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

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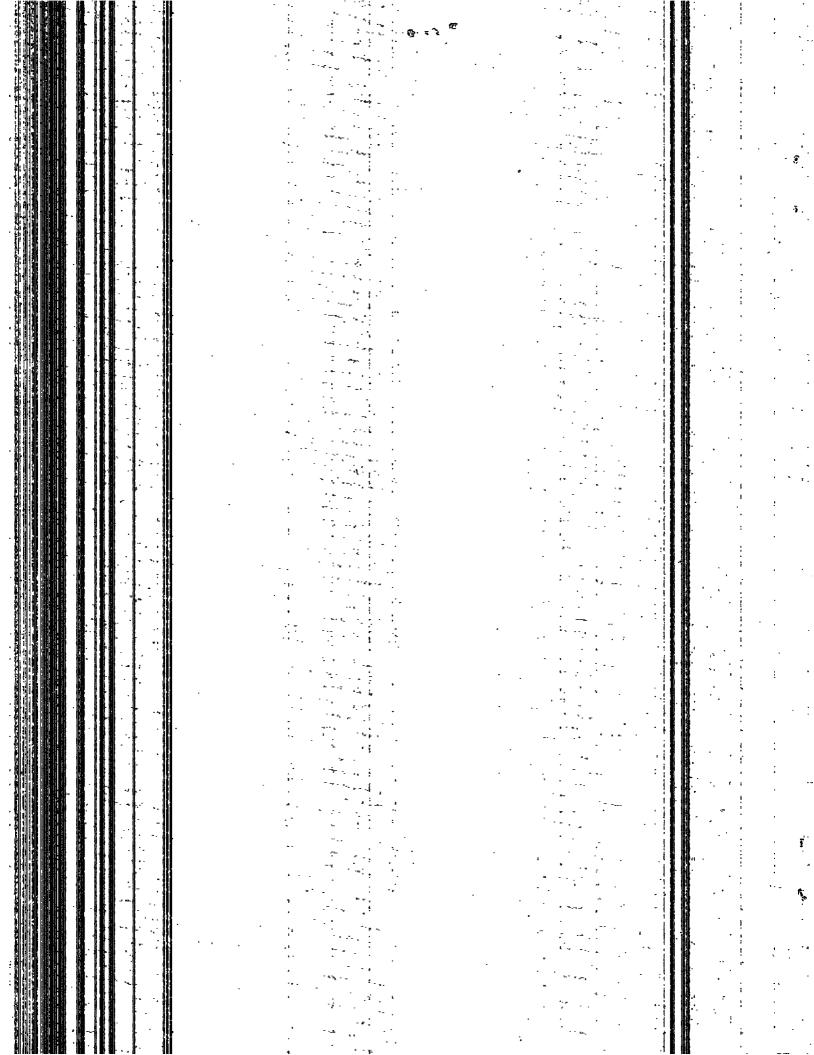
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"Structure, Motion, and Evolution of Star-Forming Dense Cores"

Under this grant 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. The following summary is excerpted from our recent application for a new three-year grant, submitted in June, 2002.

Observations of starless cores

The earliest identifiable stage of stellar evolution has been called a "starless core," a condensation of gas dense and massive enough to form a star, observed in a spectral line which is also seen in cores which harbor embedded young stellar objects (YSOs). Since the all-sky IRAS survey, it has been possible to identify cores which have no far infrared point source more luminous than about $0.1 \, L_\odot (D/140 \, pc)^2$, where D is the earth-core distance (Myers et al 1987). Starless cores have been identified according to emission in the (J, K) = (1,1) line of NH_3 (Benson & Myers 1989), the J=1-0 line of $C^{18}O$ (Tachihara et al 2000), the J=1-0 line of N_2H^+ (Caselli et al 2002), and in the submillimeter continuum (Ward-Thompson et al 1994, Shirley et al 2000). Starless cores with submillimeter emission are also known as "prestellar" or "pre-protostellar" cores (Evans 1999, Andre et al 2000).

Starless cores are prime searching grounds for inward motions. They represent the earliest possible evolutionary phase, before a core has produced a detectable star, and their infall asymmetry suffers no confusion from outflow motions. The easiest such cores to identify and study are "isolated" starless cores in complexes which lack large embedded clusters, such as the Taurus complex, or in smaller molecular clouds and Bok globules. We discuss the starless condensations in embedded clusters later in this report.

Infall asymmetry in isolated starless cores

L1544 is the first starless core whose infall asymmetry has been studied in detail. Its infall asymmetry is detectable in many lines, is extended over ~0.1 pc, and its effective inward speed is as great as ~0.1 km s^{-1} (Tafalla et al 1998). The large extent and subsonic speed of the infall asymmetry suggest condensation of the dense core, but the typical speed is greater than expected from magnetically subcritical ambipolar diffusion (e.g. Ciolek & Mouschovias 1995). Further the spatial extent of the asymmetry is much greater than expected if the infall asymmetry represents the motions of "inside-out" collapse (Shu 1977). We therefore attempted to determine whether the

unexpected motions of L1544 are unique or common, with the following observational studies.

