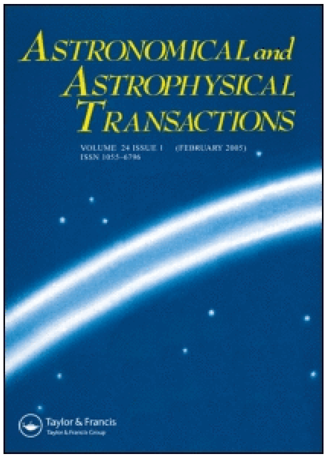

Astronomical & Astrophysical Transactions
The Journal of the Eurasian Astronomical Society
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453505

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Online Publication Date: 01 January 1992
To cite this Article: Zinchenko, I. I. (1992) 'The properties of dense molecular cloud cores', Astronomical & Astrophysical Transactions, 1:4, 253 - 267
To link to this article: DOI: 10.1080/10556799208230527
URL: http://dx.doi.org/10.1080/10556799208230527

Astronomical and Astrophysical Transactions, 1992,
Vol. 1, pp. 253–267
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THE PROPERTIES OF DENSE MOLECULAR CLOUD CORES

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(Received April 2, 1991; in final form April 18, 1991)

Results of recent studies of dense interstellar molecular clouds are discussed. Observations in molecular lines excited at high densities revealed dense cores in many clouds with gas densities $n \sim (0.3 \div 3) \times 10^5\,\text{cm}^{-9}$, kinetic temperatures $T_k \sim 10 \div 100\,\text{K}$, masses $(0.3 \div 10^4)\,M_\odot$. The cores are close to the virial equilibrium. There are correlations between velocity dispersion and size, between mass and size and some others similar to those found for less dense clouds but with different coefficients. Implicit indications of fragmentary structure on 40″ scales are obtained.

KEY WORDS Interstellar clouds, molecules, dense cores

1. INTRODUCTION

Dense cores in molecular clouds attract an astronomers' attention for a long time. Many efforts have been devoted to studies of individual objects. In recent years investigations of extended samples of dense clouds have been performed by several groups. They have revealed some correlations between core parameters and allow for the estimation of their statistical properties. Myers and co-workers have studied dense cores in many dark clouds (Myers, Linke and Benson, 1983; Myers and Benson, 1983; Benson and Myers, 1983; Benson, Myers and Wright, 1984; Myers, 1985; Benson and Myers, 1989). Richards *et al.* (1987) have surveyed some IR sources selected by certain criteria from the IRAS Point Source Catalog (Beichman *et al.*, 1985) in the $J = 1\text{–}0$ HCO$^+$ line looking for compact molecular clouds. A group of Bonn radio astronomers has investigated dense molecular cores near IR sources in Orion and Cepheus clouds (Wouterloot and Walmsley, 1986; Wouterloot, Walmsley and Henkel, 1988; Wouterloot, Brand and Henkel, 1988; Wouterloot, Henkel and Walmsley, 1989). There are some other researches.

At the Institute of Applied Physics (IAP) of the USSR Academy of Sciences, dense molecular clouds associated with Sharpless (1959) HII regions, and some others, have been studied intensively in various molecular lines excited at high densities. At first, Sharpless clouds with the CO $J = 1\text{–}0$ radiation temperature $T_R^*(\text{CO}) > 10\,\text{K}$ (Blitz, Fich and Stark, 1982) have been surveyed in the $J = 1\text{–}0$ HCN line (Burov *et al.*, 1988). Then some clouds detected in the HCN line have been observed in the $J = 1\text{–}0$ H^{13}CN line (Burov *et al.*, 1988) and in the $J = 1\text{–}0$ HCO$^+$ Line (Zinchenko *et al.*, 1989). The results have been compared with the above-mentioned CO data and with the IRAS data. Here we will summarize them taking into account data of other groups.

2. BASIC PHYSICAL PROPERTIES OF DENSE CORES

(*a*) *Temperature*

The gas kinetic temperature is estimated usually from CO observations. The CO transitions are thermalized in most cases. Besides observations of NH_3 and other molecules with metastable levels are employed (see, for example, Walmsley and Ungerechts, 1983). It should be noted that the CO data in many cases when there is no powerful energy sources on the line of sight probably do not correspond to the kinetic temperature in the cloud interior due to the high optical depth in the CO lines (Zinchenko and Lapinov, 1985; Castets *et al.*, 1990).

The kinetic temperature in the dark cloud cores is generally ~10 K (Myers, 1985) and sometimes, perhaps, drops to ~7 K (Zinchenko and Lapinov, 1985). This temperature should rise at the cloud periphery. There is observational evidence for this phenomena (Snell, 1981). The temperature of the clouds containing OB stars, or other powerful energy sources, is significantly higher. So, for the sample studied by the IAP group, the kinetic temperature lies in the range from ~10 K to ~100 K. It should be noted that the dust temperatures estimated from FIR spectra are higher than the gas temperatures for this sample (Zinchenko and Pirogov, 1991; Figure 1). This, probably, indicates an important role of the gas-dust energy exchange for gas heating.

The enhanced to 20–30 K kinetic temperature is observed sometimes also in clouds without luminous stars (in ρ Ophiuchi for example). The additional heating here can be due to the ambipolar diffusion (Shu, Adams and Lizano, 1987).

(*b*) *Density*

The density determination is a much more difficult task than the estimation of temperature. The reasons for this are the following points:

1. Observations of several lines are necessary for density determination. Observations of one line can give only limits on its value.
2. Density estimates depend strongly on cross-section for collisions of given molecule with H_2. There are significant uncertainties in them for many molecules. Frequently, cross-sections for collisions with He atoms are used instead. It is acceptable only for para-H_2. However, considerable amount of ortho-H_2 can be present in some clouds (Oka, 1980), which would lead to overestimation of the cloud density.
3. Radiative excitation through IR transitions should be important in many cases, which will affect the density estimates.
4. Density estimates depend on the cloud model. The large velocity gradient (LVG) model is most frequently used. For other models the density estimates can be several times different.
5. Strong spatial density variations on the beamsize scale are possible.

