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The Mass Spectra of Giant Molecular Clouds in the Local Group

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ABSTRACT. We reanalyze the catalogs of molecular clouds in the Local Group to determine the parameters of their mass distributions in a uniform manner. The analysis uses the error-in-variables method of parameter estimation, which accounts not only for the variance of the sample when drawn from a parent distribution, but also for errors in the mass measurements. Testing the method shows that it recovers the underlying properties of cumulative mass distribution without bias while accurately reflecting uncertainties in the parameters. Clouds in the inner disk of the Milky Way follow a truncated power-law distribution with index $\gamma = -1.5 \pm 0.1$ and maximum mass of $10^{6.5}\ M_{\odot}$. The distributions of cloud mass for the outer Milky Way and M33 show significantly steeper indices ($\gamma_{\mathrm{OMW}} = -2.1 \pm 0.2$ and $\gamma_{\mathrm{M33}} = -2.9 \pm 0.4$, respectively), with no evidence of a cutoff. The mass distribution of clouds in the Large Magellanic Cloud has a marginally steeper distribution than the inner disk of the Milky Way ($\gamma = -1.7 \pm 0.2$) and also shows evidence of a truncation, with a maximum mass of $10^{6.5}\ M_{\odot}$. The mass distributions of molecular clouds vary dramatically across the Local Group, even after accounting for the systematic errors that arise in comparing heterogeneous data and catalogs. These differences should be accounted for in studies that aim to reproduce the molecular cloud mass distributions, or in studies that use the mass spectrum as a parameter in a model.

1. INTRODUCTION

The mass distribution of molecular clouds is one of the primary characteristics of the their population. In the inner disk of the Milky Way, the mass distribution follows a power law with $dN \propto M^{\gamma} dM$, $\gamma \sim -1.5$. More recent surveys of molecular clouds throughout the Local Group find that the mass spectrum also follows a power law, but the indices are steeper than in inner Milky Way (e.g., Engargiola et al. 2003; Mizuno et al. 2001). Indeed, the mass spectrum may be the *only* feature of the molecular cloud population that varies between systems, since other cloud properties (e.g., cloud radius and line width) obey the relationships established in the Milky Way (Wilson & Scoville 1990; Rosolowsky et al. 2003; Mizuno et al. 2001). Careful attention to accurately determining the parameters of the mass spectrum is critical in using the mass spectrum to quantify differences between cloud populations. In addition, the empirically derived mass distribution is an important parameter for theoretical and modeling work. Several studies aim to reproduce the mass distribution of molecular clouds (Kwan 1979; Elmegreen & Falgarone 1996; Vazquez-Semadeni et al. 1997; Stutzki et al. 1998; Wada et al. 2000) or use the mass spectrum as inputs to models (McKee & Williams 1997; Tan 2000; Krumholz & McKee 2005). Most of these studies focus on the canonical value of $\gamma \approx -1.5$ adopted from the inner Milky Way, neglecting any variation in the distribution. Judging from the scope of these other studies, measuring the mass distribution of molecular clouds is essential for understanding both cloud formation and the importance of star-forming clouds in regulating large-scale star formation.

Since the parameters of the cloud mass distribution are widely used in the study of the star-forming interstellar medium, this paper outlines some of the pitfalls associated with the standard methods of estimating the parameters of power-law distributions and suggests improvements to minimize inaccuracy (§ 2). With these improvements, we reanalyze data from existing catalogs of molecular clouds (§ 3) and note interesting results (§ 4). This work stresses the importance of accounting for the observational uncertainties and systematic effects that bedevil the study of molecular clouds. Accurately deriving the index of a power-law distribution is also useful for studying populations of other objects. In particular, the derived mass spectrum of clumps within molecular clouds is subject to systematics that are identical to the mass distributions studied in this work. The methods developed in this study, as well as their attendant cautions, are directly applicable to the study of clump mass distributions and their relevance in the formation of individual stars (e.g., Williams et al. 1994; Stutzki & Güsten 1990). Luminosity and mass distributions of stars and galaxies are characterized by nonlinear distributions, and the techniques presented in this paper readily extend to the study of these objects.

