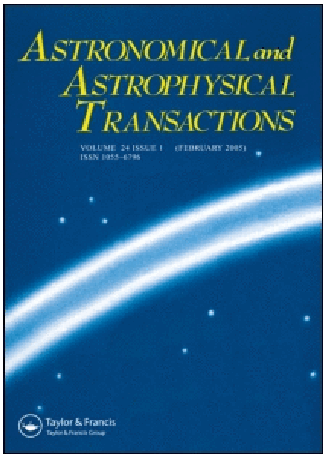

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DENSE CORES AND OUTFLOWS IN REGIONS OF HIGH MASS STAR FORMATION

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Results of systematic studies of high mass star forming cores and associated high velocity outflows are reviewed. They are based on the surveys of these objects in CS, $C^{18}O$, HNCO, SO and other molecular lines. Statistical distributions of the core parameters (mass, size, mean density, temperature, IR luminosity to mass ratio and velocity dispersion) are presented. The dependences of these parameters on galactocentric radius are analyzed. The frequency of occurrence and the basic properties of associated outflows (mass, momentum, kinetic energy) are derived. Their correlations with the bolometric luminosity of embedded IR sources are discussed.

Keywords: Stars: formation – ISM: clouds – ISM: molecules

1 INTRODUCTION

Dense cores in molecular clouds act as an interface and transition region between the young stars and the molecular gas. Very dense cores in warm molecular clouds ($n > 10^5\,\mathrm{cm}^{-3}$; $T_{\mathrm{kin}} > 10\,\mathrm{K}$) are the sites of massive star formation. The winds of and the H II regions formed by high-mass stars affect the structure and evolution of the parent molecular cloud. It is thus essential to understand the properties of dense cores if we are to understand the formation of stars and their effects on the surrounding clouds. Detailed studies of a few massive cores have yielded much information about structure, excitation and chemistry, as well as influence of the embedded stars. However, it is unclear whether the results apply to the overall population of such cores in the Galaxy because most studies have concentrated on a few, rather arbitrarily selected, dense cores.

The naive picture of star formation as a spherically symmetric collapse of dense interstellar clumps has been replaced during the last decade by a much more complicated scenario. According to the present consensus, the accretion of stellar material occurs via protostellar disks, and is associated with spectacular high-velocity ejection of matter along the disk axis which is required to remove the excess angular momentum from the system. None of these processes has yet been fully understood.

So far about 200 high-velocity outflows have been detected (Bachiller, 1996). Researchers are confident that virtually all low-mass young stellar objects (YSO) undergo periods of copious mass loss and many important characteristics of outflows have been deduced from

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observations. The situation is less clear for high mass stars. There are opposing views regarding their formation. It has been shown that a protostellar core, once it reaches about 10 solar masses, can exert enough radiation pressure to halt spherical infall and inhibit further growth of the core mass (Wolfire and Cassinelli, 1987). This led to one view that high-mass stars form by the coalescence of low- to intermediate-mass stars (Bonnell *et al.*, 1998). The other view is that since the dynamical processes near the (proto)star are not isotropic, high-mass stars could still form via infall and accretion. Currently, few observational constraints exist to discriminate between the two. Because of the connection between outflow and accretion seen in low-mass stars, surveys of molecular outflows in high-mass YSOs can shed light on this debate (Zhang *et al.*, 2001).

Most studies of outflows have been performed only in the CO lines. However, a high abundance of the CO molecule and very high optical depth in the CO lines can prevent reliable determination of the parameters. In addition, further investigations of the physical properties and chemical composition of the outflows require observations of other species which might be abundant under the specific conditions existing in these regions. These conditions are determined, in particular, by interaction of the outflows with the ambient medium. Therefore, investigations of this interaction are of primary importance if we want to understand the outflow properties.

2 SURVEYS OF HIGH MASS STAR FORMING (HMSF) CORES

There are several commonly adopted signposts of high mass star formation: (ultra)compact H II regions, luminous IR sources, molecular masers (at first, water masers). They correspond to different stages of (proto)stellar evolution. In particular, water masers probably appear earlier than detectable H II regions (Codella *et al.*, 1996; 1997). In recent years extensive molecular line surveys towards these signposts have been performed by several groups (*e.g.* Anglada *et al.*, 1996; Bronfman *et al.*, 1996; Juvela, 1996; Plume *et al.* 1992; 1997; Zinchenko *et al.*, 1995; 1998). One of the most interesting tasks is a search for and a study of massive protostars which could not produce detectable H II regions yet.