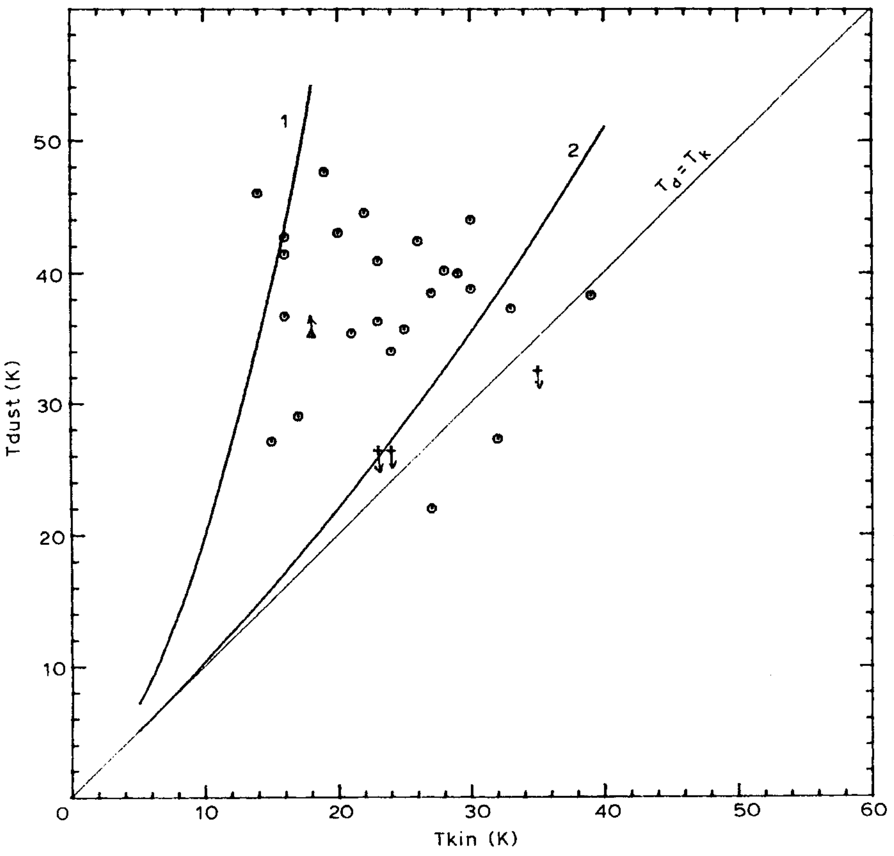

Figure 1. The gas and dust temperatures for some IRAS sources in Sharpless clouds. The solid lines correspond to the model in which gas is heated by collisions with dust grains at the gas densities 10^4 cm^{-9} (1) and 10^5 cm^{-9} (2) (Goldsmith and Langer, 1978).

In spite of these difficulties, compatible results have been obtained by several groups. The gas densities of dense regions in dark clouds are $n \sim 3 \times 10^4$ cm^{-9} (Myers, 1985). In "warm" clouds the 1–2 orders higher densities are indicated.

Myers (1985) defines the cloud core as a region with gas density $n > 10^4$ cm^{-9}. Of course, the exact value is questionable but in general it outlines correctly the range of this parameter in dense clouds.

One of the molecules suitable for dense cores studies is HCN. Firstly, it is excited only in relatively dense regions. So, the detectable HCN emission indicates the enhanced density by itself.

Secondly, intensity ratios of hyperfine components in the HCN lines give additional information about the density. At rather high densities ($n > 10^6$ cm^{-9}) the intensities of these components equalize regardless of the cloud kinematics and so on. The "anomalies," for example, relative weakening of the satellite components can be observed only at lower densities. It gives an upper limit on the density in many cases. Detailed computations of HCN excitation were performed by Zinchenko and Khersonskij (1987a, b), Zinchenko and Pirogov (1987), Lapinov (1989).

In the sample studied by the IAP group, the HCN emission has been detected in about a half of the objects. It implies existence of high density regions in them, that is dense cores. The HCN radiation temperatures are plotted versus CO temperatures at Figure 2 (Zinchenko, Lapinov and Pirogov, 1989). There is clear correlation between them. The HCN radiation temperature is 3–10 times lower than the CO temperatures. The most probable reason for this is that the HCN transitions are not thermalized unlike CO. The upper limit on the density is then $n \sim 3 \times 10^4\,\mathrm{cm}^{-9}$ for uniform models. The rather good correlation between T_R^*(HCN) and T_R^*(CO) implies that the density dispersion is not large. A similar correlation exists between T_R^*(HCO$^+$) and T_R^*(CO) (Figure 3; Zinchenko *et al.*, 1990).

The lower T_R^*(HCN) relative to T_R^*(CO) can be explained also by the difference in physical conditions in emitting regions (which can be different for

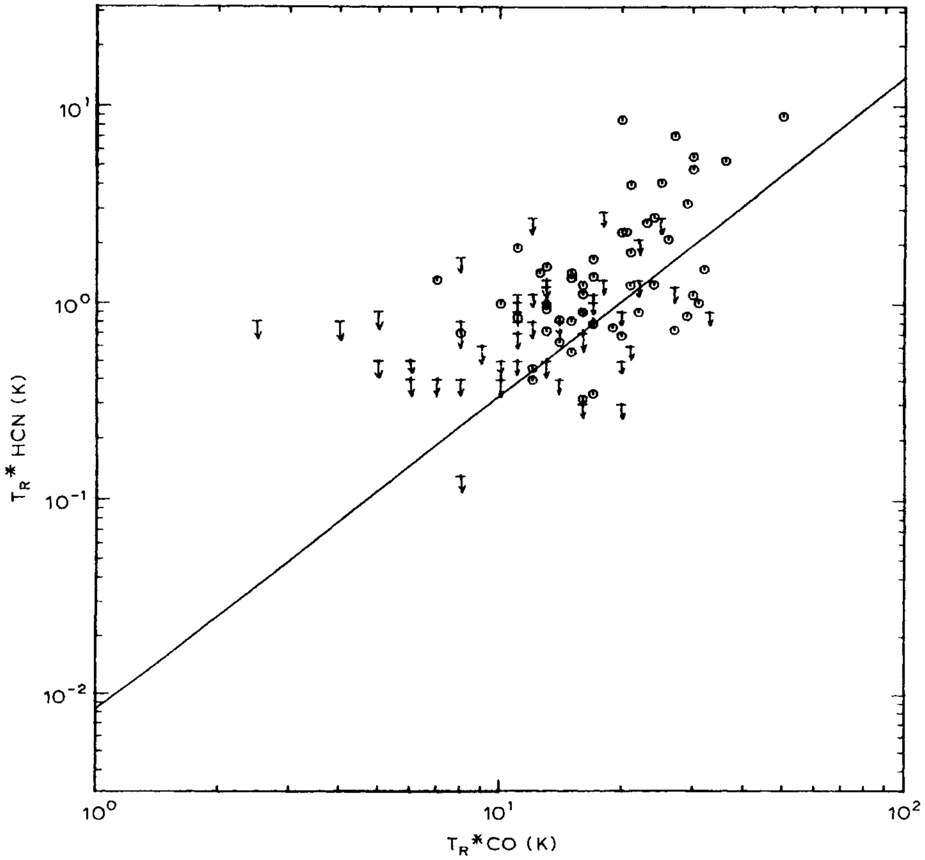

Figure 2. The HCN $J = 1$–0 radiation temperatures in Sharpless clouds versus the CO $J = 1$–0 radiation temperatures.