2. FITTING MASS SPECTRA

The mass distribution of a population of molecular clouds is usually expressed in a differential form, namely the number of clouds that would be found in a range of masses. In the limit of a small mass bin, this is expressed as

$$\frac{dN}{dM} = f(M). \tag{1}$$

This expression can be integrated to give the cumulative mass distribution

$$N(M' > M) = \int_{M_{\max}}^{M'} f(M)\, dM = g(M), \tag{2}$$

which gives the number of clouds with masses greater than a reference mass as a function of that reference mass. For molecular clouds, both forms of the mass spectrum obey power laws: $f(M) \propto M^{\gamma}$ and $g(M) \propto M^{\gamma+1}$, with $\gamma < -1$ in all known cases. Some mass distributions lack clouds above some maximum mass M_0. To account for this feature, we adopt a truncated power-law distribution as suggested by Williams & McKee (1997), and alter their formalism to our notation. The full form of the cumulative distribution is

$$N(M' > M) = N_0 \left[\left(\frac{M}{M_0} \right)^{\gamma+1} - 1 \right], \tag{3}$$

where M_0 is the maximum mass in the distribution and N_0 is the number of clouds more massive than $2^{1/(\gamma+1)} M_0$, the point where the distribution shows a significant deviation from a power law. If $N_0 \sim 1$, there is no such deviation. For this form of the cumulative mass distribution,

$$\frac{dN}{dM} = (\gamma + 1) \frac{N_0}{M_0} \left(\frac{M}{M_0} \right)^{\gamma}, \quad M < M_0. \tag{4}$$

In most studies, only the index γ is reported, since N_0 is assumed to be 1 and M_0 is the maximum-mass cloud in the sample. The index is the most important parameter, since it describes how the integrated mass is distributed between the high- and low-mass members of the cloud population. For values of $\gamma > -2$, the majority of the mass is contained in the high-mass clouds, and the reverse is true for $\gamma < -2$. When $\gamma < -2$, the integrated mass diverges as $M \rightarrow 0$, implying a break in the power-law behavior of the mass spectrum at or below the completeness limit to ensure a finite integrated mass. Distributions with $N_0 > 1$ are also physically interesting, since they have a characteristic feature in an otherwise featureless mass distribution. In the Milky Way, Williams & McKee (1997) report evidence that N_0 is significantly different from unity, implying a cutoff at high mass ($3 \times 10^6\ M_{\odot}$) in the Galaxy. The parameters of the mass distribution are important both as predictions of theories as well as inputs to models. It is critical to estimate these parameters with minimum bias from the mass measurements of a cloud population.

2.1. Binned Mass Spectra

Most studies of the mass spectrum of giant molecular clouds (GMCs) estimate the slope of the mass spectrum by fitting an approximation of the differential formulation (eq. [1]). They generate this approximation by separating the mass measurements into logarithmically spaced bins. Then the number in each bin ($N_{\rm bin}$) is divided by the width of the bin ΔM: $dN/dM \approx N_{\rm bin}/\Delta M$. The uncertainties in these bins are then assumed to arise from counting errors, so $\sigma_{\rm bin} = \sqrt{N_{\rm bin}}/\Delta M$. Studies using this technique include Solomon et al. (1987), Williams & McKee (1997), Engargiola et al. (2003), Mizuno et al. (2001), Heyer et al. (2001), and many others.

There are two principal drawbacks to this technique: (1) it is sensitive to the selected values of bin size and bin spacing, and (2) it neglects errors in the mass determination of the clouds, which can be substantial. Figure 1 shows the variation in the derived index of the mass spectrum for different choices of bin size and bin position. To generate these figures, we used the mass data from Solomon et al. (1987, hereafter SRBY), with the same completeness limit of $7 \times 10^4\ M_{\odot}$ as is quoted in their paper. For a given set of bin parameters, we fit a power-law differential mass spectrum to all data that are at least one full bin above the completeness limit. We follow the method of Williams & McKee (1997) for the fit and the determination of errors in the mass distribution. The systematic error in the parameters is comparable to the errors typically quoted in these studies. Such errors become negligible in the limit of large numbers of clouds. In the study by Heyer et al. (2001, hereafter HCS), there are over 1300 clouds above the completeness limit, as opposed to only 200 in the SRBY study. When the same experiment is performed on this much larger sample, the variation in the derived index reduces to ± 0.05 and agrees with the -1.8 quoted in the HCS paper. To use binned mass spectra to estimate the parameters of the mass distribution, the sample should have $N_{\rm clouds} > 500$ to reduce errors to less than 0.1 in the index.

In addition to large variations in derived bin parameters, the binning method also neglects the principal source of uncertainty, namely the mass measurement itself. The mass of a molecular cloud is notoriously difficult to calculate. The principal methods for deriving the mass are to use the CO-to-H_2 conversion factor and the virial theorem. The conversion factor linearly scales the integrated CO surface brightness to a column density along a line of sight. With a distance measurement, the column density of the cloud and the area on the sky are combined to calculate the cloud mass. The conversion factor is empirically tested to trace H_2 column density across a variety of environments (Bloemen et al. 1986), although variation is reported among galaxies (Arimoto et al. 1996).

