V - SMALL SCALE STRUCTURE

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CLOUDS, CORES, AND STARS IN THE NEAREST MOLECULAR COMPLEXES

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Abstract. The properties and structure of six molecular complexes within 500 pc of the Sun are described and compared. They are generally organized into elongated filaments which appear connected to less elongated, more massive clouds. Their prominent star clusters tend to be located in the massive clouds rather than in the filaments. The complexes have similar structure, but big differences in scale, from a few pc to some 30 pc. They show a pattern of regional virial equilibrium, where the massive, centrally located clouds are close to virial equilibrium, while the less massive filaments and other small clouds have too little mass to bind their observed internal motions. Complexes can be ranked according to increasing size, mass, core mass, and the mass and number of the associated stars : they range from Lupus to Taurus to Ophiuchus to Perseus to Orion B to Orion A. The cores in nearby complexes tend to have maps which are elongated, rather than round. The core size, velocity dispersion, and column density of most cores are consistent with virial equilibrium. Cores in Orion tend to exceed cores in Taurus in their line width, size, temperature, mass, and in the mass of the associated star, if any. Stars in Orion tend to be more numerous and more massive than in Taurus, while those in Taurus tend to be more numerous and more massive than in Lupus. The mass of a core tends to increase with the mass of the cloud where it is found, with the mass of the star cluster with which it is associated, and with its proximity to a star cluster. These properties suggest that complexes and their constituent cores and clusters develop together over time, perhaps according to the depth of the gravitational well of the complex.

Keywords : star formation, molecular clouds

1. Introduction

This article summarizes and compares properties of six molecular cloud complexes within 500 pc of the Sun : Lupus, Taurus-Auriga, Ophiuchus, Perseus, Orion B, and Orion A. The dimensions, density, structure, internal motions, and prevalence of equilibrium are discussed on the scale of the complex and on the scale of individual dense cores. The stellar content in individual stars and in clusters is described and compared. Interrelations among the complexes, and their cores and stars are discussed. This paper focuses on a cloud complex as a system, and touches only briefly on formation of individual stars. For more detailed discussion of star formation, see the papers in these proceedings by Evans, Lada, and Larson.

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2. Complexes

The complexes in Lupus (Murphy, Cohen, and May 1986; Krautter 1990), Taurus (Ungerechts and Thaddeus 1987), Ophiuchus (Loren 1989*a,b*), Perseus (Bachiller, Cernicharo, and Duvert 1985), Orion B (Lada 1990), and Orion A (Maddalena and Thaddeus 1986) appear similar in their overall structure, in that they are generally organized into elongated filaments. The filaments terminate in rounder, more massive structures in Taurus, Ophiuchus, and Perseus. These more massive clouds contain the embedded star clusters "Group I" in Taurus (Jones and Herbig 1979), the cluster associated with HD147889 in Ophiuchus (Lada, Wilking, and Young 1989), and the NGC1333 cluster in Perseus (Strom, Vrba and Strom 1976). Also, the Orion A filament terminates in the Trapezium and Kleinman-Low cluster, whose molecular gas environment is much denser than, although not distinct in shape from, that in the elongated cloud L1641 to the South. In Lupus, the small cluster which contains HR 5999 and some 20 lower-mass stars appears at the end of a filament of high extinction (Schwartz 1977). Thus most of the embedded star clusters in these six complexes lie at the ends of filaments, where in three cases they are surrounded by unusually massive and less elongated concentrations of gas.

These similarities of structure and stellar concentration in complexes are accompanied by marked differences in the "scale" of several complex properties : the size, column density, mass, and velocity dispersion increases significantly from Lupus to Perseus to Orion. For example, the linear extent of the CO emission map in Lupus is smaller than in Orion by a factor $\sim$5. Furthermore the properties of associated stars also increases in the same sense : from Lupus to Perseus to Orion, the number of stars, the number of massive stars, and the degree of clustering of stars also increase. For example, there are some 50 T Tauri stars known in Lupus, but some 1000 stars known in Orion A. Taking these factors into account, we can rank the "scale" of the six complexes under consideration from Lupus, where it is smallest, to Taurus, to Ophiuchus, to Perseus, to Orion B, to Orion A.

