OBSERVATIONS OF INFALL IN STAR-FORMING REGIONS

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Evidence of inward gas motions in star-forming regions is now abundant, due to improvements in sensitivity and resolution of millimeter-wavelength telescopes and spectrometers. "Infall asymmetry," a characteristic signature of certain line profiles predicted for collapsing cores, has been detected in numerous dense cores, some with no embedded stars and some with deeply embedded Class 0 and Class I objects. Infall asymmetry is fairly common in cores with highly embedded sources; further studies of less embedded sources are needed to trace the evolution of infall. In several starless cores, infall asymmetry is more extended than expected for "inside-out" gravitational collapse, and may indicate speeds greater than expected from most models of ambipolar diffusion. Interferometric observations of flattened envelopes, using optically thin lines, reveal infall and rotation as velocity gradients along the minor and major axes, on size scales < 1000 AU. Observed line profiles toward B335 match detailed radiative transfer models of emission from cores with embedded protostars undergoing inside-out collapse. Models including modest rotation can match the observations of L1527, and *IRAS* 16293 − 2422 can be modeled with substantial rotation. Models of infall in starless cores, cluster-forming cores, and cores dominated by magnetic fields and turbulent motions are being developed, but they remain to be tested against observations.

I. Introduction

The origin of stars is one of the oldest problems in astrophysics. In the last three decades this problem has begun to yield to improvements in a wide variety of observational techniques and to improvements in theoretical understanding of the gravitational, magnetic, and turbulent interactions in interstellar clouds. Star-forming regions of dense gas have been identified through observations of spectral lines of CO (Wilson et al. 1970, Kutner et al. 1977), NH_3 (Cheung et al. 1968, Ho et al. 1979, Myers and Benson 1983), and over 100 other species. Candidate protostars have been identified through observations of far-infrared and submillimeter emission (Keene et al. 1980, Lada and Wilking 1984, Beichman et al. 1986, André et al. 1993). Theoretical models detail how protostars form from dense gas by gravitational infall (Larson 1969, Penston 1969, Mouschovias 1976, Shu 1977, Boss 1982, Terebey et al. 1984, Hartmann 1998).

Despite this progress, the link is weak between the "initial conditions" or gas properties of dense cores, and the "protostars" that they form. The key information needed to account for star formation, and to distinguish among competing models, is the spatial distribution of inward gas motions, and its evolution over time. It is now becoming possible to study this process of gravitational infall through Doppler spectroscopy of molecular spectral lines that trace sufficiently dense gas, as observed with fine spectral and spatial resolution. In this chapter we describe recent progress in the study of such infall, primarily from an observational viewpoint. Closely related discussions are given by Myers (1997a,b) and Evans (1999).

The plan of this chapter is as follows. We describe the main observational techniques used to study infall (§II) and surveys of embedded sources and starless cores to identify kinematic infall candidates (§III). We then describe maps of these candidates (§IV), interferometric observations of selected regions(§V), and comparison of observations and models (§VI).

II. Inferring Inward Motions

Spectroscopic methods of inferring motion along the line of sight rely on distinguishing velocities of absorption and emission in a line profile, to obtain the sign and speed of such motions. A spectral signature of inward motion, "infall asymmetry", is observable if the foreground infalling gas has lower excitation temperature than the background gas, and if the foreground gas has sufficient optical depth (e.g. Lucas 1976, Leung and Liszt 1976, Leung and Brown 1977). If these conditions are met, the line will be skewed to the blue or double-peaked, with a stronger blue peak. The detailed line shape depends on the velocity field.

In the simplest model, two uniform layers approach each other (Myers et al. 1996). If the approach speed is less than the velocity dispersion, the absorption appears as a dip between the brighter blue peak and the fainter red peak. As the approach speed increases, more of the blue peak is absorbed by the foreground layer, and the blue peak becomes brighter while the red peak disappears into a wing or shoulder (Figure 1). If the collapse velocity is much greater than the velocity dispersion, as may occur for the Larson-Penston type collapse, two separated peaks of nearly equal strength will appear (Zhou 1992), and optically thin lines will also be double-peaked. If a static envelope surrounds the infall zone, as in inside-out collapse (Shu 1977), the dip velocity is independent of infall speed, and the line profile evolves as the infall zone expands (Zhou 1992, Gregersen 1997). If two unrelated clouds with similar velocities lie along the line of sight, their spectrum in an optically thick line can have two peaks, giving spurious infall asymmetry. However, observation of an optically thin line will then reveal two components, not one component as in true infall asymmetry.

If the observed system is known to have a flattened geometry, then further simplification is possible, using maps of optically thin lines. Then rotation and infall motions separate cleanly, revealed as velocity gradients along the projected major and minor axes (§V).

III. Surveys for infall asymmetry

The earliest reports of infall asymmetry came from observations of emission in the J=1-0 lines of ^{12}CO and ^{13}CO from gas associated with luminous infrared sources and H II regions (Snell and Loren 1977, Loren et al. 1981, Phillips et al. 1981). However these observations have not been generally accepted as indicating infall because of confusion from outflows, because of numerous CO spectra with reverse infall asymmetry toward similar sources, and because the low-density gas traced by these lines appears too extended for star-forming infall. More recently, observations of the J= 5-4 and 2-1 lines of CS toward *IRAS* $16293-2426$ (Walker et al. 1986), were reported as consistent with the "inside-out" collapse model of Shu (1977). Menten et al. (1987) challenged this claim, based on maps of CS line profiles that showed a reversal of the blue/red asymmetry. They interpreted their data by a combination of rotation and absorption by a foreground cloud. Further complications arose as this source was shown to have a quadrupolar outflow (Mizuno et al. 1990). See §VI for further discussion.

More recent observations of the deeply embedded submillimeter source in B335 (Keene et al. 1983) in lines of CS and H_2CO (Zhou et al. 1993, 1994; Choi et al. 1995) indicate a detailed match of spectral profiles with predictions of the inside-out collapse model (Shu 1977). Similar spectra of the low-luminosity source 04368+2557 in the core L1527 are reasonably consistent with radiative transfer models based on inside-out collapse (Myers et al. 1995, Zhou et al. 1995). More detailed discussion of B335 and L1527 are given in Section VI. Further claims of infall based on spectral profiles toward individual sources have been presented by Moriarty-Schieven et al. (1995), Hurt et al. (1996), Ward-Thompson et al. (1996), Wolf-Chase and Gregersen 1997, Lehtinen (1997), Tafalla et al. (1998), and Buckley (1998).

