A steeper stellar mass spectrum in the Outer Galaxy?

J. Brand

*Istituto di Radioastronomia - C.N.R., Via Gobetti 101, I-40129 Bologna, Italy (brand@ira.cnr.it)*

J.G.A. Wouterloot

*Joint Astronomy Center, Hilo, Hawaii, USA*

A.L. Rudolph

*Dept. of Physics, Harvey Mudd College, Claremont, CA, USA*

E.J. de Geus

*Neth. Found. for Research in Astronomy, Dwingeloo, The Netherlands*

Abstract. We discuss the results of high-resolution ($\sim 0.1 - 0.2$ pc) BIMA CO observations of the central regions of 3 molecular clouds in the far-outter Galaxy (FOG). We identify clumps and investigate their stability by using the virial theorem, including terms due to gravity, turbulence, magnetic field, and interclump gas pressure, and make a comparison with clumps in local clouds (RMC and Orion B South). While a reasonable combination of these forces can render most clumps stable, an interesting difference between FOG and local clumps emerges when comparing only gravity and turbulence. In the FOG these forces are in equilibrium (virial parameter $\alpha \approx 1$) for clumps down to the lowest masses found (a few $M_\odot$), but for local clumps $\alpha \approx 1$ only for clumps with masses larger than a few tens of $M_\odot$. Thus it appears that in the FOG gravity is the dominant force down to a much lower mass than in local clouds, implying that gravitational collapse and star formation may occur more readily even in the smallest clumps. This might explain the apparently steeper IMF found in the outer Galaxy.

1. Introduction

These observations are part of a long-term study in which, through a comparison of molecular clouds across the Galaxy, we aim to find the influence of a different physical environment on the properties of molecular clouds and their embedded star formation. Previously, we have studied molecular clouds at galactocentric distances $R > 15$ kpc (Brand & Wouterloot 1994) and analyzed molecular cloud properties across the Galaxy (Brand & Wouterloot 1995), using single-dish observations. Using the far-infrared luminosities of IRAS point sources in
the outer Galaxy, Wouterloot et al. (1995) derived a slope for the IMF which is steeper than that measured in the solar neighbourhood. In order to investigate this further we need to study the properties of clumps (sizes from \(0.2 \text{ to } 2 \text{ pc}\)) in molecular clouds in the outer Galaxy, and higher-resolution observations are required. Such observations are presented here.

2. Far-outer Galaxy clouds

Salient details of the three clouds we have observed in CO(1–0) are listed in Table 1. They were originally found in a single-pointing CO survey of IRAS sources in the outer Galaxy (Wouterloot & Brand 1989; WB89). In each cloud, we mapped the region around the IRAS source with BIMA, while the whole cloud was mapped in CO(1–0) (WB89-85; NRAO 12-m) or CO(2–1) (WB89-380, -437; KOSMA 3-m), to provide the zero-spacing baselines and mass estimates. The available data (radio-continuum, water masers, outflows) indicate that WB89-437 is the youngest star-forming region of the three, and WB89-85 the oldest.

| Name     | \(R_d\) (kpc) | \(M_{\text{CO}}\) \((10^4 \text{ M}_\odot)\) | \(L_{\text{H II}}\) \((10^4 \text{ L}_\odot)\) | Associated radio emission                                                                 |
|----------|---------------|---------------------------------|---------------------------------|------------------------------------------------------------------------------------------------|
| WB89-85  | 15.0          | 11.5                            | 1.6                             | Evolved (Sh 2-127) + compact; both optically visible                                          |
| WB89-380 | 16.6          | 10.3                            | 3.5                             | Compact; optically invisible                                                                 |
| WB89-437 | 16.2          | 9.1                             | 0.94                            | None. Opt. visible H\text{II} region in same cloud (WB89-436)                                |

The data were analyzed using the 3-D clump detection and analysis program CLUMPFIND (Williams, de Geus, & Blitz 1994). The program assigns virtually all emission in the BIMA maps (above a 2.5\(\sigma\) threshold) to clumps. The clump lists were trimmed to include only resolved clumps, that lie completely inside the map boundary.