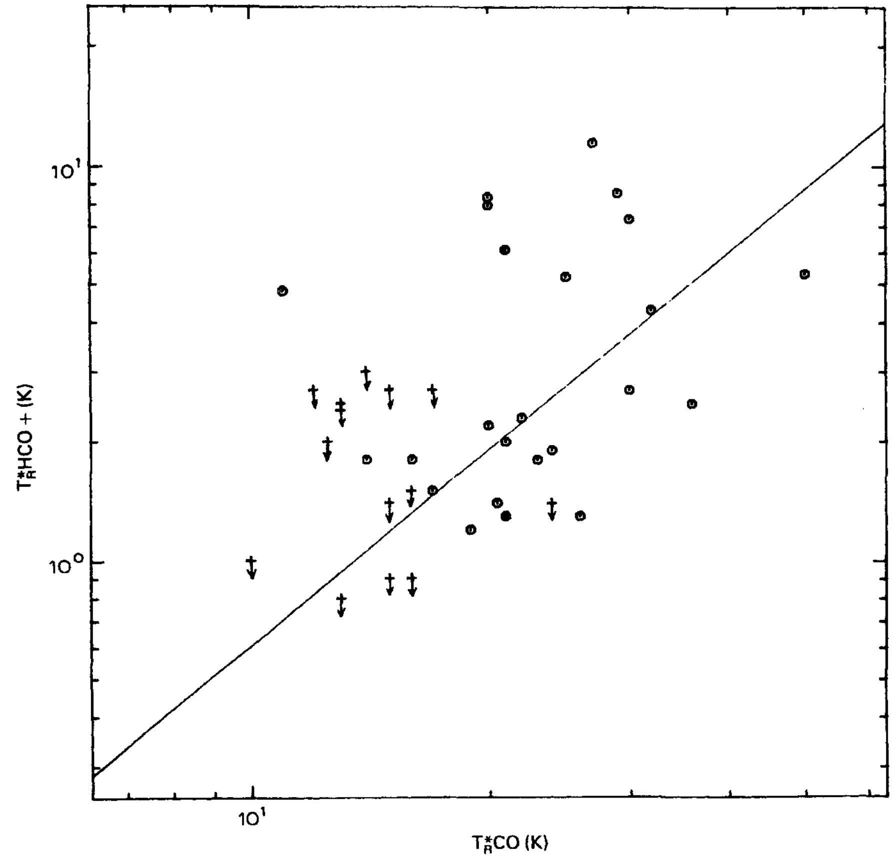

Figure 3. The same for the HCO$^+$ $J = 1\text{–}0$ lines.

these molecules) and by the fragmentary structure of the clouds. The HCN emission probably arises in dense clumps, while the CO emission also arises in the interclump low density medium. The upper limit on the clump mean density from the HCN hyperfine intensity ratios is $n \sim 3 \times 10^5\,\mathrm{cm}^{-9}$.

(c) *Mass and Size*

The size of low-mass cores in cold clouds is $0.05 \div 0.9$ pc from NH_3 observations (Benson and Myers, 1989) while more massive cores in warm clouds are $0.1 \div 3$ pc (Ho *et al.*, 1981). Their masses are $0.3 \div 7 \cdot 10^2\,M_\odot$ and $10 \div 10^3\,M_\odot$ respectively. In dark clouds the cores with embedded stars have larger masses and sizes than cores without stars (Benson and Myers, 1989). HCN and HCO$^+$ observations of some molecular clouds associated with HII regions yielded similar sizes from ~0.15 pc to ~3 pc (Zinchenko *et al.*, 1990). Their masses, estimated from the HCN, HCO$^+$ and FIR continuum observations by the IRAS are $10 \div 10^4\,M_\odot$.

(*d*) *Velocity Structure*

The width of molecular lines changes from ~0.2 km/s (in dark cloud cores) to ~10 km/s. It is interesting that the HCN lines are only ~10% narrower than the CO lines (Figure 4; Zinchenko, Lapinov and Pirogov, 1989). The HCO^+ line widths do not correlate with the CO and HCN widths (Figure 5; Zinchenko *et al.*, 1990). Perhaps, this is due to ambipolar diffusion.

The NH_3 lines in dark cloud cores with stars, are broader by a factor of ~1.6 than in such cores without stars (Benson and Myers, 1989).

There are signs of systematic motions in some cores. In particular, assymmetric and self-reversed line profiles can indicate contraction or expansion. Such features are observed in many clouds but their interpretation is usually ambiguous.

Many cores have velocity gradients which can indicate a rotation. On the scales ~1 pc these gradients are $\sim(0.1 \div 1)\ \mathrm{km\,s^{-1}\,pc^{-1}}$ but in the vicinity of young stars (~0.1 pc) interferometric observations reveal much larger gradients $\sim(20 \div 30)\ \mathrm{km\,s^{-1}\,pc^{-1}}$ (Harris *et al.*, 1983).

Besides, high velocity outflows seem to be a very common feature of regions of recent star formation (see, for example, Bally, 1987). The outflow detection rate reaches 50% for bright IRAS sources. They have also been detected in many dark cloud cores (Myers *et al.*, 1988). Several models for the outflows have been proposed.