On the other hand, observations of infall asymmetry in a few selected objects may arise from peculiarities of source structure, or from the confusing effects of outflows. Further, a few objects are not necessarily representative. Thus, it is necessary to survey objects selected by objective criteria, to search for a statistically significant excess of sources with infall asymmetry. The excess is defined as $(N_b - N_r)/N$, where N_b is the number of sources with a blue-skewed profile, N_r is the number with a red-skewed profile, and N is the total number in the sample (Mardones et al. 1997). *If* the blue-skewed profiles were caused by rotation or outflows, rather than collapse, then a sufficiently large sample, having a random distribution of angles between the line of sight and their rotation and outflow axes, should have no significant excess. Two recent surveys, conducted with this motivation, show a substantial excess of sources with infall asymmetry, supporting the collapse interpretation.

A survey of 23 Class 0 objects (André et al. 1993) was made in the J=4-3 and 3-2 lines of HCO^+, and 19 of these were observed in the optically thin J=3-2 line of $H^{13}CO^+$ (Gregersen et al. 1997). The spectral energy distributions of all of the sources satisfied within their uncertainties $T_{bol} < 70$ K – a value found by Chen et al. (1995) to correspond to known Class 0 sources. T_{bol} is the effective temperature of a blackbody with the same mean frequency as the observed spectrum (Myers and Ladd 1993). Gregersen et al. (1997) found 9 sources with infall asymmetry but 3 with the opposite asymmetry, a "blue excess" of about 0.26. This result supports the interpretation of blue-skewed profiles as indicators of collapse.

A similar survey was carried out by Mardones et al. (1997). The sources were restricted to lie within 400 pc of the Sun and to have $T_{bol} < 200$ K. The Class 0 sample of Mardones et al. (1997) included many of the Gregersen et al. (1997) sources, but it also included 24 Class I sources (Lada and Wilking 1984), with $70 < T_{bol} < 200$ K. The survey used the 1-0 line of N_2H^+ as the optically thin tracer (Caselli et al. 1995) and two independent lines as thick tracers – the 2_{12}-1_{11} line of H_2CO (47 sources) and the 2-1 line of CS (37 sources).

Mardones et al. (1997) found that each of the two optically thick tracer lines shows a statistically significant excess (0.39 for H_2CO; 0.53 for CS), when the sample is restricted to Class 0 sources. This result corroborates the findings of Gregersen et al. (1997), and indeed the three spectral line surveys agree as to the presence or absence of infall asymmetry, for most sources observed in common. No significant excess was seen among Class I sources suggesting that infall asymmetry is much more prevalent in Class 0 than in Class I sources.

Because the infall signature should become more difficult to detect at later stages, as opacities drop, infall in Class I sources might be harder to detect in lines of modest opacity. In addition, the orientation of a flattened envelope can affect the spectral appearance. An edge-on envelope will produce deeper self-absorption than a pole-on envelope. Edge-on envelopes are indeed suggested, because the outflow lies primarily in the plane of the sky, in the two best infall candidates: B335 (Hirano et al. 1988) and L1527 (Zhou et al. 1996, Tamura et al. 1996).

To test these possibilities, Gregersen et al. (1998) used the more opaque HCO^+ 3-2 line to survey 20 of the Class I sources observed by Mardones et al. (1997). Using the same criteria as Mardones et al. (1997), and combining with results from Gregersen et al. (1997), Gregersen et al. (1998) find that among 23 Class I sources, the excess in the HCO^+ line is 0.32, essentially the same as the value (0.33) found for the full sample of Class 0 sources. While further work is necessary, it is clear that infall cannot be ruled out because of the absence of an infall signature in any particular line. Important goals of future work are to understand how lines of different optical depth can give profiles with significantly different asymmetry, to study the time evolution of infall, and to test the evolutionary interpretation of the classes described by Adams et al. (1987).

The surveys of Mardones et al. (1997) and Gregersen et al. (1997) have identified or confirmed most of the known kinematic infall candidates. The following 13 cores have infall asymmetry in at least two lines, and no reverse infall asymmetry, among the lines of CS 2-1, H_2CO 2_{12}-1_{11}, HCO^+ 3-2, and HCO^+ 4-3: NGC1333-IRAS4A, NGC1333-IRAS4B, L1527, I13036-7644, VLA 1623, WL22, I16293-2422, L483, Ser SMM4, Ser SMM5, B335, L1157, and L1251B. Three of these cores (L1527, B335, L1157) have lines which are "thermally dominated" and are associated with single sources, while the rest are dominated by turbulent motions and are generally associated with clusters or small groups of young stars.

A survey of 19 regions at distances $<$ 1 kpc, known to be sites of multiple star formation, and distinct from the sources studied by Mardones et al. (1997), was carried out in lines of CS 2-1 and N_2H^+ 1-0 (Williams and Myers 1998). No statistically significant excess of sources with blue asymmetry was found, perhaps due in part to the relatively low optical depth of the CS 2-1 line in these sources: very few of the CS spectra showed significant self-absorption of either blue or red sign. However one remarkable source, Cep A, shows infall asymmetry extended over $\sim$0.2 pc, substantially greater than expected from simple models of gravitational infall.

The foregoing surveys are based on observations of infrared point sources, and are therefore sensitive to the motions associated with already formed, or forming stars. Another useful approach is to survey starless cores, or regions which show no evidence of an associated star, but which have unusually high density and column density. These cores are good candidates to form stars in the future, and observations in infall tracer lines may be expected to show infall asymmetry. Starless cores do not have embedded point sources to mark survey target positions, but on the other hand their infall signature, if detected, will not suffer confusion from stellar winds and outflows. A systematic survey of 224 starless cores, drawn from the catalog of Lee and Myers (1998), has been carried out in lines of CS and N_2H^+, indicating infall asymmetry in numerous cores (Lee et al. 1998). A survey of a smaller sample of 17 cores, using HCO^+ J=3-2 (Gregersen 1998), found a significant excess of sources with infall asymmetry. All the sources with infall asymmetry were detected in the submillimeter continuum by Ward-Thompson et al. (1994), who called them "pre-protostellar."

