On the Assumption of LTE**

Although the assumption of LTE is probably valid in the inner regions of our protostellar models, the lower densities expected in the outer envelopes of protostellar regions lead us to question the assumption of LTE and the effect it has on the line profiles. Buckley (1997) compared the line profiles generated using the LTE approximation to those produced using a full statistical equilibrium calculation which includes collisions and interactions with the radiation field explicitly. An exact, non-LTE, spherically symmetric, $\Lambda$-iteration radiative transfer code was used
to make these calculations. The code is described in outline in Ward-Thompson et al. (1996), and in more detail in Matthews (1986) and Buckley (1997). For the sake of comparing LTE and non-LTE approaches, the line profiles of the HCO+ J=4→3 and CS J=5→4 transitions were calculated using the A-iteration radiative transfer code assuming both LTE and non-LTE, for 75 different spherically symmetric models. These 75 model runs sampled the parameter space of temperature, infall velocity, density and abundance radial profiles. His results suggest that the main difference between the LTE and non-LTE spectral line profiles is in the appearance of the self-absorption dip and in the overall intensity of the line. The overall width of the lines, and the velocities and relative heights of the peaks in the double peaked lines appear to be the same in both cases. The non-LTE line profiles tend to have much deeper self-absorption dips for a given radial profile of the kinetic temperature. This is because the self-absorption dip is produced by the outer, lower density region of the envelope. If the density in this region is below the critical density of the transition, the excitation temperature will fall below the local kinetic temperature. LTE therefore assumes too high an excitation temperature in these low density regions, reducing the depth of the self-absorption. The LTE line profiles can be made to match the non-LTE profiles by assuming a lower gas temperature in the low density regions of LTE model. In other words, the temperature law needed to fit line profiles with LTE should be considered as an upper limit to the steepness of temperature gradient. The occurrence and morphology of the blue-bulge and the “polar blue-bulge” signatures in our models are more sensitive to the assumed velocity laws than the temperature law. Therefore, the assumption of LTE should not seriously impact the kinematic model of the source.

The non-LTE code described above is a spherically symmetric model that needs as input, radial power law distributions of temperature, density and velocity
conditions. Rotation is not included in the calculations. On the other hand, our TSC radiative transfer model, although using the LTE assumption, includes rotational and infall velocities naturally, and is better suited for our modeling approach. Hence, we use the LTE radiative transfer code with the TSC infall solution to constrain the infall parameters of IRAS 16293.

4.4.2. Possible Inverse P-Cygni Line Profiles?

Another classic signature of infall is the inverse P-Cygni profile, marked by red-shifted absorption of a portion of an emission line profile because of high level of background continuum and a strong infall velocity field. Welch et al. (1987) found evidence for the gravitational collapse of the molecular cloud core toward W49A using the inverse P-Cygni line profiles in HCO\(^+\) \(J=1\rightarrow0\) emission. To detect the inverse P-Cygni profile, high angular resolution of an optically thick molecular tracer that probes the hot, dense core is needed. Our JCMT H\(^{13}\)CO\(^+\) \(J=4\rightarrow3\) observations (see §4.3.2) indicate that HCO\(^+\) \(J=4\rightarrow3\) emission is very optically thick. The critical density for the HCO\(^+\) \(J=4\rightarrow3\) transition is \(6 \times 10^6\) cm\(^{-3}\) at 40 K (from collision rate coefficients in Monteiro 1985). The higher angular resolution of the JCMT observations coupled with the high critical density and large opacity observed in the HCO\(^+\) \(J=4\rightarrow3\) transition could provide the right conditions to produce an inverse P-Cygni profile. For absorption below the continuum level, the line excitation temperature must be less than the continuum brightness temperature. From the spectral energy distribution for IRAS 16293 (Walker et al. 1986, Mundy et al. 1986), we estimate the flux density of IRAS 16293 to be \(~25\) Jy at 355 GHz. With a 14" beam, this corresponds to a continuum brightness temperature of \(~0.5\) K. This suggests that with a 14" beam at 355 GHz, redshifted absorption below the continuum level, if present, will be at a very low level. Indeed, there is some
tentative evidence for the inverse P-Cygni profile in a few spectral positions close to the center of the object (see Figure 4.3). Higher signal-to-noise observations are required to verify this effect. With higher angular resolution observations of the HCO$^+$ J=4→3 line with the JCMT-CSO interferometer or the Submillimeter Array (SMA) in the future, it may be possible to unambiguously detect the inverse P-Cygni infall signature toward IRAS 16293.

4.4.3. Infall Size Scales, Velocities and Rates

From Table 4.4, the best fit infall size scale for IRAS 16293 is $r_{in} = 0.03$ pc. At the distance of 160 pc, this corresponds to an infall size of $\sim 39''$. It is interesting to note that this is the size of the HCO$^+$ J=4→3 emission region. From Table 4.4, the infall timescale is given by $t = r_{in}/a = 5.9 \times 10^4$ yrs. The lower limit to the age of the outflow system is $6 \times 10^4$ yrs (WCB 1993). This would indicate that outflow was triggered almost simultaneously with the onset of collapse in IRAS 16293. The rotational velocity, $\Omega = 5 \times 10^{-13}$ s$^{-1}$ implies that the turnover radius $r_c = a/\Omega = 0.032$ pc = $42''$. From the self-similar solution of Shu (1977), we derive a mass accretion rate of $0.975a^3/G = 2.9 \times 10^{-5}$ M$_\odot$ yr$^{-1}$. The present mass of the star-disk system can then be calculated by $\dot{M}t$ giving a mass of $\sim 1.7$ M$_\odot$. This mass compares well with the mass of 1.5 M$_\odot$ derived for the dust core from fits to the spectral energy distribution (Mezger et al 1990). The centrifugal radius (or circumbinary disk radius) is $R_c = \Omega^2G^3M^3/16a^8 \approx 300$ AU $\approx 2''$. This is more than a factor of two smaller than the projected separation of the two components of the protobinary (5''). This might indicate that the IRAS 16293 cloud core is out of equilibrium and that rotation does not offer support against collapse. From the HCO$^+$ J=4→3 centroid velocity map, we derive a dynamical mass of $\sim 2.3$ M$_\odot$ for the mass of the cloud core. If the entire cloud
will collapse into the star-disk system, then using the cloud mass of 2.3 $M_\odot$, the centrifugal radius will eventually grow to $\sim 740$ AU $\approx 4''6$.

The observed luminosity of $\sim 30$ $L_\odot$ (Walker et al. 1986, Mundy et al. 1986) is much higher than expected for two convective stars of subsolar mass. As in other protostellar systems, the process of accretion dominates the observed luminosity in IRAS 16293. If we assume all the observed luminosity arises from accretion onto one star, we can estimate the mass of the star as follows: the bolometric luminosity is given by $L_B = \frac{GM_s}{R_s}$, where $R_s \approx 3 R_\odot$, and $\dot{M} \sim 2.9 \times 10^{-5} M_\odot yr^{-1}$. This gives $M_s \sim 0.27 M_\odot$. This mass estimate is similar to that derived by Walker et al. (1986) using their infall model. Since the mass of the star-disk system is 1.7 $M_\odot$, the mass of the central disk is $\sim 1.4 M_\odot$. The maximum value of the disk mass that is stable to $m=1$ gravitational instability is given by $\frac{M_D}{M_D + M_s} \leq 0.24$ (Adams and Lin 1993; also see the discussion in WCB 1993). In the case of IRAS 16293, this ratio is 0.82, which implies that the disk should be gravitationally unstable. Indeed, there is evidence from submillimeter vibrational CS emission that there is a $m=1$ instability in the IRAS 16293 system (Walker, Maloney and Serabyn 1994). From the above discussion, it appears that both the cloud core and the disk are in a state of dynamical collapse.

Recently, Myers et al. (1996) derived a simple analytic model that allowed estimates of the characteristic infall velocity, $V_{in}$, to be made from the parameters of a two peak emission line. From their equation (9) and from our observed CS $J=5\rightarrow4$ and HCO+ $J=4\rightarrow3$ two-peak lines toward the central position of IRAS 16293, we derive $V_{in} \approx 0.18$ km s$^{-1}$. Assuming a density of $n_{H_2} = 1 \times 10^5$ cm$^{-3}$, the mass infall rate is $\dot{M} = 4\pi r_{in}^2 n_{H_2} m_H V_{in} = 1 \times 10^{-5}$ $M_\odot yr^{-1}$, which is consistent with the standard mass accretion rate derived above.
4.5. Summary of Results

We mapped the region around IRAS 16293 in CS J=5→4, J=7→6, and HCO+ J=4→3 transitions using the CSO and the JCMT. These data show both the classic, asymmetric emission line infall signature (Walker et al. 1986, Zhou 1992, Zhou et al. 1994), and the blue-bulge infall signature of WNB (1994). A 3-dimensional radiative transfer model of protostellar collapse using the TSC solution was used to model the source.

The HCO+ J=4→3 emission appears to be tracing material infalling from a lower density outer envelope onto the circumbinary disk. Lower rotational transitions of CS also trace this infalling material, while higher rotational transitions of CS appear to arise principally in the vicinity of the circumbinary disk. Based on the model results, we find the infall radius of the IRAS 16293 cloud core is ~ 39″ (0.03 pc), the infall timescale is $5.9 \times 10^4$ yrs, and the rotational rate is $5 \times 10^{-13}$ s$^{-1}$. The upper limit of the power law index of the temperature gradient in the IRAS 16293 region is 1.5. The best fit model also suggests that the CS abundance decreases linearly, and the HCO+ abundance increases linearly from the inner core to the outer envelope. The best fit infall parameters are consistent with an inside-out model of protostellar collapse in IRAS 16293 (Walker et al. 1986).

The detection of infall signatures toward a system such as IRAS 16293 suggests that detailed studies of gravitational collapse of a large number of protostellar sources may now be possible. Single-dish submillimeter observations such as that presented in this work will be useful in selecting infall candidates for follow-up high angular resolution interferometric observations. Our numerical models show that both the classic and the blue-bulge infall signatures will appear more pronounced with higher angular resolution observations.
4.6. Appendix 1: Error in Centroid Velocity Determination

The centroid velocity of an emission line is given by

\[ v_c = \frac{\sum_i v_i T_{Ai}}{\sum_i T_{Ai}} \]  \hspace{0.5cm} (4.1)

where \( i \) is summed over the velocity interval under consideration. Using standard techniques for the propagation of errors (Bevington and Robinson 1992), we determine the variance in the determination of \( v_c \) to be

\[ \sigma_c^2 = v_c^2 \left( \frac{\sigma_i^2}{A^2} + \frac{\sigma_{vt}^2}{B^2} - \frac{2\sigma_{AB}^2}{AB} \right) \] \hspace{0.5cm} (4.2)

where,

\[ A = \sum_i T_{Ai} \] \hspace{0.5cm} (4.3)

is the denominator of Equation (4.1), and

\[ B = \sum_i v_i T_{Ai} \] \hspace{0.5cm} (4.4)

is the numerator of Equation (4.1). \( \sigma_i \) is the rms error for \( A \), given by

\[ \sigma_i = \sigma_T \sqrt{i} \] \hspace{0.5cm} (4.5)

where, \( \sigma_T \) is the rms error in antenna temperature (K) of the spectrum. The error in the product term \( v_i T_{Ai} \) is given by

\[ \sigma_{ii}^2 = (v_i T_{Ai})^2 \left( \frac{\sigma_i^2}{v_i^2} + \frac{\sigma_T^2}{T_{Ai}^2} \right). \] \hspace{0.5cm} (4.6)

Due to the accuracy of the spectrometers, we can assume that there is negligible error in the determination of velocity, hence \( \sigma_v = 0 \). Thus,

\[ \sigma_{ii}^2 = v_i^2 \sigma_T^2. \] \hspace{0.5cm} (4.7)
So, the rms error of $B$ is given by,

$$
\sigma_{\nu t}^2 = \sum_i \sigma_i^2
$$

$$
= \sigma_f^2 (\sum_i v_i^2).
$$

The rms error in the term $AB$ is given by $\sigma_{AB}$, the covariance term:

$$
\sigma_{AB}^2 = \frac{1}{i} \sum_i [(v_i T_{A_i} - \bar{\nu t})(T_{A_i} - \overline{T_A})],
$$

where, $\bar{\nu t}$ is the average channel integrated intensity, and $\overline{T_A}$ is the average antenna temperature, over the velocity range used for the centroid velocity calculation.

Combining equations (4.2), (4.3), (4.4), (4.5), (4.8) and (4.9), we get the expression for the error in the determination of centroid velocity,

$$
\sigma_c^2 = v_c^2 \left[ \left( \frac{i \sigma_f^2}{(\sum_i T_{A_i})^2} \right) + \left( \frac{\sigma_f^2 (\sum_i v_i^2)}{(\sum_i T_{A_i})^2} \right) - \left( \frac{2}{i} \sum_i \left( \frac{(v_i T_{A_i} - \bar{\nu t})(T_{A_i} - \overline{T_A})}{(\sum_i T_{A_i}) (\sum_i v_i T_{A_i})} \right) \right) \right].
$$

4.7. Appendix 2: Excitation Analysis

We have C$^{34}$S data in three transitions. The C$^{34}$S excitation temperature can be constrained from the ratio of C$^{34}$S opacities with the assumption that the excitation temperature is the same in all transitions. Adding the assumption that the cloud core is in LTE, the ratio of opacities of the C$^{34}$S $J=7\rightarrow6$ and $J=5\rightarrow4$ transitions is given by,

$$
\frac{\tau_{7\rightarrow6}}{\tau_{5\rightarrow4}} = \frac{\nu_{7\rightarrow6} \exp\left(-\frac{h\nu_{7\rightarrow6}}{kT_{ex}}\right) (1 - \exp\left(-\frac{h\nu_{7\rightarrow6}}{kT_{ex}}\right))}{\nu_{5\rightarrow4} \exp\left(-\frac{h\nu_{5\rightarrow4}}{kT_{ex}}\right) (1 - \exp\left(-\frac{h\nu_{5\rightarrow4}}{kT_{ex}}\right))}
$$

(4.11)

Similar expressions can be derived for opacity ratios for $10 \rightarrow 9/7 \rightarrow 6$ and $10 \rightarrow 9/5 \rightarrow 4$. At the high densities found in the core region, CS is probably thermalized making the assumption of LTE reasonable. However, the assumption
of the constant excitation temperature throughout the cloud core, and for all the
different transitions is probably less reasonable. The excitation temperatures
derived using this method should be considered an average temperature for the
whole cloud core. From the observed J=7→6/J=5→4 optical depth ratio we derive
excitation temperatures of 23, 17 and 18 K for the blueshifted wing, line core and
redshifted wings respectively. The critical densities for the CS J=7→6 and J=5→4
transitions are 2.9 × 10^7 and 5 × 10^6 respectively (using collision cross-sections
from Green and Chapman 1978 at low temperatures). The HCO+ J=4→3 critical
density is 5.5 × 10^6 (from Monteiro 1985). Since the CS J=5→4 transition has a
lower critical density than the J=7→6 transition, any density gradient present in
the source would cause a higher column density of CS to contribute to the optical
depth of the J=5→4 line compared to the J=7→6 line. High column density in the
J=5→4 line will lead to a lower J=7→6/J=5→4 optical depth ratio than found in
LTE, and thus to a lower temperature estimate. Hence the excitation temperatures
derived from the J=7→6/J=5→4 optical depth ratio should be considered to be
lower limits to the true kinetic temperature of the gas.