Most of these surveys have been limited to one point observations towards a large number of objects. This approach does not allow for derivation of cloud size, mass and other important parameters. In contrast, our CS $J = 2 - 1$ survey towards water masers (Zinchenko *et al.*, 1994; 1995; 1998) complemented by Juvela's (1996) data, included mapping of the sources in the main CS isotope line. In addition, the peaks of the CS emission were observed in the $C^{34}S$ $J = 2 - 1$ and in the CO $J = 1 - 0$ lines. The basic cloud parameters can be reliably derived from these data.

Later many of the cores detected in this survey were observed in HNCO, $C^{18}O$, SO and other lines. The HNCO and $C^{18}O$ results have been published in Zinchenko *et al.*, 2000. A part of the SO data was analyzed by Zinchenko (2002) along with the $C^{18}O$ results in order to estimate the frequency of occurrence and physical properties of high velocity outflows in regions of high mass star formation (Sec. 5).

3 PHYSICAL PROPERTIES OF HMSF CORES

The results of our CS survey were used to analyze the statistical properties of HMSF cores (Zinchenko, 1995; Zinchenko *et al.*, 1998). The procedure is described in these papers. For a part of the objects the $C^{34}S$ emission was too weak; for them the LTE mass could not be

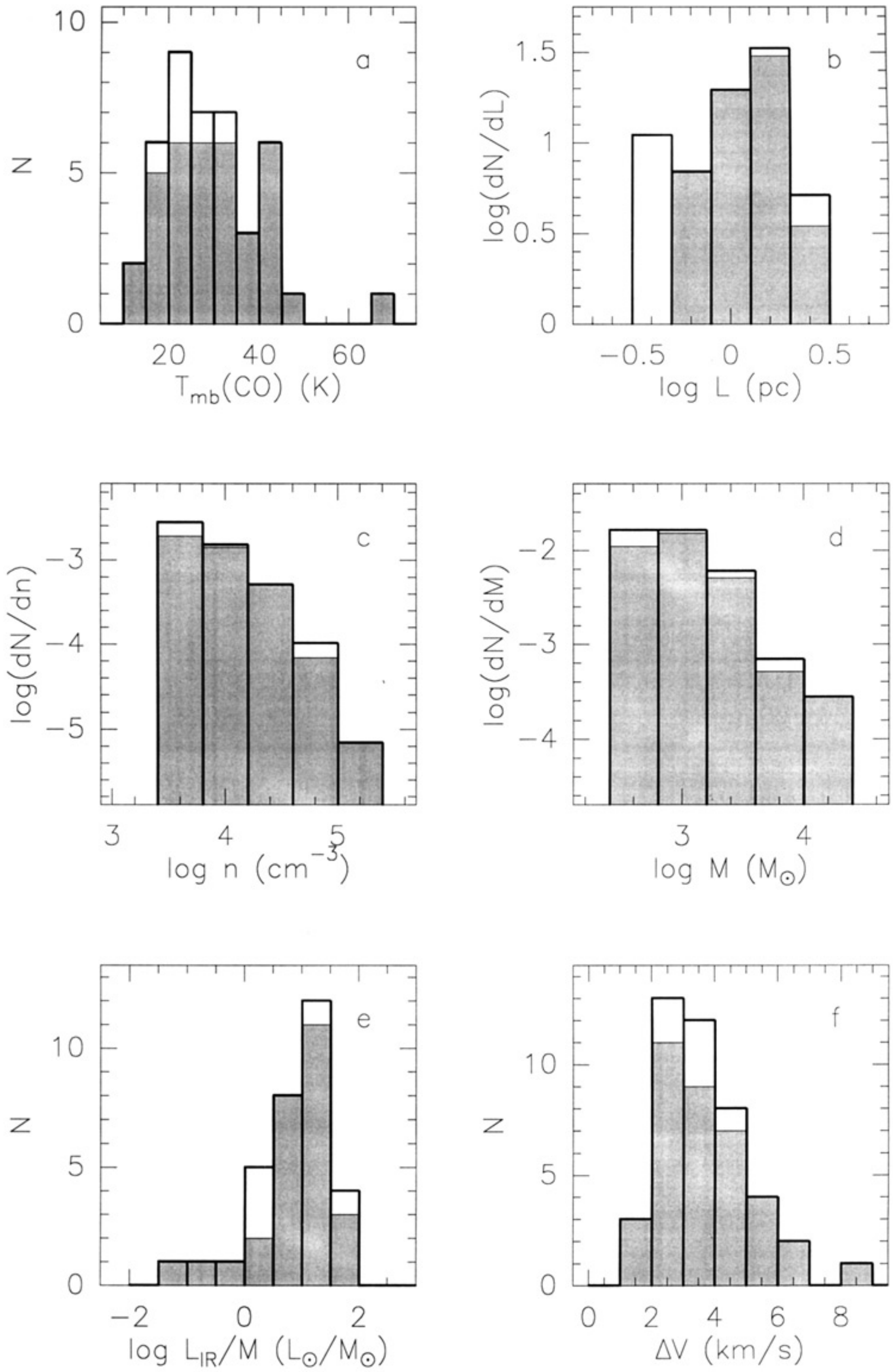

FIGURE 1 Histograms of the peak CO main beam brightness temperature (a), size (b), mean density (c), mass (d), IR luminosity to mass ratio (e) and mean CS line width (f) distributions for the CS cores observed at SEST and in Onsala located in the range 1–4 kpc from the sun (filled) and within 5 kpc from the sun (thick lines).

obtained and the mean density was derived from the virial mass (hereafter we refer to them as a category II sources), since as shown in Zinchenko *et al.* (1998) the assumption of $M = M_{\rm vir}$ is in general correct.

In addition to the CO brightness temperature, size, mean density, LTE mass and CS line width we consider the IR luminosity to mass ratio which characterizes the star formation process. The histograms of the statistical distributions for these parameters are plotted in Figure 1.

An inspection of these histograms leads to the following conclusions:

The CO brightness temperature distribution peaks at ~20–30 K. This temperature should be close to the kinetic temperature somewhere in the source (minus the background temperature). However, due to a very high optical depth in CO lines, the innermost regions can be shielded (if there is no significant velocity gradient or significant clumpiness). Therefore, the kinetic temperatures determined from CO might refer to the outer regions of the cores. It is worth noting, however, that they are rather close to the temperatures found from ammonia observations of HMSF cores in Effelsberg with a similar beam size (Zinchenko *et al.*, 1997). The CO temperatures are also close to the colour temperatures of the embedded IRAS sources determined from the ratio of the 60 and 100 μm fluxes, *i.e.* the gas kinetic temperature is close to the temperature of cold dust component which emits at these wavelengths.

Most cores have sizes of 1.0–1.5 pc. It means in particular that the angular size of a typical core equals our beam size at the distance of 3–5 kpc which supports our selection of the distance limits since many of more distant cores would be unresolved.

The *mean* density of the cores is 10^3–10^5 cm^{-3}. We emphasize that this is an average density defined as $\bar{n} = N_{\rm L}({\rm H_2})/{\rm L}$. This density is, at least at the lower edge of the distribution, too low for effective CS excitation. The densities in the regions of line formation derived from multitransitional data comprise usually $\sim 10^6$ cm^{-3} (*e.g.* Bergin *et al.*, 1996, Plume *et al.*, 1997). The fact that the mean densities are frequently lower than densities needed for noticeable CS excitation indicates that there must be practically empty voids in the cores and it is easy to see that 1–2 orders of magnitude difference between the mean density and the density in the emitting regions implies a correspondingly low volume filling factor for the CS emitting clumps. There are many other indications of small-scale clumpiness, in particular, from an analysis of HCN hyperfine anomalies in these objects (Pirogov, 1999).

The mass spectrum dN/dM for $M \gtrsim 1000\,{\rm M}_\odot$ can be approximated by a power law $dN/dM \propto M^{-\alpha}$ with $\alpha = 1.6 \pm 0.3$. This is very close to the slopes of clump mass spectra of individual molecular clouds which have been subject of several investigations on very different scales (see, *e.g.*, Blitz, 1991 and references therein; Kramer *et al.*, 1998). However, our result does not refer to clumps in an individual cloud but to a sample of objects spread throughout the Galaxy.

The distribution of the CS line widths which reflects the velocity dispersion in the cores shows at first that the internal movements are highly supersonic. If we recall the conclusion of a very low volume filling factor for the emitting clumps it would mean most probably that the line widths correspond to relative motions of these clumps.

