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The cores of ρ Ophiuchus

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Abstract. We search for dense cores and the molecular outflows which accompany stellar birth in the rho Ophiuchi cloud L1688 through two unbiased wide-field surveys. A solution to the problem of how to avoid the dissolution of brown dwarf binaries is suggested: binaries forming in the widely scattered low-mass cores are not susceptible to disruption since the region is dynamically relaxed. We also find weak H_2 outflows which may be driven by proto-brown-dwarfs.

The dense cores are detected through continuum emission from associated dust grains at 1.2 mm. Covering over 1 square degree, we detect many previously unknown sources, ranging from extended cores to those harbouring Class II young stars. We analyse the mass and spatial distributions. The core mass function resembles the stellar initial mass function, both within the tightly-packed clumps as well as within the less-crowded surroundings. The cores display a hierarchical spatial distribution with no preferred separation scale length. The orientations of the major axes of cores are consistent with an isotropic distribution whereas the orientations of core pairs possess a preferential direction on all separation scales, consistent with the filamentary cloud appearance. Our near-infrared survey for molecular hydrogen emission covers $35' \times 35'$. We detect several new H_2 flows but the total number of detected outflows is low and is consistent with the paucity of Class 0 and Class 1 sources in the molecular cloud. Most of the candidate driving sources are deeply embedded in dense cores. A very young outflow arises from the newly discovered Class 0 source MMS 126. Flow directions are generally NE–SW, perpendicular to the above preferred direction. The apparent extents of molecular flows are related to either the widths or the separation between cloud filaments.

Key words. ISM – Stars: formation – ISM: clouds – ISM: individual objects: Rho Ophiuchus – ISM: structure

1. Introduction

A large number of processes are operating in star formation regions. These work on a wide range of scales, typical of Complex Systems. There are several feedback effects from small to large scales, regulation mechanisms in the form of triggers and inhibitors, in addition to unpredictable turbulent magnetohydrodynamic flow (see Mac Low & Klessen 2004. Yet, a complex system, however complicated, can be analysed. We can first take single entities and understand the particular processes at work.

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We can then put together the components to gain an understanding of the wider picture. This requires a combination of high resolution and wide field observations with sufficient sensitivity and uniformity to provide reliable statistics.

We report here on two such surveys of one of the nearest star-forming regions. The ρ Ophiuchi molecular cloud complex contains a number of distinct dark clouds spread over several degrees on the sky. The filamentary and clumpy distribution of the molecular gas has been revealed through large-scale CO surveys (e.g. Loren 1989). Embedded in the filaments are dense clumps (Benson & Myers 1989; Loren et al. 1990; Tachihara et al. 2000) with typical masses in the range $10-30\,M_\odot$. In turn, these clumps contain fragments termed cores of mass $0.10\,M_\odot - 10\,M_\odot$, some of which already contain protostars and young stars (Motte et al. 1998; Johnstone et al. 2000).

The densest part of the L 1688 cloud also harbours a large number of young stellar objects, as studied at mid-infrared wavelengths with ISOCAM (Bontemps et al. 2001). To gain evidence on how these stars are conceived, we need to relate their properties to those of the ambient medium.

2. Surveys

The 'main cloud' of ρ Oph covers an area of roughly 480 arcmin^2 and was surveyed at 1.3 mm by Motte et al. (1998,hereafter MAN98), who uncovered 62 starless cores and 41 circumstellar structures. These observations had a resolution of just 11 $''$, corresponding to 1,400 AU. The inferred distribution of masses of these cores was found to be comparable to the *stellar* initial mass function, suggesting that stellar masses are determined at conception.

Subsequently, the results of a larger, somewhat more sensitive survey at 0.85 mm were presented by Johnstone et al. (2000,hereafter J00). This survey covered $\sim$ 700 arcmin^2 with a resolution of 14 $''$, identifying 55 cores. This survey was recently followed up by a much more extensive (4 square degrees) but significantly more shallow survey by Johnstone et al. (2004), mainly extending to the north/north-west of the main cloud cores.

Our 1.2 mm survey covers an area of 4,600 arcmin^2 with a resolution of $\sim$24$''$. The SIMBA bolometer array at the SEST telescope on La Silla/Chile was used during an observing run lasting from 2002 July 7 to 12. Similar to other (sub)millimetre surveys, our new map is sensitive only to sufficiently small structures (see also J00 for a discussion of this issue). We detect cores over the entire area (Fig. 1).