The excitation temperature can be better constrained if we know the filling
factor. We have an estimate for the source size, and hence the area filling factor for
the J=7→6 emission. From this we can estimate the excitation temperature from
the CS J=7→6 data. Using a ff of 0.29 in the velocity range of (0, 8) km s^{-1}, we
derive T_{ex} ≈ 120 K. A similar calculation for HCO+ J=4→3 using a ff of 0.88 (see
footnotes of Table 4.3) gives T_{ex} ≈ 17 K. We see that the HCO+ arises in a region
which has a lower temperature than the CS J=7→6 emission. The smaller source
size of the CS emission coupled with its higher effective excitation temperature
than HCO+ indicates that the CS J=7→6 and HCO+ J=4→3 transitions are
tracing different regions of IRAS 16293. If the kinetic temperature T_K ∝ r^{-α},
using the source sizes from the previous section and assuming that the excitation
temperatures above can be equated to kinetic temperatures of the gas, we get $\alpha \sim 2$.
However, the high opacities in HCO+ imply that the bulk of the HCO+ emission
may be tracing the kinetic temperature of the outermost layers of the cloud. For
HCO+, only photons radiated from the surface layers are received at the telescope.
The derived value of $\alpha$ should thus be considered an upper limit.
CHAPTER 5

DETECTION AND STUDY OF INFALL TOWARD SELECTED PROTOSTELLAR SYSTEMS

5.1. Introduction

The study of star formation is currently at a fascinating stage. With the advent of large millimeter and submillimeter single-dish telescopes and interferometers, the earliest stages of star formation have been under considerable observational scrutiny. One of the important aims of the study of star formation has been to order young stellar objects into an evolutionary sequence. The most widely used classification scheme is that of Lada and Wilking (1984) and Lada (1987), which divides YSOs into three categories on the basis of the slope of their infrared spectral energy distribution (SED). The oldest population of YSOs are the Class III YSOs that have a black-body like SED (with a very weak infrared excess), and are interpreted as pre-main-sequence stars without a disk. Class II YSOs have a flat or negatively
sloped SED in the infrared and are thought to be classical T Tauri stars with an optically thick disk of circumstellar dust. Class I sources have steeply rising SEDs up to 100 μm, and are thought to be collapsing protostars.

Recently, André et al. 1993 suggested a new class of protostellar objects called Class 0 sources. These sources are so deeply embedded that they are not detected in the near-infrared and mid-infrared and have blackbody-like SEDs that peak up in the submillimeter suggesting extremely low dust temperatures (~ 20 K). Barsony (1994) defined the following as characteristics of Class 0 objects:

\[ \frac{L_{bol}}{L_{1.3mm}} \leq 2 \times 10^4, \] an SED like a 30 K blackbody, undetected at \( \lambda < 10\mu m \).

and possession of a molecular outflow. In addition, Class 0 sources have bolometric temperatures \( T_{bol} \) less than 70 K (Chen et al. 1995). \( T_{bol} \) is defined as the temperature of the blackbody having the same mean frequency as the observed SED (Myers & Ladd 1993).

André and Montmerle (1994) argued that Class 0 sources have more circumstellar mass than stellar mass. They suggested that Class 0 sources are still in an active stage of accreting their mass. Indeed, it has been shown recently that there is an evolutionary trend of decreasing circumstellar envelope mass from Class 0 to Class III objects (Saraceno et al. 1996), as the eventual buildup of mass onto the central star takes place.

Various observationally quantifiable indicators of YSO evolution have been proposed: change of appearance of the SED (Lada and Wilking 1984), change in bolometric temperature (Myers & Ladd 1993), decrease in visual extinction \( A_V \) (Adams 1990), decrease in millimeter continuum emission (Saraceno et al. 1996). How do these observational quantities relate and evolve with the physical parameters of the YSO such as rotational rate \( \Omega \), sound speed \( a \), and infall radius \( r_{inf} \)? The
answer to this question will provide us with an insight into the physical evolution of a YSO from an embedded molecular cloud core to a revealed pre-main-sequence object.

In Chapter 4, we presented evidence for infall in IRAS 16293 and obtained the infall parameters for the IRAS 16293 protostellar region. In this chapter, we present a detailed observational and modeling study of a selection of Class 0 objects. In Table 5.1, we list the sources in our sample, together with the source coordinates, and other properties such as $T_{bol}$, distance, $L_{bol}$, the observed millimeter flux density, and a selected list of references. Of our sources, B335 is a confirmed infall candidate (Zhou 1995), and will serve as a baseline of reference for our technique of detecting infall. In a recent survey for the classic asymmetric blue profile signature of infall (Gregersen et al. 1997), although they are Class 0 objects, L483 and VLA 1623 came up as notable non-detections based on their HCO$^+$ line profiles. SM1N is classified as prestellar clump based on its continuum properties and the non-detection of outflows (André et al. 1993). SMM4 is a Class 0 object, but to date, has no detected outflow. L1262 is an isolated Bok globule and may be a late Class 0 object. Our source selection comprises of Class 0 sources at different stages of evolution and with varied physical properties. This selection was principally motivated to test the robustness of the blue-bulge signature in detecting infall under different circumstances, and to compare it's effectiveness to line profile techniques of detecting infall.

Using the blue-bulge infall signature, and our 3-dimensional TSC models, we will constrain the infall parameters of these objects. The goals of this study are to confirm gravitational collapse in these objects, to perform a detailed study of the kinematical motions associated with star-formation, and to use the physical
parameters obtained by modeling the observations to order our sample into an evolutionary sequence.

Table 5.1. Source List.

<table>
<thead>
<tr>
<th>Name</th>
<th>R.A. (1950.0)</th>
<th>Decl. (1950.0)</th>
<th>$T_{bol}$ (K)</th>
<th>Distance (pc)</th>
<th>$L_{bol}$ ($L_\odot$)</th>
<th>$P_{bol,1.3,mm}$ (mJy)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>VLA1623</td>
<td>16:23:24.9</td>
<td>−24:17:46</td>
<td>8 ± 2</td>
<td>160</td>
<td>0.06</td>
<td>1052</td>
<td>1, 19, 3, 9, 14</td>
</tr>
<tr>
<td>SM1N</td>
<td>16:23:25.8</td>
<td>−24:16:50</td>
<td>&lt; 10</td>
<td>160</td>
<td>3</td>
<td>1160</td>
<td>1, 19, 3</td>
</tr>
<tr>
<td>L483</td>
<td>18:14:50.6</td>
<td>−04:40:49</td>
<td>48 ± 5</td>
<td>200</td>
<td>9.5 ± 0.5</td>
<td>485</td>
<td>16, 17, 8, 9, 14</td>
</tr>
<tr>
<td>SMM4</td>
<td>18:27:24.7</td>
<td>01:11:10</td>
<td>35 ± 5</td>
<td>310</td>
<td>3.9 ± 0.3</td>
<td>1260</td>
<td>4, 12, 13, 20, 9, 14</td>
</tr>
<tr>
<td>B335</td>
<td>19:34:34.7</td>
<td>07:27:20</td>
<td>29 ± 3</td>
<td>250</td>
<td>2.5 ± 0.2</td>
<td>770</td>
<td>7, 15, 5, 10, 21, 11, 6, 9, 14</td>
</tr>
<tr>
<td>L1262</td>
<td>23:23:49.0</td>
<td>74:01:08</td>
<td>104</td>
<td>250</td>
<td>0.87</td>
<td>100</td>
<td>16, 18, 14</td>
</tr>
</tbody>
</table>


5.2. Observations and Data Reduction

Observations were made of the sources listed in Table 5.1 at the Caltech Submillimeter Observatory (CSO)\(^1\) and at the James Clerk Maxwell Telescope (JCMT)\(^2\) in March 1996 and May 1996 respectively. The HCO+ J=3→2 and

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\(^1\)The CSO is operated by the California Institute of Technology under funding from the National Science Foundation, Contract No. AST-93-13929.

\(^2\)The James Clerk Maxwell Telescope is operated by the Royal Observatories on behalf of the United Kingdom Particle Physics and Astronomy Research Council.
CO J=2→1 observations were made using the 10 m Heinrich Hertz Telescope (HHT)\(^3\) in March, 1997. The SMM4 data came solely from the JCMT. The lines we observed, along with the telescope efficiency and angular resolution, velocity resolution and frequency of the transitions are summarized in Table 5.2. Mapping in the HCO\(^+\) J=4→3 transition and in CO J=3→2 transitions was performed using the On-The-Fly (OTF) mapping technique, where the antenna was scanned in a rectangular grid centered on the source. In addition, observations were made in the isotopic H\(^{13}\)CO\(^+\) J=4→3 transition. All CSO observations were made with the low-noise 345 GHz SIS waveguide receiver (Ellison et al. 1989) and a 1000 channel, 50 MHz wide acousto-optical spectrometer. All JCMT observations were carried out with the facility B3i single channel lead-alloy SIS receiver (Cunningham et al. 1992). The spectrometer backend used was the Dutch Autocorrelation Spectrometer (DAS) configured to operate with an effective resolution of 95 kHz and total bandwidth of 125 MHz. All HHT observations were carried out using the facility 245 GHz receiver (Walker et al. 1996), and a 2048 channel 1 GHz AOS from MPIfR with an effective resolution of 1 MHz per channel. The main beam efficiencies reported in Table 5.2 were measured using observations of planets. Calibration of observations was done by the chopper wheel technique. All spectra and maps are presented in terms of $T_A^*$. The CSO and HHT data were reduced using the Grenoble CLASS package.

\(^3\)The HHT is operated by the Submillimeter Telescope Observatory (SMTO), and is a joint facility for the University of Arizona's Steward Observatory and the Max-Planck-Institut fur Radioastronomie (Bonn).
Table 5.2. List of Observed Lines.

<table>
<thead>
<tr>
<th>Molecule</th>
<th>Transition</th>
<th>Telescope</th>
<th>Beam size (&quot;)</th>
<th>$\tau_{mb}$</th>
<th>Vel. Res (kms$^{-1}$)</th>
<th>Frequency (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{12}$CO+</td>
<td>$J=4\rightarrow3$</td>
<td>CSO</td>
<td>21</td>
<td>0.66</td>
<td>0.042</td>
<td>356.734288</td>
</tr>
<tr>
<td>$^{12}$CO+</td>
<td>$J=4\rightarrow3$</td>
<td>JCMT</td>
<td>14</td>
<td>0.60</td>
<td>0.080</td>
<td>356.734288</td>
</tr>
<tr>
<td>$^{13}$CO+</td>
<td>$J=4\rightarrow3$</td>
<td>CSO</td>
<td>21</td>
<td>0.66</td>
<td>0.043</td>
<td>346.998540</td>
</tr>
<tr>
<td>$^{13}$CO+</td>
<td>$J=4\rightarrow3$</td>
<td>JCMT</td>
<td>14</td>
<td>0.66</td>
<td>0.082</td>
<td>346.998540</td>
</tr>
<tr>
<td>$^{12}$CO+</td>
<td>$J=3\rightarrow2$</td>
<td>HHT</td>
<td>28</td>
<td>0.74</td>
<td>0.280</td>
<td>267.557620</td>
</tr>
<tr>
<td>$^{12}$CO</td>
<td>$J=3\rightarrow2$</td>
<td>CSO</td>
<td>22</td>
<td>0.66</td>
<td>0.043</td>
<td>345795.991</td>
</tr>
<tr>
<td>$^{13}$CO</td>
<td>$J=3\rightarrow2$</td>
<td>CSO</td>
<td>23</td>
<td>0.66</td>
<td>0.045</td>
<td>330.587957</td>
</tr>
<tr>
<td>$^{17}$O</td>
<td>$J=3\rightarrow2$</td>
<td>CSO</td>
<td>22</td>
<td>0.66</td>
<td>0.045</td>
<td>337.06110</td>
</tr>
<tr>
<td>$^{12}$CO</td>
<td>$J=2\rightarrow1$</td>
<td>HHT</td>
<td>33</td>
<td>0.74</td>
<td>0.326</td>
<td>230.538000</td>
</tr>
</tbody>
</table>

JCMT data was reduced using the Starlink SPECX software package. In most instances, the data were written out into ascii files, and perl scripts were used to compute the centroid velocities, derive optical depths and column densities. The "linecore" of an optically thick transition, say HCO+ $J=4\rightarrow3$, is derived from the FWHM of the corresponding optically thin line ($^{13}$CO+ $J=4\rightarrow3$). In derived centroid velocity maps, the choice of the $v_{LSR}$ of the ambient cloud has a considerable effect on the morphology of the resulting maps. Considerable effort was put into obtaining the best value of the $v_{LSR}$ of the ambient cloud. An optically thin transition is expected to show a gaussian profile about the $v_{LSR}$ of the ambient cloud. Table 5.3 list the calculated centroid velocities of observed HCO+ and $^{13}$CO+ $J=4\rightarrow3$ transitions towards the list of sources. Column 1 of Table 5.3 lists the $v_{LSR}$ of the ambient cloud derived from previously reported observations (see Table 5.1 for a list of references) of optically thin species.
### Table 5.3. Calculated Centroid Velocities of Central Line Profiles

<table>
<thead>
<tr>
<th>Source</th>
<th>Transition</th>
<th>CSO $v_c$ (kms$^{-1}$)</th>
<th>JCMT $v_c$ (kms$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>($v_{LSR}$ kms$^{-1}$)</td>
<td>$v_c$ (kms$^{-1}$)</td>
<td>$v_c$ (kms$^{-1}$)</td>
</tr>
<tr>
<td>VLA 1623</td>
<td>H$^{13}$CO+ $J=4\rightarrow3$</td>
<td>3.66 ± 0.02</td>
<td>3.53 ± 0.02</td>
</tr>
<tr>
<td></td>
<td>(4.0)</td>
<td>H$^{13}$CO+ $J=4\rightarrow3$</td>
<td>4.01 ± 0.03</td>
</tr>
<tr>
<td>SM1N</td>
<td>H$^{13}$CO+ $J=4\rightarrow3$</td>
<td>3.45 ± 0.02</td>
<td>3.16 ± 0.01</td>
</tr>
<tr>
<td></td>
<td>(4.0)</td>
<td>H$^{13}$CO+ $J=4\rightarrow3$</td>
<td>3.89 ± 0.07</td>
</tr>
<tr>
<td>L483</td>
<td>H$^{13}$CO+ $J=4\rightarrow3$</td>
<td>5.73 ± 0.02</td>
<td>5.55 ± 0.01</td>
</tr>
<tr>
<td></td>
<td>(5.5)</td>
<td>H$^{13}$CO+ $J=4\rightarrow3$</td>
<td>5.68 ± 0.04</td>
</tr>
<tr>
<td>SMM4</td>
<td>H$^{13}$CO+ $J=4\rightarrow3$</td>
<td>...</td>
<td>7.40 ± 0.02</td>
</tr>
<tr>
<td></td>
<td>(8.1)</td>
<td>H$^{13}$CO+ $J=4\rightarrow3$</td>
<td>...</td>
</tr>
<tr>
<td>B335</td>
<td>H$^{12}$CO+ $J=4\rightarrow3$</td>
<td>8.41 ± 0.02</td>
<td>8.25 ± 0.01</td>
</tr>
<tr>
<td></td>
<td>(8.5)</td>
<td>H$^{13}$CO+ $J=4\rightarrow3$</td>
<td>8.56 ± 0.02</td>
</tr>
<tr>
<td>L1262</td>
<td>H$^{12}$CO+ $J=4\rightarrow3$</td>
<td>3.91 ± 0.03</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>(4.0)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
5.3. Observational Results for Individual Sources

5.3.1. VLA 1623

VLA 1623 was proposed as a prototype of a new class of YSOs, the so-called Class 0 YSOs by André, Ward-Thompson and Barsony (1993; hereafter AWB). It lies in the centrally condensed L1686 core of the nearby (160 pc) ρ Ophiuchi molecular cloud (Loren & Wootten 1986, André et al. 1990), and is known to possess a remarkably collimated and very young (~ 6000 yrs) molecular outflow (André et al. 1990, AWB). Despite the existence of a large number of YSOs in the ρ Oph cloud core (Wilking & Lada 1983), there have been only two detected molecular outflows in the cloud: one is the multilobed outflow found around IRAS 16293-2422 in the L1689 eastern streamer region (Walker et al. 1988), and the other is VLA 1623 detected first by André et al. 1990 in the L1686 main cloud core. AWB argued that based on the very low dust temperatures, high extinction, and massive envelope, all derived from millimeter continuum observations of VLA 1623, that it was an extremely young object, possibly a true collapsing protostar. However, to date, there has been no spectroscopic confirmation of infalling gas toward VLA1623.

