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LETTER

Letter to the Editor

The IRAM key project: small-scale structure of pre-star forming regions

Combined mass spectra and scaling laws

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Abstract. One objective of the IRAM key project *small-scale structure of pre-star forming regions* is to determine the continuation of the mass spectra for molecular cloud fragments and other scaling laws from large scales down to smallest scales accessible with single-dish telescopes. In this Letter we present first results of the combination of the small scale data from this project and large scale data obtained with the CfA 1.2 m and the KOSMA 3 m telescopes for the Polaris Flare analyzed using a Gaussian clump decomposition. For data in the ^{12}CO J=1→0 and 2→1 lines we find no deviation from the power law slope of the mass spectra ($\frac{dN}{dM} \propto M^{-1.84}$), over a range in masses of more than at least 5 orders of magnitudes, from masses of several 10 $M_\odot$ down to Jupiter masses. The size spectrum is in agreement with a power law of the form $\frac{dN}{dr} \propto r^{-3.0}$. The mass-size relation is a power law of the form $M \propto r^{2.31}$ over a range of more than 2 orders of magnitudes in size.

Key words: interstellar medium (ISM): structure - ISM: individual objects: Polaris Flare - ISM: kinematics and dynamics - turbulence

1. Introduction

There is general agreement that stars form from molecular clouds. The exact way how they do that is so far unknown. The process of fragmentation of an initial 10^2 to 10^5 $M_\odot$ molecular cloud into 1 to 50 $M_\odot$ fragments or clumps (both expressions are used synonymously in this letter) and possibly less massive ones plays an important role. It is directly linked to the question how the initial mass function (IMF) of stars is linked to the mass function of molecular cloud fragments. The IMF for stars with masses larger than 1 $M_\odot$ is well described by a power law of the form

$$\frac{dN}{dM} = A\, M^{-\alpha} \quad (1)$$

with α=2.7±0.5 (Scalo 1986). The form of the upper IMF seems to be universal in different environments in all types of galaxies (Larson 1991). Below 1 $M_\odot$ the IMF becomes significant flatter (Larson 1991).

There have been numerous studies to determine the mass spectrum of molecular clouds and their fragments (e.g. Casoli et al. 1984, Sanders et al. 1985, Stutzki & Güsten 1990, Williams et al. 1994, Kramer et al. 1998). Independent of the way to decompose the data set of molecular line observations into fragments these studies reveal power law mass spectra with indices α=1.4−1.8. Theses indices have been found over very wide mass ranges for clouds in different galactic environments. Even fragments in gravitationally unbound cirrus clouds follow a power law with a similar index (Kramer et al. 1998).

Decomposing molecular cloud data into fragments gives also information about the scaling laws between size r, clump mass M, and the velocity dispersion Δv of the clumps (Larson 1981). These parameters follow a mass-size relation $M \propto r^\beta$ and a size-line width relation $\Delta v \propto r^\gamma$ with β=2.2−3.7 and γ=0.3−0.6 for different clouds (Larson 1981, Elmegreen & Falgarone 1996, Heithausen 1996). It has been found that these relations hold for molecular clouds in different galactic environments and with different degrees of gravitationally binding.

All these studies have some bias, and the definition of cloud parameters is not always consistent between different authors. Results from different studies are therefore not easily comparable, especially when combining large and small scale studies. Moreover, in these studies clouds in different galactic environments are compared and it is so far not clear if the scaling laws and mass spectra hold for one single cloud over several orders of magnitudes in size and mass. This clearly demonstrates the

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necessity for a study combining high and low angular resolution data for one cloud and deriving cloud parameters in a consistent way.

The IRAM key project *Small Scale Structure of Pre-Star Forming Clouds* was specially designed to study the structure of non-star forming molecular clouds with highest presently achievable angular resolution with single dish telescopes. The data from this project are therefore well suited to study the scaling laws and mass spectra of molecular gas on smallest linear scales. Combination with larger scale maps of the same sources allows to extend these studies to cover a large range of sizes. One key question is if there is a break down of these scaling laws or a flattening of the mass spectra towards small sizes or masses.

