THE IMF OF GMCS

Leo Blitz, Erik Rosolowsky
Astronomy Department, University of California, Berkeley, CA, USA
blitz@astro.berkeley.edu, eros@astro.berkeley.edu

Abstract  The properties of GMCs in several Local Group galaxies are quantified and compared. It is found that the mass spectrum of GMCs varies from galaxy to galaxy. The variations are significant and do not appear to be the result of systematic uncertainties. Nevertheless, it appears that all of the GMCs follow the same size–linewidth and mass–linewidth relations with little scatter. The power law indices of these relations imply that the GMCs are self-gravitating, and that the mean surface density of Local Group GMCs is approximately constant. This, in turn, implies that the mean internal pressure of GMCs is also constant. If the IMF of stars is determined by a Jeans instability, this constant internal pressure suggests that the distribution of stellar masses does not vary significantly in galactic disks when averaged over suitably large areas. Thus, although the distribution of GMC masses produced by various Local Group galaxies is quite variable, the large-scale properties of the GMCs is not.

1. Introduction

The IMF in galaxies is not directly measurable except in rare cases (see Wyse this volume), but is often taken to be the same as that determined locally (Salpeter 1955) without much justification. Because the evolution of disk masses depends sensitively on the shape of the IMF at the low-mass end, knowledge about the variation of the IMF from galaxy to galaxy is an important parameter for understanding galaxy evolution.

One approach is to look at the GMCs from which the stars form. If the clouds have similar properties within and between galaxies, it would suggest that the stars that form from the GMCs might have similar properties and distributions. It is only within the last few years, however, that unbiased surveys of Local Group GMCs have been performed at sufficient angular resolution and sensitivity to determine the properties of GMCs in external galaxies (e.g., Mizuno et al. 2001a,b; Rosolowsky et
al. 2003). These surveys are large enough that comparisons can be made with GMCs in the Milky Way (Solomon et al. 1987; Heyer, Carpenter & Snell 2001). In this paper, we look at the GMC mass functions in the Milky Way, the LMC and M33, as well as the linewidth–size and linewidth–mass relations for these same galaxies to see what might be inferred from the current state of the observations.

2. The mass function of GMCs

Determination of the mass function of GMCs requires a large, unbiased survey of the molecular gas in a galaxy at sufficient angular resolution to separate the individual clouds from one another. It is not necessary to resolve the clouds in external galaxies, since the mass is proportional to the CO flux if the CO-to-H$_2$ conversion factor ($X$) is constant within a galaxy and from one galaxy to another. For the Milky Way, sufficient angular resolution has been available since the discovery of the CO line. The problem rather had been the large areas subtended by the CO emission from individual clouds compared to the telescope beams and the velocity blending produced by our edge-on view of the disk. Large surveys of the CO emission were required to obtain reliable GMC catalogues (Dame et al. 1986; Solomon et al. 1987). Nevertheless, attempts to obtain an unbiased catalogue of a sufficiently large sample of clouds suggest that the mass function $dN/dM \propto M^{-1.6}$ (Williams & McKee 1997).

More recently, Heyer et al. (2001) have completed a survey of the outer portions of the Milky Way visible from northern latitudes, and catalogued about $10^4$ molecular clouds. Again, resolution was not an issue; sky coverage required more than $1.6 \times 10^6$ spectra to complete the survey. Heyer et al. (2001) concluded that $dN/dM \propto M^{-1.9}$, but suggest without detailed analysis that the power law index is not significantly different from that found by Solomon et al. (1987).

Only a few galaxies beyond the Milky Way have had complete surveys of molecular gas done at high enough angular resolution to resolve the emission into GMCs: M33 (Engargiola et al. 2003), the LMC (Mizuno et al. 2001a), the SMC (Mizuno et al. 2001b), and IC 10 (Leroy et al. in preparation). The LMC and the SMC are close enough to be mapped with a filled aperture telescope, but each covers a large enough fraction of the sky that a dedicated program requiring many months has been necessary to map all of the molecular gas. In the SMC there are too few GMCs to obtain a reliable mass spectrum.

Beyond the Magellanic Clouds, aperture synthesis is required to separate and resolve individual GMCs. For a galaxy such as M33, however,
a great deal of observing time is needed to make a mosaic large enough to cover the 0.5 extent of the molecular emission. Wilson and Scoville (1990) mapped 17 fields in M33 with a 1' primary beam to obtain the first maps of individual molecular clouds in M33. Engargiola et al. (2003) required almost 800 fields with a 2' beam to get a nearly complete map of the galaxy. A catalogue of GMCs generated from this map, superimposed on an Hα map of the galaxy, is shown in Figure 1. Figure 2 shows the GMCs superimposed on the HI map of Deul & van der Hulst (1987).