The HNCO data reveal a presence of a hot ($T \sim 300$–500 K) and dense ($n \gtrsim 10^6$ cm^{-3}) gas in some sources which can represent so-called "hot cores".

4 GALACTIC GRADIENTS OF DENSE CORE PROPERTIES

In Figure 2 we plot the core parameters (peak CO main beam temperature, size, density, mass and mean CS line width) in dependence on the galactocentric radius using the SEST, Onsala and Metsähovi data. We use here also the category II data for mass and density.

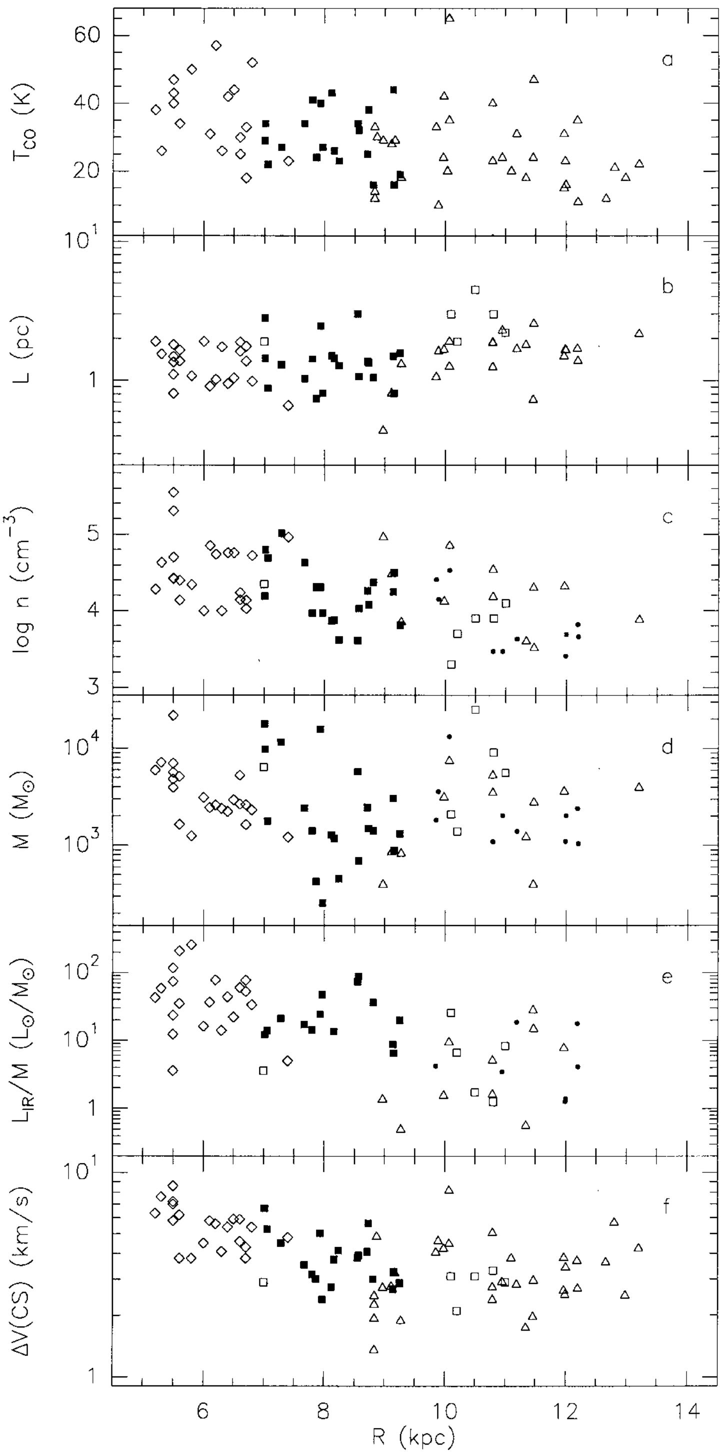

FIGURE 2 Dependences of the peak CO main beam brightness temperature (a), size (b), mean density (c), mass (d), IR luminosity to mass ratio (e) and mean CS line width (f) on the galactocentric distances for the CS cores observed at SEST (filled squares), Onsala (triangles and dots; dots mark the category II data for mass and density) and Metsähovi radio telescope (open squares) with inclusion of Juvela's (1996) data (diamonds) and with a distance limit of $d < 5$ kpc.