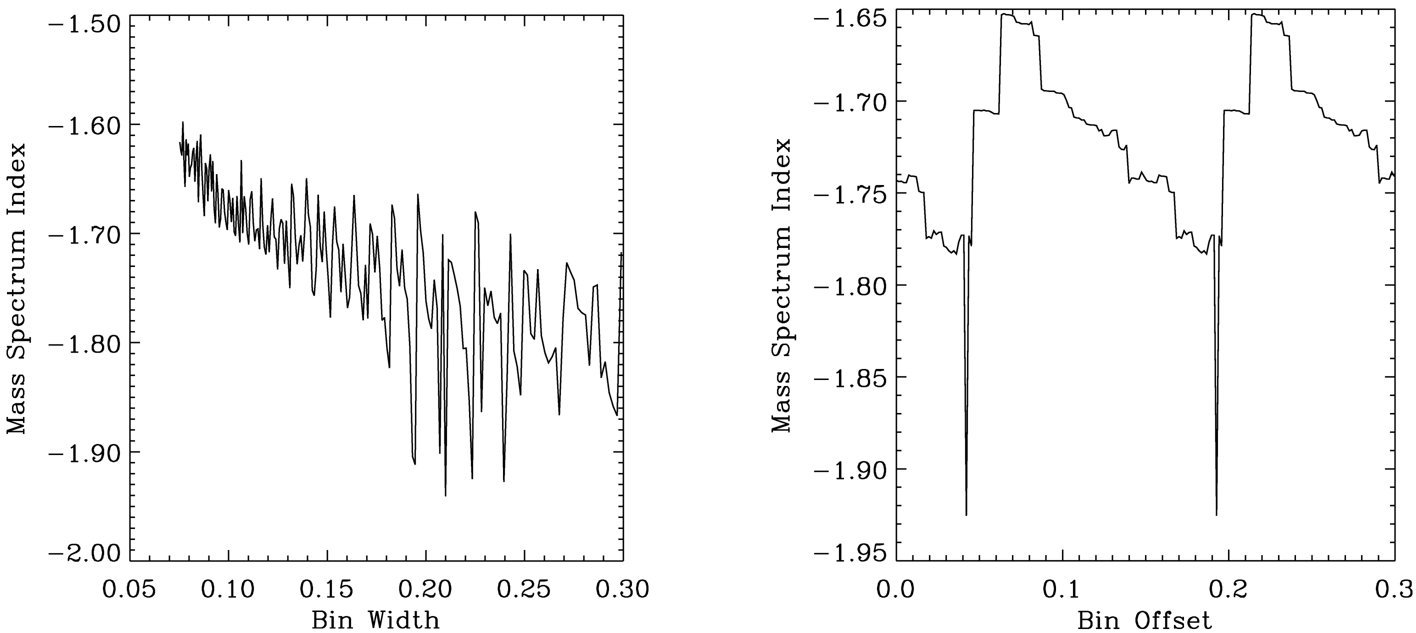

FIG. 1.—Demonstration that fitting binned mass spectra is sensitive to choice of bin size and offset. The left panel shows the derived index of the mass spectrum for the clouds in Solomon et al. (1987) as a function of the width of the logarithmic bins (in dex) used in fitting. The fits used the same completeness limit as the original study ($7 \times 10^4\ M_\odot$). The bin size ranged from a quarter octave, $0.25 \log_{10}(2)$, to a full octave, $\log_{10}(2)$. The right panel shows the variation in mass spectrum for half-octave bins and different bin positions. The bins are shifted in log space by the quoted bin offset. Both variations in parameters show significant variation in the derived index.

Within a single galaxy, however, the conversion factor has been found to be constant despite changes in the galactic environment (Rosolowsky et al. 2003). The virial mass measurement assumes that clouds are virialized and uses the resolved cloud sizes (R_e) and line widths (σ_v) to convert to a virial mass: $M_{\rm VT} = 5R_e\sigma_v^2/(\alpha G)$, where α is the virial parameter, which depends on the mass distribution within the cloud, as well as the influence of magnetic fields and external pressure on the energy balance of the cloud. HCS present evidence that molecular clouds with $M < 10^4\ M_\odot$ are not virialized and that the virial mass measurement overestimates the masses of these clouds.

Both of these methods for measuring cloud masses are subject to large ($\lesssim$50%) errors. Absolute flux calibration of CO data is rarely accurate to better than 10%. The variations of the conversion factor with physical conditions remain poorly understood, despite many attempts to quantify them (Wolfire et al. 1993; Dickman et al. 1986). Finally, the distances to most molecular clouds are difficult to measure. For Milky Way molecular clouds, most distances are determined kinematically, with the distance degeneracy for the inner Galaxy being broken by angular scale, displacement above the plane, and association with other objects of known distance (SRBY). Distance measurements are also important in measuring virial masses, since the physical size of the cloud is determined by converting an angular scale to a physical length. In addition, small or distant clouds are often poorly resolved, and great care must be taken to measure the radius of an intensity distribution that has been convolved with the telescope's beam. The largest pitfall in the virial method is the question of its applicability. Mass measurements nearly always neglect other contributions that are present in the full virial theorem, such as external pressure, changing moment of inertia, magnetic fields, the degree of virialization, and the measurement of a single size for a triaxial system. These deviations are frequently parameterized using the virial parameter (see above), which is surprisingly constant for massive molecular clouds ($\alpha \sim 1.5$; SRBY; HCS). Thus, the virial mass estimate provides a reasonable measurement of a cloud's dynamical mass. With all these potential sources of error, the masses of molecular clouds are highly uncertain, often to 50%, and this uncertainty should be included in the determination of the mass spectrum parameters.

