STRUCTURE, MOTION, AND EVOLUTION OF STAR-FORMING DENSE CORES

Grant NAG5-6266

Annual Report

For the Period 1 September 2000 through 31 August 2001

Principal Investigator

Dr. Philip C. Myers

September 2001

Prepared for

National Aeronautics and Space Administration
Goddard Space Flight Center, Greenbelt, MD

Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02138

The Smithsonian Astrophysical Observatory
is a member of the Harvard-Smithsonian
Center for Astrophysics

Progess Report - 2000-2001 - Grant NAG5-6266

"Motions and Initial Conditions in Star-Forming Dense Cores"

Under this grant in the past year we have pursued spectral-line observations of star-forming regions over size scales from 0.01 pc to 0.5 pc. Our main goal has been to measure the systematic and turbulent motions of condensing and collapsing gas. In this area, our results include (1) in 67 starless dense cores, some 19 show clear evidence of spatially extended inward motions, with typical line-of-sight inward speed 0.05-0.09 km s^{-1} and with typical plane-of-the-sky extent 0.1-0.3 pc (Lee, Myers & Tafalla 1999, 2001), (2) In some 40 nearby regions with embedded groups and clusters, we see extended infall asymmetry in lines of CS and HCO^+ clearly in 4 regions and less clearly in 4 others (Williams & Myers 2000, Bourke & Myers 2001), (3) Using finer resolution (15 arcsec or 0.01-0.02 pc) and lines tracing higher density, we see spatial concentration of infall asymmetry near the protostars in NGC 1333 IRS 4A and B, L483, and L1251B (Mardones et al 2001), and with still finer resolution (2 arcsec or 0.003 pc or 600 AU) we detect inverse P Cyg profiles, indicating absorption of continuum emission from the protostellar envelope by infalling gas in NGC 1333 IRS 4A and 4B (Di Francesco et al 2001). Further, at high resolution we identify regions of stellar mass and low turbulence ("kernels") which are good candidates to become the next generation of stars in embedded clusters (Williams & Myers 2000, Di Francesco et al 2001). In addition we have completed a survey for the OH Zeeman effect in absorption against nearby H II regions, indicating that the large-scale magnetic field may be nearly critical if it typically threads a flattened structure (Bourke et al 2001). We have also developed a model of spatially extended infall motions based on dissipation of turbulence in a magnetized, self-gravitating layer (Myers & Zweibel 2001).

In the following we describe some of these results in more detail.

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 in starless cores. A survey of some 220 starless cores, selected by their visual extinction and their lack of associated red IRAS sources, yielded 67 cores detectable in both our optically thick (CS 2-1) and thin (N_2H^+ 1-0) lines. Of these, we identified 7 "strong" and 10 "probable" infall candidates based on distortions in the CS line profile. In addition a substantial number of sources (20) have a statistically significant blue shift of their CS emission peaks while a much smaller number (3) have an equally large red shift. Thus many starless cores show evidence of inward motion, at the level of 0.05 - 0.1 km s^{-1} (Lee, Myers & Tafalla 1999). More recently we have mapped the same CS and N_2H^+ emission from infall candidates with the FCRAO 14-m telescope, and have found that the typical starless core with strong infall asymmetry on the basis of the single-dish survey described above has CS infall asymmetry extended over 0.1-0.3 pc, extending beyond the half-maximum contour of the N_2H^+ map by a factor of 2-3. Thus it appears that the infall asymmetry is associated with motions of condensation on a size scale greater than that of the dense core, as opposed to motions onto a point mass at its center (Lee, Myers & Tafalla 2001; Figure 1).

Infall asymmetry in cluster-forming regions. Observations of emission from HCO^+ 1-0 and CS 2-1 in dense cores associated with small groups and clusters indicate that 4 -8 cores have infall asymmetry extended over even larger regions than in the starless cores described above. The most remarkable case is in the region to the south of NGC 1333, where infall asymmetry is seen over 0.2 pc in CS 2-1 (Williams & Myers 2000) and over 0.5 pc in HCO^+ 1-0 (Bourke & Myers 2001). These results indicate that extended inward motions occur not just before cores form stars, but before, during and after star formation. Furthermore these results suggest that the inward motion is too extended to represent motion toward a single point source, and its variation appears too smooth to represent motion toward a collection of point sources. If so, we may be witnessing a flow driven by a spatially extended pressure gradient, as suggested by Myers & Lazarian 1998, and/or condensation of a flattened structure, as was modelled by Allen & Shu (2000).