2. The data sets and clump decomposition

For our analysis we combined high angular resolution data in the ^{12}CO (J=1→0) and (2→1) lines of one cloud core (MCLD 123.5+24.9) from the IRAM key project (Falgarone et al. 1998, Panis et al. 1998) with large scale observations obtained with the CfA 1.2 m telescope (Polaris Flare, s. Heithausen & Thaddeus 1990) and the KOSMA 3 m telescopes (Bensch et al. 1998). For the key project, over a period of about 1.5 years three cloud cores had been observed with IRAM 30 m telescope in several CO transitions, from which we select only the two lowest ^{12}CO rotational lines. The 30 m telescope has an angular resolution of 22″ at 115 GHz and of 12″ at 230GHz. Angular spacing between individual positions was 7.″5, both IRAM maps cover the same area of 6′ by 8′, slightly less than the beam of the CfA telescope at 115 GHz (8.′7) but significant larger than the beam of the KOSMA telescope at 230GHz (2.′2). All data sets selected here contain more than 3000 spectra each, thus large enough to provide statistically significant results. The IRAM (2→1) data have been corrected for contributions from the large error beam of the 30 m telescope (see Bensch et al. 1998). To increase the signal-to-noise ratio of these data we smoothed them to the same angular resolution as the IRAM (1→0) data (22″).

In the following analysis we apply the GAUSSCLUMP algorithm developed by Stutzki & Güsten (1990), which automatically decomposes the (l, b, v) data cube into fragments. The decomposition was stopped after 99.9% of the whole intensity was attributed to individual clumps. Each clump has a peak temperature of at least three times the rms determined in the baseline range. We only considered those gaussian clumps where the size after deconvolving from the instrumental resolution is larger than 40% of the instrumental resolution itself in all three dimensions; this criterium removes a large number of the smallest clumps from the mass spectrum which however attribute only about 15% to the total mass for the KOSMA and CfA data and 25% for both IRAM data sets. For a critical analysis of the algorithm we refer to Kramer et al. (1998).

We adopt a distance to MCLD 123.5+24.9 and the Polaris Flare of 150 pc. Integrated intensities of the ^{12}CO (J=1→0) line are converted to H_2 column densities using $X_{CO} \equiv N(\mathrm{H_2})/W(\mathrm{CO})$=0.6 10^{20}cm^{-2} (K km s^{-1})$^{-1}$. For the (2→1) transition we make use of the constancy of the line ratios of the two lowest rotational CO transitions (Falgarone et al. 1998) and convert the integrated line intensities of this transition to H_2 column densities using an X-factor scaled by this ratio.

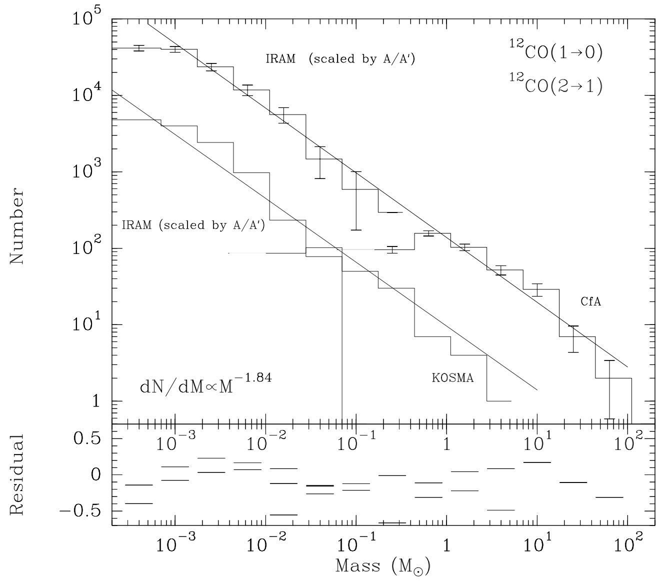

Fig. 1. Combined mass spectrum for the Polaris Flare determined from ^{12}CO J=1→0 (top histogram) and 2→1 observations (bottom). The gap between the CfA data and the IRAM data is due to the limited sensitivity of the CfA data near the noise limit. The solid lines in both mass spectra represent fits to the data with the mass spectral index α (see text) as the only free parameter. The scaling between the two data sets is determined self consistently as explained in the text. The residuals are plotted in the bottom box. Errorbars are $\sqrt{N}$.