2.2. Cumulative Mass Spectra

When a sample contains only a small number of clouds ($N_{\rm clouds} < 500$), it is still possible to derive the parameters of a mass spectrum by fitting the cumulative distribution of masses. Recent work by Fukui et al. (2001) demonstrated the utility of this method for clouds in the LMC. The principal difficulty of using this method arises in assessing errors for the data in the cumulative mass spectrum. Uncertainties appear in both the mass of the cloud and in the variance of a random sample being drawn from an infinite parent distribution. Practically, this results in fitting a truncated power-law function to data with errors in both coordinates. The mass coordinate has an uncertainty from the measurement error, and the cumulative number has an uncertainty characterized by a counting error, equal to $\sqrt{N}$.

To fit the data, we use the "error-in-variables" method for parameter estimation in nonlinear functions that have uncertainties in both coordinates. We use a method developed by Britt & Luecke (1973) that is the full development of a method originally suggested by Deming (1943). An equivalent method was developed into an algorithm by Reilly et al. (1993) that has been incorporated into StatLib.[1] It is this algorithm upon which the present work is based, although the error-in-variables method was also presented to the astronomical community in the work of Jefferys (1980). The method maximizes the likelihood that a set of data (M, N) with associated uncertainties (σ_M, σ_N) can be drawn from a distribution with parameters $\{N_0, M_0, \gamma\}$. Since the equations of condition cannot be solved algebraically for the parameters (as they can in the linear case), the minimization is performed iteratively in two interleaved phases. First, the true values of the data (i.e., without measurement errors) are estimated by maximizing the likelihood of being drawn from a distribution with some initial guess of parameters. Then, using the estimate of the true values of the data, the optimal values of the parameters are determined. The process is iterated until estimates of both the true data values and the parameters are determined.

Instead of performing the fit to the data using the model given by equation (3), we use the algebraically equivalent expression

$$y_i = \theta_1 x_i^{\theta_2} + \theta_3 \tag{5}$$

to improve independent estimates of M_0 and N_0, which are highly covariant in the original formulation. Once the algorithm has converged on a vector of parameters θ, we transform the elements of θ back to the parameters of interest. We use a bootstrapping technique to estimate uncertainties in the derived parameters, using 100 trials to sample the distribution of derived parameters, which is often non-Gaussian. The quoted values of the uncertainties in the parameters are the median absolute deviations of the transformed parameter distribution from the bootstrapping trials. Examination of the parameter distributions using a large number of bootstrap trials shows that the medians adequately characterize the uncertainties. For some distributions, there are more high-mass clouds than expected from the distribution at lower mass (i.e., the opposite of a truncation). In this case, the parameter θ_3 converges to zero. When this occurs, we fit a power law to a distribution of the form

$$N(M' > M) = (M/M_0)^{\gamma+1} \tag{6}$$

and report only M_0 and γ.

We validated our method by fitting the model to random data drawn from power-law distributions with known parameters. The trial data have normal deviates of known dispersion added to them to simulate the effects of measurement error. In these simulations, we find that the method both recovers the properties of the distribution without bias and produces error estimates from bootstrapping that agree well with the scatter in derived parameters around the known parameters. This implies that we are properly accounting for the error in the sample, as well as recovering the properties of the underlying distribution. These tests demonstrate that the error-in-variables fit to the cumulative mass distribution should be favored over a fit to the binned mass distribution.

2.3. Systematic Effects

In addition to the errors in the mass measurement, there are also systematic errors in the generation of mass spectra. The two dominant contributions to the systematic errors are the choice of the mass measurement (virial vs. luminous) and the method used to generate the cloud catalog. SRBY report $M_{\mathrm{VT}} \propto M_{\mathrm{lum}}^{0.8}$ in their sample, which implies that determinations of the index γ can vary by 10%, depending on the mass measurement.