Line Profiles

In Figure 5.1 we present a plot of our spectral observations toward the driving source of VLA 1623. Figure 5.1a shows the JCMT and CSO HCO+ $J=4\rightarrow3$ observations. Due to differences in angular resolution, we see some small scale changes in the line structure between the JCMT and CSO HCO+ observations. The noteworthy feature of the CSO HCO+ $J=4\rightarrow3$ spectrum is that it shows a red asymmetric signature consistent with expanding gas rather than collapse.
There might be a suggestion of blue asymmetry in the higher angular resolution JCMT HCO+ J=4→3 data. Higher signal-to-noise ratio observations are needed to confirm this. The blue asymmetry is expected to be stronger with increasing angular resolution (WNB 1994, chapter 2, 3). The non-detection of the “classic” asymmetric blue profile in their CSO HCO+ observations lead Gregersen et al. (1997) to conclude that there was no evidence for collapse in VLA 1623.

Using the JCMT and CSO HCO+ observations, we can constrain the size of the HCO+ emission region using the method outlined in Narayanan et al. (1997) (also see Section 4.3.2). Assuming gaussian source distribution and the ratio of the JCMT and CSO main beam temperatures, we can constrain the source size. The main beam temperatures for the JCMT and CSO HCO+ J=4→3 lines are 5 K and 3.4 K respectively (see Figure 5.1). Using 14" and 22" as the JCMT and CSO telescope beam sizes respectively, we derive that the HCO+ J=4→3 emission is arising from a region ~ 14".5 in size (this is a lower limit to the size, see Section 4.3.2 for a discussion). At the distance of VLA 1623, this size corresponds to ~ 2300 AU. Assuming that this size corresponds to the infall size, r_{in}, and that the properties (specifically sound speed, a) of the VLA 1623 cloud core are the same as IRAS 16293 (r_{in} ≈ 6000 AU), we surmise that VLA 1623 is possibly at a younger stage of evolution than IRAS 16293.

Figure 5.1b shows our corresponding H^{13}CO+ observations from the JCMT and CSO. The isotopic H^{13}CO+ emission appears more symmetric than the HCO+ emission (see Figure 5.1a). In Table 5.3, we present the calculated centroid velocities of observed HCO+ line profiles towards the central position of all our sources. For VLA 1623, the calculation was performed in the line core (2 to 6 km s^{-1}). We see that the optically thin H^{13}CO+ line has a centroid velocity which
is $\sim 0.4$ km s$^{-1}$ redshifted with respect to the main $^{12}$CO$^+$ line in both the JCMT and CSO observations. This trend of centroid velocity with the choice of main or isotopic transitions is consistent with an infall explanation (see Section 4.3.2 for a discussion of this effect).

In Figure 5.1c, we present three CO $J=3\rightarrow2$ transitions toward the central position of VLA 1623. The $^{12}$CO $J=3\rightarrow2$ line is characterized by deep self-absorption in the line core, and high velocity wing emission. The wing emission arises in the highly collimated outflow previously detected toward VLA 1623 (André et al. 1990, AWB, also see below). The $^{13}$CO spectrum also shows a self-absorption
feature and shows blue asymmetry. Even the line core of CO emission is known to trace the shells of molecular outflow (Narayanan and Walker 1996). So we should be careful about interpreting the blue asymmetry seen in CO lines as a signature of infall. The peaking of the C^{17}O J=3→2 line in the self-reversed dips of the \(^{12}\)CO and \(^{13}\)CO lines is a clear indication that the self-reversal in the CO lines is due to self-absorption and not due to two separate line-of-sight clouds. In addition, from the C^{17}O spectrum, we see that even the \(^{13}\)CO J=3→2 line emission is optically thick towards VLA 1623. From the line ratios of \(^{13}\)CO to C^{17}O, we derive an average C^{17}O optical depth\(^4\) of \(\sim 0.32\), a line excitation temperature of \(\sim 14\) K, and a \(\text{H}_2\) column density of \(1.8 \times 10^{23} \text{ cm}^{-2}\) (assuming \(^{12}\)CO/\(^{13}\)CO = 89, \([^{12}\text{CO}/\text{\text{H}_2}] = 1 \times 10^{-4}, \quad ^{12}\text{CO}/\text{C^{17}O} = 2674\), filling factor of 1, and that C^{17}O is optically thin). This gives an overall envelope mass of \(\sim 0.76 \text{ M}_\odot\), assuming a 30" size for the cloud envelope. This \(\text{H}_2\) column density derived from gas is within an order of magnitude of that derived from 1.3 mm dust continuum observations (AWB). The gas envelope mass is consistent as well with the circumstellar mass derived by AWB.

### Mapping Results

In Figure 5.2, we present the mosaic of the HCO\(^+\) J=4→3 line emission obtained using OTF mapping at the CSO. We see that the line profiles of the HCO\(^+\) emission exhibits considerable structure and variability across the source. The line emission appears to drop off towards the south-western and north-western sides of VLA 1623. A few of the HCO\(^+\) spectra also show some self-absorption,\

\(^4\)The derived optical depth is a lower limit, because \(T_A^*\) for C^{17}O is higher than that of \(^{13}\)CO in the absorption dip (see Figure 5.1a).
but predominantly most of the spectra do not show the deep self-absorption that characterized the IRAS 16293 J=4→3 spectra (see Figure 4.3). The lack of deep self-absorption in the HCO+ line profiles might be due to one or more of the following alternatives: (1) The temperature gradient toward VLA 1623 might not either be large enough to produce the self-absorption, or the temperature might not be centrally concentrated on VLA 1623. There is some evidence based on dust continuum observations (AWB 1993), that there is a rising gradient from southwest to northeast that points to a heating source located toward a young B3 star northeast of VLA 1623. (2) The VLA 1623 core might be very young, and hence the outer regions that are responsible for causing the self-absorption might not have acquired high enough density to be excited in the HCO+ J=4→3 transition.

Figure 5.2 Mosaic of the CSO HCO+ J=4→3 spectra toward VLA 1623. Angular offsets in RA and Dec from the central position of VLA 1623 are shown in the outer box. For each spectrum, the displayed velocity extent is −2 to 10 km s⁻¹, and the temperature range is −1 to 5 K.

From Figure 5.2 we see no clear axis of rotation, across which the sense of
asymmetry of the line profiles are reversed. The remarkably collimated and small extent outflow toward VLA 1623 (André et al. 1990) mapped in CO J=2→1 emission is roughly oriented in a southeast to northwest direction. In their maps, André et al. (1990) found that the blueshifted and redshifted lobes largely overlap each other and surmised that the outflow was mostly in the plane of the sky. We obtained large scale submillimeter $^{12}$CO J=3→2 maps at the CSO to probe the outflow dynamics and establish the direction of the outflow. The direction of the outflow in turn would constrain the position angle of the rotational axis. In Figure 5.3, we present the extremely high velocity (EHV) lobes of CO J=3→2 in the central 140” × 140” region centered on VLA 1623. Blueshifted emission is shown in dashed contours, and redshifted emission is shown in solid contours. We see a separation of the blueshifted EHV lobe to the southeast and the redshifted EHV lobe in the northwest. From the half-power contours of the EHV flow and the maximum velocity in the CO line wings, we derive an outflow dynamical age of ~ 4000 - 6000 years.

Does the molecular outflow mapped in CO have an effect on the HCO+ line profiles? To determine this, we made integrated intensity maps using the CSO HCO+ J=4→3 data. In Figure 5.4, the integrated intensity maps based on the spectra of Figure 5.2 are presented. The maps are shown in three velocity bins (blueshifted wing: -2 to 3 km s$^{-1}$; line core: 2 to 6 km s$^{-1}$; redshifted wing: 6 to 10 km s$^{-1}$). The line core map is shown in grayscale, the blueshifted emission is shown in dashed contours, and the redshifted emission is shown in solid contours. The line core HCO+ emission shows a three-lobed structure, as a result of the superposition of two elliptical lobes of emission. Two of the lobes are oriented in the direction of the outflow mapped in CO (see Figure 5.3). The other lobe is orthogonal to the outflow axis and has a major axis oriented in a north-eastern
Figure 5.3 CSO CO J=3→2 Integrated Intensity Maps toward VLA 1623. Extremely high velocity (EHV) blueshifted wing emission (−12 to 0 km s\(^{-1}\)) is shown in dashed contours, and redshifted emission (7 to 20 km s\(^{-1}\)) is shown in solid contours. The central 140" × 140" is shown centered on VLA1623 (marked with a star). The contour levels are 2 to 7 by 0.5 K·km s\(^{-1}\) for the blueshifted emission, and 3 to 20 by 2 K·km s\(^{-1}\) for redshifted emission.

to south-western extension. From this we conclude that the even the line core of HCO+ emission is being affected by the molecular outflow. The component of the line core emission orthogonal to the outflow may be tracing the rotating cloud core. If so, the elongation along the outflow may be interpreted as morphological evidence for the disruption of the cloud core by the high velocity bipolar molecular outflow. Emission in the line wings of the HCO+ J=4→3 in Figure 5.4 also shows a complicated morphology. There is a component of redshifted line wing emission in the northeast and a component of blueshifted wing emission in the southwest that may be tracing rotation. However, some portion of the HCO+ wing emission seems to be extended partly in the direction of the outflow. From the above discussion, we can conclude that HCO+ J=4→3 emission toward VLA 1623 may be tracing both
Figure 5.4 CSO HCO+ $J=4\rightarrow3$ Integrated Intensity Maps toward VLA1623. Blueshifted wing emission ($-2$ to $3$ km s$^{-1}$) is shown in dashed contours, linecore emission ($2$ to $6$ km s$^{-1}$) is shown in grayscale, redshifted emission ($6$ to $10$ km s$^{-1}$) is shown in solid contours. The contour levels are 0.5 to 3 by 0.5 K-km s$^{-1}$ for the blueshifted emission, 3.5 to 7 by 0.7 K-km s$^{-1}$ for linecore emission, and 0.25 to 0.7 by 0.075 K-km s$^{-1}$ for redshifted emission.

the underlying high density cloud core and possibly the high density components of the molecular outflow.

In Figure 5.5, we present the centroid velocity map of HCO+ emission toward VLA1623. The centroid velocities are expressed with respect to the $v_{\text{LSR}}$ of the source, i.e., we have subtracted the $v_{\text{LSR}}$ (4 km s$^{-1}$) from the centroid velocities, making negative velocities (shown with dashed lines) blueshifted, and positive velocities (shown with solid lines) redshifted. In an effort to separate out the effect of outflow velocity fields from the dynamics of the cloud core, the velocity centroids were computed over linecore velocities. The centroid velocity map shown in Figure 5.5 is consistent with the detection of the blue-bulge infall signature toward VLA1623. There is an increasing gradient in velocity from the southwest to
the northeast. The contours are parallel to the direction of the EHV outflow lobes (see Figure 5.3). This is consistent with the HCO$^+$ centroid velocity map tracing rotation in the cloud core. Furthermore, blue-shifted velocities have pushed out the redshifted velocities to only the northeastern half of the cloud core, as predicted by the blue-bulge infall signature. Furthermore, the bowing of the contours away from the "equatorial" plane of the rotating core might also be tracing the predicted morphology of the "polar blue-bulge" effect when there is underlying Keplerian rotation in an embedded cloud core (cf. Section 3.3.6). Larger scale mapping with higher angular resolution is needed to confirm this effect.

Figure 5.5 CSO HCO$^+$ J=4→3 Centroid Velocity Map toward VLA 1623. The centroid velocities only in the line core (2 to 6 km s$^{-1}$) are shown. The central 60" × 60" is shown. The velocity of the ambient cloud (4 km s$^{-1}$) has been subtracted in the maps. Blueshifted velocities are shown in dashed contours, and redshifted velocities are shown in solid contours. Contour levels are -1.2 to 0.5 km s$^{-1}$, in steps of 0.1 km s$^{-1}$. 
Optical Depth Profiles

Recently, Mardones et al. (1997) suggested a new quantitative indicator of infall: the normalized difference in the velocity of peak emission between main and isotopic lines. In the presence of infall, isotopic line emission would always be expected to be redshifted with respect to the main line, and this normalized difference would be negative. Indeed, in the case of VLA 1623, we do see that the $^{13}$CO$^+$ line is redshifted with respect to the main line (see Figure 5.1). In the presence of infall alone, both the emergent line intensity and the emergent optical depth profiles must be asymmetric; the line intensity would be greater at blueshifted velocities, and correspondingly, the line optical depth would be greater at redshifted velocities. In the presence of pure expansion (outflow), the converse would be true: the line profile would be red asymmetric, and the optical depth profile blue asymmetric.

To determine the nature of the optical depth profile, we performed an optical depth analysis using the JCMT and CSO HCO$^+$ and $^{13}$CO$^+$ observations. In Figure 5.6, we present the optical depth profiles. The optical depth calculations were performed only over the FWHM of the isotopic line. For reference, the line profile of the main line, HCO$^+$ J=4$\rightarrow$3, is also shown in each case. The opacities were calculated for the HCO$^+$, assuming that $^{13}$CO$^+$ is optically thin.

From Figure 5.6a, we see that while the CSO HCO$^+$ J=4$\rightarrow$3 line profile shows a red asymmetric line profile that is consistent with expansion (outflow), the optical depth profile is asymmetric with opacities in the redshifted side higher than opacities in the blueshifted side of the line. In the case of pure spherical expansion, where there is a decreasing temperature gradient from inside-out, we would expect two effects (a) a line profile that exhibits red asymmetry and (b) an optical depth profile...
Figure 5.6 Optical Depth Profiles toward the Central position of VLA 1623. The velocity extent of the displayed profiles is 1 to 7 km s\(^{-1}\). The line profile of the main isotopic transition is shown in *light dashed histograms*, while the optical depth of the main isotopic transition is shown in *heavy solid histograms*. The temperature scale of the line profile is shown on the left-hand side Y axis, while the opacity scale is shown on the right-hand side Y axis. The velocity of the ambient cloud (4 km s\(^{-1}\)) is shown as a vertical line (*dash-dot line*) in each panel. (a) CSO HCO\(^+\) J=4–3 line profile and optical depth profile. (b) JCMT HCO\(^+\) J=4–3 line profile and optical depth profile.

profile that exhibits blue asymmetry. In Figure 5.6, effect (a) is satisfied, but effect (b) is not. We infer therefore that if the CSO HCO\(^+\) data is tracing expansion, that expansion is certainly not isotropic. The red asymmetry in the optical depth profiles of the CSO HCO\(^+\) J=4–3 emission could be tracing the infall velocity fields in VLA 1623. The higher angular resolution JCMT data (see Figure 5.6b) shows (a) a trace of blue asymmetry in the line profile; and (b) the redshifted optical depth is higher than the corresponding blueshifted optical depth especially at larger velocities from the line center. One possible explanation of the optical depth plots of Figure 5.6 is that they are consistent with tracing both infall and expansion.

Summarizing our observations on VLA 1623, we conclude that it is an intriguing source which demonstrates the effectiveness of the blue-bulge technique in detecting infall. The HCO\(^+\) J=4–3 line profiles and mosaics do not provide
clearcut evidence for infall, when using the traditional asymmetric blue line profile technique. However, centroid velocity maps made with line core HCO+ J=4→3 emission exhibits the blue-bulge infall signature. The relative youth of this protostellar system and the collimated outflow makes the problem of disentangling the kinematical motions difficult. Nevertheless, the blue-bulge signature was shown to be a robust indicator of collapse even in the presence of outflow.