IV. Maps of infall asymmetry

Detailed tests of consistency between observations of infall asymmetry and models of collapse require maps in both optically thick and thin spectral lines. The maps reveal the center, shape, and extent of the zone of infall asymmetry and allow comparison to models. Mapping observations are also needed to discriminate infall from rotation and bipolar outflows, each of which can create the appearance of infall asymmetry in line profiles at particular positions. For example, a differentially rotating cloud with rotation axis in the plane of the sky can have line profiles with blue asymmetry on one side of the axis and red asymmetry on the other, while a non-rotating, contracting cloud will have blue asymmetry in all directions from the center of infall. Similarly, emission by low-velocity gas in the blue lobe of a bipolar outflow region can be absorbed by quiescent foreground gas, yielding spectra with infall asymmetry. The spectra arising from these various motions may be identical in a particular map position, but the motions can be readily distinguished by comparing the maps (Adelsen and Leung 1988, Cabrit and Bertout 1986, Walker et al. 1995, Myers et al. 1995, Gregersen et al. 1997).

An important consideration is the sensitivity of infall asymmetry to line optical depth and excitation temperature. The spatial extent of the infall asymmetry in a cloud can vary greatly from tracer to tracer, as the optical depth of the tracer increases. For example the extent of the infall asymmetry in the starless core L1544 increases from $\sim$0.01 pc in the 1-0 line of N_2H^+, to $\sim$0.1 pc in the 2-1 line of CS, due probably to differences in the spatial extent of the optically thick emission of the two species (Tafalla et al. 1998; Williams et al. 1998). Therefore maps in more than one optically thick tracer are needed to distinguish spatial variations in optical depth from spatial variations in the velocity field.

In the nearest star-forming complexes, the 10-30$''$ angular resolution of large filled-aperture antennas, is 0.007 - 0.02 pc, at a distance of 140 pc, suitable for probing the inward motions expected for gravitational infall. For example the diameter of a low-mass NH_3 core is $\sim$0.1 pc, which is well-resolved in one of the nearest star-forming regions. On the other hand, resolution of circumstellar envelope gas in more distant star-forming regions, or of the motions associated with circumstellar disks in nearby regions, requires finer resolution than filled-aperture telescopes can provide. For these observations it is necessary to use interferometers. With angular resolution generally 1-5$''$, these instruments can probe much finer scales than can the filled-aperture telescopes. In a few cases single-antenna and interferometer maps have been combined (e.g., Zhou et al. 1996), yielding maps sensitive to a range of spatial scales spanning a factor of $\sim$30 (e.g. Gueth et al. 1997). Such interferometric observations are discussed in §V.

We illustrate several features of infall asymmetry with maps of three distinctly different sources. L1544 is a starless dense core with no known *IRAS* point source or embedded T Tauri star. The nonthermal motions in its spectral lines which trace dense gas ($n > 10^4$ cm^{-3}) are smaller than the thermal motions of the molecule of mean mass, so it is "thermally dominated" (Myers et al. 1991). Its likely stellar product, if any, is a single star or binary, as opposed to a stellar group or cluster, based on the star-forming character of its neighboring cores in the Taurus complex. L1527 is another thermally dominated core in Taurus, but with a single embedded Class 0 *IRAS* source 04368+2557. L1251B is a core whose lines are dominated by turbulent motions, and which has a Class I *IRAS* source and an associated group of $\sim$5 additional young stellar objects (Hodapp 1994).

Figure 2 illustrates the variety of spectral profiles taken at the position of peak emission in L1544, ranging from extremely optically thick (HCO^+ 1-0) with strong infall asymmetry, to optically thin ($C^{34}S$ 2-1) with no infall asymmetry. This sequence indicates that the optical depth of the spectral line is critically important to the degree of infall asymmetry.

Figure 3 shows a grid of spectra illustrating the large extent of infall asymmetry in the CS 2-1 line, $\sim$0.15 pc, or well beyond the extent of the dense core, $\sim$0.04 pc, as indicated by the half-maximum (HM) integrated intensity contour of the optically thin N_2H^+ 1-0 emission. This core definition is arbitrary, but useful because it allows comparison with N_2H^+ maps of other cores. The CS map has no well-defined center of line asymmetry, and the position of maximum asymmetry lies outside the HM of the dense core emission (Tafalla et al. 1998). In contrast to this behavior, interferometric observations of the N_2H^+ emission shows that infall asymmetry and line intensity peak up at the same position. Remarkably, the N_2H^+ line indicates an inward speed similar to that of the much more extended CS infall asymmetry, $\sim$0.1 km s^{-1} (Williams et al. 1998).

It is difficult to account for the large extent of the infall asymmetry in L1544 with the simplest models of gravitational infall, or gravitational motion limited by ambipolar diffusion (Tafalla et al. 1998). If the extent of the L1544 infall asymmetry were comparable to the diameter of the rarefaction wave associated with inside-out collapse (Shu 1977), then a protostellar point source with luminosity of several $L_\odot$ should have already formed, whereas none is known. Similarly, models of ambipolar diffusion, such as the detailed numerical model of Ciolek and Mouschovias (1995), predict line-of-sight inward speeds < 0.02 km s^{-1} at the largest observed radius $\sim$0.08 pc, where the observed speed is as much as 0.1 km s^{-1}. It may be possible for ambipolar diffusion to account for these motions under different initial conditions (Basu 1998, personal communication; Li 1998, personal communication). On the other hand, lines of the ions HCO^+, DCO^+, and N_2H^+ all show infall asymmetry in L1544, thus ruling out ambipolar diffusion in its most extreme form, where the ions are stationary while the neutrals flow inward.

Alternatively, such extended, subsonic, inward motion may start as a pressure-driven flow, arising from differential dissipation of turbulence. Starless cores may gradually dissipate the nonthermal motions in their line widths, due, e.g., to ion-neutral friction or to nonlinear interactions among MHD waves (Nakano 1998). If core turbulence dissipates at a greater rate than in its surroundings, the resulting inward pressure gradient should lead to an inward flow. If the resulting increase in core density further increases the turbulent dissipation, then the flow should be self-sustaining (Myers and Khersonsky 1995, Myers and Lazarian 1998). The predicted flow speeds are similar to the sound speed and larger than expected for ambipolar diffusion.