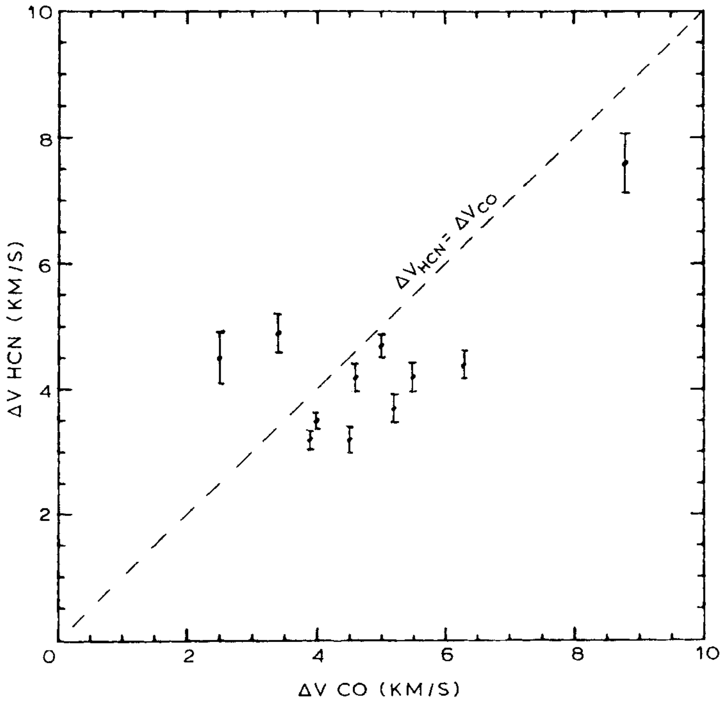

Figure 4. The HCN $J = 1\text{–}0$ line widths in Sharpless clouds versus the CO $J = 1\text{–}0$ line widths.

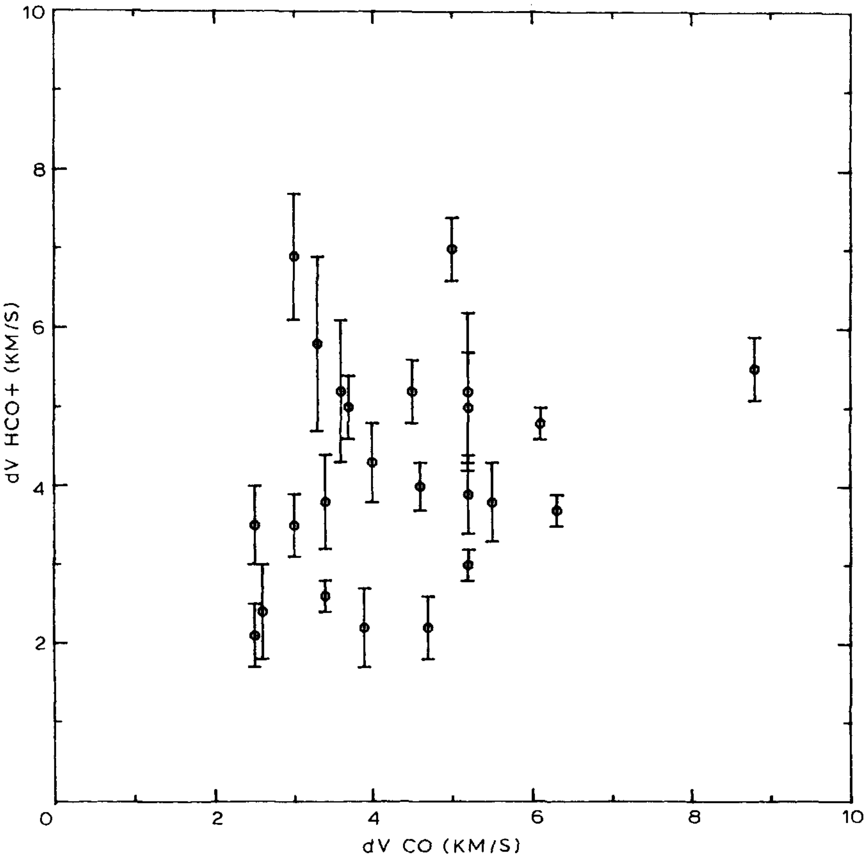

Figure 5. The same for the HCO$^+$ $J = 1$–0 line.

(e) Ionization

The HCO$^+$ observations allow for the estimation of electron abundance. These estimates are rather crude because of uncertainties in some parameters. The IAP group results yield $X_e < 10^{-(6-7)}$ (Zinchenko *et al.*, 1990). Similar values have been obtained by other authors (for example, Wootten *et al.*, 1979).

(f) Magnetic Field

Magnetic field can play an important role in molecular clouds. Unfortunately observational data on the magnetic field strength in dense cores are very scarce. However, there are evidences for magnetic and virial equilibrium in molecular clouds (Myers and Goodman, 1988a, b), which are probably applicable for dense cores also. The observations seem to be consistent with $B \propto n^{1/2}$ law which follows in particular from the assumption of magnetic and kinematic energy equipartition.

3. SOME CORRELATIONS BETWEEN PHYSICAL PARAMETERS OF THE CORES AND THEIR STABILITY

Observations of molecular clouds in CO, NH_3 and other lines have revealed tight correlations between size L and velocity dispersion σ, between size and mean density n and others (Larson, 1981; Myers, 1983; Dame, 1985). Results of CO and NH_3 observations of molecular clouds ranging from ~0.1 pc to ~100 pc in size are fitted by the following expressions (Myers, 1985):

$$n = 3900 L^{-1.2}\,\text{cm}^{-3} \tag{1}$$

$$\sigma = 1.2 L^{0.3}\,\text{km/s} \tag{2}$$

(L is in parsecs). Correlations coefficients for these relations are ~0.9. Besides, the clouds are close to virial equilibrium on the average.

Similar correlations have been found for dense cores observed in the HCN and HCO^+ lines (Zinchenko and Pirogov, 1991). For example, the HCO^+ line width