5.3.2. SM1N

SM1N was identified by AWB (1993) as a prestellar clump in the 1.3 mm continuum map made toward the ρ Oph cloud core. In addition to SM1N, two other prestellar clumps, SM1 and SM2 were identified as possible prestellar clumps on the verge of collapse (see Figure 1 of AWB). The basis for this identification was that there no evidence for a central heating source (i.e. a protostar) in the clumps SM1N, SM1 and SM2, as opposed to VLA 1623, which showed a central peaking at multiple wavelengths in the dust continuum. SM1 is just 25″ north of VLA 1623, while SM2 is 30″ due east of VLA 1623. SM1N is 10″ east and 60″ north of VLA 1623. Of the three possibly prestellar clumps, SM1N is probably least affected by the dynamics of the VLA 1623 protostellar system. The CO J=2→1 mapping search by André et al. (1990) did not yield any molecular outflow associated with SM1N. If indeed SM1N is a prestellar clump, it may offer the opportunity of studying the earliest stages of collapse.

Line Profiles

In Figure 5.7, we present a plot of our spectral observations toward the central position of SM1N. Figure 5.7a shows the JCMT and CSO HCO+ J=4→3
observations. Both the CSO and JCMT HCO$^+$ $J=4\rightarrow3$ line profiles show no marked asymmetry. The CSO and JCMT H$^{13}$CO$^+$ $J=4\rightarrow3$ lines are redshifted with respect to the corresponding main line (see Figure 5.7b). In Table 5.3, the calculated centroid velocities of the HCO$^+$ transitions towards the central position of SM1N are listed. As was the case in VLA 1623, the centroid velocities of the isotopic HCO$^+$ transitions are $\sim 0.5$ km s$^{-1}$ redshifted with respect to the main line. In addition, as predicted for an infalling envelope, the centroid velocities of the same transition gets bluer when observed with higher angular resolution (i.e. with the JCMT).

Figure 5.7 Observed Line Profiles toward the Central position of SM1N. The velocity extent of the displayed spectra is $-4$ to $12$ km s$^{-1}$. The velocity of the ambient cloud (4 km s$^{-1}$) is shown as a vertical line (dotted line).

Since both the CSO and JCMT HCO$^+$ $J=4\rightarrow3$ lines do not show a well defined
line peak temperature, we will use the JCMT and CSO H$^{13}$CO$^+$ spectra to derive an estimate for the source size. Using the line peak temperatures of 2 K and 1.4 K for the JCMT and CSO H$^{13}$CO$^+$ (derived using gaussian fits), we estimate a source size of $\sim 15''$ for the region of HCO$^+$ emission (see Section 4.3.2 for a description of the technique). By analogy with our treatment of infall in IRAS 16293 and VLA 1623, we estimate that the infall radius of SM1N is also $\sim 15'' \approx 2400$ AU at the distance of $\rho$ Oph.

The $^{12}$CO J=3→2 line toward the central position of SM1N is blue asymmetric and shows a very deep self-reversal which is due to self-absorption (because the $^{13}$CO line peaks up in the absorption dip of the $^{12}$CO line; see Figure 5.7c). From the line ratios of $^{12}$CO to $^{13}$CO, we derive an average $^{13}$CO optical depth of $\sim 0.58$, a line excitation temperature of $\sim 16$ K, and a H$_2$ column density of $1.2 \times 10^{22}$ cm$^{-2}$ (assuming $^{12}$CO/$^{13}$CO = 89, $^{12}$CO/H$_2$ = $1 \times 10^{-4}$, filling factor of 1, and that $^{13}$CO emission is optically thin). This gives an overall envelope mass of $\sim 0.1$ M$_\odot$, assuming a 30" size for the cloud envelope. The mass derived from dust continuum observations toward SM1N is $0.6 \pm 0.3$ M$_\odot$ (AWB 1993). If we assume a higher excitation temperature and filling factor of less than 1, our mass estimate for gas will increase. Indeed, the dust temperature towards SM1N, $T_d$ is $27 \pm 5$ K (AWB 1993), twice as high as the dust temperature derived for VLA 1623. Using 30 K as the excitation temperature, we derive a mass of 0.2 M$_\odot$, closer to the mass estimate from dust. The lower gas mass might be possibly due to the depletion of gas onto dust grains in the inner parts of the SM1N cloud core, because of the lack of a central heating source.
Optical Depth Profiles

As we did for VLA 1623, we performed opacity analysis using the main and isotopic transitions of HCO+. In Figure 5.8, we present the optical depth profiles obtained using the CSO and JCMT HCO+ data towards SM1N. Again, as was seen in VLA 1623 (see discussion above), the JCMT optical depth profile shows the expected red asymmetry of infall. Once again, this emphasizes the importance of obtaining data in isotopic transitions to rule out line-of-sight optical depth effects. The red asymmetry in the opacity profile is only seen in the JCMT data, indicating perhaps that the higher angular resolution of the JCMT is probing the small size scales of the infalling material better than the CSO.

Figure 5.8 Optical Depth Profiles toward the Central position of SM1N. For description of other features of the plot see Figure 5.6. (a) CSO HCO+ J=4→3 line profile and optical depth profile. (b) JCMT HCO+ J=4→3 line profile and optical depth profile.

Mapping Results

In Figure 5.9, we present the mosaic of the HCO+ J=4→3 line emission obtained using OTF mapping at the CSO. We also obtained similar OTF map at
the JCMT with lower signal-to-noise. The JCMT HCO+ mosaic (not shown) is similar to the CSO mosaic, except that overall the JCMT data shows more blue asymmetry across the region. However, because of the higher noise in the JCMT spectral mosaic, we do not use the JCMT HCO+ for centroid velocity analysis. The HCO+ spectra show some structure, but lack the pronounced self-absorption dips that characterized the IRAS 16293 HCO+ spectra (see Figures 4.3 and 4.4).

![Figure 5.9 Mosaic of the CSO HCO+ J=4→3 spectra toward SM1N. Angular offsets in RA and Dec from the central position of SM1N are shown in the outer box. For each spectrum, the displayed velocity extent is −2 to 10 km s⁻¹, and the temperature range is −1 to 5 K.](image)

Although André et al. (1990) did not find evidence for outflow toward SM1N, we decided to probe the region around SM1N for outflow activity using high angular resolution submillimeter CO J=3→2 mapping with the JCMT. Higher sensitivity and higher angular resolution observations might be able to uncover any weak outflow driven by SM1N. Indeed we detect a low mass bipolar outflow in our JCMT CO integrated maps (see Figure 5.10). The blueshifted lobe is seen
to the north of the SM1N position and the redshifted lobe is mostly to the south. Since the full extent of the outflow was not established in our mapping, we cannot make estimates on the time scales of this newly discovered outflow. In addition, the signal-to-noise limits on our JCMT OTF observations prevent us from studying the EHV components of the outflow. The high velocity (HV) lobes appear to originate from a point approximately 20" east of the SM1N position. It is possible that this flow is not associated with the SM1N clump. Large scale mapping of the SM1N region in CO is required to confirm the driving source of this outflow. The redshifted emission seen in the southwestern portion of the map arises from the redshifted lobe of the VLA 1623 outflow system.

Assuming that the wing emission of CO seen in Figure 5.10 is associated with a bipolar outflow from the SM1N clump, the position angle of the rotational axis of SM1N can be derived from the orientation of the bipolar lobes of the outflow. This position angle is not the same as seen in VLA 1623. The SM1N flow is more N-S, whereas the VLA 1623 flow is NW-SE. Recently, Holland et al. (1996) recorded a change in the position angle of 800μm polarization vectors observed toward the ρ Oph cloud core from VLA 1623 (approximately NW-SE) to SM1N (approximately E-W). It is not surprising in light of this evidence that the position angle of molecular outflow has changed from VLA 1623 to SM1N, although they are only an arcminute apart. Larger scale mapping is required toward the SM1N system to fully probe the dynamics of its outflow.

To determine if the HCO+ emission traces some component of the CO outflow, we made integrated intensity maps using the CSO HCO+ data. In Figure 5.11, we present integrated intensity maps of blueshifted, linecore and redshifted emission based on the spectra presented in Figure 5.9. Indeed, the blueshifted and redshifted
Figure 5.10 JCMT CO J=3→2 Integrated Intensity Maps toward SM1N. High velocity (HV) blueshifted wing emission (−1 to 3 km s⁻¹) is shown in dashed contours, and redshifted emission (5 to 8 km s⁻¹) is shown in solid contours. The central 60" × 60" is shown centered on the position of SM1N. The contour levels are 36 to 54 by 4 K·km s⁻¹ for the blueshifted emission, and 12 to 19 by 1.5 K·km s⁻¹ for redshifted emission.

lobes of HCO+ emission do seem to follow the orientation of the CO outflow, possibly tracing the dense shells being swept up by the underlying jet. The origin of the outflow traced by HCO+ wing emission seems to be located about 10" north of the central position of SM1N, coincident approximately with the peak of the linecore HCO+ emission (shown in grayscale). The linecore emission seems to be elongated in a north-south direction and is similar in appearance to the 1.3 mm continuum map of AWB (1993). The clump 20" south of SM1N is coincident with the position of SM1. We see that that the HCO+ linecore emission peaks up at a position north of SM1N, and is a brighter peak of emission than SM1. From the above discussion, we deduce that the linecore HCO+ emission toward SM1N is tracing the dust core, but is also associated with the outflow system.

Finally, in Figure 5.12, we present the centroid velocity map of HCO+ linecore
emission toward SM1N. We see that blueshifted velocities are seen through most of the map. The velocity gradients are not well ordered into a gradient consistent with a clear sign of rotation. In addition, the orientation of the contours is not parallel to the expected rotational axis, as expected for the blue-bulge signature. In fact, the gradient in the velocity contours, with blueshifted velocities in the north and redshifted velocities to the south, seem to trace the outflow presented in Figures 5.10 and 5.11. A similar gradient in linecore velocities was seen towards Cepheus A in CO $J=3\rightarrow2$ emission by Narayanan and Walker (1996), who interpreted the low velocity CO linecore emission as arising from the slow-moving, dense, swept-up shells of the molecular outflow in that source. The blue-bulge is not seen.

Summarizing our observations on SM1N, we conclude that there is tentative
Figure 5.12 CSO HCO$^+$ J=4→3 Centroid Velocity Map toward SM1N. The centroid velocities only in the line core (2 to 6 km s$^{-1}$) are shown. The central 60″ × 60″ is shown. The velocity of the ambient cloud (4 km s$^{-1}$) has been subtracted in the maps. Blueshifted velocities are shown in dashed contours, and redshifted velocities are shown in solid contours. Contour levels are −1 to 0.5 km s$^{-1}$, in steps of 0.1 km s$^{-1}$.

Evidence for infall in this pre-protostellar clump. We present a detection of a new bipolar outflow toward the SM1N region. The trends of centroid velocities of observed transitions with optical depth and angular resolution, and HCO$^+$ J=4→3 optical depth profiles are consistent with the occurrence of infall in the SM1N region. However, the blue-bulge signature is not seen in SM1N.

5.3.3. L483

L483 is associated with the IRAS source 18148-0440, and was first identified as a protostellar source by Parker et al. (1988, 1991), who detected a bipolar outflow and suggested its protostellar nature based on its IRAS colors. The source has an IRAS luminosity of 9 $L_\odot$, and is located at a distance of 200 pc. Strong outflow
activity is also suggested by the presence of water maser emission (Wilking et al. 1994). The source has neither an optical or near-infrared counterpart (Parker 1991). Observations of NH$_3$ and HC$_3$N show the IRAS source to be well centered in the region of dense gas (Fuller & Myers 1993, Anglada et al. 1997). The source is surrounded by a bipolar near-infrared reflection nebula, and a jet-like region of H$_2$ emission (Fuller et al. 1995). From the coincidence of the near-infrared emission with the bipolar outflow lobes, and the brightness ratios of near-infrared emission between the two lobes, Fuller et al. (1995) estimate that the outflow has an inclination angle of ~ 40° to the plane of the sky. Myers et al. (1995) suggested a possible collapse interpretation in L483, based on the blue asymmetry observed in their H$_2$CO line profiles. However, recent CSO observations by Gregersen et al. (1997) in HCO$^+$ J=3→2 and J=4→3 display a red asymmetry, and they suggest that this evidence weakens the case for collapse.

In Figure 5.13 we present a plot of our spectral observations toward the driving source of L483. Figure 5.13a shows the JCMT and CSO HCO$^+$ J=4→3 observations. The noteworthy feature of both the CSO and JCMT HCO$^+$ J=4→3 spectra is that they shows a red asymmetric signature consistent with expanding gas rather than collapse. The corresponding H$^{13}$CO$^+$ lines (see Figure 5.13b) do not exhibit this pronounced red asymmetry. The JCMT H$^{13}$CO$^+$ spectrum shows a trace of blue asymmetry. It is seen from Figure 5.13 that the isotopic H$^{13}$CO$^+$ lines are not redshifted with respect to the main line, as expected for a pure infall scenario. This is indeed confirmed by our centroid velocity calculations presented in Table 5.3. We estimated the source size of HCO$^+$ J=4→3 emission from the ratio of line peak temperatures of the JCMT and CSO HCO$^+$ J=4→3 observations. We derive an HCO$^+$ source size of ~ 18" (see Section 4.3.2 for a description of the technique), which gives 3600 AU at the 200 pc distance to L483.
Figure 5.13 Observed Line Profiles toward the Central position of L483. The velocity extent of the displayed spectra is $-5$ to $15 \, \text{km s}^{-1}$. The velocity of the ambient cloud ($5.5 \, \text{km s}^{-1}$) is shown as a vertical line (dotted line).

The $^{12}$CO spectrum in Figure 5.13c shows deep self-absorption and extremely high velocity wings. In Figure 5.14, we present the integrated intensity maps of the HV blueshifted ($-5$ to $4 \, \text{km s}^{-1}$) and redshifted ($7$ to $15 \, \text{km s}^{-1}$) line wings from our CSO OTF maps obtained toward L483 in CO J=$3\rightarrow2$ emission. As seen in previous outflow maps made toward L483, the outflow is highly collimated and bipolar. The blueshifted lobe is to the west and the redshifted lobe is to the east. Using the half power contours of the lobes, and the maximum velocity in the line wings we derive an estimate of $5000 \sim 10000$ years for the dynamical timescale of the outflow, in agreement with the estimates of Fuller et al. (1991) and Parker et al. (1991). Noting that the near-infrared emission in the western blueshifted lobe
of the outflow is significantly brighter than the eastern lobe, Fuller et al. (1995) derived an angle $\alpha \sim 40^\circ$ for the inclination of the outflow angle to the plane of the sky. By connecting the maxima of the blueshifted and redshifted EHV lobes of our CO maps, we derive that the outflow axis is at a position angle of $\psi \sim -80^\circ$ in the plane of the sky.

![Figure 5.14](image)

Figure 5.14 CSO CO $J=3\rightarrow2$ Integrated Intensity Maps toward L483. High Velocity (HV) blueshifted wing emission ($-5$ to $4$ km s$^{-1}$) is shown in dashed contours, and redshifted emission ($7$ to $15$ km s$^{-1}$) is shown in solid contours. The central $60'' \times 40''$ is shown centered on the position of L483. The contour levels are 4 to 15 by 1 K-km s$^{-1}$ for the blueshifted emission, and 3 to 10 by 0.75 K-km s$^{-1}$ for redshifted emission.

From the line ratios of $^{12}$CO to $^{13}$CO, we derive an average $^{13}$CO optical depth of $\sim 0.2$, a value almost a factor of 10 higher than that obtained by Parker et al. (1991) with CO $J=2\rightarrow1$ observations. The optical depth in CO lines towards outflows is expected to increase with higher transitions and higher angular resolution (Phillips et al. 1981). We also derive a line excitation temperature of $\sim 10$ K, and a H$_2$ column density of $5.7 \times 10^{21}$ cm$^{-2}$ (assuming $^{12}$CO/$^{13}$CO = 89, $[^{12}$CO/H$_2$] = $1 \times 10^{-4}$, filling factor of 1, and that $^{13}$CO emission is optically thin). This gives an overall flow mass of $\sim 0.1$ M$_\odot$, using the half-power sizes of the outflow lobes (the derived mass is a lower limit because the full extent of the outflow is not mapped; see Figure 5.14). The excitation temperature, and flow
mass are consistent with that obtained by Parker et al. (1991) using their J=2→1 observations.