The process used to generate the catalogs is likely the dominant systematic in measuring the parameters of the mass distribution. In particular, the resulting parameters of the mass distribution depend on which algorithm is used to assign flux to the physically significant substructures for which the masses are determined. Such decompositions include (1) human assignment to clouds (e.g., Wilson & Scoville 1990), (2) assignment by grouping neighboring pixels above a cut in brightness (SRBY; HCS), and (3) computer algorithms such as `clumpfind` (Williams et al. 1994) or `gaussclumps` (Stutzki & Güsten 1990). Assigning multiple distinct structures to a single cloud artificially drives the index of the mass spectrum toward more positive values. Such blending is most likely to occur when using kinematic data to untangle emission in the inner Milky Way. Conversely, overzealous decomposition of objects can erroneously split high-mass objects into lower mass objects, decreasing the value of the index or creating an artificial truncation in the distribution. Predicting the quantitative impact of these systematics is beyond the scope of this work.

Ideally, the mass distribution should be derived using the same decomposition algorithms and mass determinations from both observations and simulations in order to minimize these systematic effects. However, the magnitude of these systematic effects can be estimated by analyzing the same data set with different methods. Using the derived parameters from the het-

[1] See http://lib.stat.cmu.edu.

TABLE 1
Parameters of Mass Spectra for GMCs in Local Group Studies

Object	Name	Type	Number	γ	N_0	$M_0/(10^5\ M_\odot)$
Inner MW	SRBY	VT	190	-1.53 ± 0.07	$36. \pm 12.$	$29. \pm 5.0$
		CO	173	-1.53 ± 0.06	$27. \pm 11.$	$41. \pm 9.5$
Inner MW	SYSCW	VT	107	-1.58 ± 0.15	$14. \pm 10.$	$26. \pm 7.6$
		CO	97	-1.41 ± 0.12	$21. \pm 13.$	$29. \pm 7.2$
Outer MW[a]	HCS	VT	227	-2.56 ± 0.11	...	3.2 ± 0.78
		CO	81	-2.06 ± 0.15	...	6.3 ± 3.1
Outer MW	BKP	VT	336	-2.29 ± 0.08	4.5 ± 3.5	2.9 ± 1.0
		CO	81	-2.16 ± 0.17	2.7 ± 2.9	2.0 ± 1.0
M33	EPRB	CO	58	-2.85 ± 0.36	2.5 ± 2.7	8.6 ± 3.3
LMC	NANTEN	VT	44	-1.71 ± 0.19	$10. \pm 6.5$	$23. \pm 4.6$
		CO	55	-1.72 ± 0.12	6.1 ± 3.6	$82. \pm 32.$

[a] The mass distribution shows an excess of clouds at high mass, implying there is no truncation in the sample. A pure power law has been fit to the data (eq. [6]).

erogeneous data sets in this study, we find that the index can be robustly determined, in spite of these systematic effects. Identifying truncations and maximum masses are complicated by these systematic effects and require care to accurately recover them (see below).

3. LOCAL GROUP MASS SPECTRA

Using fits to the cumulative mass distribution, we have reanalyzed the catalogs of GMCs in the Local Group. Our results show significant differences in the mass distributions of the GMC populations. For each of the catalogs discussed below, we fit a power law to the cumulative mass distribution, including a truncation if appropriate (see above). Unless otherwise stated, when both virial and luminous measurements of the mass are reported, we use an error equal to half the difference between the two mass measurements, plus a 10% flux-calibration error added in quadrature. The results of the new fits to the Local Group mass distributions are summarized in Table 1. The reported errors are the median absolute deviation of the derived parameters for 100 bootstrapping trials. To illustrate a fit to the data, we plot the results of the fit to the virial mass data of SRBY in Figure 2.

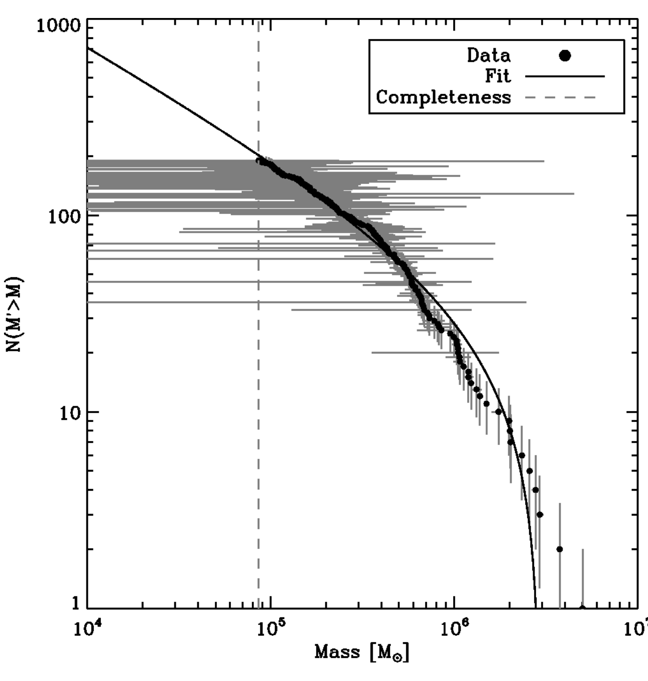

Fig. 2.—Mass distribution of the SRBY virial mass measurements. A truncated power-law fit to the data using the methods of this study is shown as a solid line. The data show a significant break around $N = 50$, and the fit recovers this feature well.