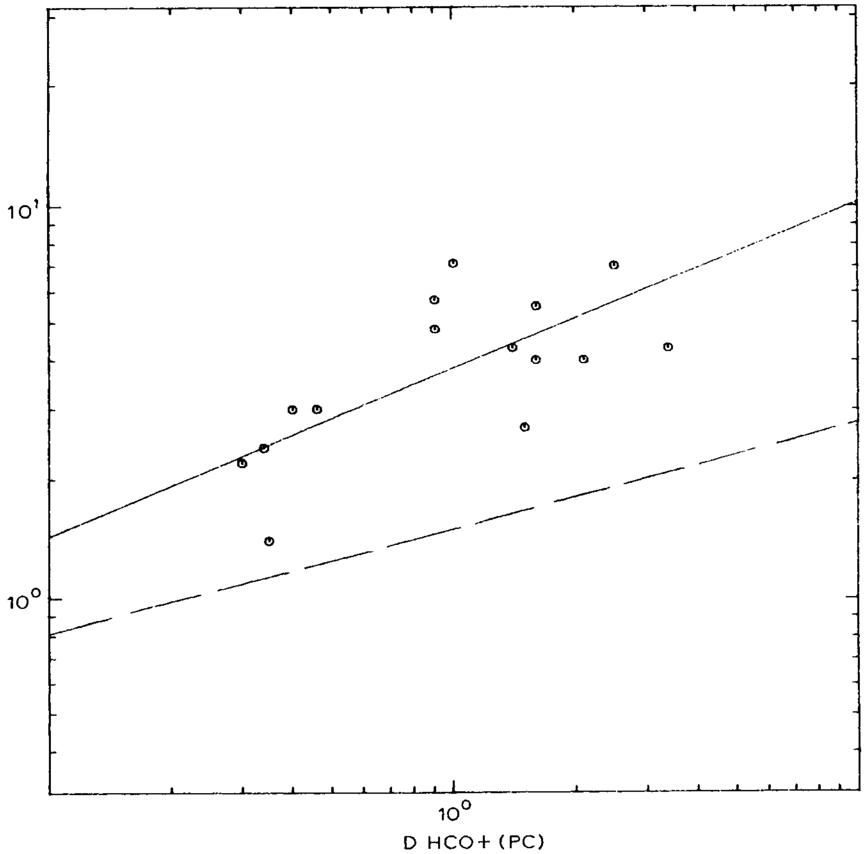

Figure 6. The dependence of the HCO^+ $J = 1\text{–}0$ line widths in Sharpless clouds on the size of the emitting regions. The dashed line corresponds to the expression (2).

correlates well with the size of the emitting region (Figure 6). The best fit is obtained with the relation:

$$\Delta v = 3.8L^{0.49}\ \mathrm{km/s} \qquad (3)$$

Taking into account that $\Delta v^2 = \sigma^2(8/3)\ln 2$, one can see that the coefficient in (3) is a few times higher than in (2). The same is true for the relation between n and L (Figure 7).

In principle this can be explained by the higher external pressure P_e on the HCN and HCO$^+$ cores as compared to the CO and NH$_9$ clouds (Fleck, 1988; Elmegreen, 1989). According to Elmegreen (1989):

$$\sigma \simeq 0.67 \pm 0.17\left(\frac{P_e/k}{10^4\ \mathrm{K\,cm^{-3}}}\right)L^{1/2}\ \mathrm{km/s\ pc^{1/2}} \qquad (4)$$

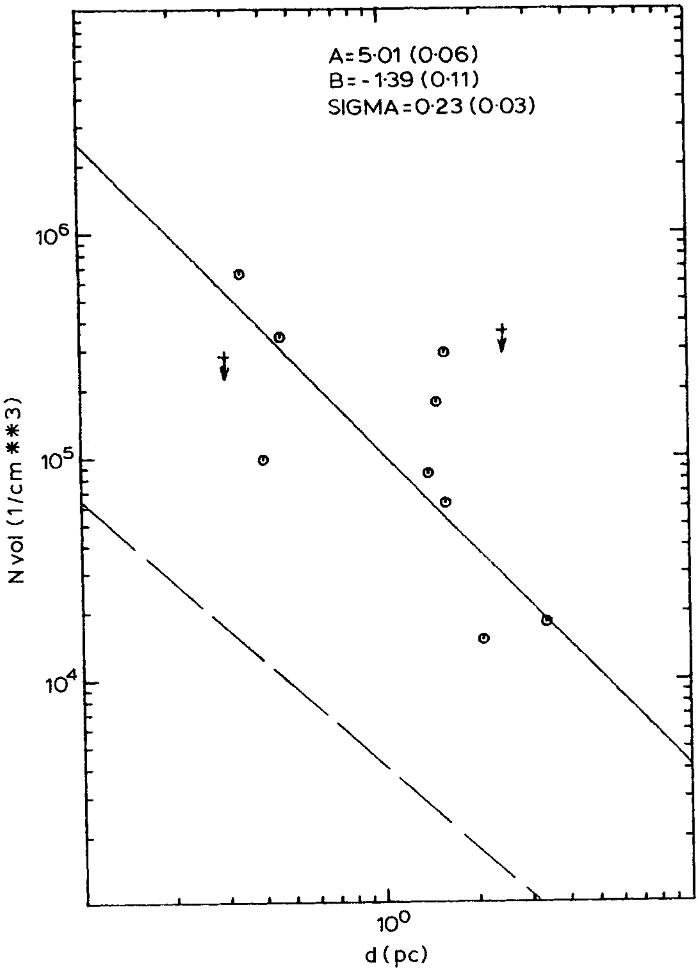

Figure 7. The dependence of the gas density estimated from the HCO$^+$ and FIR IRAS observations on the size of the emitting region. The dashed line corresponds to the expression (1).

Therefore, the external pressure should be $P_e \sim 10^7\,\mathrm{k\,K\,cm^{-3}}$ to fit the data. It corresponds to velocity dispersion at the core edge $\sigma_e \sim 3.5\,\mathrm{km/s}$ if the edge density is $n_e = 10^4\,\mathrm{cm^{-9}}$ ($P_e = mn_e\sigma_e/3$). The relation between n and L can be explained in the same way.

The core masses determined from the HCN and HCO^+ observations are close to virial ones on the average (Figure 8; Zinchenko and Pirogov, 1991). Carr (1987) found for CO clumps in Cep OB3 cloud that $M/M_{\mathrm{vir}} \propto L$ and $M < M_{\mathrm{vir}}$. But these clumps hardly can be considered as dense cores because their density is $n \sim (2 \div 5)\,10^3\,\mathrm{cm^{-9}}$.

So dense cores observed in HCN and HCO^+ lines are close to the viriial equilibrium.

The origin of these correlations is not clear. The $\sigma(L)$ relation can be based on turbulent energy cascade as in the Kolmogorov case. Estimating P_e, we assumed in fact, that the clouds are in equilibrium under gravitational and external pressure forces. Then the expression (4) and similar for $n(L)$ can be deduced. Other interpetations are also possible (Myers, 1985).