The brightest and most massive parts of many molecular cloud complexes appear close to virial equilibrium (Larson 1981), but detailed mapping of complexes shows that in many cases the less massive and filamentary clouds farther from the center of a complex tend to be subvirial : they have too little mass to bind the internal motions in their line widths. This property is evident in Taurus from the CO maps of Ungerechts and Thaddeus (1987), and in Ophiuchus from the ^{13}CO maps of Loren (1989*a, b*). This interesting property is not fully understood. It is also of interest because it is related to the presence or absence of the well-known correlation between the line width Δv and the size R. For example, in Ophiuchus Loren (1989*a*) found that 13 of the 89 clouds he catalogued have line widths within a factor of 2 of the value expected in virial equilibrium, and that the 89 clouds show no correlation between Δv and R . But examination of the 13 clouds close to virial equilibrium shows that they exhibit such a correlation, approximately as $\Delta v \propto R^{0.5}$. This property is easily understood, since one can write the identity

$$\Delta v^2 \propto NR \left(\frac{\mathsf{K}}{\mathsf{G}}\right)$$

where N is the mean column density over the map of size R , and where **K** and **G** are respectively the kinetic and gravitational energy density in the cloud. Thus a cloud close to virial equilibrium has $\Delta v \propto NR$. When the clouds under consideration have a relative range of N smaller than the relative range of R, it follows that $\Delta v \propto R^{0.5}$ as observed in Ophiuchus. This result follows regardless of the reason for the small range of N, which could arise from selection, sensitivity limits, or from equipartition between magnetic and kinetic energy and a relatively small range of magnetic field strength.

3. Dense Cores

Comparison of properties of dense cores in the nearby complexes reveals significant differences in core size, line width, column density, temperature, and mass, depending on which complex one considers, and also on position within the complex.

Before comparing core properties, it is important to recognize that a comparison requires a consistent definition of core identity. The spectral line emission which is used to define cores can have a complex spatial distribution, and any definition is somewhat idealized. Thus a statistic as basic as the number of cores in a cloud can vary greatly from definition to definition. For example, an emission region with two peaks separated by a "valley" higher than half the height of the higher peak would have one core, if the core is defined by the contour of half-maximum intensity. It would have two cores, if a core is defined by a distinct local maximum of intensity. It would have three or more cores if a core is defined by application of a "clean" iteration procedure. In such a procedure, a two-dimensional Gaussian is fit to each local maximum, subtracted from the observed map, and then a new fit is applied to the residual profile. All three of these definitions are in current use. In the following discussion we use the half-maximum contour of line intensity.

The shape of a core map is generally elongated, with aspect ratio about 2 : 1, in Taurus, Ophiuchus, and other smaller dark cloud regions, according to a study of 16 cores, each mapped in lines of NH_3, CS, and $C^{18}O$ (Fuller 1989; Benson and Myers 1989; Myers *et al* 1991). In at least six cores, this elongation probably corresponds to a prolate, rather than oblate, shape in three dimensions. Prolate shape is especially interesting because it implies that the core cannot be modelled by an isolated self-gravitating region in stable equilibrium with a simple combination of isotropic motions, rotation, and magnetic fields. Models which include the effects of the core environment are needed.

Despite the uncertainty about core geometry, most cores appear near to virial equilibrium, independent of which geometrical model one adopts. Equilibrium models of the relation between core line width, size, and column density were compared

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with observed values of these quantities for spheres with various power laws of density with radius; for rotationally supported oblate spheroids; for magnetically supported oblate spheroids; and for segments of an infinitely long, magnetically supported, prolate cylinder. In all cases the observed quantities are consistent, within their scatter, with the range of possible values for each equilibrium geometry (Myers *et al* 1991).