3.1. The Inner Milky Way

There are two major studies of GMCs in the inner Milky Way. Both SRBY and Scoville et al. (1987, hereafter SYSCW) analyzed FCRAO survey data from the first quadrant of the Galaxy, decomposing the emission into clouds using different algorithms. Comparing the results of these two studies highlights the systematic effects of using different decomposition algorithms. Both studies identified clouds as contiguous regions above a fixed antenna temperature cutoff, but chose different thresholds and methods for decomposing substructure. We use their measurements for virial mass and luminous mass, correcting for differences in virial definitions and Galactic scales, as summarized in Williams & McKee (1997). The index of the power law is unaffected by the choice of conversion factor. Typical mass errors are factors of ~15%. We fit all clouds with masses greater than $1 \times 10^5\ M_\odot$ in the SRBY study, which approximates their reported completeness level. For the SYSCW study, we compared the virial and luminous mass measurements after scaling the data, and we find that the virial mass estimates are a factor of 2 higher than the luminous mass measurements for the high-mass clouds. To place the samples on equal footing, we scaled the luminous mass of the clouds by a factor of 2 to bring the mass estimates into agreement. We then examined the distributions and established a completeness limit of $5 \times 10^4\ M_\odot$, based on where the distribution departed from a power law on the low-mass end. Fitting to both the virial and luminous masses for both studies finds an index $\gamma \approx -1.5$ and a significant cutoff, with ~25 clouds at the cutoff. For all four fits, $M_0 \approx 3 \times 10^6\ M_\odot$. The relatively small differences between the derived parameters, despite the different catalog methods, suggests that systematic effects are small in this case. Since the cataloging methods are conceptually similar in the two studies, this result is not surprising. The derived value of N_0 is slightly higher in the SRBY method than in SYSCW, suggesting that there is some influence of the catalog method on the cutoff values.

The mass distribution for the inner Milky Way is shallower than that found for other systems. Two effects may bias the results toward a shallower index. First, line-of-sight blending will make several less massive clouds appear as a single, more massive cloud, shifting the index toward shallower values. The methods used to generate the SRBY and SYSCW catalogs do little to split up blends of emission. Second, incorrectly resolving the distance ambiguity will also bias the mass distribution toward shallow indices. If every cloud has the same probability of having its distance incorrectly determined, then more low-mass clouds in the near distance will be erroneously counted as a high-mass clouds at the far distance than in the reverse, simply because there are more low-mass clouds. This latter bias can increase the index of the mass distribution by as much as 0.2 for 20% of the clouds that are assigned the wrong distance. Thus, the index of the mass distribution for the inner Milky Way very likely is steeper than can be derived from the current observational data.

3.2. Outer Milky Way

The data used for the outer Milky Way are from an FCRAO survey of a section of the second quadrant (Heyer et al. 1998) that were subsequently analyzed by both HCS and Brunt et al. (2003, hereafter BKP). HCS used a cloud extraction algorithm similar to SRBY, but defined cloud properties from the intensity distributions slightly differently. In contrast, BKP used a modified `clumpfind` algorithm to identify peaks in the emission distribution as the nuclei of distinct clouds. Their algorithm extracts roughly ~50% more sources than the work of HCS. They assign cloud properties to the emission distribution in a fashion similar to HCS. Mass errors in the HCS study are given as half the difference between mass measurements plus a flux error, and errors in BKP are reported in their study. Since clouds in the outer Galaxy with masses smaller than $10^4\ M_\odot$ are not virialized, we set $10^4\ M_\odot$ as the lower mass limit for the fits to these catalogs. Adopting this truncation includes many more virial mass measurements than luminous mass measurements, since the virial mass tends to overestimate the mass of clouds with $M_{\rm lum} < 10^4\ M_\odot$. Thus, the luminous mass distribution likely represents the underlying mass distribution better than the virial mass distribution. We also require the kinematic distance to be larger than 2 kpc to minimize errors in the distance determination. We find that the index of the mass distribution is steeper than reported in HCS, which is due to the improved fitting methods ($\gamma = -2.1$ vs. -1.8 in HCS). Since the luminous mass is likely a better tracer of cloud mass, we also perform a fit to the luminous mass data alone, using a lower limit of $2 \times 10^3\ M_\odot$, and derive an index of $\gamma = -2.05 \pm 0.06$.