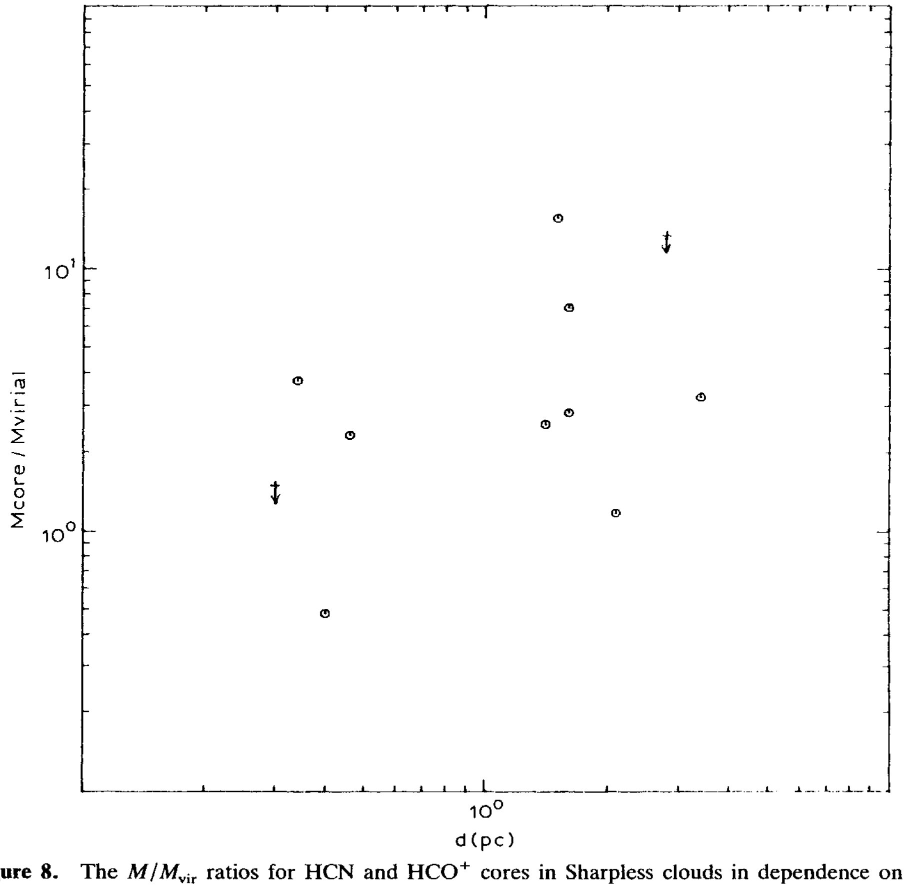

Figure 8. The M/M_{vir} ratios for HCN and HCO^+ cores in Sharpless clouds in dependence on the core size.

4. INTERNAL STRUCTURE

The fragmentation of molecular clouds should occur in the course of their evolution. Many observational data can be preferably explained in the framework of fragmentary models implying clumpy structure on the beamsize scale (Martin, Sanders and Hills, 1984; Kwan and Sanders, 1986; Zinchenko, Lapinov and Pirogov, 1989). In particular, it follows from comparison of line profiles for different transitions of one molecule (Plambeck *et al.*, 1977; Martin, Sanders and Hills, 1984), from density estimates based on observations of different molecules (Goldsmith *et al.*, 1975), from comparison of rotational and radiation NH_3 temperatures (Schwartz *et al.*, 1977), and so on.

A clumpiness can be expected for dense cores also. The comparison of HCN and $H^{13}CN$ intensities and line widths provides probably an implicit evidence for this (Zinchenko, Lapinov and Pirogov, 1989). The ratios $\Delta v(HCN)/\Delta v(H^{13}CN)$ are plotted versus $T_R^*(H^{13}CN)/T_R^*(HCN)$ on Figure 9. Several curves are drawn corresponding to various types of models assuming terrestrial $H^{13}CN/HCN$ abundance ratio. It can be seen that fragmentary models agree better with the observations than others.

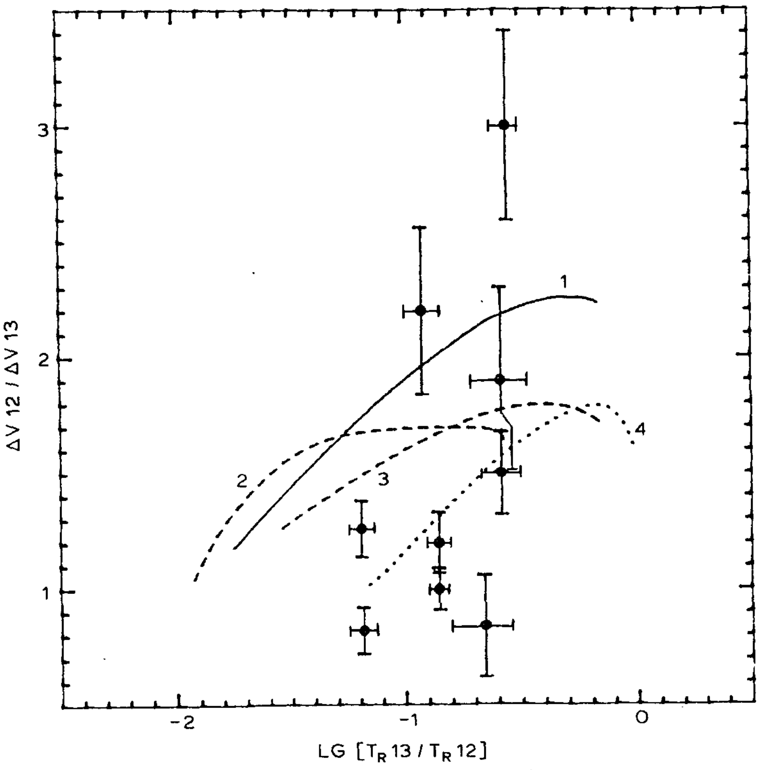

Figure 9. The $\Delta v(HCN)/\Delta v(H^{13}CN)$ ratios versus $T_R^*(H^{13}CN)/T_R^*(HCN)$ ratios for some Sharpless clouds. The lines correspond to the following models: (1)—uniform model with $T_{ex}(HCN) = T_{ex}(H^{13}CN)$, (2)—microturbulent model with $T_k = 30$ K and $n = 10^5$ cm^{-9}, (3)—the same with $n = 3 \cdot 10^5$ cm^{-3} and (4)—fragmentary model, $T_{ex}(HCN) = T_{ex}(H^{13}CN)$, $\tau_{eff}(HCN)/\tau_{eff}(H^{13}CN) = 15$.

The fragmentary models have been considered quantitatively by Martin, Sanders and Hills (1984), Kwan and Sanders (1986). The fragment size in these models is rather uncertain because the results depend on some combination of parameters including size. In the model proposed by Kwan and Sanders (1986) for Orion A, the fragment size is 8×10^{16} cm. From the HCN observations, the upper limit on the size is $\sim$0.1 pc which corresponds to the beam size (40″). On the other hand the lower limit can be obtained taking into account that the minimal fragment mass is $\sim 0.01\ M_\odot$ (Spitzer, 1978). Then, if $n \leq 3\ 10^5\ \mathrm{cm}^{-3}$, the fragment size should be $\geq$0.01 pc.