**HCO+ Optical Depths and Maps**

From our model calculations of Chapters 2 and 3 we predicted that in the absence of outflow, the spectroscopic and blue-bulge signatures of infall are best seen when the rotational axis of the protostellar system is at a large angle of inclination to the plane of the sky (the best case is when we have a pole-on line of sight to the source). In the case of L483, the rotational axis is at a large angle to the plane of the sky (~40°). However, L483 also possesses a vigorous outflow system. What effect does the outflow have on the direct detection of infall motions? In Figure 5.15, we present the calculated HCO+ optical depths obtained from ratios of H^{12}CO+ and H^{13}CO+ J=4→3 observations at the CSO and JCMT respectively. We see that the HCO+ line profiles are red asymmetric, and the optical depth profiles are blue asymmetric, both of which are consistent with tracing a region of expanding gas.

In general, the HCO+ J=4→3 transition, because of its high critical density (6 × 10^6 cm\(^{-3}\) at 40 K; from Monteiro 1985), is not expected to be excited in molecular outflows. In an effort to understand the distribution of high density gas in the L483 region, we made maps of the blueshifted, linecore and redshifted emission from our CSO HCO+ J=4→3 observations. The linecore emission (shown in grayscale in Figure 5.16) is seen to be extended in the direction of the CO outflow, indicating that the cloud core is being disrupted by the outflow. The blueshifted and redshifted lobes of HCO+ emission have a more complicated morphology. Blueshifted and redshifted emission appear to extend in the direction
of the outflow. In addition, the lobes are seen to overlap each other. From the morphology of the wing emission seen in Figure 5.16, we suggest that the HCO+ line wings are primarily tracing the limb-brightened swept-up outflow shells of the L483 outflow system. The overlapping blue and redshifted components of emission in this scenario trace the near and far sides of the shells of outflow. Cabrit and Bertout (1986) have explained overlapping blue and redshifted lobes of outflow in terms of a biconical model of outflowing gas in which the opening angle of the outflow is greater than the angle of inclination of the outflow axis from the plane of the sky.

From Figures 5.15 and 5.16, we conclude that in L483, the HCO+ line profiles are primarily affected by outflow motions. The large angle of inclination of the outflow system effectively results in larger line-of-sight component of expansive motions in the HCO+ line profiles. In Figure 5.17, we show the mosaic of HCO+ J=4→3 spectra obtained toward L483 using CSO OTF mapping. Most of the spectra display red asymmetry. In Figure 5.18, we show the centroid velocity map.
Figure 5.16 CSO HCO+ J=4→3 Integrated Intensity Maps toward L483. Blueshifted wing emission (1 to 5 km s$^{-1}$) is shown in dashed contours, linecore emission (4 to 7 km s$^{-1}$) is shown in grayscale, redshifted emission (6.5 to 9 km s$^{-1}$) is shown in solid contours. The contour levels are 0.4 to 0.95 by 0.075 K km s$^{-1}$ for the blueshifted emission, 2 to 3.6 by 0.3 K km s$^{-1}$ for linecore emission, and 0.3 to 0.55 by 0.075 K km s$^{-1}$ for redshifted emission.

made in the linecore of HCO+ emission towards L483 using the spectra shown in Figure 5.17. The centroid velocity map shows a velocity gradient approximately orthogonal to the direction of the outflow, i.e. in the NE-SW direction. Such a velocity gradient was seen recently in lower angular resolution NH$_3$ observations toward the dense cloud core of L483 (Anglada et al. 1997). Goodman et al. (1993) report a velocity gradient ($\sim 1.9 \pm 0.2$ km s$^{-1}$, PA = 52°) in the region. Although most of the velocities in the map seen in Figure 5.18 are redshifted, the morphology of the curved iso-velocity contours toward the driving source is reminiscent of the blue-bulge morphology. It is tempting to speculate in the case of L483 that we see a "biased" blue-bulge in that the strong outflow velocities tend to bias the velocity field to redder values, but the expected morphology of the blue-bulge signature of infall is still observed in the central regions, where infall velocities are expected to be high.

Summarizing our observations of L483, we report that because of the tilting
of the outflow axis to our line of sight, traditional line profile methods of detecting infall fail to detect collapse motions. In addition, our calculated optical depth profiles of the HCO+ J=4→3 transition towards the central position of L483 indicate expansive motions due to the outflow system. In spite of the failure of other methods, there is some tentative evidence that the blue-bulge signature of infall is detected toward L483. The expansive motions bias the blue-bulge toward redder values, but the morphological appearance of the HCO+ centroid velocity map suggests that collapse motions are indeed taking place in this source.

5.3.4. SMM4

The Serpens cloud core at a distance of 310 pc is a region of great interest for star formation studies because of the striking variety of young stellar objects (see
Figure 5.18 CSO HCO+ J=4→3 Centroid Velocity Map toward L483. The centroid velocities only in the line core (4 to 7 km s\(^{-1}\)) are shown. The central 20" × 20" is shown. The velocity of the ambient cloud (5.5 km s\(^{-1}\)) has been subtracted in the maps. Blueshifted velocities are shown in dashed contours, and redshifted velocities are shown in solid contours. Contour levels are −0.35 to 0.55 km s\(^{-1}\), in steps of 0.015 km s\(^{-1}\).

Eiroa 1991 for a complete review). New submillimeter and millimeter continuum observations have revealed six new dust continuum peaks, labelled SMM1 through SMM6 that have no known near-infrared counterparts (Casali et al. 1993). A recent multi-transitional H\(_2\)CO study of the dust continuum peaks confirms the presence of central heating sources and substantial masses of circumstellar masses in five of these objects, suggesting that they may be among the youngest known protostellar objects (Hurt et al. 1996). High resolution molecular line studies have shown multiple outflows in the cloud core and do not seem to show clear alignment with the millimeter sources (White et al. 1995). SMM4 has the strongest overall H\(_2\)CO \(3_03 \rightarrow 2_02\) emission of all the observed sources in Serpens, and its line profile shows the blue asymmetric signature of infall (Hurt et al. 1996). Recently, Gregersen et al. (1997) have observed central line profiles of HCO+ J=3→2 and J=4→3
towards SMM4, and observe them to display blue asymmetric line profiles as well.

**Line Profiles**

In Figure 5.19, we present the line profiles of observations towards the central position of SMM4. All observations were performed at the JCMT. The HCO+ J=4→3 lines appear asymmetric with a blue peak to red peak ratio of ~ 3.8, which is the largest such ratio obtained in HCO+ J=4→3 observations reported in this work. In Table 5.3, the calculated centroid velocities of HCO+ transitions are listed. The H^{13}CO+ line profile is also slightly asymmetric blue, indicating that it too is probably optically thick. The H^{13}CO+ centroid velocity is ~ 0.5km s^{-1} redshifted with respect to the main isotope. Although we did not obtain complementary CSO observations, we could use the CSO HCO+ J=4→3 observation of Gregersen et al. (1997) to derive a source size. From their Figure 2 and their efficiencies, we calculate their CSO main beam temperature, T_{mb,C} ~ 7.3 K. From our JCMT observations, we derive T_{mb,J} ~ 13.4 K. From this, we derive an approximate source size for HCO+ emission to be 12" or 3700 AU at the distance of the Serpens cloud core. From a ratio of the main isotopic lines of HCO+, we derive an average H^{13}CO+ optical depth of ~ 0.06 in the velocity interval 4 to 12km s^{-1}, a line excitation temperature of ~ 10 K, and a H$_2$ column density of $9.6 \times 10^{22}$ cm$^{-2}$ (assuming $^{12}$C/$^{13}$C = 89, [H^{12}CO+/H$_2$] = $5 \times 10^{-9}$, filling factor of 1, and that H^{13}CO+ emission is optically thin). This gives an overall envelope mass of ~ 0.6 M$_\odot$, which compares well with the 0.9 M$_\odot$ mass estimate of Hurt et al. (1996) from H$_2$CO observations.

The $^{12}$CO lines show deep self-absorption and EHV line wings. Even the $^{13}$CO spectrum shows self-absorption and is also asymmetric like the main line, implying
Figure 5.19 Observed Line Profiles toward the Central position of SMM4. The velocity extent of the displayed spectra is $-20$ to $30\, \text{km}\, \text{s}^{-1}$. The velocity of the ambient cloud ($8.1\, \text{km}\, \text{s}^{-1}$) is shown as a vertical line (dotted line).

that it is optically thick as well. The absorption dip at $\sim 1\, \text{km}\, \text{s}^{-1}$ in the $^{12}\text{CO}$ line is probably due to absorption by a foreground cloud. In Figure 5.20, we present the integrated intensity maps of EHV blueshifted ($-15$ to $2\, \text{km}\, \text{s}^{-1}$) and EHV redshifted ($13$ to $25\, \text{km}\, \text{s}^{-1}$) emission in the $^{12}\text{CO}$ line. The EHV flow is clearly bipolar, with the blueshifted emission to the north and redshifted emission to the south. This is the first detection of molecular outflow that can be associated with SMM4. The previous search for outflows by White et al. (1995) probably did not have the sensitivity of our observations. Unfortunately our JCMT OTF maps are not large enough to establish the full extent and hence the dynamical time scale of the outflow system toward SMM4. We derive from the appearance of the outflow
lobes, the position angle of the rotational axis to be $\sim 45^\circ$ in the plane of the sky.

![Figure 5.20 JCMT CO J=3→2 Integrated Intensity Maps toward SMM4. Extremely High Velocity (EHV) blueshifted wing emission ($-15$ to $2$ km s$^{-1}$) is shown in dashed contours, and redshifted emission $13$ to $25$ km s$^{-1}$) is shown in solid contours. The central 60'' x 60'' is shown centered on the position of SMM4. The contour levels are 12 to 30 by 4 K-km s$^{-1}$ for the blueshifted emission, and 12 to 32 by 4 K-km s$^{-1}$ for redshifted emission.](image)

From line ratios of $^{12}$CO to $^{13}$CO, we derive an average $^{13}$CO optical depth of $\sim 0.08$, a line excitation temperature of $\sim 16$ K, and a H$_2$ column density of $3.4 \times 10^{21}$ cm$^{-2}$ (assuming $^{12}$CO/$^{13}$CO = 89, $[^{12}$CO/H$_2] = 1 \times 10^{-4}$, filling factor of 1, and that $^{13}$CO emission is optically thin). This gives an outflow mass of $\sim 0.02$ M$_\odot$, in each outflow lobe using the half-power sizes of the outflow lobes.

**HCO+ Opacities and Maps**

In Figure 5.21, we present the calculated line optical depths for HCO+ J=4→3 obtained from ratios of $^{12}$HCO+ and $^{13}$HCO+ J=4→3 JCMT observations. We see that the optical depth profile exhibits a red asymmetry, which together with the
blue asymmetry of the main line, can be interpreted as evidence for infall.

Figure 5.21 Optical Depth Profiles toward the Central position of SMM4. For description of other features of the plot see Figure 5.6. JCMT HCO+ J=4→3 line profile and optical depth profile.

We present the mosaic of our JCMT OTF observations regridded to 10" spacing in Figure 5.22. The emission is seen to be centrally peaked on SMM4. Unlike the spectral mosaics seen in IRAS 16293 (see Figures 4.1 through 4.4), we do not see deep self-absorption in the line profiles. The lack of deep self-absorption implies that the outlying gaseous layers are not sufficiently warm or dense enough to significantly populate the J = 3 levels of HCO+. Since the density wave grows from inside-out, the lack of deep self-absorption can be interpreted as evidence for the relative youth of this protostellar system. In the central regions most of the line profiles show blue asymmetry, while the line profiles are mostly symmetric in the outer regions.

In Figure 5.23, we present the integrated intensity maps of the blueshifted, linecore and redshifted emission based on the HCO+ J=4→3 spectra shown in Figure 5.22. The linecore emission (shown in grayscale in Figure 5.23) is seen to be extended in a direction orthogonal to the direction of the CO outflow. The
blueshifted and redshifted lobes of HCO+ emission have a more complicated morphology. There are two distinct lobes of redshifted HCO+ emission. The one in the north is probably associated with the redshifted component also seen to the north in the CO map (see Figure 5.20). The northern redshifted lobe may be associated with the SMM3 source. The other redshifted lobe is SE of SMM4, while the blueshifted lobe is to the NW of SMM4. Essentially, the line wings of HCO+ \( J=4\rightarrow3 \) seem to be more associated with the extended cloud core traced by the linecore HCO+ emission, and may be tracing rotation in the SMM4 cloud core. The extended linecore emission of HCO+ \( J=4\rightarrow3 \) in SMM4 is clearly unassociated with the bipolar outflow detected in CO.

In Figure 5.24, we present the centroid velocity map of linecore HCO+ \( J=4\rightarrow3 \) emission toward SMM4. The cloud \( v_{LSR} \) (8.1 km s\(^{-1}\)) has been subtracted from the
Figure 5.23 JCMT HCO+ J=4→3 Integrated Intensity Maps toward SMM4. Blueshifted wing emission (2 to 6 km s\(^{-1}\)) is shown in dashed contours, linecore emission (6 to 10 km s\(^{-1}\)) is shown in grayscale, redshifted emission (10 to 14 km s\(^{-1}\)) is shown in solid contours. The contour levels are 1.5 to 3.2 by 0.3 K·km s\(^{-1}\) for the blueshifted emission, 7 to 13 by 1 K·km s\(^{-1}\) for linecore emission, and 1 to 1.4 by 0.1 K·km s\(^{-1}\) for redshifted emission.

centroid velocities. As was shown above, the line core velocities of HCO+ J=4→3 largely exclude the outflow components. The centroid velocity map shown in Figure 5.24 is consistent with the detection of the blue-bulge infall signature toward SMM4. There is a gradient in velocity from the northwest to the southeast. The contours are parallel to the direction of the EHV outflow lobes (see Figure 5.20). This is consistent with the HCO+ centroid velocity map tracing rotation in the cloud core. Furthermore, blue-shifted velocities have pushed the redshifted velocities in the southeastern half of the cloud core, as predicted by our blue-bulge infall signature. The bowing of the contours away from the “equatorial” plane of the rotating core might also be tracing the predicted morphology of the “polar blue-bulge” effect when there is underlying Keplerian rotation in an embedded cloud core (cf. Section 3.3.6). Larger scale mapping with higher angular resolution is needed to confirm
this effect.

Figure 5.24 JCMT HCO+ J=4→3 Centroid Velocity Map toward SMM4. The centroid velocities only in the line core (6 to 10 km s\(^{-1}\)) are shown. The central 50'' \(\times\) 50'' is shown. The velocity of the ambient cloud (8.1 km s\(^{-1}\)) has been subtracted in the maps. Blueshifted velocities are shown in dashed contours, and redshifted velocities are shown in solid contours. Contour levels are —1 to 0.5 km s\(^{-1}\), in steps of 0.1 km s\(^{-1}\).

In Figure 5.25, we present the centroid velocity cuts obtained along the equatorial and polar axis of SMM4 in HCO+ J=4→3 emission. The polar cut was made from the map shown in Figure 5.24, with a P.A. of 45°. The equatorial cut is orthogonal to the polar cut. The error bars show the computed error in determining the centroid velocity. The linear gradient in the equatorial cut is consistent with tracing a rotational motion. Using the gradient of 0.5 km s\(^{-1}\) over 40'', we derive a rotational rate of \(\Omega \approx 3 \times 10^{-13}\) s\(^{-1}\). In the absence of infall, the curve would be expected to pass through zero velocity at the position of the source. The infall velocity field is seen to "bias" this to \(-0.7\) km s\(^{-1}\)(blueshift). The rotational curve is seen to flatten out and change sign, where the cloud core merges with the ambient
medium. The polar cut of Figure 5.25 clearly shows the blue-bulge. The infall velocities are highest in the central regions, and that is where, the velocities are most blueshifted.