The catalog of HCS shows more clouds than would be expected at high mass, given a power-law extrapolation from lower masses. Such an excess is not seen in the BKP catalog, because of the more aggressive decomposition algorithm employed in the latter study. Without careful analysis of the individual clouds, it is impossible to say what represents the true distribution of clouds at high mass in the outer Galaxy. Since evidence for a cutoff appears in the BKP catalog but not in the HCS catalog, comparing these two studies illustrates the systematic effects of different catalog methods. The strong evidence for a truncation that is found for the inner Galaxy data is lacking in the outer Galaxy. This is likely because there are too few molecular clouds to populate the distribution up to the truncation mass. Nonetheless, the index of the mass distribution is well determined and is significantly steeper than that found in the inner Milky Way.

3.3. M33

M33 is the only spiral galaxy for which a catalog of GMCs exists with a known completeness limit (Engargiola et al. 2003, hereafter EPRB). Since the galaxy is seen from an external perspective, blending effects are dramatically reduced compared to Milky Way studies. However, there are only 59 clouds above the reported completeness limit of $1.5 \times 10^5\ M_\odot$, and the clouds have only CO masses reported, since the individual clouds are not resolved. A follow-up study (Rosolowsky et al. 2003) has shown that the virial mass is proportional to the luminous mass for GMCs in M33, and that the $M_{\rm CO}/M_{\rm VT}$ does not vary significantly over the galaxy. We estimate the error in their measurements as the difference between the measured and corrected mass discussed in EPRB, plus their quoted 25% calibration error in the flux scale of the interferometer. The derived value of the mass index ($\gamma = -2.9$) is very steep. M33 is also the most distant galaxy in this reanalysis, and observational biases may affect the index of the mass distribution. However, the potential biases would only make the mass spectrum appear shallower than it actually is. In particular, blending effects will make several less massive clouds appear as a single massive cloud, and underestimates of the completeness limit will cause the number of low-mass clouds to be underestimated. The influence of either of these effects would imply that the mass index is actually steeper than what is measured, $\gamma \leq -2.9$.

It is likely that the extremely steep slope of the mass distribution is actually the tail of a distribution with a cutoff mass below the completeness limit of the survey. EPRB estimate a characteristic mass between 3×10^4 and $7 \times 10^4\ M_\odot$, which could simply be a cutoff mass in a truncated power-law distribution. To illustrate the effects of fitting a truncated power-law distribution above the cutoff mass, we repeated the analysis of clouds in the inner Milky Way, restricting the sample to clouds near the cutoff mass ($M > 2 \times 10^6\ M_\odot$). Fitting to the restricted sample gives $\gamma = -2.2$ with no evidence of truncation, instead of $\gamma = -1.5$ with a truncation. This supports our conjecture that the steep slope of the M33 mass distribution can be attributed to fitting a power-law distribution above the mass cutoff.

3.4. Large Magellanic Cloud

The only other complete survey of GMCs in a galaxy was completed using the NANTEN 4 m telescope to observe the LMC. Mizuno et al. (2001) report the most recent catalog of GMCs, including 55 resolved GMCs for which virial masses can be measured. A subsequent paper (Fukui et al. 2001) reports an index of $\gamma = -1.9$, using CO and virial masses from a currently unavailable catalog of more GMCs. All of the resolved clouds have masses above the completeness limit of the survey. Using the virial masses for the 55 clouds reported, we derive a mass spectrum index that is consistent with Fukui et al. (2001), with some evidence of truncation. The index on the mass distribution derived from the virial masses is likely a lower limit (i.e., $\gamma > -1.9$), because the reported virial mass measurements do not account for beam convolution. The error-in-variables fit to the data finds that the mass distribution is shallower ($\gamma = -1.7 \pm 0.2$) than that reported in Fukui et al. (2001), with some evidence of a cutoff. The maximum mass in the LMC is similar to that in the inner Milky Way ($3 \times 10^6\ M_\odot$), but the value is poorly constrained by the limited number of clouds in the catalog.

4. DISCUSSION

There is a real variation in the mass distribution of GMCs across the Local Group, with indices ranging from $\gamma = -2.9$ to -1.5. There are cutoffs at a maximum mass of $10^{6.5}\ M_\odot$ in catalogs from the inner Milky Way and the LMC. In general, the differences in the mass distributions have been unappreciated or trivialized; but they are, in fact, significant. In the inner Milky Way, the top-heavy mass distribution means that studying the most massive clouds encompasses most of the star formation in that part of the Galaxy. In contrast, low-mass clouds contain a substantial fraction of the molecular mass in the outer Milky Way and M33. In systems with bottom-heavy mass distributions, the star-forming properties of these low-mass clouds must be examined to obtain a complete picture of the star-forming interstellar matter. Using $\gamma \approx -1.5$ is appropriate for the inner Milky Way, but not for all galaxies.