Inverse P Cyg profiles toward NGC 1333 IRS 4A, 4B. Using the IRAM Plateau de Bure Interferometer we found strong evidence for infall in absorption against the continuum emission from the protostellar envelopes of IRS 4A and 4B (Figure 2), confirming the weaker absorption reported toward these sources by Choi, Panis, & Evans (1999) in HCO^+ and HCN 1-0. The absorption appears at nearly the same velocity as that of the self-absorption dip seen in the extended single-dish spectra, suggesting that the extended, slow motion of contraction is closely related to the localized fast motion responsible for the inverse P Cyg profiles. A two-layer model of the absorption indicates infall speed of 0.5 - 0.7 km s^{-1}, consistent with gravitational free fall onto a point mass of 1 $M_{\odot}$ from a distance equal to the beam radius (Di Francesco et al 2001).

Small dense regions of low turbulence in young clusters. In Serpens, Orion B9, Oph A, and NGC1333 our high-resolution N_2H^+ maps indicate the presence of small (< 0.03 pc) regions of remarkably low turbulence. From the scale of single-dish to interferometer resolution in Serpens, 0.07 to 0.01 pc, the N_2H^+ line width is reduced by a factor of 1.5-2 (Williams & Myers 2000), and in NGC1333 from resolution scale of 0.02 to 0.003 pc the N_2H^+ line width is reduced by a factor of 2-3 (Di Francesco et al 2001). These line width reductions on small size scales resemble those of nearly thermal "kernels" in turbulent regions of cluster formation (Myers 1998), Their mass is similar to that of low-mass stars, so they may mark gas destined to form the next generation of stellar cluster members.

Model of extended inward motions. A quantitative model has been developed which accounts for the prevalence of nonthermal line broadening and for extended inward motions in the dark clouds which surround starless dense cores. In this model a centrally condensed self-gravitating layer is threaded by a uniform magnetic field. Alfven waves propagate on the field lines and their pressure combines with thermal pressure to support the layer against its self-gravity. As the waves dissipate the layer condenses quasistatically. This model predicts vertical settling motions of order 0.1 km s^{-1}, in the direction of the mean magnetic field. These systematic motions are faster than those across field lines due to subcritical ambipolar diffusion, and are in better agreement with the observations described above. This model also reproduces observed nonthermal line widths, in contrast to models which are based on thermal motions and purely static magnetic fields (Myers & Zweibel 2001).

Plan for the coming year. In this next year our main activity will be to use observations of finer angular resolution and line tracers sensitive to higher gas density, to resolve in more systems the localized fast motions which seem to represent gravitational formation of the star-disk system, and to better define the transition from extended slow motions to localized fast motions. We will apply this approach to starless cores, isolated protostars, and protostars in groups.

REFERENCES

Allen, A., & Shu, F. H. 2000, ApJ, 536, 368

Bourke, T. L., & Myers, P. C. 2001, in preparation.

Bourke, T. L., Myers, P. C., Robinson, G., & Hyland, A. R. 2001, ApJ, 554, 916

Choi, M., Panis, J., & Evans, N. J. 1999, ApJS, 122, 519

Di Francesco, J., Myers, P. C., Wilner, D. J., Ohashi, N., & Mardones, D. 2001, ApJ, in press

Lee, C. W., Myers, P. C., & Tafalla, M. 1999, ApJ, 526, 788.

______________2001, ApJS, in press

Leung, C. M., & Brown, R. L. 1977, ApJ, 214, L77.

Mardones, D., Myers, P. C., Tafalla, M., Bachiller, R., Wilner, D. J., & Garay, G. 2001, in preparation

Myers, P. C. 1998, ApJ, ApJ, 496, L109.

Myers, P. C., & Lazarian, A. 1998, ApJ, 507, L157.

Myers, P. C., & Zweibel, E. G. 2001, submitted to ApJ.

Williams, J. P., & Myers, P. C. 2000, ApJ, 537, 891.