Figure 5.25 HCO+ J=4→3 Centroid Velocity Cuts towards SMM4. The X-axis shows the angular offsets along the cuts from the position of SMM4. The Y-axis shows the velocities with \( \nu_{\text{LSR}} = 8.1 \, \text{km s}^{-1} \) subtracted.

Summarizing our results for SMM4, we present the detection of the blue-bulge signature of infall toward SMM4. We present the first detection of a bipolar outflow towards this source using CO J=3→2 observations. The infall picture is relatively secure in this source due to many lines of evidence: the asymmetric line profiles and optical depth profiles of HCO+ J=4→3 and the blue-bulge centroid velocity signature.

5.3.5. B335

The dark cloud B335 contains a clearly defined bipolar molecular outflow first studied by Frerking & Langer (1982), and then mapped in CO by several groups (Goldsmith et al. 1984, Langer et al. 1986, Moriarty-Schieven & Snell 1989, Hirano et al. 1992). Outflow studies toward B335 indicate that the outflow is in the plane of the sky and is oriented east-west. At the center of the outflow there is a far-infrared and submillimeter continuum source that is elongated N-S, orthogonal
to the outflow, and has been proposed as the cloud core that is powering the outflow (Chandler et al. 1990). The high visual extinction and lack of near-infrared emission (Chandler & Sargent 1993, Anglada et al. 1992) indicates that it may be a Class 0 source. Using H$_2$CO and CS observations, Zhou et al. (1993) provided evidence for protostellar collapse in B335. Subsequently, Zhou (1995) improved upon the infall models for B335 by including rotation and was able to confirm the earlier suggestion for infall. B335 is one of the best studied candidates for infall, for which multiple lines of evidence exist for the collapse scenario (Velusamy et al. 1995, Choi et al 1995, Gregersen et al. 1997). We studied B335 using CSO HCO$^+$ J=4→3 observations in order to confirm the blue-bulge signature of infall.

**Line Profiles**

In Figure 5.26, we summarize the results of our line profile observations towards the central position of B335. The JCMT and CSO HCO$^+$ J=4→3 observations show the blue asymmetric profiles characteristic of infall. The whole of the line profile of the CSO HCO$^+$ J=4→3 spectrum appears a little redshifted with respect to the JCMT spectrum. Using the ratios of line peak temperatures of JCMT and HCO$^+$ J=4→3 spectra, we derive a source size of ~ 9.2" (≈ 2300 AU) for the size of HCO$^+$ emission. In Table 5.3, the calculated centroid velocities for observed HCO$^+$ profiles towards the central position of B335 are listed. The trends in centroid velocity, i.e. the JCMT HCO$^+$ J=4→3 centroid velocity being bluer than the corresponding CSO one, and the isotopic H$^{13}$CO$^+$ centroid velocity being redder than the main line, are indicative of collapse. From a ratio of the CSO main and isotopic lines of HCO$^+$, we derive an average H$^{13}$CO$^+$ optical depth of ~ 0.18 in the velocity interval 7 to 9 km s$^{-1}$, a line excitation temperature of ~ 9.2 K, and
a H$_2$ column density of $4.2 \times 10^{22}$ cm$^{-2}$ (assuming $^{12}$C/$^{13}$C = 89, $[^{12}$CO+/H$_2] = 5 \times 10^{-9}$, filling factor of 1, and that H$^{13}$CO+ emission is optically thin). This gives an overall envelope mass of $\sim 0.2$ M$_\odot$, which compares well with the 0.17 M$_\odot$ mass estimate of Chandler & Sargent (1993) using high resolution C$^{18}$O observations. The CSO H$^{13}$CO+ J=4$\to$3 spectrum appears symmetric, and its centroid velocity is redshifted with respect to the main line (see Figure 5.26b and Table 5.3).

Figure 5.26 Observed Line Profiles toward the Central position of B335. The velocity extent of the displayed spectra is 5 to 12 km s$^{-1}$. The velocity of the ambient cloud (8.5 km s$^{-1}$) is shown as a vertical line (dotted line).

**HCO+ Opacities and Maps**

In Figure 5.27, we present the calculated line optical depths for HCO+ J=4$\to$3 obtained from ratios of our H$^{12}$CO+ and H$^{13}$CO+ J=4$\to$3 CSO observations. We see that the optical depth profile exhibits a red asymmetry, which together with the blue asymmetry of the main line, can be interpreted as evidence for infall.

We present the mosaic of our CSO OTF observations in Figure 5.22. The
emission is seen to be centrally peaked on B335. The emission is only present in the central 20" × 20", which together with the ~9" source size we derived (see above), implies a very young protostellar system. Most of the line profiles exhibit blue asymmetry.

In Figure 5.29, we present the centroid velocity map of linecore HCO+ J=4→3 emission toward B335. The cloud v_{LSR} (8.5 km s^{-1}) has been subtracted from the centroid velocities. The line core velocities of HCO+ J=4→3 are expected to largely exclude the outflow components. Also shown in grayscale is the integrated intensity map in the linecore velocities. It is seen that the linecore integrated intensity is extended in the direction of the outflow, probably indicating that the outflow is affecting the linecore emission to some extent. The centroid velocities in Figure 5.29 show a gradient with velocities increasing from the south to north. The contours are parallel to the direction of the outflow lobes. This is consistent with the HCO+ centroid velocity map tracing rotation in the cloud core. Furthermore, blue-shifted velocities have pushed the redshifted velocities completely out of the

Figure 5.27 Optical Depth Profiles toward the Central position of B335. For description of other features of the plot see Figure 5.6. CSO HCO+ J=4→3 line profile and optical depth profile.
Figure 5.28 Mosaic of the CSO HCO+ $J=4\rightarrow3$ spectra toward B335. Angular offsets in RA and Dec from the central position of B335 are shown in the outer box. For each spectrum, the displayed velocity extent is 5 to 12 km s$^{-1}$, and the temperature range is $-1$ to $6$ K.

Zhou (1995) derived a very low rotational rate in B335 ($\Omega = 1.4 \times 10^{-14}$ s$^{-1}$; see also Frerking et al. 1987). The appearance of the centroid velocity map in Figure 5.29 is remarkably similar to the TSC models presented in Chapter 3 with low rotational rate (see for instance Figure 3.15a). The outflow's effects are seen in the distorting of the contours immediately east and west of the driving source in B335. However, the strong infall velocities are seen in the complete blueshifting of the velocity field of dense gas.

Summarizing our results for B335, we detected the blue-bulge signature of infall in the centroid velocities of HCO+ $J=4\rightarrow3$ emission toward B335. As in SMM4 and IRAS 16293, the infall picture is relatively secure in this source due to many lines of evidence: the asymmetric line profiles and optical depth profiles of HCO+ $J=4\rightarrow3$ and the blue-bulge centroid velocity signature.
Figure 5.29 CSO HCO+ J=4→3 Centroid Velocity Map toward B335. The centroid velocities only in the line core (7 to 10 km s\(^{-1}\)) are shown. The central 20") × 20") is shown. The velocity of the ambient cloud (8.5 km s\(^{-1}\)) has been subtracted in the maps. Blueshifted velocities are shown in dashed contours, and redshifted velocities are shown in solid contours. Contour levels are −0.25 to 0.1 km s\(^{-1}\), in steps of 0.015 km s\(^{-1}\).

5.3.6. L1262

L1262 is an isolated Bok globule with a very high visual extinction located at a distance of 200 pc (Parker et al. 1991). It has a well-collimated bipolar molecular outflow approximately 2'.5 in extent (Parker et al. 1988, Parker et al. 1991). Interferometric \(^{12}\)CO observations reveal a more compact (∼ 20") outflow. The outflow is elongated in the northeast to southwest direction, and is centered at the position of the source IRAS 23238+7402, which is proposed to be the exciting source of the outflow. The velocity of the outflow decreases as one moves away from the driving source (Parker et al. 1988, Parker et al. 1991), which is cited as evidence for deceleration of the flow. The derived dynamical outflow timescale of ∼ 2 × 10\(^4\) yrs (Parker et al. 1991) indicates that L1262 may be an evolved Class
0 to early Class I object. Two radio continuum peaks, one centered on the source and two NH$_3$ peaks, one centered on the source (Anglada et al. 1997) have been observed toward this region. In their C$^{18}$O and H$_2$CO survey for infall in Bok globules, Wang et al. (1995) identified L1262 (called CB244 in their paper) as a good candidate for infall.

We only obtained CSO HCO$^+ J=4\rightarrow3$ observations of the L1262 region. Without isotopic observations, we cannot make estimates of the optical depths in HCO$^+$. However, the spectral mosaic of HCO$^+ J=4\rightarrow3$ shown in Figure 5.30 shows evidence for infall. Although the HCO$^+$ lines are quite weak and centrally concentrated, they show the blue asymmetric signature of infall in their line profiles. HCO$^+ J=4\rightarrow3$ emission is detected only in the central 20" x 20". This evidence taken along with the long timescale of the outflow may be interpreted as evidence for the dynamical clearing of much of the dense gaseous envelope surrounding L1262.

In order to constrain the orientation and position angle of the rotational axis of L1262, we mapped the outflow in $^{12}$CO emission with high signal-to-noise ratio observations at the HHT. The EHV lobes of CO are shown in Figure 5.31. The orientation of the outflow lobes are consistent with previously published HV maps of the outflow in L1262, i.e. predominantly NE-SW.

In Figure 5.32, we present the centroid velocity map in the linecore HCO$^+ J=4\rightarrow3$ emission towards L1262, based on the spectra shown in Figure 5.30. The cloud $v_{LSR}$ (4.0 km s$^{-1}$; Parker et al. 1991) has been subtracted from the centroid velocities. The line core velocities of HCO$^+ J=4\rightarrow3$ are expected to largely exclude the outflow components. There is a gradient with centroid velocity increasing from the NW to the SE, orthogonal to the molecular outflow seen in Figure 5.31. The
iso-velocity contours are indeed parallel to the outflow axis. Thus, the morphology of the contours in the central regions of L1262 is consistent with the detection of the blue-bulge signature of infall in L1262.

To summarize our observations on L1262, we have detected the blue-bulge infall signature as well as the classic asymmetric blue profile signature of infall toward L1262. Observations in isotopic H^{13}CO+ J=4→3 are needed to obtain the optical depth profiles and confirm the detection of infall.
Figure 5.31 HHT CO J=2→1 Integrated Intensity Maps toward L1262. Extremely High Velocity (EHV) blueshifted wing emission (-10 to 2 km s⁻¹) is shown in dashed contours, and redshifted emission 7 to 20 km s⁻¹ is shown in solid contours. The central 60" × 60" is shown centered on the position of L1262. The contour levels are 2 to 3.5 by 0.15 K km s⁻¹ for the blueshifted emission, and 4 to 9 by 1 K km s⁻¹ for redshifted emission.

5.4. Discussion

5.4.1. Infall Parameters Using TSC Models

In Table 5.4, we present the results of fitting our observations with the 3-dimensional TSC infall models introduced in Chapter 3. The infall radius r_{inf}, sound speed a, the time since onset of infall t_{inf} (t_{inf} = r_{inf}/a), rotational rate \Omega, the angles \alpha and \psi of the rotational axis with respect to our line of sight (see Figure 2.1), and the turbulent velocity used in the radiative transfer solution are summarized in Table 5.4. For each source, many model runs were made by varying the infall parameters. The best fits were obtained by eye, by constraining the models with observed H^{12}CO⁺ and H^{13}CO⁺ J=4→3 spectral profiles, and comparing model centroid velocity maps with observed centroid velocity maps. The CO observations
Figure 5.32 CSO HCO+ J=4→3 Centroid Velocity Map toward L1262. The centroid velocities only in the line core (2 to 6 km s⁻¹) are shown. The central 20" × 20" is shown. The velocity of the ambient cloud (4.0 km s⁻¹) has been subtracted in the maps. Blueshifted velocities are shown in dashed contours, and redshifted velocities are shown in solid contours. Contour levels are −0.8 to 0.7 km s⁻¹, in steps of 0.06 km s⁻¹.

were only used to establish the position angle of the outflows. In a future study (Narayanan and Walker 1997), we will combine our 3-dimensional outflow models (Narayanan and Walker 1996) with the TSC models to treat combined infall, rotation and outflow motions.

In the fitting process, observational constraints when available, were used to set the initial values of the infall parameters. The initial value of the infall radius $r_{inf}$, was usually constrained by the HCO+ source sizes derived in §5.3. The pure infall phase before the onset of molecular outflows is now believed to be extremely short-lived or even non-existent (André et al. 1993, Saraceno et al. 1996). Hence, we use when available, the dynamical time-scale of the observed outflows, to derive an estimate of $t_{inf}$. In combination with an estimate of the cloud core size we can constrain sound speed $a$. The infall parameters for B335 are taken from the
modeling results of Zhou (1995), and serve as a baseline for our fitting method. We achieve an excellent agreement to our submillimeter observations of B335 using our TSC models and the infall parameters proposed by Zhou (1995) using his millimeter observations. The values of the angles $\alpha$ and $\psi$ are well constrained by the outflow observations reported in this chapter and references listed in Table 5.1. The best value of $v_{\text{turb}}$ was chosen based on the linewidth of optically thin tracers reported in the references, or in some instances from the linewidth of our H$^{13}$CO$^+$ observations. In all model fits, the initial parameters listed above was iteratively modified by comparing the model line profiles and maps to observations, to yield the best-fit parameters listed in Table 5.4. Model runs were convolved to the angular resolution of the observations.

For all our model fits we used a temperature distribution of $T = 24(r/0.01\text{pc})^{-0.4}$ K. The exception was SMM4, for which we had to use a much steeper temperature profile of $T = 15(r/0.01\text{pc})^{-2.0}$ K. HCO$^+$ to H$_2$ abundances of 5 to $8 \times 10^{-10}$ was

<table>
<thead>
<tr>
<th>Source</th>
<th>$t_{\text{in}}$</th>
<th>$\alpha$</th>
<th>$v_{\text{in}}$</th>
<th>$\Omega$</th>
<th>$\alpha$</th>
<th>$\psi$</th>
<th>$v_{\text{turb}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(pc)</td>
<td>(km s$^{-1}$)</td>
<td>(pc)</td>
<td>(s$^{-1}$)</td>
<td>(°)</td>
<td>(°)</td>
<td>(km s$^{-1}$)</td>
</tr>
<tr>
<td>VLA 1623</td>
<td>0.01</td>
<td>0.45</td>
<td>$2.2 \times 10^4$</td>
<td>$3 \times 10^{-14}$</td>
<td>0</td>
<td>-70</td>
<td>0.3</td>
</tr>
<tr>
<td>SM1N</td>
<td>0.005</td>
<td>0.45</td>
<td>$1.1 \times 10^4$</td>
<td>$3 \times 10^{-14}$</td>
<td>0</td>
<td>30</td>
<td>0.6</td>
</tr>
<tr>
<td>L483</td>
<td>0.025</td>
<td>0.35</td>
<td>$4.9 \times 10^4$</td>
<td>$7 \times 10^{-14}$</td>
<td>40</td>
<td>-80</td>
<td>0.35</td>
</tr>
<tr>
<td>SMM4</td>
<td>0.04</td>
<td>0.5</td>
<td>$7.9 \times 10^4$</td>
<td>$7 \times 10^{-14}$</td>
<td>0</td>
<td>45</td>
<td>0.75</td>
</tr>
<tr>
<td>B335</td>
<td>0.036</td>
<td>0.5</td>
<td>$7.1 \times 10^4$</td>
<td>$1.4 \times 10^{-14}$</td>
<td>0</td>
<td>90</td>
<td>0.25</td>
</tr>
<tr>
<td>L1262</td>
<td>0.05</td>
<td>0.35</td>
<td>$1.4 \times 10^5$</td>
<td>$1.3 \times 10^{-14}$</td>
<td>0</td>
<td>45</td>
<td>0.25</td>
</tr>
</tbody>
</table>
usually adequate for model fits. The exceptions to this rule were SMM4 and L1262. SMM4 required an HCO+ abundance of $3 \times 10^{-9}$ to fit the large blue peak to red peak ratio of its HCO+ J=4→3 line profiles (see Figure 5.19). L1262 has a very deep self-absorption that almost goes to 0 K (see Figure 5.30), which required a linearly increasing abundance gradient of $1 \times 10^{-10}$ from the inner radii to $1 \times 10^{-9}$ at the outer radii.