2.1. Local comparison sample

The physical parameters of the clumps found in the FOG clouds were compared to those of clumps in two local clouds: the Rosette Molecular Cloud (RMC: Williams, Blitz, & Stark 1995, \(^{13}\)CO(1–0) at 0.8 pc resolution; Schneider et al. 1998, \(^{13}\)CO(2–1) at 0.12 pc resolution) and Orion B South (Kramer, Stutzki, & Winnewisser 1996, \(^{13}\)CO(2–1) at 0.14 pc resolution). The original data were provided by the authors, and on both clouds we performed the same clump analysis as on the FOG clouds.

3. Clump stability

A simplified picture of a molecular cloud is that of an ensemble of relatively high-density clumps, moving about in a low-density (interclump) medium. Various forces are at work on the clumps: their (self-\()\text{ gravity and the pressure of}
Figure 1. Ratio of the pressures balancing a clump’s equilibrium.

(a, b) Virial parameter (= ratio of turbulent and gravitational pressures) as a function of mass for two outer Galaxy clouds (a) and two local clouds (b). Symbols are for WB89-85 (open squares), WB89-380 (open triangles), Orion B South (crosses), and the RMC low-resolution (open circles) and high-resolution data (stars). The dotted lines are a visual aid to mark the lower envelope of points in the local sample.

(c, d) as (a, b), but now the gravitational pressure is the sum of that due to the clump’s self-gravity, and the pressure on the clumps exerted by the cloud’s interclump gas;

(e, f) as (c, d), but the pressure term of a 10 µG magnetic field has been added to the turbulent pressure.

the interclump medium try to compress the clumps, while the pressures due to turbulent and thermal motions, and due to magnetic fields work in the opposing direction. The virial theorem for a clump, with external pressure \( P \), can therefore be written as

\[
P/k = P_{turb}/k + P_{grav}/k + P_{magn}/k = \bar{\rho} \sigma^2/k - GM_{CO} \bar{\rho}/3rk + B^2/8\pi k,
\]

where the \( P_{turb} \) includes both thermal and (dominant) non-thermal contributions, and with \( \sigma \) the 1-D velocity dispersion, \( \bar{\rho} \) the average mass density, and \( M_{CO}, r \) the clump mass and radius. The ratio between turbulent and gravitational pressures is the virial parameter \( \alpha \). In Fig. 1 we plot \( \alpha \) and various pressure ratios as a function of clump mass. If a clump is in virial equilibrium with external surface pressure \( P=0 \) and in the absence of a magnetic field, the turbulent pressure is exactly balanced by the gravitational pressure, and \( \alpha=1 \). In both FOG and local clouds the most massive clumps meet this condition (Fig. 1 a, b), while lower-mass clumps have \( \alpha > 1 \) and would need some external pressure to be confined. Fig. 1 c, d shows that when the pressure-term due to the interclump medium is taken into account, virtually all clumps can be brought in or near equilibrium.

In fact, for many clumps in the local clouds (Fig. 1 d) \( P_{turb} \) is more than compensated for by the total \( P_{grav} \), and some stabilizing force is needed to prevent large-scale collapse. As shown in Fig. 1 e, f this can be achieved by adding the magnetic field-term to the pressure equation. The field may be stronger, especially in the more massive clumps and in the local clouds, while it
Figure 2. Plot (left), based on the NIR (JHK) image of the cluster around IRAS07257−2033 (WB89-997; R, d=15.7, 9.3 kpc; Brand & Wouterloot 2002). Size is ≈ 4.5 × 4.5 pc². Symbol size is proportional to K-magnitude; filled circles indicate stars with intrinsic IR-excess. On the right is the derived colour-colour diagram. The size of the circles is proportional to K-magnitude. The drawn curve is the unreddened main sequence; the dotted lines indicate the direction of normal interstellar reddening, and define the reddening band for normal stellar photospheres. Crosses indicate increments of 5 mags of visual extinction. Objects outside and to the right of this band have intrinsic IR-excess may be lower in the FOG clouds, but already with the presently used relatively low value it is clear that the magnetic field is an important ingredient in the pressure balance.