Catalog of isolated starless cores. Using the STScI Digitized Sky Survey we imaged a 30 × 30 arcmin square around each entry in the Lynds (1962) catalog of dark clouds with opacity code 5 or 6, around each entry in the Hartley et al (1986) catalog of southern dark clouds with opacity code A, and around entries in numerous molecular line studies of cores (Lee & Myers 1999). This procedure generally identified several local minima of intensity for every dark cloud entry searched. The result is a comprehensive catalog of 407 core positions. We searched these cores with the IRAS point source catalog, using criteria of YSO association similar to those of Beichman et al (1986) and Benson & Myers (1989), yielding 292 starless cores. Some of these were already known from earlier surveys, while others such as L694-2, have proven to be new and useful infall candidates.

Survey. We used the optically thick line of CS 2-1 and the thin line of N_2H^+ 1-0 as tracers of gas denser than $10^4\,cm^{-3}$ (Evans 1999) to identify cores with infall asymmetry. In a single-pointing survey of 220 starless cores with the 37-m Haystack Observatory we detected emission from both lines in 69 cores, and identified 7 "strong" and 10 "weak" cases of infall asymmetry (Lee, Myers & Tafalla 1999). A survey of 17 starless cores having submillimeter continuum emission was also carried out in lines of HCO^+, giving similar results (Gregersen & Evans 2000).

Maps. We mapped emission from 37 starless cores in CS 2-1 and N_2H^+ 1-0, selected because they were infall candidates in the single-pointing survey or because they were relatively bright in either line, using the 14-m FCRAO telescope. We found numerous cores which resemble L1544 in its pattern of extended inward motions--10 "strong" and 9 "probable" candidates. Eleven of the 15 infall candidates in the single-pointing survey proved to be infall candidates in the mapping survey. The typical infall speed was found to be in the range 0.05 - 0.09 km s^{-1} with spatial extent of the infall asymmetry 0.1-0.3 pc (Lee, Myers & Tafalla 2001; hereafter LMT01).

Only in a few cases do the maps of LMT01 show a systematic pattern of infall asymmetry-- either weaker toward the core, as in L1544, or stronger toward the core, as in L694-2 or L1696B. In most cases the spatial distribution of infall speeds is neither uniform nor systematic.

The foregoing detection statistics, inward speeds, and spatial extents suggest that a period of extended inward motions is a common feature in the evolution of starless cores, with time scale of order a few times 0.1 Myr. The physical basis of these motions is still unclear, and both gravitational and non-gravitational origins have been suggested. A more detailed interpretation also depends strongly on the spatial distribution of CS in the core, as indicated by the following recent

results on selective depletion of molecular species in starless cores.

Density structure and selective depletion

Observations of isolated dense cores in different molecular species have long been known to present maps with significant differences in peak position, spatial extent, and shape from one species to the next (e.g. Little et al 1979, Swade 1989, Myers et al 1991). Until recently these differences were attributed to variations in chemical time scales and to radiative transfer effects. A major advance has come from sensitive, high-resolution mapping of the dust density structure, both via submillimeter emission (Ward-Thompson et al 1994, Shirley et al 2000) and near-infrared absorption of background starlight (Alves, Lada & Lada 2001, Harvey et al 2001). These maps indicate that the density structure of the dust and H_2 molecules in a typical starless core is roughly "flat" inside a radius of a few thousand AU, surrounded by a declining power-law envelope with exponent > ~2 (Shirley et al 2000, Tafalla et al 2002). With these sensitive observations it is now evident that some species, including NH_3 and N_2H^+, follow the dust emission closely while others, such as CO, CS, and their isotopic variants, depart strongly over regions of extent ~0.05 pc (Kuiper, Langer, & Velusamy 1996, Kramer et al 1999, Caselli et al 1999). The departure is characterized by molecular emission maps which have a plateau, valley, or hole where the dust emission map has a peak.

This differentiation among maps is demonstrated in maps of emission from dust, $C^{18}O$, $C^{17}O$, CS, NH_3, and N_2H^+ in the core L1498, which is typical of the five cores studied (Tafalla et al 2002). The maps of dust, N_2H^+, and NH_3 show a slightly elongated core with a well-defined peak, and strong correlation from map to map. In contrast the maps of $C^{18}O$, $C^{17}O$, and CS show diffuse emission, with a poorly defined peak or peaks displaced from the dust peak.

This pattern of strong map concentration for some species and diffuse emission for others has a simple explanation in terms of molecular depletion onto dust grains. Once the gas is denser than a few times 10^4 cm^{-3}, the time scale for a molecule to hit a grain decreases below ~0.1 Myr, shorter than most times scales of the core evolution (Leger 1983). For gas as cold as 10 K in a starless core, a relatively polar molecule such as CO or CS has a high probability of binding to the grain surface, while a nonpolar molecule such as H_2 or N_2 (the parent molecule of N_2H^+ and NH_3) can more easily desorb. The result is a pattern of selective depletion of most molecules but not N_2H^+ or NH_3 (Bergin & Langer 1997), in good agreement with recent observations. It remains to be seen how the depth and size of the depletion zone varies from one core to the next in a larger and more diverse sample of cores, and from one species to the next, for molecules other than CO, CS, N_2H^+ and NH_3.