As an example of the quality of our fits, we present in Figure 5.33 the results of our fits to our JCMT observations toward SMM4. The top part of the figure shows the TSC model fits (heavy solid lines) to the observed JCMT HCO+ J=4→3 mosaic (reproduced from Figure 5.22). The lower left shows the model HCO+ J=4→3 centroid velocity map (compare with Figure 5.24). The lower right shows the model H$^{13}$CO+ line profile compared with observations.

Excellent fits were obtained for SMM4, B335, and L1262 for almost all velocities in their line profile, except the high velocity wings. For L483 and VLA 1623, where the outflow clearly affects the HCO+ line wings, care was taken to fit the line core alone. The linewidth of the observed H$^{13}$CO+ J=4→3 line was used to set limits on the width of the linecore of H$^{12}$CO+ for which a good fit was attempted. While we were able to fit the saturated appearance of the linecore of HCO+ emission for VLA 1623 and SM1N, we were not able to reproduce the red asymmetric profiles using our models. Models with outflows included may be able to reproduce this effect. Overall the model fits in the linecore emission of HCO+ J=4→3 for VLA 1623 and SM1N were good. From our model fits to L483, we conclude that even in the linecore, HCO+ is quite severely affected by molecular outflow. The parameters listed in Table 5.4 for L483 is our best fit, but should be interpreted with caution. However, in all cases, the morphological appearance of
Figure 5.33 TSC Model fits for SMM4. In the top figure, observed HCO+ J=4→3 (histograms) and model HCO+ J=4→3 (solid lines) spectral mosaics are shown. The displayed velocity extent is 0 to 15 km s⁻¹, and temperature scale is 0 to 6 K. In the lower left, we show the centroid velocity map based on the model HCO+ J=4→3 lines shown in the top. Contour intervals are -0.45 to 0.15 by 0.05 km s⁻¹. In the lower right, we show the observed JCMT H^{13}CO+ (histogram) and model SMM4 spectrum (solid lines). Infall parameters for the SMM4 model are listed in Table 5.4.
the centroid velocity signature was reasonably reproduced using our models.

5.4.2. Robustness of the Infall Interpretation

The observational identification of dynamical collapse in the early stages of star formation has been a subject of repeated controversy (see Zhou & Evans 1994 for a review). Given the history of the subject, it is natural to worry about whether our identification of collapse in our sources is indeed the only unique conclusion. Below we discuss some alternate models and methods of their elimination.

In identifying the classic asymmetric blue peak signature of an observed line profile with infall, we have to worry about four possible alternatives: (1) two cloud components along our line of sight, and the blueshifted cloud happens to be stronger; (2) a background component that is being absorbed by an unassociated foreground component that happens to be redshifted; (3) an outflow source with a stronger blue lobe; (4) the blueshifted part of a rotating cloud. Statistically speaking, all four models listed above have a 50% chance of producing the asymmetric blue profile. The infall scenario has a 100% chance of producing the asymmetric blue signature. In observing a large number of infall candidates, the preponderance of blueshifted asymmetry in the central line profiles can be statistically interpreted as identification of infall (Gregersen et al. 1997). However, for individual sources, the blue asymmetric line profile alone is not unique evidence for infall.

If we observe a second line that is optically thin, we can start eliminating some of the models mentioned above. In model (1), the optically thin line would have two peaks or a single peak aligned in velocity with one of the two cloud components. In model (2), the optically thin line should show a single peak aligned in velocity with the background component. On the other hand, if the observed optically thin
line has a single peak in the absorption dip of main line, this would eliminate both models (1) and (2). Another effect to study when observing an isotopic line is to use line ratios of main to isotopic transitions, as was done in this work, to derive an optical depth profile. Infall would be expected to produce an asymmetric red profile in optical depth, in addition to an asymmetric blue peak in the line profile. In models (3) and (4) we would not expect the red asymmetry a-priori in the optical depth profile. For instance, a strong blueshifted lobe (model 3), in the presence of an increasing temperature gradient toward the center of the source, would be expected to have an asymmetric blue optical depth profile as well as an asymmetric blue line profile. However, to eliminate models (3) and (4) convincingly, we need line maps to determine the effect of outflows and rotation.

Effects of outflows are not expected to be seen orthogonal to the outflow. For sources, where outflow is in the plane of the sky, its effects are expected to be somewhat reduced. One way to get around the problem of outflow contamination is to choose molecular species that are not very abundant in outflows (cf. §4.4.1). We have adopted this technique in our study by choosing the HCO+ J=4→3 transition, which because of its high critical density is not expected to be excited in outflows. Detailed study of maps of the HCO+ transition along with high velocity CO maps from outflows, as was done in this work, will help us understand the effect of outflows on the identification of the infall signature.

The blue-bulge signature obtained by mapping an optically thick transition naturally takes into account the effect of rotation. Are there other interpretations other than infall when we observe the morphology of the blue-bulge signature? Outflows can produce a gradient from blueshifted to redshifted velocities (e.g. Narayanan and Walker 1996). However, such a gradient should be in the same
direction as the outflow. The choice of the $v_{LSR}$ of the cloud is somewhat critical in determining the distribution of blueshifted and redshifted velocities in the centroid velocity maps. By obtaining careful observations of an optically thin tracer (which would show a gaussian profile about the $v_{LSR}$), such systematic errors can be reduced. To zeroeth order, however, we have found from models and observations that the overall morphology of the gradient and bowing of the velocity contours towards the center of the source is independent of the choice of both the velocity window and the cloud velocity. When the velocity gradient is orthogonal to the outflow, and the blue-bulge morphology is seen, the simplest explanation is one that involves infall.

Gregersen et al. (1997) listed a truth table of evidence for infall towards their collapse candidates based on their search for asymmetric blue line profiles. In Table 5.5, we summarize the different lines of evidence for infall towards our candidates using a truth table. Table 5.5 includes information on whether the blue asymmetric line profile and red asymmetric optical depth profile was seen, whether the blue-bulge centroid velocity mapping signature was seen, and the effect of molecular outflows on the HCO+ line profiles. It is seen that SMM4 and B335 are the prototypical infall candidates in that all three conditions, viz. the right sense of asymmetry in line profile and optical depth profile, and the blue-bulge signature are seen. The presence of an outflow in L483, oriented out of the plane of the sky results in negative detections of the line and optical depth profile infall signatures. However, we still have tentative evidence for the blue-bulge toward L483. The line profile signature fails, but the optical depth profile and blue-bulge signatures suggest infall in VLA 1623, which too has a vigorous outflow system. The relative youth of the pre-protostellar SM1N system may have resulted in saturated, flat-topped spectral profiles, but we still detect the optical depth profile indicative
of collapse. However, the blue-bulge signature is not detected in SM1N, where the HCO+ J=4→3 centroid velocity map is seen to trace outflow rather than infall. In L1262, we did not obtain isotopic observations, and hence cannot compute the optical depth profile, but the other two lines of evidence suggest infall.

In summary, unique evidence for infall requires both mapping and obtaining isotopic transitions. The blue-bulge signature of infall is seen in five of the six observed sources, and is shown to be a robust indicator of collapse.

Table 5.5. Evidence For Infall – Truth Table

<table>
<thead>
<tr>
<th>Source</th>
<th>Blue Asymmetric Line Profile</th>
<th>Red Asymmetric Opacity Profile</th>
<th>blue-bulge Centroid Map</th>
<th>Outflow Affects HCO+ Line</th>
</tr>
</thead>
<tbody>
<tr>
<td>VLA 1623</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>P</td>
</tr>
<tr>
<td>SM1N</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>P</td>
</tr>
<tr>
<td>L483</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>A</td>
</tr>
<tr>
<td>SMM4</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>NA</td>
</tr>
<tr>
<td>B335</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>P</td>
</tr>
<tr>
<td>L1262</td>
<td>Y</td>
<td>..</td>
<td>Y</td>
<td>NA</td>
</tr>
</tbody>
</table>

Note. — “Y” = Yes, satisfies condition; “N” = No, does not satisfy condition; “A” = Affects, Outflow affects the HCO+ J=4→3 line; “NA” = Outflow does not affect HCO+ line; “P” = Partial, outflow partially affects the HCO+ line; “..” = No observations
5.4.3. Quantitative Indicators of Collapse

In recent surveys for infall using the classic blue asymmetric line profile, observational quantities that quantify the spectral line asymmetries have been proposed. Myers et al. (1995) proposed the ratio of blue peak to red peak in brightness temperature of the optically thick tracer. Gregersen et al. (1997) proposed the skewness of the optically thick line as a method of quantifying spectral line asymmetry. Skewness is defined as the ratio of third moment of the line and the 3/2 power of its second moment, both normalized by the first moment. A pure gaussian profile has zero skewness. Lines with red asymmetry have positive skewness and lines with blue asymmetry have negative skewness. Lines with pronounced blue asymmetry have larger negative values of skewness. Mardones et al. (1997) proposed the quantity, \( \delta V = (V_{\text{thick}} - V_{\text{thin}})/\Delta V_{\text{thin}} \), which is the velocity difference between the peaks of the optically thick and optically thin lines, normalized by the FWHM of the optically thin line.

In Table 5.6, we list the calculated blue/red ratio, the skewness and \( \delta V \) for our sources using our \(^{12}\text{CO}\) and \(^{13}\text{CO}\) \( J=4 \rightarrow 3 \) observations. When available, quantities for both CSO and JCMT observations are listed. We include in Table 5.6, the calculations for IRAS 16293 using JCMT HCO+ observations presented in Chapter 4, and our new CSO HCO+ observations (unpublished).

From Table 5.6, we list the following results and trends:

1. The best candidates for infall, IRAS 16293, SMM4, and B335 have blue/red ratios greater than 1, negative skewness and negative \( \delta V \), all of which are consistent with infall.

2. Only L483 fails the line profile infall test in all three quantities.
Table 5.6. Quantifying Spectral Line Asymmetry

<table>
<thead>
<tr>
<th>Source</th>
<th>Telescope</th>
<th>Blue/Red Ratio</th>
<th>Skewness</th>
<th>$\delta V$</th>
</tr>
</thead>
<tbody>
<tr>
<td>VLA 1623</td>
<td>CSO</td>
<td>0.43</td>
<td>-1.10</td>
<td>-0.35</td>
</tr>
<tr>
<td></td>
<td>JCMT</td>
<td>0.5</td>
<td>-1.40</td>
<td>-0.60</td>
</tr>
<tr>
<td>SM1N</td>
<td>CSO</td>
<td>0.71</td>
<td>-1.28</td>
<td>-0.58</td>
</tr>
<tr>
<td></td>
<td>JCMT</td>
<td>1.05</td>
<td>-1.41</td>
<td>-0.65</td>
</tr>
<tr>
<td>IRAS 16293</td>
<td>CSO</td>
<td>2.89</td>
<td>-0.29</td>
<td>-0.15</td>
</tr>
<tr>
<td></td>
<td>JCMT</td>
<td>3.67</td>
<td>-0.30</td>
<td>-0.14</td>
</tr>
<tr>
<td>L483</td>
<td>CSO</td>
<td>0.2</td>
<td>0.18</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td>JCMT</td>
<td>0.38</td>
<td>0.25</td>
<td>0.04</td>
</tr>
<tr>
<td>SMM4</td>
<td>JCMT</td>
<td>4.2</td>
<td>-0.89</td>
<td>-0.40</td>
</tr>
<tr>
<td>B335</td>
<td>CSO</td>
<td>2.67</td>
<td>-0.38</td>
<td>-0.40</td>
</tr>
<tr>
<td></td>
<td>JCMT</td>
<td>2.34</td>
<td>-0.53</td>
<td>-</td>
</tr>
<tr>
<td>L1262</td>
<td>CSO</td>
<td>1.62</td>
<td>-0.38</td>
<td>-</td>
</tr>
</tbody>
</table>
3. While the blue/red ratios are less than 1 for VLA1623 and SM1N, their skewness and $\delta V$ are negative and consistent with infall. If we start with the hypothesis that infall is indeed occurring in VLA1623 and SM1N, we can conclude that the blue/red ratio is not as reliable an indicator of infall as skewness or $\delta V$.

4. With higher angular resolution, the trend is usually to see a higher blue/red ratio, a larger negative skewness and $\delta V$. Higher angular resolution observations probe the inner regions of the protostar which have higher infall velocities, and hence would result in larger line asymmetries.

5. While L483 has a reasonably large positive line skewness (red asymmetry), it has a $\delta V$ value close to zero, suggesting that infall and expansion velocity fields are almost cancelled out. The optically thin H$^{12}$CO$^+$ line is expected to be less contaminated by outflow. Since the calculation of $\delta V$ involves both main and isotopic observations, we suggest that $\delta V$ is a more effective quantification of infall than the skewness of the optically thick line.

5.4.4. Evolutionary Trends

In the past few years, there has been some effort to progress beyond the Class 0 through Class III classification of YSOs based on their SEDs to an evolutionary diagram that could be applied to all embedded YSOs. The Hertzsprung-Russell (H-R) $L_{bol}$-$T_{eff}$ diagram cannot be used for YSOs since many of them cannot be observed optically, and their SEDs are much broader than a stellar blackbody at a constant temperature of $T_{eff}$. Myers & Ladd (1993) proposed the $L_{bol}$-$T_{bol}$ diagram as a direct analog to the H-R diagram, where general evolution takes place from low to high $T_{bol}$. In another approach, Adams (1990) suggested the
use of visual extinction towards the central sources instead of temperature, and plotted evolution in an $L_{bol}$-$A_V$ diagram. Because of the anisotropic distribution of circumstellar matter around YSOs, both $T_{bol}$ and $A_V$ depend strongly on the viewing angle. Recently, Saraceno et al. (1996) suggested the use of the $L_{bol}$-$F_{mm}^D$ diagram where $F_{mm}^D$ is the millimeter flux scaled to a distance D (equivalent to millimeter luminosity). The millimeter flux is almost always optically thin and hence is independent of viewing angle. Millimeter flux is a good tracer of circumstellar envelope mass, which would decrease with protostellar age.

We have constrained the physical properties of a small selection of Class 0 objects. How do these physical properties relate with observationally obtained quantities such as $T_{bol}$, $L_{bol}$ and $F_{mm}^D$? The physical parameters $\Omega$ and $a$ are strongly dependent on the environment, and are not expected to evolve significantly. For instance, high mass cores would have larger $a$ than low mass cores. $\Omega$ depends to some extent on the magnetic field strength and the angular momentum of the parent cloud, and for a given cloud is not expected to evolve significantly. However, $r_{in,f}$ and hence, $t_{in,f}$ are physical parameters that can be naturally related to other evolutionary quantities such as $T_{bol}$, $L_{bol}$, and $F_{mm}^D$. Such a study can help us understand and quantify the evolutionary progress of protostars from a deeply embedded protostar to revealed pre-main-sequence object.