The data are consistent with an exponential decrease of the mean core density with the galactocentric radius for $R \approx 7$–14 kpc. The characteristic scale length is ~ 3 kpc. This trend should not be due to the beam dilution or selection effects because their influence should be more or less symmetric relative the Sun position. In principle, such a trend could arise from a possible galactic gradient of CS abundance since the LTE masses are calculated assuming a constant value $\chi(\mathrm{CS}) = 4 \times 10^{-9}$. However, in this case we would see a similar trend in the M/M_{vir} ratio because M depends on $\chi(\mathrm{CS})$ while M_{vir} does not. However, we found no dependence of this ratio on R. The decrease of the mean density is accompanied by a corresponding increase of the core size. The IR luminosity to mass ratio changes probably in about the same proportion as the mean density. The velocity dispersion in the cores probably increases towards the inner Galaxy at least at $R \lesssim 7$ kpc.

Our old HCN survey of molecular clouds towards Sharpless H II regions (Zinchenko *et al.*, 1989) indicated a significant galactic gradient in HCN detection rate which can be interpreted as an evidence for density gradient. Galactic gradients of molecular cloud properties have been a subject of several other studies in recent years (see, *e.g.*, discussions in Helfer and Blitz, 1997; Sakamoto *et al.*, 1997). Briefly, the results are somewhat contradictory but there are unambiguous gradients in the HCN/CO, CS/CO (Helfer and Blitz, 1997) and $\mathrm{HCO^+}/^{13}\mathrm{CO}$ (Liszt, 1995) emission line ratios which resemble our HCN result mentioned above. While Liszt interprets his result as an abundance effect, Helfer and Blitz conclude that the contrast between the bulge and the disk is most likely caused by a combination of higher gas densities as well as higher kinetic temperatures in the bulge.

The most recent extensive CO $J = 2-1$ survey by Sakamoto *et al.* (1997), when combined with the Columbia CO $J = 1-0$ survey performed with the same angular resolution, shows a gradient in the CO($J = 2-1$)/CO($J = 1-0$) line ratio which is interpreted by the authors as an evidence of gradient in the high-density to low-density gas ratio.

A possible explanation for the density gradient involves an influence of galactic density waves responsible for the formation of the spiral structure as suggested by Sakamoto *et al.* (1997).

5 FREQUENCY OF OCCURRENCE AND PHYSICAL PROPERTIES OF HIGH VELOCITY OUTFLOWS IN REGIONS OF HIGH MASS STAR FORMATION

As mentioned above statistical studies of high velocity outflows from massive YSOs are very important for understanding high mass star formation. Our SO and $\mathrm{C^{18}O}$ survey provides a valuable information in this respect. The SO abundance is greatly enhanced in post-shock gas, so that it can be a good indicator of high velocity outflows, not affected by confusion, as CO. Then, the parameters of outflows can be derived from optically thin $\mathrm{C^{18}O}$ lines, more reliably than from CO (Henning *et al.*, 2000).

Our analysis of the survey data for 54 southern sources shows that in 23 from them the SO line profiles possess enhanced wing emission in comparison with $\mathrm{C^{18}O}$. This is a convincing evidence for high velocity outflows in these objects. Thus, the frequency of occurrence of outflows in this sample is $\gtrsim 40\%$ (our estimate is a lower limit because flows oriented nearly perpendicular to the line of sight cannot be detected in this way). This value agrees with other available estimates.

The $\mathrm{C^{18}O}$ spectra were fitted by 2-component gaussians as in Henning *et al.* (2000). The broad component can be identified with high velocity gas. Next, the basic flow parameters were derived from these spectra: mass (M), momentum (P) and kinetic energy (E_{kin}). Our estimates for these parameters are in the range of known values for massive outflows.

