DENSE CORE STRUCTURE AND FRAGMENTATION IN THE RHO OPHIUCHI MOLECULAR CLOUD

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Abstract. About a dozen distinct dense cores have been identified in the Rho Ophiuchi molecular cloud. The properties of these cores are summarized and compared to the properties of cores in the Taurus molecular cloud, a less efficient region of star formation, and in DR21(OH), a more massive region of star formation. The data are consistent with a picture in which more massive clouds have a higher surface density of cores, which in turn are more massive. The adjacent cores in L1689N have been studied with very high resolution; one has formed stars and one never has. The structure of these cores shows a tendency for duplicity of structures from the largest scales (1 pc) to the smallest (50 AU).

Keywords : Star Formation, Dense Molecular Cores, Ophiuchus Molecular Complex

1. Cores in Molecular Clouds

Locally, stars form in molecular clouds. These clouds encompass structures of many densities, but certainly the densest large objects within them are the stars which have formed there. Less dense, though spanning the density range of twenty orders of magnitude between stellar densities and 10^4 cm^{-3} are the molecular cloud cores. Understanding the connection between these dense cores and the stars we suppose to form within them poses a difficult challenge. How does the character and extent of star formation in a region depend upon the number and physical properties of these dense cores? What is the structure of the cores–are they clustered and do they fragment? How many stars form within each core–do more massive cores produce more massive stars, less massive stars, or do they reproduce the initial mass function? Do all cores produce stars, or are there processes which inhibit star formation in some cores?

As a first step toward the answer to these questions we have begun a census of dense cores and their properties in the ρ Ophiuchi and DR21(OH) molecular clouds. One survey (Loren, Wootten and Wilking 1990) focussed on identification of cold cores which have not yet created stars. This was accomplished through mapping of DCO$^+$ emission in the ρ Oph complex. A second survey, in progress, has mapped the central region of the complex in ammonia emission. A third, recently begun, concentrates on CS emission. In DR21(OH) Mangum (1990) has completed an interferometric survey in C^{18}O and NH$_3$ emission, and in the millimeter dust continuum.

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2. The ρ Oph Cores : General Properties

2. 1. CLUSTERING

Twelve well-defined cores lie in the central star-forming region of the ρ Oph molecular complex. These twelve dense cores lie within the boundaries of four dense clumps of material defined by Loren (1989) from maps of ^{13}CO emission. Each ^{13}CO clump which contains a denser core encompasses at least two denser cores. In turn, each of the denser cores which has been mapped at higher resolution shows evidence for further fragmentation, usually into pairs of similar structures. On scales of 10,000 AU (0.05 pc), the mean separation between closest pairs of dense cores is 0.3 ± 0.13 pc. In the Taurus molecular cloud, with the exception of two close cores in L1495, separations exceed 0.6 pc (Benson and Myers 1989). For the DR21(OH) cores listed by Mangum (1990), the mean separation is 0.25 ± 0.14 pc. The surface density of cores measured by Loren *et al.* (1990) is 3-4 cores pc^{-2} in the ρ Oph complex, in contrast to the 1.3 cores pc^{-2} in Taurus and the 11.3 cores pc^{-2} in DR21(OH) found by Mangum (1990). Mangum (1990) also notes that in the OMC1-OMC2 complex, the core density is 9.2 cores pc^{-2}. The sequence of increasing core surface density Taurus→Ophiuchus→DR21(OH) is also a sequence of mass and luminosity in the star-forming complexes. The conclusion which emerges is that *cores are more tightly clustered in more massive star-forming regions.*

2. 2. MASS

Loren *et al.* (1990) determined masses for their cores both from their study of the excitation of DCO$^+$, and from the virial theorem. The mean core mass lay near 25 $M_\odot$ with a range $8 < M_{core} < 44\ M_\odot$. In contrast, the mass of the ammonia cores in Taurus tabulated by Benson and Myers (1989) spans a range $0.3 < M_{core} < 33\ M_\odot$ with a mean of 6 $M_\odot$. Mangum (1990) finds that the DR21(OH) cores are substantially more massive, with an average mass of 500 $M_\odot$. Individual cores appear to be more massive in more massive star-forming regions. Further study of cores and their masses will be necessary to determine if less massive cores also exist in the massive regions.

2. 3. STELLAR CONTENT

Loren *et al.* (1990) noted the strong tendency of the infrared objects with the coldest spectra to lie within cores. In fact, there are several young stars within the boundary of the typical core in the ρ Oph cloud, while there is seldom more than a single young star near the Taurus cores. The locations of young stars in DR21(OH) are unknown as no sensitive survey of the region exists. The data suggests the existence of a trend for more massive cores to produce several stars, but this trend must be confirmed.

2. 4. STERILE CORES

Several cores, or core fragments, in the ρ Oph cloud have no luminous infrared sources within their boundaries although sensitive searches have been made. As these cores have apparently not produced stars, we refer to them as sterile. Such cores are particularly hard to locate. However, study of their physical conditions may uncover differences between these and star-forming cores, differences which may lead to a better understanding of how cores form stars.