In Table 5.1, we listed $T_{bol}$, $L_{bol}$ and $F_{obs}^{1.3mm}$ for our list of sources. Here, $F_{obs}^{1.3mm}$ is the 1.3 mm flux density at the real distance of the source. Observationally, the sizes of the emitting region of 1.3 mm continuum are larger than typical observed beam sizes. Thus for objects that are farther away, a relatively larger amount of mass is contained within the telescope beam. Following Saraceno et al. (1996), we adopt the scaling law, $F_{mm}^{160pc} = F_{obs}^{1.3mm}(d/160)^{0.7}$ to derive the scaled millimeter...
luminosity of all our sources at the distance of 160 pc. The model derived time since onset of collapse, $t_{\text{inf}}$, for our list of sources are listed in Table 5.4. In addition, we add IRAS 16293 to the observed list. IRAS 16293 has the following properties: $T_{\text{bol}} = 42$ K; $L_{\text{bol}} = 11L_\odot$; $F_{1.3\text{mm}}^{\text{obs}} = 6356$ mJy. In Chapter 4, we derived $t_{\text{inf}} = 5.9 \times 10^4$ yrs for IRAS 16293.

In Figure 5.34a, we present the $L_{\text{bol}}$-$F_{160\text{pc}}^{\text{mm}}$ diagram for our list of sources. This diagram is equivalent to a bolometric luminosity versus millimetric luminosity plot. General time evolution progresses form right to left on such a plot. As shown by Saraceno et al. (1996), Class I sources lie to the left of the locus of Class 0 objects in the diagram shown in Figure 5.34a. In Figures 5.34b through 5.34d, we plot the millimeter flux, bolometric luminosity and bolometric temperature of our sources against the derived infall times. There is a clear trend of increasing $T_{\text{bol}}$ with $t_{\text{inf}}$. There is hint of a decreasing trend of envelope mass with age. Bolometric luminosity appears independent of the age. Bolometric luminosity is primarily determined by the mass of the central object. It should be noted that the diagrams in Figure 5.34 clearly suffer from small number statistics, and are preliminary results of an ongoing study. Constraining the infall parameters of a large sample of YSOs would be very useful in establishing the evolutionary trends of observationally derived parameters such as $T_{\text{bol}}$, $L_{\text{bol}}$ and $F_{\text{mm}}$.

In the previous section we derived parameters that quantified the infall signature. In an effort to study how the infall caused asymmetries evolve with bolometric temperature, luminosity, envelope mass and infall time, we made plots of skewness and $\delta V$ vs. $T_{\text{bol}}$, $t_{\text{inf}}$, $L_{\text{bol}}$, and $F_{1.3\text{mm}}^{\text{obs}}$ (Figure 5.35). We removed L483 from these plots because of the non-detection of the line profile infall signature. There is a nice trend of skewness and $\delta V$ approaching zero (decreasing line
Figure 5.34 Evolution of bolometeric temperature, bolometric luminosity and millimeter luminosity. (a) Bolometric luminosity vs. 1.3 mm continuum flux; (b) 1.3 mm continuum flux vs. \( t_{\text{inf}} \); (c) Bolometric luminosity vs. \( t_{\text{inf}} \); (d) Bolometric temperature vs. \( t_{\text{inf}} \).

Line asymmetry) with increasing bolometric temperature (Figure 5.35a). We note that \( \delta V \) is a more sensitive tracer of evolution than skewness. We also observe decreasing line asymmetries with the age of the protostellar system (Figure 5.35b). A weaker trend of decreasing asymmetry with decreasing envelope mass is also suggested by the plot shown in Figure 5.35d. Line asymmetry seems to be reasonably independent of source bolometric luminosity.

5.5. Conclusions

We have performed a detailed study of six nearby Class 0 objects in HCO+ J=4→3 emission. We also mapped the submillimeter CO emission in the central regions.
Figure 5.35 Evolution of infall asymmetry. Skewness (filled squares) and $\delta V$ (open squares) of the observed HCO+ lines are plotted against (a) Bolometric temperature; (b) infall time; (c) Bolometric luminosity; and (d) millimeter luminosity. IRAS 16293 is dropped in (d) due to its anomalously high millimeter flux density.

of five sources to determine the effect of outflows on HCO+ line profiles, and to establish the position angle of the molecular outflows.

We suggest that spectroscopic evidence for infall is seen in all six sources. Among these, SMM4 and B335 are known infall candidates. SM1N, VLA 1623, L483 and L1262 are new sources for which infall is suggested with this work. We detected the predicted blue-bulge infall signature in five of the six sources we studied, and suggest that this signature is more robust in detecting infall than traditional line profile techniques. Of the six sources, only three, SMM4, B335 and L1262 exhibited the classic blue asymmetric line profile signature of infall.

Of the remaining three candidates that did not exhibit the classic blue
asymmetric line profile, SM1N is proposed to be a very early Class 0 object with saturated, “flat-topped” line profiles. We have made a tentative detection of a new bipolar outflow towards SM1N. VLA 1623 has red asymmetric line profiles dominated by outflow rather than infall. However, the optical depth profiles obtained using ratio of main and isotopic line observations towards both SM1N and VLA 1623 have the right “sense” of asymmetry for an infall interpretation. L483 has a molecular outflow at a large angle of inclination to the plane of the sky. This offsets the effects of infall in the line and optical depth profiles, and makes the identification of collapse difficult using traditional line profile methods.

We have derived the infall parameters for our sources using 3-dimensional infall models based on the TSC solution of collapse that includes rotation. We discussed evolutionary trends of observationally obtainable source parameters with derived timescales. Such a study when extended to a larger sample of YSOs will help in the understanding of the evolution of YSOs from the embedded protostellar stage to revealed pre main-sequence objects.
CHAPTER 6

CONCLUSIONS AND FUTURE WORK

6.1. Conclusion

The average density in stars is nearly a factor of $10^{20}$ greater than the average density of molecular clouds. Therefore, the process of star formation must involve a phase of dynamical collapse when a large amount of gas is channeled into the forming star. Since the first efforts of Leung and Brown (1977), there have been many attempts to detect protostellar infall. At the start of this work, convincing kinematic evidence for infall existed only for two protostellar sources, IRAS 16293 (Walker et al. 1986) and B335 (Zhou et al. 1993). Maybe anticipating the difficulty of identifying infall, Wynn-Williams (1982) described the identification of a collapsing protostar as the Holy Grail of Infrared Astronomy. Unambiguous identification of infall, though difficult, is but one piece of the puzzle in the bigger picture of understanding the process of star formation. However, observational identification and separation of infall from other dynamical motions like rotation, outflow and turbulence in star forming regions is of the utmost importance in providing constraints for testing theories of star formation. This is the task we set
for ourselves at the beginning of this work. What has this work done to advance our understanding of star formation? We reported results at the end of each chapter. Below we summarize our major results.

1. We presented the first radiative transfer calculations of millimeter and submillimeter CS, HCO+ and dust emission from collapsing, rotating protostellar systems. In Chapter 2, we combined our flexible LTE radiative transfer program with the “self-consistent” 3-dimensional hydrodynamic collapse simulations of Boss (1993). In Chapter 3, we combined our radiative transfer program with the parameterized, semi-analytic TSC (1984) perturbational solution for the collapse of a slowly rotating cloud core.

2. The 3-d model results show that the morphology of molecular line emission is a very strong function of collapse time. At early collapse times, the model lines appear gaussian and uniform, and becomes more and more self-absorbed and asymmetric with time. In spectral mosaics obtained from models, the “sense” of asymmetry (i.e., which side of the line is brighter) is directly traceable to a combination of the rotation and infall velocity fields. Submillimeter transitions of HCO+ and CS are better than millimeter transitions in detecting infall, especially at early collapse times.

3. Iso-velocity centroid maps can be used to detect the presence of infall in the vicinity of protostellar sources. Using model centroid velocity maps, we proposed the “Blue-Bulge” signature – a new technique of identifying infall even in the presence of rotation. The blue-bulge can be seen at most stages of collapse and at all inclinations. Indeed, if it were not for the presence of outflow, the optimum orientation of the protostellar disk for infall detections would be pole-on. However, because the blue-bulge occurs
preferentially in the equatorial plane of the protostellar system, it may be observable even if the protostar under study possesses a molecular outflow. The blue-bulge signature was shown to be much more robust to changes in infall parameters in our parameterized models than the classic asymmetric blue line profile signature of collapse. For the nearest protostellar systems, the blue-bulge infall signature should easily be seen using the current generation of single-dish submillimeter telescopes.

4. The appearance of the line profiles and the resulting centroid velocity maps is a strong function of the angular resolution used to perform the observations. At high angular resolutions, models with moderate to high rotational rates exhibit the "polar blue-bulge" signature - a powerful new morphological signature for detecting underlying Keplerian rotation in an embedded cloud core. The polar blue-bulge should be observable with the current generation of millimeter interferometers and the proposed submillimeter array (SMA).

5. The unambiguous detection of infall toward binary systems becomes more difficult with increasing binary separation. The greater the separation between binary stars, the smaller becomes the blue-bulge in the velocity centroid contours. However, the blue-bulge is still more prominent than infall asymmetries in the line profiles. The ability to detect infall is not significantly affected by the orbital position of the binary members.

6. In Chapter 4, we reported the first detection of the predicted blue-bulge signature toward a protostellar source. We mapped the region around IRAS 16293 in CS J=5→4, J=7→6, and HCO+ J=3→2 and J=4→3 transitions using the CSO, JCMT and HHT. These data show both the classic, asymmetric blue profile infall signature and the blue-bulge infall signature.
Using observations and our 3-dimensional radiative transfer model based on the TSC solution, we deduce that the HCO+ $J=4\rightarrow3$ emission appears to be tracing material infalling from a lower density outer envelope onto the circumbinary disk. Lower rotational transitions of CS also trace this infalling material, while higher rotational transitions of CS appear to arise principally in the vicinity of the circumbinary disk. Based on the model results, we find the infall radius of the IRAS 16293 cloud core is $\sim 39''$ (0.03 pc), the infall timescale is $5.9 \times 10^4$ yrs, and the rotational rate is $5 \times 10^{-13}$ s$^{-1}$. The best fit model also suggests that the CS abundance decreases linearly, and the HCO+ abundance increases linearly from the inner core to the outer envelope. The best fit infall parameters are consistent with an inside-out model of protostellar collapse in IRAS 16293 (Walker et al. 1986).

7. In Chapter 5, we performed a detailed study of six nearby Class 0 objects in HCO+ $J=4\rightarrow3$ emission. We also mapped the submillimeter CO emission in the central regions of five sources to determine the effect of outflows on HCO+ line profiles, and to establish the position angle of the molecular outflows. We detected the blue-bulge signature of infall in five sources. Using multiple lines of evidence, we suggest that infall is occurring towards all six sources. Among these, SMM4 and B335 are known infall candidates. SM1N, VLA 1623, L483 and L1262 are new sources for which evidence for infall is derived in this work. Of the six sources, only three, SMM4, B335 and L1262 exhibited the classic blue asymmetric line profile signature of infall. Traditional line profile techniques failed in the case of VLA 1623 and L483, but the blue-bulge signature was still seen in these infall candidates, confirming our prediction that the blue-bulge signature is more robust in detecting infall than traditional line profile techniques.
6.2. Future Work

Although there are now, many more cases of confirmed infall than when we started this work, many questions and issues still remain unaddressed. Below we address some of the questions, unresolved problems and suggest strategies to address them.

1. Our ideas concerning the time of onset of the outflow phenomenon have changed in recent years. Shu et al. (1987; see their Figure 7) outlined a four-stage process in which the pure collapse phase precedes the “breakout” of the stellar wind that drives the observed molecular outflows. However, the length of this pure-infall phase is not well constrained by either theory or observation. Sources of well-developed outflows have been found to have larger amounts of circumstellar mass than “non-outflow” embedded sources on average (Cabrit & André 1992), suggesting that they are younger. It is now known that the fastest and most collimated CO outflows are detected around the youngest (Class 0) objects (André et al. 1990, Bachiller & Gómez-González 1992). This shows that vigorous outflows occur very early on when the star has attained a very small fraction of its final mass, and that the pure-infall phase is extremely short or non-existent. All the Class 0 sources reported in this work possess molecular outflows. Although we performed a careful analysis of the distribution of our infall tracer with respect to the outflow, in some extreme cases like L483, it is clear that outflow motions need to be included in our models to disentangle the kinematics satisfactorily. Recently, we presented (Narayanan and Walker 1996), a fully three-dimensional outflow model that was used to treat the swept-up shells of episodic outflows towards Cepheus A. The outflow contamination in the line wings of HCO+ emission probably arises from the dense swept-up shells of the
underlying stellar wind. So it is a natural extension of our work to combine the infall models described in this work and the outflow models described in Narayanan & Walker (1996). Such a "complete" study will be the first of its kind, and would be able to predict the optimal combination of molecular tracers to choose in studying various aspects of the star formation process.

2. Our radiative transfer program has thus far treated simple diatomic molecules. We need to extend the code to analyse the emission from more complicated molecules like H$_2$CO, which also is a good tracer of infall motions (Zhou et al. 1990, Wang et al. 1994).

3. Although the assumption of LTE is probably valid in the inner regions of our protostellar models (see §4.4.1), the lower densities expected in the outer envelopes of YSOs call for a non-LTE approach to the generation of line profiles. Lower angular resolution observations of protostellar objects are heavily weighted by emission from the outer, cooler low density envelopes, where a non-LTE radiative transfer code is required. The Sobolev approximation has been used successfully in deriving radiative transfer solutions that are coupled with equations of statistical equilibrium in star-forming regions (Zhou 1995). A more self-consistent, but computationally more intensive approach is to use Monte Carlo techniques to model the star-forming cloud (Choi et al. 1995). We will study both of the aforementioned methods and refine our radiative transfer code using a non-LTE approach.

4. Our radiative transfer code has thus far been limited to using constant abundances or linear abundance variations for the molecular tracers of choice. One of the interesting results of the infall study in IRAS 16293 (see §4.4.1), is that there is evidence for considerable differences in the variation
of abundances between tracers like CS and HCO+. Our models will benefit from the use of abundance variations that are predicted by well-accepted chemical models of protostellar nebulae. Such a study will also serve to test chemical evolution theories of star formation (for e.g. Bergin & Langer 1997). We would also need additional observational constraints. The HHT with its next generation of focal plane array receivers at 345 GHz, is very well suited to making large scale maps of protostellar cores and environs in different molecular species. On an instrumentation level, the author is also involved in the design and development of this sophisticated focal plane array receiver, which will be a powerful tool for sensitive mapping studies of protostellar clouds. Such a combined observational and theoretical program will help us shed more light on the problem of abundance variation and chemical evolution in protostellar systems.

5. It is now known that a large fraction of young stellar objects (YSOs) have circumstellar disks around them (Beckwith et al. 1990, Beckwith & Sargent 1993). Standard collapse models of star formation like the TSC solution predict the existence of 100 AU disks around older (> 10^5 yrs) YSOs. In the TSC model, these disks are centrifugally supported. Magneto-hydrodynamic collapse models (e.g. Galli & Shu 1993) rely on magnetic pinching forces to support “pseudodisks” extending to 1000 AU. Recent submillimeter interferometric observations made with the CSO/JCMT interferometer have led to the detection of accretion disk structures in the “Class 0” objects, VLA 1623 and IRAS 4A/4B (Pudritz et al. 1996, Lay et al. 1995). The CSO/JCMT interferometer was also used in the detection of accretion disks in the Class I object L1551-IRS5 and in the Class II object HL Tau (Lay et al. 1994). Extending the inner boundary of our TSC collapse calculations to
the protostellar disk solution of Cassen & Moosman (1981) would be useful in deriving molecular line and dust continuum emission that can used to constrain observations of accretion disks.

6. A natural extension to the work reported in Chapter 5 is to conduct a large-scale survey of collapse towards other Class 0 and Class I sources. In collaboration with researchers at JCMT, we are undertaking such a large scale survey using the HHT and JCMT. Using our infall models we can derive physical parameters of the protostellar system under study. We can use these constraints to study in detail the variation of infall parameters such as $\Omega$ and $a$ with the parent environment, such as isolated Bok globules (e.g. B335) or formation in a cluster (e.g. VLA 1623, SMM4). Extending the study of evolution presented in Chapter 5 (see §5.4.4) to a larger sample of sources, we can construct a global picture of evolution of stars from the embedded protostellar stage to revealed pre-main-sequence objects.
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