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Observational and Theoretical Studies of Low-Mass Star Formation

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Under this grant we have pursued studies of low-mass star formation with observations of candidate star-forming regions, (1) to determine the incidence of "infall asymmetry" in the spectral lines from very red young stellar objects; (2) to make detailed maps of candidate infall regions to determine the spatial extent of their infall asymmetry; (3) to compare the spatial and velocity structure of candidate infall regions with single dish and interferometer resolution; and (4) to begin a program of observations of starless dense cores to detect the presence or absence of infall motions.

1. Incidence of infall asymmetry . The best-known spectroscopic signature of a contracting cloud is the "infall asymmetry" in a pair of optically thick and optically thin molecular spectral lines, each of which requires density > 10^4 cm^{-3} for excitation. In this pair, the optically thin spectral line has a single peak and a symmetrical shape about its velocity v_0 of peak emission. The optically thick line is asymmetrical with respect to v_0: its peak is shifted to the blue, and it may have a self-absorption dip at v_0 (e.g. Leung & Brown 1977).

Infall asymmetry has been observed in many candidate protostars, but such asymmetry is not a unique indicator of infall because most candidate protostars also have powerful outflows. If the outflow emission in a given source is brighter in the blue than in the red, it can cause the profile of a region without infall to have spurious infall asymmetry. But in a large sample of sources, it is expected that blue-shifted and red-shifted peaks due to outflows will be equally likely. Therefore we have surveyed a sample of about 50 candidate protostars to see whether the blue- and red-shifted peaks occur equally often (outflow interpretation) or whether there is a significant excess of blue-shifted peaks (infall interpretation).

The observations were made in the 2 mm line of H_2CO (generally optically thick) , the 3 mm line of CS (optically thick) and the 3 mm line of N_2H^+ (generally thin), toward all known IRAS sources within 400 pc having very red broadband spectra. We used the IRAM 30-m telescope and the Haystack 37-m telescope for northern sources and the SEST 15-m telescope for southern sources. The redness criterion is expressed in terms of the bolometric temperature, T_{bol} < 200 K (Myers & Ladd 1993, Chen et al 1995), corresponding to extreme Class I sources (Lada 1987) and Class 0 sources (André, Ward-Thompson & Barsony 1993).

Our main finding is that the velocity of the H_2CO peak is shifted from that of the N_2H^+ peak to the blue significantly more often than to the red, as expected if asymmetry due to infall dominates over asymmetry due to outflow. This trend is seen in both the CS and the H_2CO samples. In each case the trend is due almost entirely to the class 0, as opposed to the class I sources. These results constitute the first statistically significant evidence for infall in a group of young sources, where the evidence for infall is stronger for the younger sources. (Mardones et al 1997).

2. Spatial extent of infall asymmetry. We have mapped nine regions which are infall candidates on the basis of their spectra in the surveys described above, in lines of H_2CO and N_2H^+ with the IRAM 30-m and SEST 15-m telescopes, and have also mapped several of these regions in lines of CS and N_2H^+ with the Haystack and FCRAO telescopes, in lines of C_3H_2 with Haystack, and in CS 5-4 with the NRAO 12-m telescope. In a few cases we have observations of $C^{34}S$ and $H_2{}^{13}CO$ to better define the optically thin emission profile (Mardones 1998; Tafalla et al 1998, ApJ, submitted; Williams & Myers 1998, in draft).

Our findings are:

(a) Sources which have significant infall asymmetry in the H_2CO 2-1 line at the YSO position, according to the survey, also have infall asymmetry extended over most of the spectra in a zone of typical radius 0.03 pc, defined by the HM contour of the optically thin 1-0 line of N_2H^+. This behavior is seen in B335, I13036-7644, I16293-2422, L483, L1157, L12521B, L1527, NGC1333-IRAS4a,b, andSerpens.

(b) Sources which dominant infall asymmetry usually have a minority of positions with "line reversal" in which the asymmetry is red, rather than blue. These reversals are of two types. One, localized to the YSO, is associated with bipolar outflows;. The other, at or beyond the HM contour of the dense core, appears to be associated with regions of high velocity gradient, and may reflect motion of the dense core through its less dense environment.

(c) Infall zones have typical density 2×10^5 cm^{-3} and median infall speed 0.05 km s^{-1} according to a two-layer model (Myers et al 1996), corresponding to median mass infall rate 2×10^{-6} M_O yr^{-1}, as expected for "inside-out" collapse at temperature 10 K. However, most of the cores with infall motions have highly supersonic line widths, and have infall asymmetry extending beyond the expected radius of inside-out collapse.

3. Interferometric resolution of infall regions. To study the structure of infall regions on smaller scales (a few hundred AU - a few thousand AU) we have observed the candidate protostars in L1527, B335, Serpens, L1251B, NGC1333IRAS4a,b and the starless core L1544 in high-density-tracer lines of HC_3N, H_2CO, CS, N_2H^+, and NH_3, with the OVRO, NRO, IRAM, and BIMA arrays, and with the VLA (Wilner et al 1997, Williams et al 1998, in prep, Di Francesco et al 1998, in prep). The main results thus far are:

(a) In L1527, the 1 mm H_2CO line profile has infall asymmetry in both the interferometric (4" beam) and single-dish (12") observations, and the J=11-10 line of HC_3N, which is most likely optically thin, has a single peak which lies between the two H^2CO line peaks. The interferometric emission is more compact (10" × 20") than the single-dish emission; its elongation is perpendicular to the direction of the outflow. Its spectral peaks are brighter by a factor of ~3, and are separated by a slightly greater velocity than in the single-dish spectra. The interferometeric emission has a higher proportion of spectra with infall asymmetry: the blue peak is brighter than the red in nearly every detected spectrum, while the single-dish spectra are more variable.

(b) In B335, CS 5-4 maps indicate extensive outflow emission, which challenge the claim by Zhou et al (1993, ApJ 404, 232) that the spectral broadening of the 1 mm H2CO line is due to infall motions.

(c) In L1544, N_2H^+ maps show pronounced infall asymmetry over a region of radius ~0.01 pc, suggesting the presence of a compact high-density zone of infall where there is no known young stellar object.

4. Survey of starless cores. The cores with no known embedded source represent an earlier evolutionary phase than the class 0 protostars. We have surveyed about 50 starless cores in lines sensitive to infall asymmetry, including CS 2-1, HCO^+ 1-0, $H^{13}CO^+$ 1-0, $C^{18}O$ 1-0 and N_2H^+ 1-0, using the FCRAO, Haystack, and TRAO(Korea) telescopes. We selected the peak position in the optically thin-tracer map ($C^{18}O$ 1-0 or N_2H^+ 1-0), and then integrated on the thick-tracer lines to achieve a high signal-to-noise ratio line profile. We discovered several starless cores with infall asymmetry in addition to L1544, notably L1521, L183, and L1696. We found that the distribution of velocity differences between thick and thin tracers is shifted to the blue, as it is for the class 0 protostars, but not with as high an incidence of blue-shifts. As with the YSO survey, the incidence of significant blue shifts increases with the N_2H^+ line optical depth, as expected from infall models. We plan to observe a larger sample next year to improve the statistical basis of this experiment (Lee, Tafalla, & Myers 1998).

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