Infall in cores with depletion

Species such as CO and CS have much lower abundance inside their "depletion zone" than they do outside, so their emission lines are not sensitive to motions inside this zone. Thus the CS inward motions described above refer mainly to lower-density gas surrounding the densest part of the core probed by N_2H^+. This effect almost certainly accounts for the extended nature of the CS infall asymmetry and its lack of spatial concentration. It will be important to explore further the physics of these extended inward motions, and to understand how they relate to the smaller-scale star-forming motions in denser core gas.

Starless cores in cluster-forming regions

Identification and study of starless condensations in cluster-forming regions is of interest for the same reasons as in isolated regions, and also because most stars probably form in groups and clusters, with a mass distribution indistinguishable from the stellar initial mass function (IMF: Meyer et al 2000). The mass distribution of such starless cores is important, since estimates based on dust emission yield a power-law distribution similar to that of the IMF in Ophiuchus (Motte, André & Neri 1998), in Serpens (Testi & Sargent 1998), and in Orion B (Johnstone et al 2001). If confirmed, this result suggests a one-to-one correspondence between starless cores and stars forming in clusters, and that at least part of the IMF is set by processes in the star-forming gas.

Among kinematic studies, it is desirable to probe the inward motions of individual condensations, just as for isolated cores. In addition is is important to measure the relative motions of condensations in order to understand their degree of interaction, and to probe their motions through their surrounding envelopes to determine whether they gain mass by moving accretion (Bonnell et al 2001). It is also useful to measure how much their line widths are reduced compared to those of the surrounding gas, to test the idea that cluster-forming cores form by dissipation of their turbulence (Nakano 1998, Myers 1998).

The nearest embedded groups and clusters include L1688 and L1689 in Ophiuchus, NGC 1333 and IC348 in Perseus, the groups in Serpens and RCrA, and the numerous clusters and groups in Orion A (L1630) and B (L1641). Near-infrared imaging of these regions reveals tens to hundreds of optically invisible embedded YSOs (Lada, Strom & Myers 1993, Allen et al 2002), and submillimeter imaging shows a smaller number of candidate protostars (Sandell & Knee 2001). High-resolution observations of molecular lines shows that these regions have complex structure which varies strongly from one tracer to the next (e.g. McMullin et al 2000), reflecting molecular

depletion, effects of outflows and winds, and the close proximity to numerous young stars.

Despite these difficulties, two recent developments appear promising. Wide-field line imaging has become practical in single-dish observations via focal-plane arrays such as SEQUOIA at the FCRAO (Erickson 1999), and in interferometer observations via "mosaicked" fields (Helfer et al 2002). These techniques allow sensitive high-resolution imaging of line emission over the size scale of nearby embedded clusters (tens of arcmin) in a practical amount of observing time. Also, it has become clear that the N_2H^+ 1-0 line is a useful probe of the dense gas in young clusters, as it is in isolated regions. Its intensity follows the dust emission in the cluster-forming regions in Serpens (Williams & Myers 2000), in NGC1333 (Di Francesco et al 2001), and in several other regions with embedded protostars and small groups (Mardones et al 2002). Thus N_2H^+ differs from species such as CS, HCO^+, and H_2CO which are depleted in dense cores in NGC 1333, even when they have embedded protostars (Blake et al 1995). Furthermore N_2H^+ 1-0 lines show little confusion due to outflow motions from nearby protostars: N_2H^+ line profiles toward class 0 and class I protostars show far less wing emission than do lines of CS and H_2CO (Mardones et al 1997).

Among nearby cluster-forming regions the NGC 1333 complex in Perseus is well-suited for a detailed study of starless core properties and motions. It shows large-scale infall asymmetry in lines of CS and HCO^+ extended up to 0.5 pc (Bourke et al 2002), and its small-scale motions are consistent with gravitational free-fall toward its brightest protostars IRAS 4A and 4B (Choi, Panis & Evans 1999, Di Francesco et al 2001). We have completed preliminary analysis of a wide-field mosaic of the southern portion of the embedded cluster, using the BIMA interferometer in the 3-mm lines of HCO^+ to trace flows and envelopes, and of N_2H^+ to trace cores. In each line we have detected more than 100 condensations. We used the program CLUMPFIND (Williams, de Geus & Blitz 1994) to identify candidate clumps in the 3D space of Right Ascension, Declination, and LSR velocity. We examined each candidate individually and rejected those having too much noise, too much sidelobe confusion, or velocity structure indicative of an outflow as opposed to a clump. We found that the 125 remaining clumps are distributed along lumpy filaments. These filaments closely match those in the 850 μm dust emission map of Sandell & Knee (2001). Only 10-20% of the 125 clumps have an associated submm or mm continuum point source. The "starless" clumps having no such embedded source have mean radius 0.02 pc, FWHM velocity 0.3 km s^{-1}, and virial mass 0.4 M-Sun, and are smaller and more quiescent than those with embedded sources (Walsh et al 2002). These properties are suggestive of protostellar condensations.

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