The NH_3 line mapping studies of cores in Taurus by Benson and Myers (1989) and in L1641 in the Orion A region by Harju, Walmsley, and Wouterlout (1990) offer a good comparison of core properties between regions with substantially different size scale and stellar content, especially because the studies were made with nearly the same linear resolution, FWHM about 0.08 pc. These observations indicate that cores in Orion have significantly broader lines (median line width 0.75 km s^{-1}) and larger sizes (median FWHM 0.17 pc) than do cores in Taurus (median line width 0.29 km s^{-1}, median FWHM 0.08 pc). Figure 1, adapted from Harju, Walmsley, and Wouterlout (1990), illustrates these properties. Furthermore, the Orion cores are substantially hotter and more massive than their Taurus counterparts, and are associated with IRAS sources substantially more luminous, and thus presumably with stars substantially more massive, than those in Taurus. Thus the cores in Orion and Taurus show a ranking of properties similar to those already evident in the larger-scale properties of the complexes.

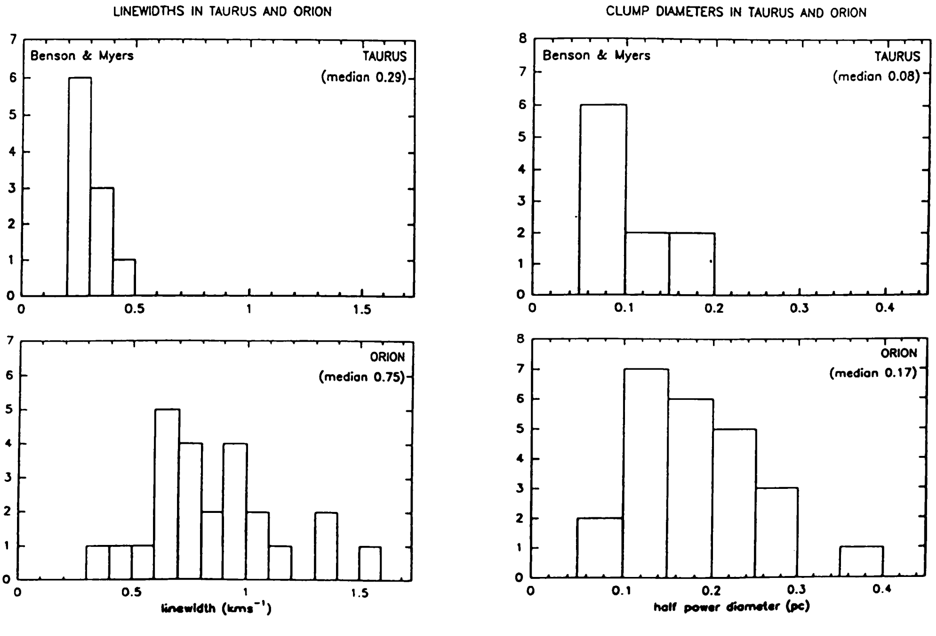

Fig. 1. Distributions of NH_3 Line Width and Map Size in Taurus and Orion

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In Taurus, Ophiuchus, and other relatively small, nearby complexes, surveys for cores based on criteria independent of the presence or absence of an embedded star found that about half of the cores have of the cores have associated stars, and half are "starless" (Myers and Benson 1983; Beichman *et al* 1986). To date, most of the surveys for cores in larger, more distant complexes have been based on the presence of an embedded star. A notable exception is that of E. Lada (1990) in the Orion B region. In order to compare "initial conditions" for star formation from region to region it will be necessary to carry out more unbiased surveys, to allow more starless cores to be identified and compared with their counterparts in other regions.

4. Stars

The T Tauri stars in Orion, Taurus, and Lupus differ in their distributions of spectral type, in the sense that Orion exceeds Taurus, and Taurus exceeds Lupus, in the number of stars, and in the mass of the typical star. Comparison of the number distributions in Orion and Taurus-Auriga, from Cohen and Kuhi (1979), and in Lupus, from Krautter (1990), shows that Orion, Taurus, and Lupus have respectively 112, 81, and 58 T Tauri stars with known spectral types, and have median spectral type respectively K4, K7-M0, and M1.5.

Furthermore, comparison of the circumstellar reddening of *IRAS* sources in L1641 in Orion and in Taurus indicates that the Orion sources are considerably redder than those in Taurus, suggesting that the Orion sources have significantly higher column density of circumstellar dust than the Taurus sources (Strom, Margulis, and Strom 1989).

These differences among young stars in Orion, Taurus, and Lupus appear consistent with the differences in properties of the complex gas, and core gas, in the sense that the larger, more massive complexes tend to have larger, more massive cores, and to have a greater number of young stars, and on average stars of greater mass.