4. The importance of self-gravity

As seen in Fig. 1 a, b lower-mass clumps have α >1 and would need some external pressure to be confined (Fig. 1 c–f). However, in the FOG clouds there are clumps with small values for α even down to the lowest masses: in the high-resolution RMC data the lowest-mass clump with α ≤2 has M≈23.4 M☉, while this is 2.0 M⊙ and 4.7 M⊙ in WB89-380 and -85, respectively, i.e. up to an order of magnitude smaller. Moreover, in WB89-380 there are 14 clumps with M< 23.4 M☉ and α ≤2; in WB89-85 there are 5 clumps that fall within these constraints. In these clumps, gravity is the dominant force balancing internal turbulence; this implies that gravitational collapse and star formation may occur more readily even in the smallest of these outer Galaxy clumps. Since a clump of mass M can only form stars of mass less than M, this would mean that an excess of low mass stars is expected to form in the outer Galaxy with respect to local clouds. This would provide an explanation for the results of those (Garmany, Conti, & Chiosi 1982; Wouterloot et al. 1995) who find that the IMF steepens in the outer Galaxy.
5. Embedded star clusters

Do we actually find stars of $M \lesssim 1 \, M_\odot$ in the far-outer Galaxy, and are there more of them than what is seen locally? There is indeed ongoing star-formation in these, and other FOG clouds. Brand & Wouterloot (2002) have imaged 5 embedded clusters in 4 clouds in the J, H, K-bands with the ESO 2.2-m telescope. An example is shown in Fig. 2. The advantage of observing clusters in distant outer Galaxy clouds is that there is negligible contamination by background stars. We find stars with visual extinction $A_V$ up to about 19 mags. The completeness limit of our data is around $K \approx 16.5 - 17.5$. At a typical distance of 10 kpc and with $A_V \approx 10$ mags. this corresponds to spectral types A0V–A5V, i.e. $M \approx 2.9 - 2 \, M_\odot$; with $A_V \approx 20$ mags. this is about B8V, or $M \approx 3.8 \, M_\odot$. To find stars of masses low enough to be formed from the clumps discussed above, i.e. $0.5 - 0.8 \, M_\odot$ or types M0V–K0V, one needs to go down to at least $K \approx 21 - 20$ mags. (at 10 kpc and with $A_V=10$), which is a job for VLT/ISAAC.

6. Future work

The results discussed above are necessarily derived from a rather inhomogeneous data base, where effects of resolution, sensitivity and isotopomers and transitions play a role. For a detailed discussion of the observational biases we refer to Brand et al. (2001). Homogeneous observations of a larger sample of outer- and inner Galaxy clouds and their embedded stellar population are needed to verify if the difference in mass spectra reported here are a truly general phenomenon.

Acknowledgments. We thank Jonathan Williams, Carsten Kramer, and Nicola Schneider for making their original data available for analysis.

References

Brand, J., & Wouterloot, J.G.A. 1994, A&AS 103, 503
Brand, J., & Wouterloot, J.G.A. 1995, A&A 303, 851
Brand, J., & Wouterloot, J.G.A. 2002, A&A in preparation
Brand, J., Wouterloot, J.G.A., Rudolph, A.L., & de Geus, E.J. 2001, A&A 377, 644
Garmany, C.D., Conti, P.S., & Chiosi, C. 1982, ApJ 263, 777
Kramer, C., Stutzki, J., & Winnewisser, G. 1996, A&A 307, 915
Schneider, N., Stutzki, J., Winnewisser, G., & Block, D. 1998, A&A 335, 1049
Williams, J., Blitz, L., & Stark, A.A. 1995, ApJ 451, 252
Williams, J., de Geus, E.J., & Blitz, L. 1994, ApJ 428, 693
Wouterloot, J.G.A., & Brand, J. 1989, A&AS 80, 149 (WB89)
Wouterloot, J.G.A., Fiegle, K., Brand, J., & Winnewisser, G. 1995, A&A 301, 236 (Erratum in 1997, A&A 319, 360)