3. Results

The combined mass and size spectra are shown in Fig. 1 and 2. To merge the mass spectra from the different telescopes, we assume that the IRAM field is a representative region of the Polaris Flare as a whole with regards to the clump statistics. We do not assume the IRAM field to be typical in terms of its contained mass or other properties; in fact the field was selected as being one of the coldest cores in terms of IRAS colors. The two data sets are matched by proper scaling of the pre-factor A in Eq. 1. A is determined by the total mass, M_{tot}, in the field observed, and the maximum and minimum clump mass, M_{max} and M_{min}, identified, via $M_{tot} = \int_{M_{min}}^{M_{max}} M \frac{dN}{dM} dM = \frac{A}{(2-\alpha)}(M_{max}^{2-\alpha} - M_{min}^{2-\alpha})$. Assuming a unique clump mass spectrum from largest to smallest scales and assuming the small scale observations to be representative for the small scale structure of the whole region implies α to be the same for the large and small scale observations. The ratio of the pre–factors A and A' of the different observations is thus given by $\frac{A}{A'} = \frac{M_{tot}}{M'_{tot}} (\frac{M'_{max}}{M_{max}})^{2-\alpha} \frac{1-(M'_{min}/M'_{max})^{2-\alpha}}{1-(M_{min}/M_{max})^{2-\alpha}}$. The assumption of equal α for the data sets has been verified by independently fitting the sets; this gave $\alpha(CfA) = 1.76 \pm 0.1$, $\alpha(IRAM, 1 \rightarrow 0) = 1.78 \pm 0.09$, $\alpha(IRAM, 2 \rightarrow 1) =$

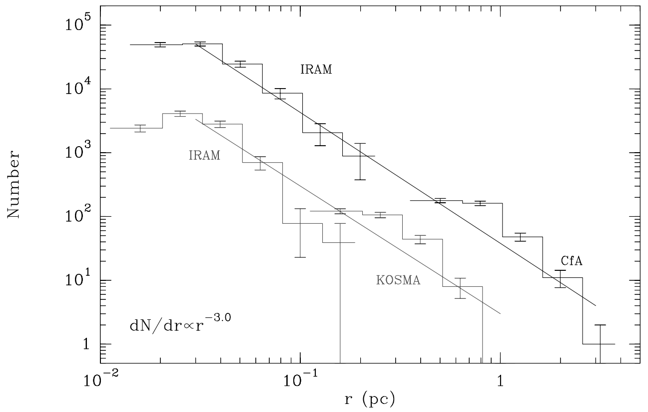

Fig. 2. Combined size spectrum for the Polaris Flare in the ^{12}CO (1→0) and (2→1) lines. The solid lines represent fits to the data.

1.86 ± 0.12, $\alpha(KOSMA) = 1.83 \pm 0.1$. Note that the ratio A/A' mainly depends on the ratio of the total masses in both fields, and only weakly on the minimum and maximum clump mass identified in each data set. This is due to the $M^{2-\alpha}_{min,max}$–dependence, $2 - \alpha \approx 0.2$ being a rather small exponent. The maximum clump mass in each data set is rather well determined, agreeing to within a few percent independent of the control parameters actually used for the GAUSSCLUMP decomposition. The M_{min}–dependence is additionally reduced due to $M_{min}/M_{max} << 1$. We thus fit the mass spectrum of both the large and small scale observations simultaneously with a single power law index α with the prefactors A and A' being linked to α via the above relation. In Fig. 1, we have already shifted the mass spectrum of the small scale data set according to the A/A'–scaling discussed above, so that the mass spectrum appears continuous across the different data sets.

For the first time we are able to determine the mass spectrum for a single cloud over more than 5 orders of magnitudes in masses (s. Fig. 1). The slopes determined from the fits are identical within the errors for both transitions; $\alpha = 1.84 \pm 0.06$ for the 1→0 line and $\alpha = 1.83 \pm 0.08$ for 2→1. It is remarkable that there is no flattening of neither mass spectra towards lower masses, down to masses less than that of Jupiter ($\approx 10^{-3}$ $M_\odot$). Fig. 1 includes the residuals of the fit to show that there is no discontinuity (to within the noise) at the mass scale were both data sets overlap. Both segments of the mass spectrum match well with a unique mass spectral index. This demonstrates that our assumption of the small scale data being representative for the whole cloud is indeed valid.