From the perspective of our study of molecular outflows, the protostellar stages of star formation are critical. From the near-infrared spectra, Luhman & Rieke (1999) conclude that roughly 17% of the YSOs are Class I sources, which implies a lifetime of about 0.1 Myr for this stage and the availability of over 20 potential driving sources for powerful molecular outflows.

In order to detect the outflows in ρ Oph, a range of surveys at millimetre, infrared and optical wavelengths have been undertaken. Some 15 CO outflows have so far been recorded, where the most prominent examples arise from IRS 44 (Terebey et al. 1989), VLA 1623 (Andre et al. 1990; Dent et al. 1995) and GSS 30 (Tamura et al. 1990). The optical studies suggest that the outflows extend over scales up to one degree. Atomic jets and Herbig-Haro (HH) objects have been discovered through optical searches at the perimeter of the cloud (Wilking et al. 1997; Gómez et al. 1998; Phelps & Barsony 2004; Wu et al. 2002). HH 550 and HH 551 are located more than 1 pc away from the cloud and possibly form a parsec-scale HH flow. It is plausible that optical emission lines from embedded flows in the denser clumps are not observed because of the large extinction of $A_V = 50 - 100$ mag in the clumps (Wilking & Lada 1983).

In contrast, near-infrared (H_2 2.12 μm) imaging observations have detected and explored shock-excited knots and jets located in highly obscured areas (Davis & Eisloeffel 1995; Dent et al. 1995; Davis et al. 1999; Grosso et al. 2001). These searches have been confined to small regions, typically $5' \times 5'$. However, Gómez et al. (2003) presented the results from near-infrared observations of three

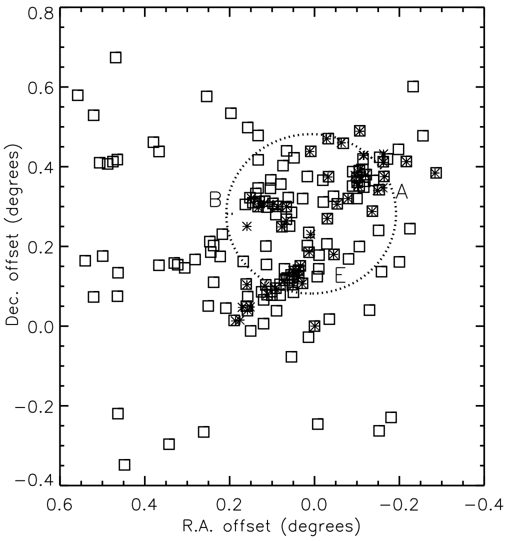

Fig. 1. The locations of all the cores detected here (squares) compared to the all the cores detected by Johnstone et al. (2000) (asterisks). The coordinates are centred on -16:26:58.41, -24:45:36.2 (2000). A, B and E mark the location of clumps.

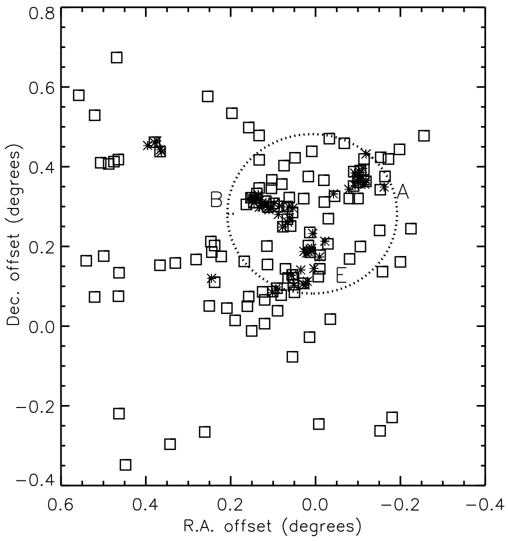

Fig. 2. The locations of all the *starless* cores detected here (squares) compared to the the *starless* cores detected by Motte et al. (1998) (asterisks). The circle is that employed to separate inner cores from the outer regions.

partly adjoining regions with a combined area of 480 square arcminutes.With an integration time of 480 seconds, many new H_2 emission knots which could constitute 13 distinct H_2 outflows were detected.