5. Interrelations Among Clouds, Clusters, and Cores

The core size, velocity dispersion, extinction, and mass appear to increase with increasing complex size and mass, as described above. Furthermore, these same core properties also increase from one part of a complex to another, in two ways related to the mass of an associated star cluster. The core mass and its correlated properties appear to increase with the mass of its associated star cluster. Also, a core associated with a star cluster tends to be more massive than cores in the same complex, located in the less massive filaments extending away from the cluster. Table I presents examples of these two kinds of core mass variation.

In Table I, the cluster mass increases from top to bottom, roughly in proportion of the number of associated stars. Similarly, the mass, size, velocity dispersion, and extinction of the associated core also increase from top to bottom. Further, the core in each nearby cloud is distinctly smaller and less massive than the core associated with the cluster.

Table I suggests that in addition to the variation in core mass and other properties from complex to complex, the core mass increases with the mass of the associated star cluster, and with proximity to the cluster. These variations can be understood if the cores, stars, clusters, and complexes all scale together in response to a common cause. If so, the simplest explanation is that the gravitational well of a complex sets the scale of the core and star formation in the complex. Within a complex, the biggest concentration of mass occurs where the well is deepest. There, the most massive cores tend to form, and thence the most massive stars. Of course this picture is extremely idealized, and many other factors may also be at work. Nonetheless, this picture has the virtues of simplicity and the ability to be checked by observational data.

TABLE I
Cores Associated With Clusters, and With Nearby Clouds

Complex	Cluster	Stars	Ref.	Core	Ref.	Nearby Core	Ref.
Tau-Aur	AB Aur	5	1	L1517	2	—	—
Tau-Aur	HK Tau	10	3	TMC2	4	L1506	5
Oph	HD147889	80	6	L1688	7	L1709	7
Per	N1333	30	8	L1450	9	B1	10
Orion	Trapezium	500	11	OMC-1	12	OMC-2	12

References–1, Herbig and Bell (1988); 2, Benson and Myers (1989); 3, Jones and Herbig (1979); 4, Ho *et al* (1977); 5, Greenberg (1988); 6, Lada, Wilking, and Young (1989); 7, Loren, Wootten, and Wilking (1990); 8, Strom, Vrba, and Strom (1976); 9, Ho and Barrett (1980); 10, Bachiller, Menten, and del Rio (1990); 11, McCaughrean (1989); 12, Batrla *et al* (1983).
Note–Each cluster is named by its NGC name, or the name of its most prominent star.

6. Conclusion

The six nearby molecular cloud complexes discussed here appear to have similar rank in their size, column density, mass, and velocity dispersion on scales from ~10 pc to 0.1 pc. Their stellar content appears also to follow this ranking in their number of stars, in their typical stellar mass, in the degree of stellar clustering, and in their circumstellar column density. The core properties also increase with increasing mass of their associated star cluster, and with proximity to the star cluster. These tendencies suggest that over a wide range of spatial scales, molecular gas in a complex is densest where the gravitational potential well is deepest, and embedded star clusters tend to lie close to these concentrations of gas.

Many of these properties can be understood if the mass of a molecular cloud increases throughout nearly all of its lifetime, in contrast to the mass of a star. If so, relatively small complexes like Lupus and Taurus start out with relatively shallow gravitational wells, which favor the formation of relatively small, low-density cores and relatively low-mass stars, which appear singly or in sparse clusters. As the complex grows, its mean density increases. Its regions of denser gas, which have already begun to form small groups of stars, increase in mass faster than do their neighboring regions. These denser clouds tend to form larger and denser cores, perhaps by accretion and mergers of smaller, preexisting cores, and perhaps by dispersal of cores too small to survive tidal forces, now stronger than they were in the past. As long as low-density peripheral gas is available to feed the increasing gravitational pull of the complex, the growth of the complex and its constituent clouds, cores, stars and clusters should continue until the effects of stellar winds and luminosity disperse the gas. This picture is similar to that proposed by Herbig (1962), but with two new ingredients : the continual growth of the molecular cloud complex and the role of dense cores as intermediaries in forming stars.

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