The size spectrum (Fig. 2) for the clumps identified from the (1→0) data is also of power law form, ($\frac{dN}{dr} \propto r^{-3.0\pm0.2}$). A fit to the 2→1 data gives the same index. Last, the masses of molecular cloud fragments as a function of their sizes are presented in Fig. 3. Due to the high dynamic range in sizes we are able to follow this relation over several orders of magnitude in size and mass. There is no obvious difference between the 1→0 and 2→1 data sets. Previous studies covering a smaller dynamic range gave much more uncertain values (e.g. Elmegreen & Falgarone 1996) for this relation; a fit to the data gives a power law of the form $M \propto r^{(2.31\pm0.05)}$, consistent with a relation between size and average density found for cirrus clouds (Heithausen 1996). Fits to the individual surveys give higher values for the power law index of the clump mass-size relation, an effect similarly already seen by Elmegreen & Falgarone (1996) for a wide range of data sets. We attribute this to the fact that clump masses as an integral quantity are much better determined than clump sizes. Within a given data set the size of the small, low intensity objects close to the resolution limits tends to be overestimated due to the contribution of noise. This leads to a steepening of the mass-size relation. Only the combination of several independent surveys helps to overcome this problem.

4. Discussion

In conjunction with supplementary large scale data the IRAM key project has allowed to build up an unique data set which enabled us to determine mass spectra and scaling laws over several orders of magnitudes in size and mass in an uniform way. The results of this Letter are based on observations in ^{12}CO lines of one cloud because only for these transitions and this cloud large and small scale data with sufficient area coverage are available. We find that the mass-size relation, and the mass and size spectra can be described with power laws with single indices from largest to smallest scales. We do not find a characteristic mass or size scale for molecular clumps down to at least Jupiter masses and sizes of about 2000 AU.

One uncertainty in the combined mass spectra comes from the calibration uncertainties between the temperature scales of the different telescopes. The fact that the IRAM map does not completely cover the CfA beam does not allow to directly compare the averaged high resolution spectrum with the corresponding spectrum from the CfA-survey. Intermediate scale KOSMA observations of MCLD 123.5+24.9 (Großmann et al. 1990) show that the variation of the integrated CO intensity is small inside the CfA beam, and the CO luminosity of the IRAM field is in good agreement with that of the KOSMA observations as well as the CfA observations. We estimate the influence of this uncertainty by varying the calibration between the large and small scale data sets by $\pm 30\%$: α changed from -1.79 to -1.87, well within the errors of the above described one-parameter fit. An additional uncertainty arises from the low mass cutoff for the smallest clumps close to the resolution limit (see Sect. 2); varying the threshhold only marginally influences the fit result because the reduction of the total mass in the mass spectra is compensated by the adjustment of the smallest mass bin.

When calculating masses for the different clumps we applied the same X factor for all clumps, down to scales of 0.03 pc. For the Polaris Flare this factor has, so far, been determined only on larger scales using γ-ray data (angular resolution $30'$, Digel et al. 1996) or infrared data (angular resolution $4'$, Meyerdierks & Heithausen 1996). For the present analysis we assume that the calibration for the X-factor also holds for the smallest scales of the IRAM data. The value we choose is in between the lower limit for the Polaris Flare found by Meyerdierks & Heithausen and the upper limit found by Digel et al. One might speculate

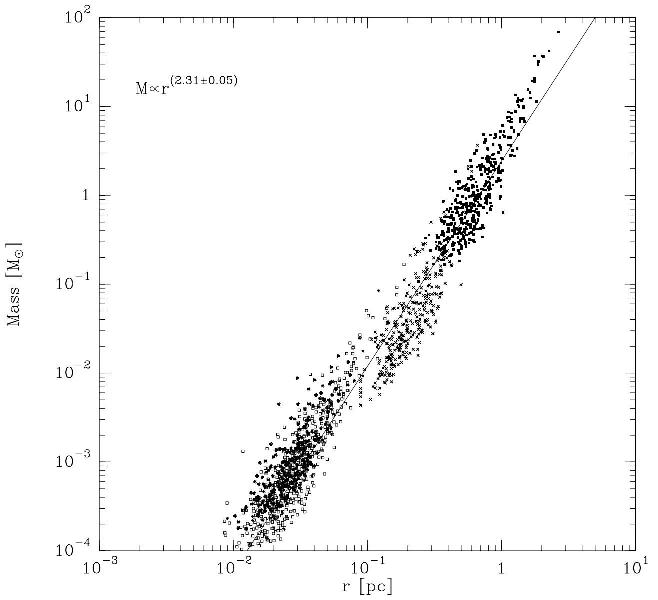

Fig. 3. Mass-size relation for the Polaris Flare. Data from the CfA 1.2 m telescope are marked as filled squares, data from the IRAM key project as open squares (1→0) and as ∗'s (2→1), KOSMA data as x's. The line drawn is a fit to the data.

that X varies systematically with the size of a clump due to systematically varying excitation conditions, in the sense that X increases with decreasing size. As long as this variation again scales as a power law with clump size or mass, it would simply change the indices of the clump mass spectrum and the mass-size relation. Our basic result would however still hold, namely that there is a single mass spectrum and a single mass-size relation from smallest to largest scales.