However, the close distance to the ρ Oph molecular cloud suggests that typical flow extensions in ρ Oph are of the order of one degree (i.e. a linear flow extent of 2 pc at a distance of 130 pc). Therefore, we require an unbiased search over a field of 1 square degree in order to carry out a complete census of the molecular outflows. Our near-infrared survey was conducted in August 2001 using SOFI at the NTT on La Silla. Additional data were secured at high airmass using the OmegaPrime camera at the Calar Alto 3.5m telescope. The result is an unbiased 600 second H_2 survey of an area of 1,320 square arcminutes.

3. Results: spatial distribution

The cores we detect within the inner core-crowded region are generally coincident with those found in previous surveys. Figs. 1 and 2 show that this is true for separate samples of all cores and starless cores. This confirms the reliability of our core-finding technique.

At first sight, the identified cores are strongly clustered. Following J00, we calculate the two-point correlation function, determining the number of core pairs with given separation. This is divided by the model distribution for a random sample of cores spread over the same apparent area. The two-point correlation function Φ is shown in Fig. 3.

The correlation function is positive on scales under $\sim 10^5$ AU. On small scales. this result is consistent with the results obtained by J00, also plotted on the Figure. The inferred power law index of -0.63 is somewhat flatter than found by J00,In contrast to J00, however, we exclude the existence of a preferential scale near to 3×10^4 AU, which could correspond to a Jeans length. Instead, the hierarchical clustering is consistent with the generation of cores in turbulence.

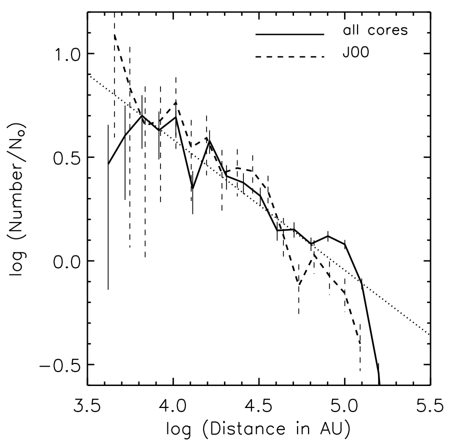

Fig. 3. The two point correlation function for the ρ Ophiuchus cores, as defined in the text. The error bars correspond to $\sqrt{N}$ statistics. The dotted straight line corresponds to a power-law of the form $\omega \propto \Delta r^{-0.63}$.

4. Results: mass distribution

Fig. 4 displays the mass functions for the 118 starless cores. These results make no presumption about the stratification of the envelopes or their subsequent evolution.

We find that the mass function is similar to that found by MAN98 and J00 for the inner zone. The power law fit with two breaks is comparable to the approximation for the stellar initial mass function (IMF) derived by Kroupa (2001), where the power law indices are 0.7, −0.3, and −1.3. Note that the flatter power law holds for masses below ~ 0.14 M$_\odot$, in comparison to the value of 0.08 M$_\odot$ quoted for the IMF (Kroupa 2001). The derived masses are, however, sensitive to the assumed dust temperature, opacity and distance. If we assume the break in Φ and the opacity are accurate, we can speculate that just about one half of a core mass ends up constructing the star. The other half is dispersed in (i) jets (up to 30%), (ii) dispersal by jet impact, (iii) early stellar and disc winds and (iv) other stars, brown dwarves and planets.

The mass functions within and external to the circle are similar. Thus, while the compactness of a core varies in space (Stanke et al. 2005) the mass distribution does not. This must be reconciled with the fact that the inferred surface pressures are, on average, lower in the external region which would suggest a higher Jeans mass.

An IMF has been inferred for Class II young stellar objects in ρ Oph by Bontemps et al. (2001) from ISOCAM data. They found an upper break in the IMF at 0.55 M$_\odot$ separating power law slopes with indices -0.35 ± 0.25 and -1.7 below and above the break, respectively. This IMF is 'statistically indistinguishable' from the core mass function derived by MAN98 and is also clearly consistent with the present data sets.

5. Results: outflows

We find that 10 outflows are sufficient to account for all the H_2 emission. Even so, there are alignments which could reduce the number. In fact, if the average size of a protostellar outflow were 0.6 pc, (e.g. Stanke 2003), then it would extend 15 arcmin. In other words, the driving protostar may be located far from the molecular hydrogen features. On the other hand, quite compact H_2 outflows are also identified. One of these appears to stem from what we suspect is a Class 0 protostar within the core MMS 126. Fig. 5 shows the three extended H_2 emission knots `f05-04a`–`c` which is one of the most intriguing flows discovered in our survey.