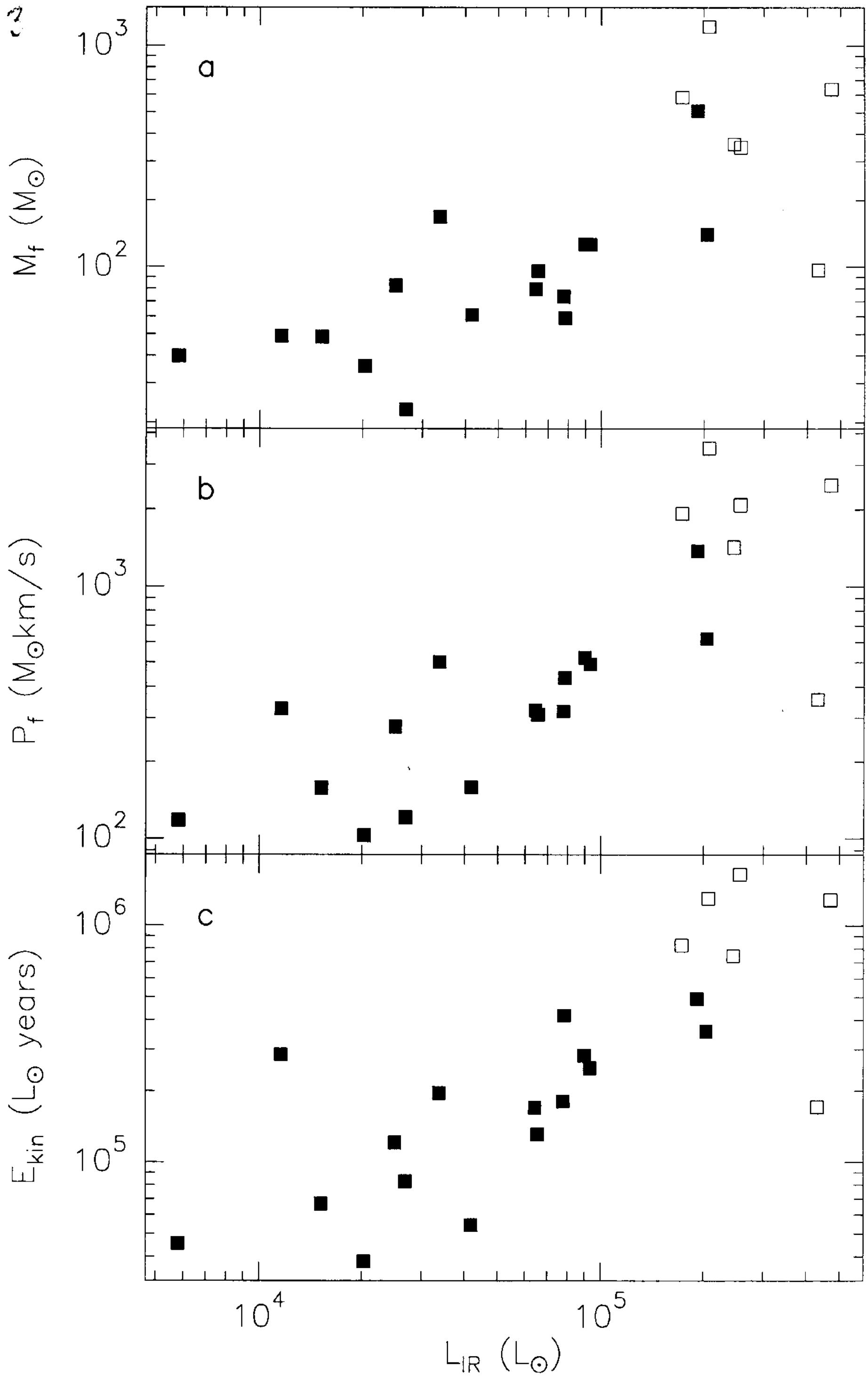

FIGURE 3 Dependences of outflow mass (a), momentum (b) and kinetic energy (c) on bolometric luminosity of associated IR sources. Filled squares correspond to objects at distances $d < 4$ kpc and open squares to objects at $d > 4$ kpc.