5. Conclusions

Both the Polaris Flare and MCLD 123.5+24.9 as part of it are gravitationally unbound clouds, their virial masses being 1 to 2 orders of magnitudes above their actual masses (Heithausen & Thaddeus 1990, Großmann & Heithausen 1992). Nevertheless, the mass spectrum shows the same form and a similar slope as those for other molecular clouds (Kramer et al. 1998) closer to gravitational equilibrium. These results have important consequences: (i) whatever the structure forming agent for molecular clouds is, it is not dominated by gravity; and (ii) the flattening of the stellar IMF below $0.5\,M_\odot$ is not intrinsically present in the mass spectrum of pre-star forming molecular cloud clumps, for which it should occur at higher masses than that of the stars forming out of the clump.

As suggested by Falgarone & Phillips (1990) there is substantial evidence that turbulence plays an important role in the dynamics of molecular clouds; it may be responsible for self similar structure on all observable scales down to the scale where the injected energy is dissipated. The fractal characteristic of the observed cloud structure has been shown by studying the area-perimeter relation of molecular line iso-intensity contours over several orders of magnitudes (Falgarone et al. 1991,Zimmermann & Stutzki 1992). More recently, Stutzki et al. (1996) and Elmegreen & Falgarone (1996) have argued that the fractal structure of molecular clouds leads to a mass spectrum of molecular cloud fragments of power law form. The similarity between the mass spectra for gravitationally unbound cirrus clouds and gravitationally bound clouds in conjunction with the similarity of the scaling laws for both types of clouds, further supports the fact that mechanisms other than than pure self-gravity are important in the fragmentation process of molecular clouds, a conclusion also suggested by Langer et al. (1995).

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References

Bensch F., Panis J.F., Stutzki J., Heithausen A., Falgarone E., 1998, A&A (in prep.)
Casoli F., Combes F., Gerin M. 1984, A&A 133, 99
Digel S.W., Grenier I.,A., Heithausen A., Hunter S.D., Thaddeus P., 1996, ApJ 463, 609
Elmegreen B.G., Falgarone E., 1996, ApJ 471, 816
Falgarone E., Phillips T.G., 1990, ApJ 359, 344
Falgarone E., Phillips T.G., Walker C.K., 1991, ApJ 378, 186
Falgarone E., Puget J.-L., Pérault M., 1992, A&A 257, 715
Falgarone E., Panis J.F., Heithausen A., Perault M., Stutzki J., Puget J.-L., Bensch F., 1998, A&A (in press)
Großmann V., Heithausen A., Meyerdierks H., Mebold U., 1990, A&A 240, 400
Großmann V., Heithausen A. 1992, A&A 264, 195
Heithausen A., Thaddeus P., 1990, ApJL 353, L49
Heithausen A., 1996, A&A 314, 251
Kramer C., Stutzki J., Röhrig R., Corneliussen U., 1998, A&A 329, 249
Larson R. B., 1981, MNRAS, 194, 809
Larson R.B., 1991, in *Fragmentation of molecular clouds and star formation*, IAU Symp 147, Eds. E. Falgarone & F. Boulanger, p. 261
Langer W.D., Velusamy T., Kuiper T.B.H., Levin S., Olsen E., 1995, ApJ 453, 293
Meyerdierks H., Heithausen A., 1996, A&A 313, 929
Panis J.F., Heithausen A., Bensch F., Falgarone E., Stutzki J., 1998, A&A (in prep)
Sanders D.B., Scoville N.Z., Solomon P.M., 1985 ApJ 289, 373
Scalo J.M., 1986, Fundam. Cosmic Phys. 11, 1
Stutzki J., Güsten R., 1990, ApJ 356, 513
Stutzki J., Heithausen A., Bensch F. 1996, in *IAU Symp. 170, CO: 25 years of mm-wave spectroscopy*, Eds. W.L. Latter et al. p. 50
Williams J.P., de Geus E.J., Blitz L., 1994, ApJ 428, 693
Zimmermann T., Stutzki J., 1992, Physica A 191, 79