The minimum jet power required to drive the H_2 shocks can be estimated here. The integrated 1–0 S(1) H_2 fluxes for the flows `f05-4`, `f08-01` and `f10-04` are 3.4, 12.9 and 29.5 $\times 10^{-17}$ W m^{-2}. These convert to the very small line luminosities of 1.8, 6.8 and 15.6 $\times 10^{-5}$ L$_\odot$, respectively, for the distance of 130 pc. The total H_2 luminosity from the radiating shocked layers is 10–20 times these values (Smith 1995). Jet powers are probably 1000 times the observed 1-0 S(1) luminosity. We thus conclude that driving jet powers are

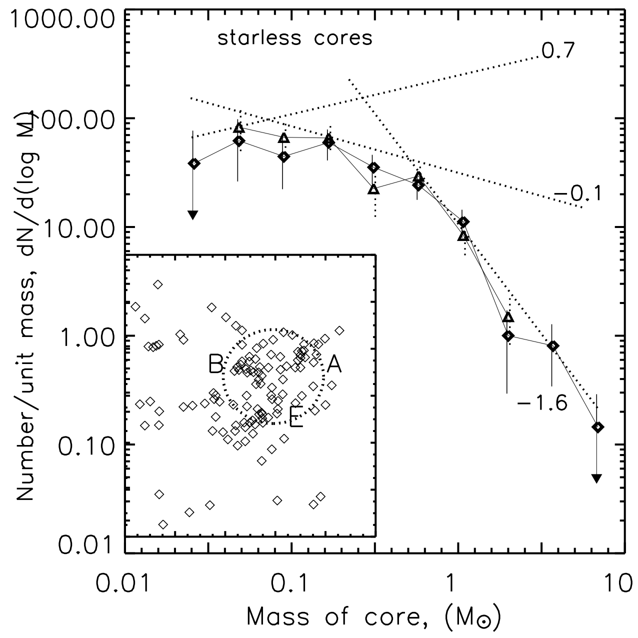

Fig. 4. The mass function (number distribution) by mass and location of the cores in ρ Ophiuchus for 118 starless cores. The dotted circle drawn in the inset divides the cores into an inner zone of 61 objects (diamond symbols) and an outer area of 57 objects (triangles).

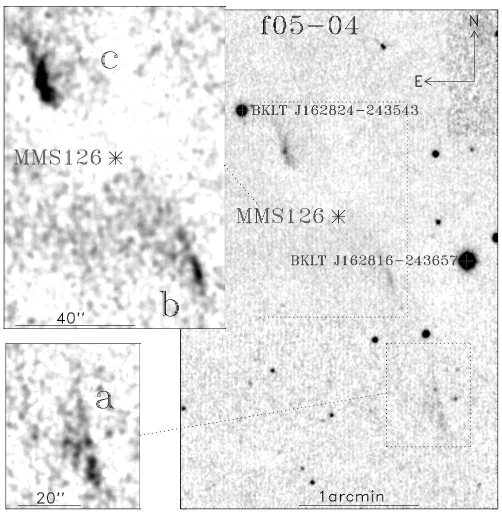

Fig. 5. The f05-04 outflow. The main grayscale image is H_2 1-0 S(1) line + Continuum and the inserts are smoothed pure H_2 1-0 S(1) line images.

in the range 0.02–0.2 $L_{\odot}$. We thus suggest that the weaker outflows are driven by proto-brown-dwarves.

6. Conclusions

Further results and implications are discussed in detail by Khanzadyan et al. (2004) and Stanke et al. (2005). Deeper and wider surveys will prove revealing. Unbiased surveys of all cores in tracers of molecular outflow and inflow would provide the type of statistical information still lacking.

Low mass objects may form in the low mass cores recorded here. It is interesting to note that the core distribution is probably dynamically relaxed (Belloche et al. 2001). Hence, the low mass products of the cores probably remain bound to the cloud. This is the basis for a solution to the problem of how to avoid the dissolution of brown dwarf binaries. Binaries forming in the widely scattered low-mass cores are not dismantled through dynamical interactions.

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