Figure 1. The molecular clouds catalogued by Engargiola et al. (2003), shown at black dots enclosed by white circles, superimposed on a continuum subtracted Hα map from Massey et al. (2002). The diameter of each dot is proportional to the H2 mass of each GMC. Note the good correspondence between the HII regions and the location of the GMCs.

The mass spectra for M33, the LMC and the Milky Way are derived from the GMC catalogues of Engargiola et al. (2003), Mizuno et al. (2001a), Heyer et al. (2001) and Solomon et al. (1987) under the assumption of a single value of $X = N(H_2)/I_{CO} = 2 \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$. The total molecular mass varies greatly among the three galaxies. Thus,
Figure 2. The molecular clouds catalogued by Engargiola et al. (2003) superimposed on a map of H\textsc{i} surface density from the data of Deul & van der Hulst (1987). Note how the H\textsc{i} is arranged along filaments and how the GMCs are located almost exclusively on the filaments.

to compare the mass spectrum of each galaxy on an equal footing, we make a plot of the cumulative mass distributions normalized to the most massive cloud in each galaxy. A plot comparing the mass spectra of the three galaxies (showing the inner and outer Milky Way separately) is shown in Figure 3. It can be clearly seen that the mass spectra of all three galaxies can be well described by a power law: $dN/dM \propto M^{-\alpha}$. The index $\alpha$ of 2.3 for M33 is significantly steeper than that of the inner Milky Way.

As a check, we ask the following question: Scaling the H$_2$ mass of the Milky Way to that of M33, how many GMCs would one expect with a mass greater than that of $7 \times 10^5$ $M_\odot$, the largest GMC mass in M33? From the observations of Dame et al. (1986) for the largest GMCs in the Milky Way to M33, we would expect to find 15 clouds with masses larger than the largest mass GMC in M33; these 15 clouds would have a
IMF of GMCs

Figure 3. The cumulative mass spectrum for the inner and outer Milky Way, the LMC and M33. Each mass spectrum is normalized to the most massive cloud observed. Note that the mass spectra for the LMC is identical to that for M33 for the 7 most massive clouds, consistent with the results of Mizuno (2001a). There seems to be little question that the mass spectrum of M33 is very different from that of the inner Milky Way.

large fraction of the total mass in GMCs in M33. It is very unlikely that these would have been produced by the same parent population; the difference in the mass spectra between the inner Milky Way and M33 is apparently real. It is unclear why these differences occur, and it is also useful to know whether the clouds themselves have different gross properties.

The particular differences in power law index also imply fundamental differences in the way molecular gas is distributed in the Milky Way and in M33. In the Milky Way, a power law index $< 2$ implies that most of the mass in molecular gas is in the highest mass clouds. In M33, the power law index is $> 2$, which implies that most of the mass is in the lowest mass clouds. However, to avoid an infinite mass when integrating
the mass distribution requires either a mass cutoff or a change in index of the mass distribution. From a knowledge of the total molecular mass in M33, Engargiola et al. (2003) estimate that this change occurs at about $4-6 \times 10^4 \, M_\odot$. There is thus a knee in the mass distribution and most of the GMC mass in the galaxy occurs near the knee. This implies that there is a characteristic mass of the molecular clouds in M33; for some reason, M33 primarily produces GMCs with masses of about $5 \times 10^4 \, M_\odot$.

3. The Properties of GMCs

One way to compare the gross properties of individual GMCs in various galaxies is to look at the size–linewidth relation, a comparison of the radius of a cloud with its linewidth for many clouds. That such a relation exists was first suggested by Larson (1981). In the Milky Way, several investigators obtain a size–linewidth relation for GMCs with a power law index close to 0.5 with little scatter among the various determinations (e.g. Blitz 1993). This value is to be compared with that determined in other galaxies. Comparisons are complicated by several factors, however. First, most extragalactic GMCs are only marginally resolved and it becomes necessary to deconvolve the beam from the measurements. Second, it is important to correct the data for observations made with different sensitivities. These would likely leave the linewidths unchanged, but can give differing results for the diameters of the clouds. A comparison of the size–linewidth relation is shown in Figure 4 for the Milky Way, the LMC and M33. For the LMC, we take the catalogue of Mizuno et al. (2001a) and apply a correction for the beamsize of the telescope they used. We have only included clouds from the outer Galaxy study of Heyer et al. (2001) that have reliable kinematic distances and show no signs of blending. The GMCs in M33 and the LMC fall nicely on the relationship found for the Milky Way.