Figure 4 shows spectra of the 2_{12}-1_{11} line of H_2CO in L1527, in relation to the Class 0 *IRAS* source 04368+2557 and the half-maximum contour of its N_2H^+ integrated intensity (Mardones et al. 1998). The L1527 and L1544 cores are similar in their thermally dominated line widths and in their dense core sizes ($\sim$0.05 pc), but different in their extents of infall asymmetry (0.04 and 0.15 pc). In L1527, the infall asymmetry is much more localized than in L1544, as expected if the inward motions in L1527 are primarily gravitational in origin. The infall asymmetry is more pronounced in the north-south direction, whereas the outflow is concentrated in the east-west direction, as is evident in the H_2CO spectral line wings. Thus confusion by the outflow cannot account for most of the spectra with infall asymmetry. As discussed in Section VI, L1527 resembles B335 in the relatively good agreement of its spectral profiles, spatial extent of infall asymmetry, and stellar luminosity with the inside-out collapse model. On the other hand, many H_2CO spectra in L1527 have ratios of blue and red peak line intensities significantly greater than the model predicts (§VI).

Figure 5 shows spectra of the 2_{12}-1_{11} line of H_2CO in L1251B, in relation to the Class I *IRAS* source 22377+7455 and the half-maximum contour of its N_2H^+ integrated intensity (Mardones et al. 1998). The infall asymmetry is about as extended as the dense core, thus resembling L1527, but with a wider line, suggestive of higher turbulence, than in L1527. Furthermore a second zone of infall asymmetry is seen about one core diameter to the east, where no infrared source is known and where a map of N_2H^+ emission indicates very little dense gas (Caselli et al. 1999). In this respect L1251B shows infall asymmetry beyond the zone of dense core gas and so resembles L1544. Extended infall asymmetry, beyond the dense core half-maximum boundary, is also seen in a zone about $1'$ NW of NGC1333 IRS4A (Mardones et al. 1998).

V. Interferometric Imaging of Infall Candidates

A. Overview

In addition to single-dish telescopes, interferometers are powerful tools to observe infall. The finer angular resolution provided by interferometers enables us to distinguish infall from rotation or outflow, motions sometimes confused in filled-aperture maps.

As with filled-aperture observations, moderately optically thick molecular lines have been observed with interferometers to detect the infall asymmetry. Two good examples are B335 (^{13}CO 1–0, Chandler and Sargent; HCO^+ 1–0 and HCN 1–0, Choi et al. 1998) and L1527 (^{13}CO 1–0, Zhou et al. 1996; H_2CO 3_{12}–2_{11}, Wilner et al. 1997). These observations showed clear infall asymmetries, which are consistent with the prediction from collapse models. Some sources, however, show only blueshifted peaks in interferometric observations even though they show clear infall asymmetries in single-dish observations. This could be because optical depths of their redshifted emissions are too high (Choi et al. 1998), or because the redshifted emissions are more spatially extended than the corresponding blueshifted emissions, so that the redshifted emissions are resolved out by interferometers (Ohashi et al. 1997a). It is also important to note that central dips of infall asymmetries observed with interferometers can be spurious because the interferometer's spatial filtering resolves out the extended ambient gas (e.g., Gueth et al. 1997).

The ability of interferometers to image with fine angular resolution is valuable in observing infall. Since interferometers can resolve the kinematical structure of gaseous envelopes, infalling motions can be *directly* imaged with interferometers. In fact, interferometric observations have shown that gaseous envelopes often have flattened structures, oriented perpendicular to the associated outflow axis (Sargent and Beckwith 1987, 1991; Sargent et al. 1988; Mundy et al. 1992; Ohashi et al. 1991, 1996b). Note that this flattened envelope is substantially larger than the rotationally supported circumstellar disk, of radius ~100 AU, which it may contain. Thus, if infalling motions exist in such a flattened envelope, then blueshifted emission due to infall is observed in the far side of the envelope and redshifted emission is observed in the near side. Thus infall is identified as a velocity gradient along the projected minor axis of the flattened envelope. Rotation is well distinguished from infall because rotation contributes to a velocity gradient along the projected major axis of the envelope.

The above strategy allows us to directly image infalling motions. Thus interferometric observations of HL Tauri indicate a flattened envelope perpendicular to the associated optical jet, and a velocity gradient along the minor axis of the envelope. This pattern was interpreted as indicating infall (Hayashi et al. 1993). It is possible for outflow to contaminate infall because outflow shows the same velocity gradient as infall (Cabrit et al. 1996). Nevertheless, the fraction of emission from outflowing gas may be small judging from velocity-channel maps because the *entire* flattened envelope shows a simple kinematic pattern suggestive of infall, with emission basically residing in the flattened envelope at *all* velocities. After the observations of HL Tauri, more sources, including infall candidates identified through single-dish observations, have been observed with interferometers, demonstrating that infalling envelopes represent distinctive kinematical features in position-velocity diagrams (Ohashi et al. 1996a, 1997a, 1997b; Ohashi 1997; Saito et al. 1996; Momose et al. 1998). In addition to the velocity gradient along the minor axis, these observations show that line widths of the observed line emission get wider toward the inner radii of the envelopes, consistent with acceleration toward the central gravitational source. Note that these observations have been made in relatively optically thin lines, such as $C^{18}O$ or $H^{13}CO^+$, because optically thin lines allow us to examine the whole velocity structure of the envelope, without suffering self-absorption. Since some sources show kinematical structure due to infall in their interferometric maps even though no infall asymmetries have been observed with single-dish telescopes, systematic searches for infall candidates with interferometers are very important.

B. Physical Properties of Envelopes around Infall Candidates: The Case of L1551 IRS5

Interferometric imaging of envelopes around infall candidates provides information on the detailed physical properties of infalling envelopes. Infalling envelopes tend to be characterized by elongated, flattened structures with a scale of thousands of AU, while their kinematics are explained by dynamical infall with slow rotation.

Figure 6 shows an excellent example of interferometric images of an infalling envelope, which shows the above characteristics, recently obtained in $C^{18}O$ 1–0 from L1551 IRS5 with the Nobeyama Millimeter

Array (Momose et al. 1998). The envelope around L1551 IRS5 has a clear flattened structure, 2400 AU$\times$1100 AU in size, which is elongated in the direction perpendicular to the axis of the associated outflow (Fig. 6a). The southern half of the envelope is blueshifted, while its northern half is redshifted, as shown in the intensity weighted mean velocity map (Fig. 6b): the overall velocity gradient of the envelope is in the north-south direction, which is different from either the direction of the minor or major axis. This suggests that both infall and rotation exist in the envelope because pure infall yields a velocity gradient along the minor axis while pure rotation yields a gradient along the major axis.