5. DISTRIBUTION IN THE GALAXY

The Sharpless clouds observed in the HCN line lie at very different galactocentric distances R (from $\sim$5 kpc to $\sim$20 kpc). At Figure 10a the ratio of cloud number with $T_R^*(\mathrm{HCN}) > 1$ K to the total number of the clouds observed (with $T_R^*(\mathrm{CO}) > 10$ K) is plotted in dependence on R (Zinchenko, Lapinov and Pirogov, 1989). There is a clear tendency for decreasing HCN detection rate with increasing R. Probably, it is due to the mean cloud density decrease but it can also be caused by

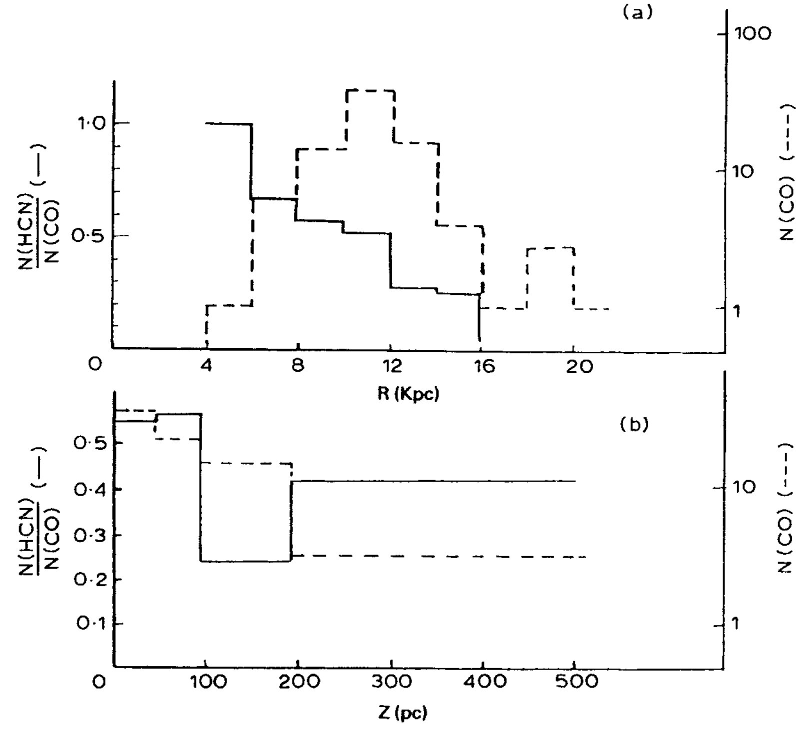

Figure 10. The number of the clouds with $T_R^*(\mathrm{HCN}) > 1$ K relative to the total number of the clouds observed in dependence on the galactocentric distance (a) and on the height above the galactic plane (b) (solid lines). The total number of the observed clouds is shown by the dashed lines.

the HCN relative abundance decreasing. Besides, the beam filling factor can change. There is no evidence for significant temperature decrease from the CO observations.

In the direction perpendicular to the galactic plane the HCN detection rate does not change significantly (Figure 10b).

The mean HCN detection rate in the Sharpless clouds observed is ~50% (~65% with tentative detections). However these clouds have been selected in advance by certain criteria. A similar detection rate 44% (52%) has been achieved in the NH_3 observations of opaque regions in dark clouds (Benson and Myers, 1989).

The estimates of the number density of dense cores detected so far in the solar neighbourhood are the following. Within 1 kpc from the Sun 7 HCN dense cores in molecular clouds associated with Sharpless HII regions have been detected (11 with tentative detections) by Burov *et al.*,1988. This yields the mean surface density of such cores ~2–3 kpc^{-2}. Averaging over larger radius yields lower values, but it can be due to the filling factor and other effects. From the NH_3 observations of dark clouds (Benson and Myers, 1989), the surface density of cold cores detected in these objects is much higher (50–100 kpc^{-2}).

6. INFRARED SOURCES IN DENSE CORES

The results of the IRAS mission (Beichman *et al.*, 1985) show that many, perhaps the most dense cores in molecular clouds, have associated IR sources. In dark clouds 68% of the cores with the strong NH_3 emission contain such sources (Benson and Myers, 1989). For the HCN cores in Sharpless clouds this value reaches 72%.

The cores with and without IR sources have somewhat different properties as has been mentioned above. On the average the cores with stars are larger, more massive, and have larger velocity dispersion than other cores.

The large fraction of dense cores with IR sources implies probably that the cores without such sources are in the process of forming stars. This conclusion stresses the importance of a search for the signs of star formation in cold cores without internal IR sources.

7. CONCLUSIONS

Dense cores with $n \geq 10^4\ \mathrm{cm}^{-3}$ are present in a large part of molecular clouds, in particular, in about half of the clouds associated with Sharpless regions with rather strong CO emission ($T_R^*(\mathrm{CO}) > 10\ \mathrm{K}$). Their kinetic temperatures are $10 \div 100\ \mathrm{K}$, masses $0.3 \div 10^4\ M_\odot$, gas densities $(0.3 \div 3) \times 10^5\ \mathrm{cm}^{-3}$ and sometimes higher, electron abundance $\leq 10^{-(6-7)}$.

There are correlations between core sizes, densities and velocity dispersion. For HCN and HCO^+ cores in Sharpless clouds, they imply probably higher external pressure than for CO and NH_3 clouds. The cores seem to be in the virial equilibrium on the average. Some data indicate implicitly fragmentary structure of dense cores at the scales ~40″. The fragment size should be $0.01 \div 0.1$ pc, the gas density $n \leq 3 \times 10^5\,\mathrm{cm}^{-3}$. The HCN core detection rate decreases when the galactocentric distance increases.

Many, perhaps, most cores have associated infrared sources. The properties of the cores with and without such sources that are embedded stars, obviously, differ in some respect. The cores with stars have broader lines and larger sizes than do cores without stars.

What are the future prospects of this research? It is important to study the mass and size distribution of the cores as well as their distribution in the Galaxy. The properties of the cores can depend on the galactocentric radius. Additional investigations of the association with infrared sources and visible stars, are necessary to estimate the star formation efficiency in these cores. It is not quite clear what is the relative role of turbulent motions, magnetic fields and other factors in stabilizing the cores. Some cores should be collapsing. There are data that probably imply the contraction but this interpretation is usually ambiguous. It is important to search for collapsing cores and to investigate them. The related problem is the probable fragmentary structure of the cores.