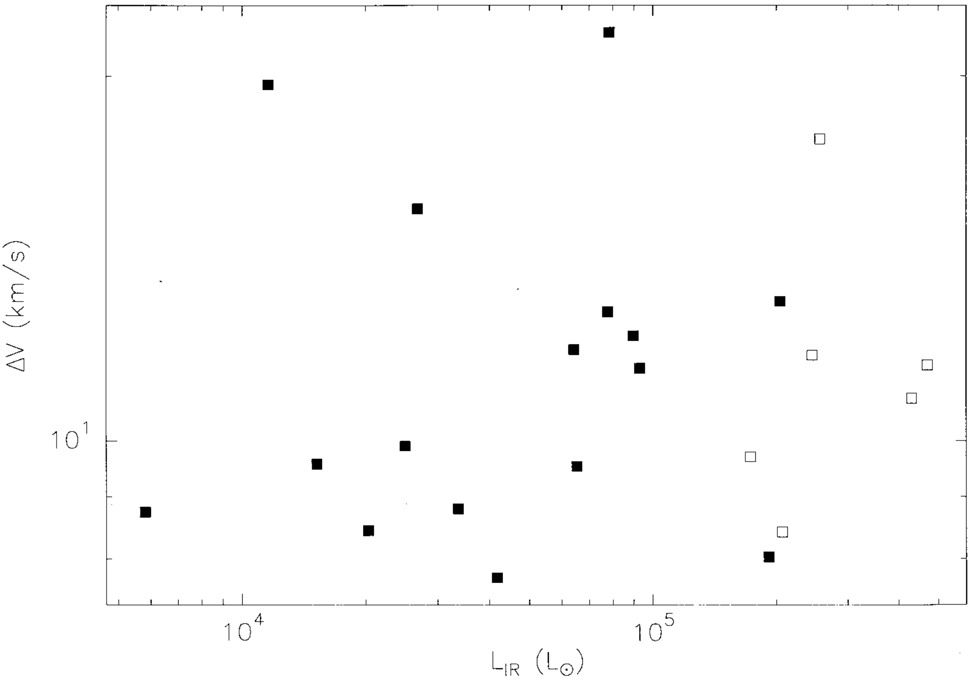

FIGURE 4 The width of the broad Gaussian components in the $C^{18}O$ spectra versus the bolometric luminosity of associated IR sources. The markers are the same as in Fig. 3.

In Figure 3 we plot these parameters in dependence on bolometric luminosity of associated IR sources. The data for objects with distances $d < 4$ kpc and $d > 4$ kpc are represented by different markers. In all cases there is a clear correlation, independently on the data for distant objects. The slope for all relationships is close to unity ($M \propto L_{IR}^{1.1\pm0.3}$, $P \propto L_{IR}^{0.9\pm0.2}$, $E_{kin} \propto L_{IR}^{1.2\pm0.3}$). At the same time there is no correlation between the outflow velocity (the width of the broad gaussian component) and the IR luminosity (Fig. 4).

The parameters which are discussed most frequently in the literature include mass loss rate ($\dot{M} = M/t$), "force" ($F = P/t$) and mechanical luminosity ($L = E_{kin}/t$) where t is the so-called "dynamical age" of an outflow. This age is derived from source maps. However, in our survey most of the sources were not mapped, so that this parameter cannot be determined. It is worth noting, that there are also tight correlations between these "dynamical" parameters and the IR luminosity with similar slopes for massive outflows (Ridge and Moore, 2001). This means that a scatter in the "dynamical age" for them is not so large. From this comparison the mean "dynamical age" is $\sim 710^3$ years which is close to independent estimates (*e.g.* Ridge and Moore, 2001). A small scatter of this age can imply that this stage of evolution corresponds to a peak of IR emission and maser activity. Also it is possible that SO enhancement peaks at this age.

6 CONCLUSIONS

The performed studies enabled us to derive statistical properties of dense cores towards young massive star. They show, in particular, that the cores are close to virial equilibrium and are clumpy (the *mean* density lies in the range $n \sim 10^3$–$10^5\,\mathrm{cm}^{-3}$ which is much lower than densities needed for CS excitation from multitransitional analysis). The size of most cores is $L \sim 1.0$–$1.5\,\mathrm{pc}$. The slope of the mass spectrum for $M \gtrsim 1000\,\mathrm{M}_\odot$ is 1.6 ± 0.3. The CS line widths are highly supersonic ($\sim$1.5–9 $\mathrm{km\,s^{-1}}$). The data hint on the dependences of some of these parameters on galactocentric distance R. In particular, the mean density of the cores decreases with increasing R in agreement with an exponential law with a scale length of $\sim$3 kpc. A hot ($T \sim 300$–$500\,\mathrm{K}$) and dense ($n \gtrsim 10^6\,\mathrm{cm^{-3}}$) gas is present in some sources. The frequency of occurrence of high velocity outflows in the studied sample is $\gtrsim 40\%$.

Many important aspects of high mass star formation remain poorly known. In particular, the number of formed stars is probably related to the degree of clumpiness in star-forming clouds. However, it has not been practically investigated observationally. Very little work has been done on the core structure and kinematics (density and temperature profiles, velocity fields), relationship between low and high mass star-forming cores, etc.

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