Detailed velocity structures of infall and rotation can be examined by using position-velocity (PV) diagrams. The PV diagram along the major axis of the envelope (Fig. 6c) shows a velocity shift due to rotation. A remarkable feature is that the amount of velocity shift increases as the position approaches the central star, indicative of rotation velocity getting higher toward inner radii. On the other hand, the PV diagram along the cut offset by $1''.65$ southwest (the far-side of the envelope) from the major axis (Fig. 6d) shows mainly blueshifted emission getting much bluer as the position approaches the center. This feature can be explained by infalling motions, which accelerate toward the center. In addition, the most blueshifted emission is not located at the center but is slightly shifted to the southeast ($\Delta < 0''$ in Fig. 6d). This deviation is naturally explained by rotation.

A simple analysis on the assumption of a geometrically thin envelope shows that the rotation velocity, $V_{rot} \propto r^{-1}$, which is the case of angular momentum conservation, while the radial dependence of the infall velocity is consistent with dynamical infall ($V_{inf} \propto r^{-0.5}$) onto a 0.1-0.5 $M_{\odot}$central star. The infall and rotation velocities at $r = 700$ AU are 0.5 km s^{-1} and 0.24 km s^{-1}, respectively. The infall rate was estimated to be 6.4×10^{-6} $M_{\odot}$ yr^{-1}.

Note that there is an additional redshifted emission in Fig. 6d. This emission originates from infalling gas in the near-side of the envelope, which is observable when the envelope is geometrically thick and nearly edge-on with respect to observers. In fact, model infalling envelopes with vertical structures can reproduce both blueshifted and redshifted emission in the diagram (see Fig. 8 in Momose et al. 1998). Such a geometrically thick, nearly edge-on, flattened, infalling structure was directly imaged toward L1527 (Ohashi et al. 1997a; Wilner et al. 1997; Choi et al. 1998).

C. Specific Angular Momenta of Infalling Envelopes: The Typical Size Scale for Dynamical Collapse

In a dynamically infalling envelope with slow rotation, specific angular momentum of each gas element is considered to be conserved, as was shown in the case of L1551 IRS5, until the infall motion shifts to the centrifugally supported motion around the radius where the rotation velocity is comparable to the infall velocity. On the other hand, star forming dense cores with larger scales often show solid-body rotation, which seems not to conserve its specific angular momentum. Where does specific angular momentum start being conserved in a dense core?

Ohashi et al. (1997b) examined the size dependence of local specific angular momentum in dense cores over a wide range of the size (200 AU to 80,000 AU in radius). In Fig. 7, local specific angular momenta, $j_{local} = V_{rot} R_{rot}$ where V_{rot} is the rotation velocity at a radius of R_{rot}, are plotted for three kinds of objects in Taurus, i.e., infalling envelopes, rotationally supported disks, and NH_3 dense cores, as a function of the rotation radius. Fig. 7 shows a clear difference in the size dependence of the local specific angular momentum between large scales of the dense cores and smaller scales of envelopes and disks: while the local specific angular momentum for the dense cores systematically varies with radius as a power law with an index of ∼1.6 (Goodman et al. 1993), it is almost constant at $\sim 10^{-3}$ km s^{-1} pc for infalling envelopes and rotationally supported disks. This result suggests that a star-forming dense core can be divided into two zones by the dependence of the local specific angular momentum: an inner region where gas has relatively constant angular momentum, and an outer region where the power-law relation applies. Fig. 7 suggests that the two zones are divided at ∼0.03 pc (6000 AU) in radius.

Why do the infalling envelopes and rotationally supported disks have similar specific angular momenta in Fig. 7? Suppose the angular momentum distribution of pre-star-forming dense cores, from which the envelopes and disks formed, is consistent with the power-law relation. If a dynamically collapsing region of a dense core is limited to only within 0.03 pc, then the specific angular momentum of a gas element in the infalling region will be set to $\sim 10^{-3}$ km s^{-1}, resulting in the similar specific angular momenta of the envelopes and disks in Fig. 7 (see Ohashi et al. 1997b for more details). This radius of 0.03 pc encloses a typical stellar mass in Taurus, namely, a Bonnor-Ebert condensation at $T = 10$ K with a radius of 0.03 pc contains a mass of ∼0.6 $M_\odot$.

VI. Comparison of Observations and Models

A. Expected Collapse Signatures

Even if we restrict ourselves to the spherical collapse of an isolated, non-fragmenting, isothermal cloud core, there are many different models for how the collapse proceeds. Here we consider the question of whether any of these predict the observed properties of star forming regions. The main uncertainties in the modeling are in the initial conditions and in what processses are included. In pioneering work on protostellar collapse, Larson (1969) and, independently, Penston (1969) developed similarity solutions for the collapse of a uniform density cloud with a fixed outer boundary. The solutions indicated that such a cloud would develop large infall velocities ($3.3a$, where a is the sound speed) at all radii and a power law density gradient ($n(r) \propto r^{-\alpha}$) with $\alpha = 2$. In contrast, Shu (1977) began with an equilibrium configuration for a singular isothermal sphere, in which the density gradient has reached $\alpha = 2$ by a quasistatic process, presumably ambipolar diffusion (Lizano and Shu 1989). If collapse begins in such a centrally condensed configuration, the collapse begins at the center where an opaque core forms and propagates outward, (the "inside-out" collapse), leading to an infalling inner region, with α approaching 1.5 asymptotically, surrounded by a static envelope with the original $\alpha = 2$. The Larson-Penston and Shu solutions represent the extremes of a whole class of solutions (Hunter 1977; Whitworth & Summers 1985). The main observable differences between the solutions of Larson-Penston and Shu are the nature of "pre-collapse" cores (uniform versus centrally condensed) and the velocities of collapse (high and extended over the core versus low and confined to the inner regions at early stages).

