GIANT MOLECULAR CLOUDS ARE MORE CONCENTRATED TOWARD SPIRAL ARMS THAN SMALLER CLOUDS

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ABSTRACT

From our catalog of Milky Way molecular clouds, created using a temperature thresholding algorithm on the Bell Laboratories 13CO survey data (Lee et al. 2001) using a thresholding technique13 CO survey, we have extracted two subsets: (1) clouds that are definitely larger than 10^5 M_☉, even if they are at their “near distance” (i.e., giant molecular clouds [GMCs]), and (2) clouds that are definitely smaller than 10^5 M_☉, even if they are at their “far distance.” The positions and velocities of these clouds are compared to the loci of spiral arms in (l, v)-space. The radial velocity separation of each cloud from the nearest spiral arm is introduced as a “concentration statistic.” Almost all of the GMCs are found near spiral arms. The density of smaller clouds is enhanced near spiral arms, but some clouds (~10% of the smaller clouds) are unassociated with any spiral arm. The median velocity separation between a GMC and the nearest spiral arm is 3.4 ± 0.6 km s^{-1}, whereas the median separation between smaller clouds and the nearest spiral arm is 5.5 ± 0.2 km s^{-1}. These separations in radial velocity are composed partly of the velocity dispersion of the cloud populations and partly of velocity differences due to spatial separations between the clouds and the spiral arms in the Galactic rotation field. A simple estimate indicates that the spatial separation component is relatively unimportant. The data are therefore consistent with the hypothesis that most molecular clouds in the Milky Way are spatially located in the spiral arms and that the velocity dispersion of the GMCs within the arms is less than that of the smaller clouds.

Subject headings: Galaxy: structure — ISM: clouds — ISM: molecules

1. INTRODUCTION

The Galaxy as a whole affects star formation through the mechanism of spiral structure. Stars in galactic disks tend to develop spiral-shaped density waves that result either from spontaneous instability of the disk or from gravitational perturbations induced by a quadrupole mass distribution such as a central bar or a companion galaxy. The spiral density wave modulates the gravitational potential in the disk, and the interstellar medium reacts nonlinearly to the varying potential, gathering and concentrating the gas. Giant molecular clouds (GMCs) form, leading to a local increase in the star formation rate and the creation of giant H II regions. The cloud formation process is not well understood and is the subject of ongoing investigation (Elmegreen 2000, 2002; Pringle et al. 2001; Hartmann et al. 2001; Zhang et al. 2002; Ostriker & Kim 2004). In this Letter, we measure the degree to which GMCs and smaller molecular clouds are concentrated in the spiral arms of the Milky Way, to provide a quantitative comparison with theoretical models of molecular cloud formation.

2. CLOUD IDENTIFICATION AND MASS ESTIMATION

A catalog of clouds was generated from the Bell Laboratories 13CO survey data (Lee et al. 2001) using a thresholding technique described in Stark & Lee (2005). This survey contains 2.3 × 10^7 pixels of 13CO data, each 0.005 × 0.005 × 0.68 km s^{-1} in size. Survey pixels having T_{A} > T_{th} are identified and grouped together in (l, b, v)-space to make a “cloud,” where all the pixels constituting the cloud are above the threshold and also adjacent to at least one other pixel that is also above the threshold. A cloud is then a connected volume of pixels, all of which are above the threshold. Applying the thresholding method with T_{th} = 1 K on the Bell Laboratories 13CO survey yields a catalog of 1400 clouds. As further described in Stark & Lee (2005), we assign several possible distances to each cloud based on our knowledge of the velocity field of the Galaxy. Essentially, the distances correspond to the “near” and “far” points of the distance ambiguity (e.g., Mihalas & Routly 1968), plus some additional uncertainty due to random motions. Each cloud has a range of possible distances.

We want to distinguish GMCs from smaller clouds, but the distances are uncertain, and, therefore, so are the luminosities and estimated masses. We can, however, derive a subset of the catalog that contains only GMCs and another subset that contains only clouds less massive than a GMC. For the purposes of this Letter, we define a GMC as a member of our catalog with L(13CO) > 5 × 10^3 K km s^{-1} pc^2. This mass corresponding to this luminosity is 1 × 10^5 M_☉, based on the mass-luminosity relation M_☉ ~ [20 M_☉ (K km s^{-1} pc^2)^{-1} L(13CO)] derived in Stark & Lee (2005) for clouds identified by the method we use here. For each cloud in the catalog, we calculate the range of luminosities corresponding to the range of possible distances. If all these possible luminosities exceed the luminosity threshold L(13CO) > 5 × 10^3 K km s^{-1} pc^2, the cloud is definitely a GMC, regardless of the distance uncertainties. Applying this criterion to the catalog yields 56 GMCs. If all the possible luminosities fall below the threshold, the cloud is definitely not a GMC but is included in the “definite small cloud” set. This second criterion yields 1257 small clouds. Our catalog also contains 87 clouds that do not fulfill either criterion. These are moderately large clouds whose distance is not well determined, and we exclude them from further consideration.
Fig. 1.—Distribution in and of two sets of clouds selected from the Bell Laboratories $^{13}$CO survey. The area of each symbol is proportional to the velocity width of the corresponding cloud. The red clouds have a mass $>10^5 M_{\odot}$, even if they are at their near distance; the blue clouds have a mass $<10^5 M_{\odot}$, even if they are at their far distance. The green curves indicate the loci of spiral arms: A and B are the local arm, C is the Sagittarius arm, D is the Scutum arm, E is the 3 kpc arm, and F is the Perseus arm.