The B1 core and its more massive neighbor B2 (see Loren *et al.* 1990 for locator maps of the cores and infrared sources) each have several solar masses of material. There are no luminous sources within the B1 core, although Rieke and Rieke (1990) have located a very faint, possibly substellar, object there. No sources have yet been located within the B2 core (see Mezger, Sievers and Zylka, 1990). However, the infrared sources WL 3, 4, 5, 6, and YLW12A (Wilking, Lada and Young 1989) lie in a cavity between B1 and B2. This geometry suggests that these cores are fragments remaining from a larger core which once produced stars industriously. The cores may appear sterile as the fragments reorganize under the influence of, among other things, gravity and the nearby infrared sources.

The two cores of the L1689S cloud center to the south and west of two near-IR sources corresponding to IRAS16288, the easternmost of which is a 6 $L_\odot$ star (Wilking 1990) accompanied by a bipolar CO outflow (Loren *et al.* 1990, Wootten *et al.* 1991). There is no evidence for an infrared source at 2.2 μm (Wilking 1990) within the very dense SE component where a water maser is found (Wootten *et al.* 1991). Since no water masers are known to exist very far from infrared sources, any star which is present must lie embedded deeply enough to escape detection. Presumably, a star so deeply located within the cloud is quite young. This core may appear sterile owing to the lack of a survey at the long infrared wavelengths necessary to probe to the core interior.

The L1689N cloud contains two cores, one of which contains the young IRAS16293-2422 binary star. The other, discussed by Wootten and Loren (1987), contains no infrared sources, although its dense core does contain compact features. This core, cold but gravitationally evolved, is the best candidate for a sterile core.

Centrally condensed cores which have not formed stars, "sterile" cores, appear to be scarce in the ρ Oph complex, accounting for three, at most, of the twelve cores. Cores may appear to be sterile for several reasons : they may be fragments of larger star-forming cores, they may have formed substellar objects, or they may just not have been probed deeply enough in the infrared to detect luminosity sources.

Because the L1689N cloud has been well-mapped and structures defined over a wide range of scales, and because the adjacent cores offer a contrast in their stellar content, we examine them more closely in the next section.

3. Structure of Cores within the L1689N Cloud

Loren designated a region of enhanced ^{13}CO emission in the northern part of the L1689 cloud as clump R55, containing 200 $M_\odot$ of material. Toward the western edge of the clump lies the dense double core, one of which has apparently not produced a star, mentioned in the previous paragraph. In this section we review the heirarchy of structure in these cores, noting the remarkable pairing of structures from the 1 pc scale down to the 50 AU scale.

The sterile core contains about 10 $M_\odot$ of material. Interferometric ammonia observations have shown it to contain cold (13K) substructures of size $\sim$ 3000 AU (Wootten and Loren 1987), elongated perpendicularly to the magnetic field in the region, with densities not exceeding $5 \times 10^5 cm^{-3}$.

In contrast, Mundy, Wootten and Wilking (1990) found the ammonia emission about IR16293, 0.7 pc to the west, to be oriented in a smaller disk-like structure of similar density and orientation but warmer (15-20K). Over much of the 6000 AU extent this structure is quiescent, with narrow lines stationary in velocity. Toward the northwest end, however, ammonia emission broadens and weakens, and the weak line wings hint at the presence of a rotating component. Mundy, Wilking and Myers (1986) had found a disk-like dust distribution here, encompassing the infrared source and mimicing the geometry of the outer disk on smaller ($\sim$1500 AU) scales. Mundy *et al.* (1990) showed that C^{18}O emission from this structure was strong, and apparently centered on one of two radio continuum sources discovered by Wootten (1987). The C^{18}O structure rotates quite rapidly, contains $\sim$ 2 $M_\odot$ of material, and appears to be warmed by the young star it envelops. Dynamically, the inner disk is distinct from the outer disk–the transition region between the non-rotating outer ammonia disk and the rapidly-rotating inner disk was unresolved in a 6" beam.

On smaller scales, the inner disk has recently been resolved (Mundy *et al.* 1991) at OVRO ($\lambda 2.75mm$) into smaller dust condensations centered on the 2cm radio sources. The IR16293A source, brighter at frequencies below 20 GHz and centered on the C^{18}O emission, is marginally resolved (640 AU). The IR16293B source, 830 AU to the northwest remains unresolved (<400 AU at 2.75mm). IR16293B shows higher *surface* brightness at frequencies higher than 20 GHz; at 22 GHz the region of free-free emission is less than 16 AU in extent.

IR16293A, the southeastern component of this protobinary system, has been resolved into two 2cm sources separated by 50 AU along a line perpendicular to the major axis of the disk (Wootten 1987). These sources lie 50 AU northeast of the center of a cluster of twelve water masers spread about their position centroid with an rms offset of 45 AU. The centroid position of the positive velocity masers (with respect to ambient cloud velocity) lie southwest of the centroid of negative velocity masers, a pattern mimicking the spatial structure the continuum sources, and the dynamical structure of the CO outflow mapped on larger scales. Hence, the source of the outflow is undoubtedly IR16293A, and the flow is collimated on scales less than that of Saturn's orbit within our solar system.

4. Summary

A census of the cores in the ρ Oph cloud has shown that the surface density of cores lies between that in the Taurus clouds, which have been relatively inefficient in star production, and that in the Orion or DR21(OH) molecular clouds, which have apparently been more productive. The masses of the cores lie in the intermediate region between the Taurus and DR21(OH) cores also.

The core structure becomes more complex on finer scales. In the L1689N cores the structures are generally similar and show a tendency to be paired at successively finer levels down to scales smaller than the solar system.

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