In a seminal paper, Zhou (1992) used the Larson-Penston and Shu solutions to predict line profiles of CS transitions as a function of time, identifying the particular features indicative of collapse. The higher velocities in the Larson-Penston solution make the peaks more separated than in the Shu solution, and the resulting linewidths from the Larson-Penston solution are inconsistent with observations of low mass star-forming cores (Zhou 1992). Thus, most recent comparisons of observations to models have focused on the Shu model. However, regions forming higher mass stars do have wider lines and Zhou's conclusion should not be over-generalized. In addition, Hunter (1977) noted that numerical calculations tended to give results between the two extreme similarity solutions. Further, calculations with non-singular isothermal spheres tend toward the Larson-Penston solution, but only at the center, and $\dot{M}$ decreases with time after core formation unless the outer radius is more than 20 times the core radius (Foster and Chevalier 1993).

In another approach, Walker, Narayanan, and Boss (1994) took a numerical hydrodynamic calculation of collapse with rotation as input to a line simulation program to predict line profiles of CS lines. They were limited to LTE excitation, but they were able to consider the effects of viewing angle in aspherical geometries. They noted that maps of the line centroid velocity displayed a distinctive "blue-bulge" when infall dominated over rotation.

B. The Theoretician's Dream: B335

B335 is a relatively isolated, spherical globule with a Class 0 infrared source (Keene et al. 1983) of low luminosity, $L \sim 3L_\odot$ (Chandler et al. 1990). The narrow lines imply a turbulent velocity much less than the sound speed, and rotation is very slow, ($\Omega \sim 1.4 \times 10^{-14}$ s^{-1}, Frerking et al. 1987). In other words, B335 looks like the perfect test case.

H_2CO absorption in a $\Delta J = 0$ transition at 6 cm wavelength provided evidence that the density increased toward the center and detailed models of the spatial variation of absorption indicated that power laws with $\alpha = 1.5$ matched the observations best (Zhou et al. 1990). Since this value was consistent with the inner part of an inside-out collapse, the full solution, including the static envelope, was tested. It provided an even better fit to the data. The models predicted that the $\Delta J = 1$ transitions of H_2CO at millimeter wavelengths should appear in emission. Observations of these lines verified the predictions and showed a double-peaked profile with a stronger blue peak. These observations were modeled with the full Shu solution, producing model line profiles consistent with both H_2CO and CS (Zhou et al. 1993, 1994). The luminosity predicted from the infall rate implied by the data matched that of the source, leading Zhou et al. to claim B335 as the first clear-cut case of a collapsing protostar.

Subsequent observational work has generally confirmed the existence of collapse in B335 (Chandler and Sargent 1993; Velusamy et al. 1995), with the caveat (Velusamy et al. 1995, Wilner et al. 1998) that the cloud may have significant clumpy structure superposed on the overall density gradient. Meanwhile, the modeling was improved by including thermal and turbulent line broadening in a self-consistent way, using Monte Carlo techniques (Choi et al. 1995). By considering a grid of models, Choi et al. established the best values, within the context of the Shu model, for the infall age (1.3×10^5 yr), mass of the protostellar core (0.37 $M_\odot$), and abundances of CS and H_2CO. The fact that the physical conditions are so well established leads to the idea that B335 can be used as a test bed for interstellar chemistry (Rawlings et al. 1994; Hartstein and Liseau 1998), and other collapse models (§VID) can also be tested against the observations of B335.

C. Rotating Collapse: L1527 and IRAS $16293-2422$

As discussed in §IV, L1527 is probably the second best case for being a collapsing protostar (Zhou et al. 1994; Myers et al. 1995). Myers et al. used an inside-out collapse model to predict line profiles of several lines toward the central object. The model is generally consistent with the observations, except that some lines have a larger blue/red asymmetry than predicted. Gregersen et al. (1997) used a 1D Monte Carlo code to model the line profiles of HCO^+, including rare isotopomers. They found a reasonable fit to the inner parts of the line, including the deep self-absorption, but the blue/red ratio of the observed line was again higher than predicted. In addition, contamination by the outflow was clearly a problem, as the observed lines of the main isotope had extensive wings not produced by the models.

The rotation rate in L1527, $\Omega \sim 1.1 \times 10^{-13}$ s^{-1}, (Goodman et al. 1993) is about 8 times greater than in B335, prompting Zhou et al. (1996) to use a generalization of the inside-out collapse model that includes rotation (Terebey et al. 1984), hereafter the TSC model, to model interferometric observations of ^{13}CO and C^{18}O. The model that fit the single-dish and interferometer data best gave an infall age (10^5 yr) and stellar mass ($0.36 M_{\odot}$) similar to those of B335. The TSC model predicts that a disk should appear at a distance from the forming star approximated by the centrifugal radius (R_c), where infall equals rotation. For the best-fitting model of Zhou et al., $R_c = 34$ AU.

Ohashi et al. (1997a) provided more clear evidence for infall and rotation in L1527, finding evidence in their interferometer maps of C^{18}O for a flattened envelope about 2000 AU in radius (see §V). Similar results were found by Choi et al. (1998) in interferometer maps of HCO$^+$ and HCN. By comparing position-velocity diagrams to models with rotation and infall, Ohashi et al. were able to separate the effect of the two motions. At 2000 AU, infall (0.3 km s^{-1}) dominated rotation (0.05 km s^{-1}), suggesting that the flattening was not caused by rotation. Moreover, the sense of rotation is opposite to what is seen on larger scales. They found an age similar to that found by Zhou et al. (1996), but a slower infall rate and smaller central mass (0.1 $M_{\odot}$).

How much does rotation affect the models of B335? Zhou (1995) used TSC models to compare to a spatial grid of CS spectra of B335, finding that he could explain some changes of the blue/red ratio at off-center positions. The parameters such as age and mass were not much affected, and the predicted $R_c = 3$ AU, too small to be detected.

Zhou (1995) also applied TSC models to *IRAS* $16293-2422$, finding that rotating infall provided an excellent fit to the spatial array of CS spectra (Menten et al. 1987) with rotation, $\Omega \sim 3 \times 10^{-13}$ s^{-1}, still more rapid than in L1527. The combination of rotation and infall produces the reversal of the blue/red asymmetry used by Menten et al. to argue against collapse. Thus, Zhou's modeling supported the original claim of Walker et al. (1986) that this source is collapsing. Recently, Narayanan, Walker, and Buckley (1998) used the blue-bulge technique on *IRAS* $16293-2422$, also supporting the original claim of collapse. They modeled a large grid of spectral lines with TSC models and an LTE, aspherical code, assuming $\Omega = 5 \times 10^{-13}$ s^{-1}. The best fit age is 6×10^4 yr and the predicted $R_c = 300$ AU, about half the binary separation. Zhou (1995) found numbers within a factor of 2 of these, suggesting that TSC models provide a reasonable first approximation even for such rapid rotation. However, the fast rotation and evident formation of a binary indicates that models for single star formation can not be applied literally to this object.