Since molecular clouds *of a given mass* appear to be similar across the Local Group (Heyer et al. 2001; Rosolowsky et al. 2003), variation among the mass distributions is one of the only distinguishing features among molecular cloud populations. Owing to relatively short molecular cloud lifetimes (Blitz & Shu 1980; Leisawitz et al. 1989; Yamaguchi et al. 2001), molecular clouds have little time to increase significantly in mass, due to cloud collisions and accretion. However, the destruction of molecular clouds by their stellar progeny will change their mass through photodissociation and hydrodynamic effects. Observations show that the star formation rate scales roughly with cloud mass in the Milky Way (Mooney & Solomon 1988). If this is approximately correct throughout the Local Group, then differences in the mass distribution of molecular clouds are not likely to arise from different star formation rates. It seems likely that differences observed in the mass distributions must be due primarily to the formation mechanism of molecular clouds. Since many studies seek to explain the mass distribution of molecular clouds (Kwan 1979; Elmegreen & Falgarone 1996; Vazquez-Semadeni et al. 1997; Stutzki et al. 1998; Wada et al. 2000), these explanations must be expanded in scope to encompass the variety of mass distributions observed in the Local Group.

It is interesting to note that the environment with the steepest index of the mass distribution (M33) is also the region that is most gravitationally stable with respect to gravitational instability (Martin & Kennicutt 2001). This behavior might be expected if two mechanisms dominated the cloud formation process, each producing different mass distributions, and if one of the mechanisms were regulated by gravitational instability. For example, if the molecular clouds that form in spiral arms are more massive than those that form in the field, then a steeper mass index is expected in M33 where the disk is stable. Another possibility is that the galactic environment establishes the cutoff mass for the mass distribution. In both the inner Milky Way and the LMC, where there is reasonably clear evidence for a cutoff mass, that mass is roughly $3 \times 10^6\ M_\odot$. However, in M33 the characteristic mass of molecular clouds must be smaller than the completeness limit in the study ($1.5 \times 10^5\ M_\odot$) and is likely $\sim 5 \times 10^4\ M_\odot$. The outer Milky Way does not appear to show a characteristic mass that could be attributed to the absence of sufficient molecular material to populate the distribution at masses near the cutoff. It remains an open question as to what physics would establish the characteristic mass in these systems and why the characteristic mass in M33 would be 2 orders of magnitude less massive than in the Milky Way and the LMC.

5. CONCLUSIONS

This study emphasizes the importance of performing a uniform analysis to generate mass spectra. Using the error-in-variables method of parameter determination, we reanalyzed the molecular cloud catalogs for the Local Group of galaxies and report the following conclusions:

1. Fits to the cumulative mass distribution using the error-in-variables method produce a reliable estimate of the parameters of the mass distribution. Bootstrapping produces reasonable uncertainties these parameters. The adopted method is

superior to the standard technique of fitting a binned approximation to the differential mass spectrum, since it is insensitive to bin selection and it also accounts for uncertainties in the mass estimate.

2. There is significant variation in the mass distributions of molecular clouds across the Local Group, even after accounting for systematic effects and biases. Differences in the method used to catalog the molecular emission affect the derived parameters of the mass distribution. In particular, the presence and magnitude of a cutoff in the mass distribution is affected by the decomposition algorithm. Unless the cutoff is quite significant (as it is in the inner Milky Way), the presence of a truncation should be regarded with some suspicion. However, the index of the mass distribution is far less sensitive to the particulars of the mass determination and decomposition algorithm, resulting in systematic errors in the index (γ) of ± 0.1.

3. The mass distribution in the inner Milky Way has a measured index of $\gamma = -1.5 \pm 0.1$, with good evidence for a truncation in the distribution setting a maximum mass of $10^{6.5}\ M_{\odot}$. Systematic errors particular to the study of the inner Milky Way suggest that the true mass distribution may be steeper than this derived value. Using $\gamma \approx -1.5$ is appropriate for the inner Milky Way but does not approximate the mass distribution of molecular clouds across all galaxies.

4. The mass distribution of molecular clouds in the outer Milky Way is significantly steeper than that found in the inner Galaxy. The mass distribution has an index of $\gamma = -2.1 \pm 0.2$, steeper than previously claimed, and shows no evidence of a cutoff at high mass.

5. The GMCs in M33 show the steepest distribution found in this study, with no evidence of a cutoff. It is possible that the distribution actually has a cutoff below the completeness limit of the sample, which accounts for the derived index.

6. The LMC has a mass distribution that is steeper than that of the inner Milky Way ($\gamma_{\mathrm{LMC}} = -1.7 \pm 0.2$), but also shows some evidence of a cutoff near $10^{6.5}\ M_{\odot}$ that was previously unknown. An expanded catalog of clouds is needed to confirm this result.

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