Other perspective directions of research include studies of the core energetics, their age, variations of the chemical composition and so on.

References

Bally, J. (1987). In: Evolution of Galaxies. X European regional astronomy meeting, ed. J. Palous, Praha, 1987.

Beichman, C. A., Neugebauer, G. and Habing, H. J. *et al.* (1985). IRAS Point Source Catalog, 1985.

Benson, P. J. and Myers, P. C. (1983). *Astrophys. J.*, **270,** 589.

Benson, P. J. and Myers, P. C. (1989). *Astrophys. J. Suppl.*, **71,** 89.

Benson, P. J., Myers, P. C. and Wright, E. L. (1984). *Astrophys. J.*, **279,** L27.

Blitz, L., Fich, M. and Stark, A. A. (1982). *Astrophys. J. Suppl.*, **49,** 183.

Burov, A. B., Kislyakov, A. G., Krasil'nikov, A. A., Kukina, E. P., Lapinov, A. V., Pirogov, L. E., Vdovin, V. F. and Zinchenko, I. I. (1988). *Sov. Astron. Lett.*, **14**(3), 209.

Carr, J. S. (1987). *Astrophys. J.*, **323,** 170.

Castets, A., Duvert, G., Dutrey, A., Bally, J., Langer, W. D. and Wilson, R. W. (1990). *Astron. Astrophys.*, **234,** N 1–2, 469.

Dame, T. M., Elmegreen, B. G., Cohen, R. S. and Thaddeus, P. (1986). *Astrophys. J.*, **305,** 892.

Elmegreen, B. G. (1989). *Astrophys. J.*, **338,** 178.

Fleck, R. C. Jr. (1988). *Astrophys. J.*, **328,** 299.

Goldsmith, P. F. and Langer, W. D. (1978). *Astrophys. J.*, **222,** 881.

Goldsmith, P. F., Plambeck, R. L. and Chiao, R. Y. (1975). *Astrophys. J.*, **196,** L39.

Harris, A., Townes, C. H., Matsakis, D. N. and Palmer, P. (1983). *Astrophys. J. Lett.*, **265,** L63.

Ho, P. T. P., Martin, R. N. and Barrett, A. H. (1981). *Astrophys. J.*, **246,** 761.

Kwan, J. and Sanders, D. B. (1986). *Astrophys. J.*, **309,** 783.

Lapinov, A. V. (1989). *Astron. Zh.*, **66,** 264.

Larson, R. B. (1981). *Mon. Not. Roy. Astron. Soc.*, **194,** 809.

Martin, H. M., Sanders, D. B. and Hills, R. E. (1984). *Mon. Not. Roy. Astron. Soc.*, **208,** 35.

Myers, P. C. (1983). *Astrophys. J.* **270,** 105.

Myers, P. C. (1985). In: Protostars and Planets II, ed. D. C. Black and M. S. Matthewes. Univ. Ariz. Press, 1985.

Myers, P. C. and Benson, P. J. (1983). *Astrophys. J.*, **266,** 309.

Myers, P. C. and Goodman, A. A. (1988a). *Astrophys. J. Lett.*, **326,** L27.

Myers, P. C. and Goodman, A. A. (1988b). *Astrophys. J.*, **329,** 392.

Myers, P. C., Heyer, M., Snell, R. L. and Goldsmith, P. F. (1988). *Astrophys. J.*, **324,** 907.

Myers, P. C., Linke, R. A. and Benson, P. J. (1983). *Astrophys. J.*, **264,** 517.

Oka, T. (1980). In: Interstellar molecules, ed. B. H. Andrew, Reidel Publ., 1980.

Plambeck, R. L., Snell, R. L. and Loren, R. B. (1983). *Astrophys. J.*, **266,** 321.

Plambeck, R. L., Williams, D. R. W. and Goldsmith, P. F. (1977). *Astrophys. J.* **213,** L41.
Richards, P. J., Little, L. T., Toriseva, M. and Heaton, B. D. (1987). *Mon. Not. Roy. Astron. Soc.,* **228,** 43.
Schwartz, P. R., Cheung, A. C., Bologna, J. M., Chui, M. F., Waak, J. A. and Matsakis, D. (1977). *Astrophys. J.,* **218,** 671.
Sharpless, S. (1959). *Astrophys. J. Suppl.,* **4,** 257.
Shu, F. H., Adams, F. C. and Lizano, S. (1987). *Ann. Rev. Astron. Astrophys.,* **25,** 23.
Snell, R. L. (1981). *Astrophys. J. Suppl.,* **45,** 121.
Spitzer, L. Jr. (1978). Physical Processes in the Interstellar Medium. Wiley-Interscience Publ., 1978.
Walmsley, C. M. and Ungerechts, H. (1983). *Astron. Astrophys.,* **122,** 164.
Wooten, A., Snell, R. L. and Glassgold, A. E. (1979). *Astrophys. J.,* **234,** 876.
Wouterloot, J. G. A., Brand, J. and Henkel, C. (1988). *Astron. Astrophys.,* **191,** 323.
Wouterloot, J. G. A., Henkel, C. and Walmsley, C. M. (1989). *Astron. Astrophys.,* **215,** 131.
Wouterloot, J. G. A. and Walmsley, C. M. (1986). *Astron. Astrophys.,* **168,** 237.
Wouterloot, J. G. A., Walmsley, C. M. and Henkel, C. (1988). *Astron. Astrophys.,* **203,** 367.
Zinchenko, I. I. and Khersonskij, V. K. (1982a). *Astrofiz. issl. Izv. SAO,* **16,** 65.
Zinchenko, I. I. and Khersonskij, V. K. (1982b). *Astron. Zh.,* **59,** 676.
Zinchenko, I. I., Krasil'nikov, A. A., Kukina, E. P., Lapinov, A. V. and Pirogov, L. E. (1990). *Astron. Zh.,* **67,** 908.
Zinchenko, I. I. and Lapinov, A. V. (1985). *Astron. Zh.,* **62,** 860.
Zinchenko, I. I., Lapinov, A. V. and Pirogov, L. E. (1989). *Astron. Zh.,* **66,** 1142.
Zinchenko, I. I. and Pirogov, L. E. (1987). *Astron. Zh.,* **64,** 483.
Zinchenko, I. I. and Pirogov, L. E. (1991) (in preparation).