D. Other Collapse Models

Recent interest in this subject has called forth a new group of collapse models, distinguished by different initial conditions or by including different processes. Stimulated by observational evidence for flatter density profiles (Ward-Thompson et al. 1994) and sharp outer edges (Abergel et al. 1996) in pre-collapse cores, Henriksen et al. (1997) considered collapse from a broken power law with three regimes: $\alpha = 0$ for small r, $\alpha = 2$ at intermediate r, and $\alpha > 2$ at large r. They found an initial phase of rapid $\dot{M}$, coinciding with the Class 0 phase, relaxing to the constant $\dot{M}$ of the Shu models at later times, matching the Class I sources in Taurus. They also argued that sources in the ρ Oph cluster have a different accretion history from sources in Taurus. André (1997) has summarized these developments.

McLaughlin and Pudritz (1996) argued that the properties of pre-collapse cores are better described as a logatropic sphere, in which the total pressure, including non-thermal, follows $P/P_c = 1 + A\ln(\rho/\rho_c)$. The density distributions in such objects are well approximated by power laws with $\alpha = 1$. McLaughlin and Pudritz (1997) considered inside-out collapse from such a configuration, and found $n(r) \propto r^{-1.5}$ and $v(r) \propto r^{-0.5}$ at small radii, inside the infall radius. While the form is the same as in the Shu solution, the density increases in absolute terms inside the infall radius, rather than decreasing, and the velocities are lower than in the Shu solution, providing a possible test of which model describes observations. Also, the accretion rate is not constant, but instead $\dot{M} \propto t^3$, implying very slow growth at early times. With this model, the age of B335 would increase to 1.2×10^6 yr. Since Henriksen et al. (1997) favor ages around 10^4 yr for Class 0 sources, like B335, there are now estimates spanning two orders of magnitude, but we consider the largest age estimates unlikely.

Magnetic fields will no doubt modify the nature of the pre-collapse core (e.g., Mouschovias 1995, Li and Shu 1996), as well as the collapse (Li and McKee 1996, Li 1998, Ciolek and Konigl 1998). Safier et al. (1997) and Li (1998) considered magnetic effects in a spherical cloud, finding that a long, quasi-static phase precedes a short dynamical phase, in which the inner envelope collapses rapidly from the outside in to form the protostar. This phase is followed by an inside-out collapse of the rest of the envelope. A magnetic accretion shock (Li and McKee 1996) is driven outward causing a pile up of material on a scale of about 10^3 AU. The density profile in the pre-collapse phase approaches a power law that is slightly steeper than that of an isothermal sphere ($\alpha \sim 2.4$).

While spherical clouds provide some insight, the pre-collapse cores of magnetic clouds are likely to be flattened (Fiedler and Mouschovias 1993; Li and Shu 1996), necessitating aspherical radiative transfer models. In addition, collapse from an initially spherical, magnetized cloud will produce flattened structures on scales of $\sim 10^3$ AU (e.g., Galli and Shu 1993a,b). These latter structures, commonly called "pseudodisks" may account for the flattened, mass concentrations seen in some collapsing regions (e.g., L1527, §V). In addition, Hartmann et al. (1996) have considered more generally the collapse from sheet-like structures.

Weisemeyer (1997) has included some of these aspherical effects, using an accelerated Λ-iteration method to solve the radiative transfer in cylindrical geometry. He produced a grid of simulated line profiles for both sheet collapse (Hartmann et al. 1996) and a model with a magnetic accretion shock (Li and McKee 1996). He compared these simulations to observations of two condensations within the L1082 (GF9) globular filament, favoring the sheet collapse picture in one and the magnetic accretion shock picture in the other.

It is clear that theoretical models incorporating magnetic fields and/or rotation must be compared with observational data, via detailed line profile modeling in aspherical radiative transfer codes. Such codes are, at present, time-consuming, and the larger number of free parameters, including both theoretical parameters and issues like orientation relative to the observer, make comparison with observations problematic. Very complete data sets, with tracers sensitive to different aspects of the region, will be necessary to constrain the full range of theoretical imagination.

VII. Summary

The quality and quantity of evidence for inward motions in star-forming regions is much greater than in years past, and their study with observations and models is now a serious undertaking, with activity by numerous groups. Our main conclusions follow:

1. Surveys of candidate protostars yield significant numbers of sources with infall asymmetry, a skewing of an optically thick line profile toward the blue when the line-forming gas has sufficient inward motions, optical depth, and gradient in excitation temperature. At least 13 infall candidates have infall asymmetry in two or more lines, among rotational lines of CS, H_2CO, and HCO^+. Most of these candidates have substantial turbulent motions, unlike the best-known infall source B335. Infall asymmetry is fairly common in the most embedded sources; further studies of less embedded sources are needed to trace the evolution of infall.

2. Infall asymmetry is also seen in numerous starless cores. As in cores with embedded sources the incidence depends on the spectral line used. The best-studied starless core, L1544, shows infall asymmetry on scales from 0.01 to 0.1 pc in numerous lines. The largest extent is too large for consistency with inside-out collapse. The infall speed in a two-

layer model is 0.05-0.1 km s^{-1}, which appears too fast for consistency with ambipolar diffusion on the largest scales.

3. Single-dish maps of kinematic infall candidates generally show a zone of extent 0.03-0.1 pc where infall asymmetry predominates. In L1251B and NGC1333 IRS 4, the zone of infall asymmetry is more extended than the corresponding map of optically thin dense gas, suggesting large-scale inward motions which are larger than expected from simple gravitational infall. In L1527 and B335, infall asymmetry is less extended than the dense core map, and is well-centered on the embedded YSO, suggesting consistency with gravitational infall.