One way to get around the problem of observing clouds with only a few resolution elements across them is to look at the mass–linewidth relation. In this case, we plot the CO luminosity ($L_{CO}$) against linewidth ($\Delta V$) and assume that $L_{CO}$ faithfully traces $H_2$ mass. If GMCs are self-gravitating, we have

$$\Delta V^2 = \alpha GM/R$$

(1)

where $\alpha$ is a constant near unity that depends on the mass distribution. If the clouds obey a size–linewidth relation with a power law index of 0.5, then $\Delta V \propto R^{0.5}$. Together, this implies that

$$M/R^2 = \text{constant}; \quad M \propto \Delta V^4$$

(2)
Figure 4. The size-linewidth relation for GMCs in the galaxies indicated. The solid line is not a fit but rather has a power law index of 0.5 showing that such a slope is a good fit to the data.

The first condition implies that the surface density of GMCs is constant, the second, that a relation for molecular clouds exists similar to the Faber-Jackson relation for elliptical galaxies (Faber & Jackson 1976). The assumption of self-gravity seems fairly safe; The best argument for Milky Way GMCs comes from comparisons of their internal pressures with the external pressures in the disk that come from the hydrostatic equilibrium of the gas in the disk. In the solar vicinity, internal pressures are generally an order of magnitude greater than the external pressure and the clouds must therefore be self-gravitating if they are older than a crossing time. Since the properties of the catalogued extragalactic GMCs are not grossly different from those in the Milky Way, nor are the values of hydrostatic pressure expected to be very different, this assumption seems reasonable.

Figure 4 shows a plot of $L_{CO}$ vs. $\Delta V$ for the catalogued GMCs in the Milky Way, M33 and the LMC. The solid line is not a fit to the data,
but a line with a power law index of 4. Clearly, this index represents the GMCs quite well; a single power law seems to describe all of the Local Group GMCs with no offset and with a scatter of only about a factor of two.

Figure 5. The mass–linewidth relation for GMCs in the galaxies indicated. The solid line is not a fit, but rather has a power law index of 4 showing that it is a good fit to the data. A slope of 4 suggests that the clouds have a size–linewidth relation such that \( R \propto \Delta V^2 \) and that the clouds are self gravitating.

Thus, the two relations suggest that the GMCs in M33 and the LMC are similar to those in the Milky Way in that they are self-gravitating, that they obey the same size–linewidth relation and they have the same mean surface density with a relatively small scatter about the mean \((\sim 100 \, M_\odot \, \text{pc}^{-2})\). That is, even though the GMCs in the three galaxies under consideration here produce GMCs with different distributions of mass, the GMCs themselves have rather similar properties.
Recall, though, that the mean internal pressure $P$ in a self-gravitating gas cloud is proportional to the square of the surface density $\Sigma_{\text{gas}}$ only.

$$P = \beta \frac{\pi}{2} \Sigma_{\text{gas}}^2$$

(3)

where $\beta$ is a constant near unity depending on the geometry of the cloud. Thus, the internal pressure of the GMCs in these galaxies show little variation because their measured surface densities show little variation. If star formation is the result of a Jeans instability, as many astronomers believe, then the constancy of the mean internal pressure suggests that the range of physical conditions among star-forming GMC is quite small. This, in turn, suggests that the ability to form stars with mass distributions different from those found in the Milky Way is also small. The IMF, therefore may show little change from galaxy to galaxy within the Local Group, and very likely, in galactic disks with properties similar to three galaxies discussed here.

References
Blitz, L. 1993, Protostars and Planets III, 125
Dame, T. M., Elmegreen, B. G., Cohen, R. S., & Thaddeus, P. 1986, ApJ, 305, 892
Deul, E. R. & van der Hulst, J. M. 1987, A&AS, 67, 509
Engargiola, G., Plambeck, R. L., Rosolowsky, E., & Blitz, L. 2003, ApJS, 149, 343
Faber, S. M. & Jackson, R. E. 1976, ApJ, 204, 668
Heyer, M. H., Carpenter, J. M., & Snell, R. L. 2001, ApJ, 551, 852
Larson, R. B. 1981, MNRAS, 194, 809
Massey, P., Hodge, P. W., Holmes, S., Jacoby, J., King, N. L., Olsen, K., Smith, C., & Saha, A. 2002, Bulletin of the American Astronomical Society, 34, 1272
Mizuno, N., et al. 2001, PASJ, 53, 971
Mizuno, N., Rubio, M., Mizuno, A., Yamaguchi, R., Onishi, T., & Fukui, Y. 2001, PASJ, 53, L45
Rosolowsky, E., Engargiola, G., Plambeck, R., & Blitz, L. 2003, ApJ, 599, 258
Salpeter, E. E. 1955, ApJ, 121, 161
Solomon, P. M., Rivolo, A. R., Barrett, J., & Yahil, A. 1987, ApJ, 319, 730
Williams, J. P. & McKee, C. F. 1997, ApJ, 476, 166
Wilson, C. D. & Scoville, N. 1990, ApJ, 363, 435