4. Interferometric observations achieve higher resolution than can single-dish maps ($<$ 1000 AU in nearby regions), and filter out large-scale structures. Many interferometric studies interpret optically thin line emission in the context of a flattened structure, identifying infall from a velocity gradient along the projected minor axis, and rotation from a velocity gradient along the projected major axis. Such observations of L1551 IRS5 suggest a combination of infall and rotation ($\sim$0.5 km s^{-1} and 0.2 km s^{-1} respectively at radius 700 AU), with each speed increasing inward.

5. Detailed radiative transfer modeling of line profiles has been attempted for only a few cores with embedded sources, including B335, L1527, and *IRAS* 16293 − 2422. The observed line profiles of B335 agree reasonably well with models of "inside-out" gravitational collapse. L1527 and *IRAS* 16293 − 2422 require models with rotation. None of the models currently include outflows, turbulence, or magnetic fields. Models assuming different initial density profiles have yet to be thoroughly tested against observations. Theoretical models will be needed for comparison to many cores, including starless cores and cores which form multiple sources.

In the coming years, we may expect more observational studies of infall, extending our knowledge in space, time, and source multiplicity. Interferometers will reveal details on size scales of circumstellar disks (cf. chapter by Wilner et al., this volume) and of the interaction between infall and outflow. Observations of starless cores and of Class I sources will reveal the earliest and latest indications of infall, and will help to understand infall evolution. Observations of higher rotational lines at submillimeter wavelengths will probe infall in gas with higher densities. Observations of submillimeter continuum emission will provide important information on the density distribution, without the uncertainties that depletion and opacity cause in interpreting molecular line data. High-resolution observations of cluster-forming regions may allow us to resolve simultaneous inward motions onto multiple centers. We expect that we will also achieve a fuller understanding of the role of turbulence and magnetic fields on the motions and structure of infalling gas in star-forming regions.

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FIGURE CAPTIONS

Figure 1. Variation of infall asymmetry (a) with peak optical depth τ_0 and (b) with infall speed V_{in}. In a radiative transfer model of two uniform layers with velocity dispersion σ and approach speed V_{in}, the line profile is symmetric for $\tau_0 < 1$, but its peak skews to the blue as τ_0 increases beyond 1. For $V_{in} < \sigma$ and increasing τ_0, the profile has two peaks, with increasing ratio of blue to red peak intensity. As V_{in} increases for fixed $\tau_0 > 1$, the blue-red intensity ratio increases until the red peak disappears into a red shoulder (Myers et al 1996).

Figure 2. Spectral profiles of dense gas tracer lines in the starless core L1544. These lines vary from HCO^+ 1-0, with high optical depth and strong infall asymmetry, to $C^{34}S$ 2-1, with low optical depth and no infall asymmetry (Tafalla et al 1998).

Figure 3. Spectral profiles of CS 2-1 in L1544, in relation to the half-maximum integrated intensity contour of the optically thin N_2H^+ 1-0 line, taken as a tracer of the dense core gas. Each spectral window has velocity range 5.7 to 8.7 km s^{-1} and brightness temperature range -0.5 to 4.0 K. The (0,0) position, epoch 1950, is $(\alpha, \delta) = (05^h01^m12^s.5, 25°06'40")$. Profiles with infall asymmetry are extended over ~0.15 pc, substantially greater than expected from "inside-out" collapse" and substantially greater than the extent of the dense core (Tafalla et al 1998).

Figure 4. Spectral profiles of H_2CO 2_{12}-1_{11} in the "thermal" core L1527, in relation to the half-maximum integrated intensity contour of the optically thin N_2H^+ 1-0 line. Each spectral window has velocity range 4.5 to 7.5 km s^{-1} and brightness temperature range -0.8 to 5.0 K. The vertical line marks the velocity of optically thin N_2H^+ emission. The (0,0) position, epoch 1950, is $(\alpha, \delta) = (04^h36^m49^s.3, 25°57'16")$. Profiles with infall asymmetry have extent ~0.04 pc, less than that of the dense core (~0.06 pc), and well-centered on the single embedded Class 0 source, at position offset (3.9", 4.6") (Mardones et al 1999).

Figure 5. Spectral profiles of H_2CO 2_{12}-1_{11} in the "turbulent" core L1251B, in relation to the half-maximum integrated intensity contour of the optically thin N_2H^+ 1-0 line. Each spectral window has velocity range -7.0 to -1.0 km s^{-1} and brightness temperature range -0.8 to 4.0 K. The vertical line marks the velocity of optically thin N_2H^+ emission. The (0,0) position, epoch 1950, is $(\alpha, \delta) = (22^h37^m40^s.8, 74°55'50")$. Profiles with infall asymmetry have extent similar to that of the dense core (~0.06 pc), and are well-centered on the embedded IRAS source and small stellar group at position offset (0,0) (Mardones et al 1999).

Figure 6. Interferometric $C^{18}O$ 1–0 maps of L1551 IRS5 (Momose et al. 1998). The angular resolution is $2''.8 \times 2''.5$, corresponding to ~370 AU, while the velocity resolution is ~0.2 km s^{-1}. The contour spacing is 1.5σ, starting from 1.5σ in (a), (c), and (d). (a) The total intensity map. The

direction of the outflow measured by optical observations (Stocke et al. 1988) is indicated by arrows. The cross indicates the position of IRS5. (b) The intensity-weighted mean velocity map. Bluer velocities are drawn in darker grey contours. The systemic velocity of IRS5 is 6.2 km s^{-1}. The 1.5σ contour of the total intensity is drawn in the dashed contour. (c) The position-velocity diagram along the major axis of the $C^{18}O$ envelope[A_1A_2 in (a)]. The dashed curves indicate the distribution of the rotation velocity proportional to r^{-1}, while the thin solid curves show the Keplerian rotation velocity yielded by a 0.15 $M_\odot$central star. (d) The position-velocity diagram along the cut B_1B_2 in (a) offset by 1.″65 southwest from the major axis. The two dashed curves indicate distributions of dynamical infall velocities; the inner curve is the velocity yielded by a 0.1 $M_\odot$central star, and the outer one is that yielded by a 0.5 $M_\odot$star.

Figure 7. Local specific angular momentum plotted as a function of the rotation radius. Open squares, filled circles, and filled triangles indicate data for NH_3 dense cores, infalling envelopes and rotationally supported disks, respectively(NH_3 cores not associated with the Taurus molecular cloud are indicated by small squares.). The solid line shows a power-law relation with an index of 1.6 for all the NH_3 cores (see Goodman et al. 1993).

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