3. SPIRAL ARM LOCI

Drawing the spiral arms onto the $(l, v)$-diagram of the Milky Way has been controversial. No one knows the location of the local minima in the gravitational potential, the underlying driver of the dynamics. Instead, surveys of 21 cm atomic hydrogen and radio recombination lines have been used to identify dense regions in the interstellar medium. These are connected with curves that deproject through the rotation curve to spirals in space. The spatial spirals and the $(l, v)$-plane curves are taken to have zero width. Here we adopt the analyses of Reifenstein et al. (1970), Burton & Shane (1970), Shane (1972), Lindblad et al. (1973), and Simonson (1976); we adopt locations defining the spiral arms from these references, and we interpolate using cubic spline functions. The spiral arms are plotted in Figure 1 and are identified by letters, as in Cohen et al. (1980). In the region of overlap with Cohen et al. (1980), our spiral arms agree with theirs. There is, in fact, good agreement among all authors about spiral arms in the region $20^\circ < l < 140^\circ$, but not for the Galactic center region. We therefore exclude from further analysis all clouds with $l < 20^\circ$. This reduces the sample sizes to 39 GMCs and 932 smaller clouds. The locations of these clouds are also plotted in Figure 1.

There is some circularity here: choosing the locations of the densest H II and H I regions makes it likely that the arms pass through the densest H$_2$ regions as well, and if there is some offset between the stellar spiral arm and the molecular spiral arm, we will not see it. Note too that arms “A” and “B,” the local arm and the Lindblad Ring, respectively, are not large-scale features of the Galaxy but local spurs that loom large because they are close to the Sun. Spiral arms “A” through “F” are adopted here because the literature is in agreement about their existence and location. The analysis below will be seen to support this choice.

As described by Dame et al. (1986), almost all the GMCs (red circles) lie close to spiral arms, like “beads on a string.” The most notable exceptions are the GMCs in the bridge between the Sagittarius (C) and Scutum (D) arms near $l = 38^\circ$, $v = 90$ km s$^{-1}$. The local spiral arm and Lindblad Ring (A and B) contain no GMCs within the area of sky covered by the Bell Labs survey. As noted by Cohen et al. (1980), the Perseus arm (F) is particularly distinct and well separated from the surrounding material.

4. CONCENTRATION OF CLOUDS TO THE ARMS

There is at least one spiral arm at some velocity for each value of $l$ in Figure 1. We can therefore define a “concentration statistic” for each cloud: the absolute value of the separation in radial velocity between that cloud and the nearest spiral arm, $|\Delta v|$. These values of $|\Delta v|$ can be interpreted as a projected distance, in one dimension of six-dimensional phase space, between the molecular cloud and the spiral arm. Such values could be determined in computer simulations of cloud formation and compared to those derived here. The set of $|\Delta v|$ for each of our cloud samples is the statistical distribution of separations of those clouds from the spiral arm loci. These distributions are plotted in Figure 2 for the GMC and small cloud samples.

The small cloud distribution has a long tail, containing about 10% of all clouds, that extends to large values of $|\Delta v|$. Most of these are near $l \approx 55^\circ$, $v \approx 30$ km s$^{-1}$, where a long segment of the line of sight falls between spiral arms and includes the tangent point (where a large range of distances project onto a small range of velocities). These are clear examples of interarm clouds. All but five of the GMCs have $|\Delta v| < 14$ km s$^{-1}$. Of those five, four are clouds in the Sagittarius-Scutum bridge (Cohen et al. 1980).
The Kolmogorov-Smirnov statistic (Press et al. 1992) is the largest vertical separation between the two distributions, as shown in Figure 2. The hypothesis that the two sets of $|\Delta v|$ are drawn from the same parent distribution is rejected at the 94% level by the Kolmogorov-Smirnov test—it is highly likely that the GMCs are distributed differently with respect to the spiral arms than are the small clouds. The two distributions have significantly different medians. The median $|\Delta v|$ for the GMCs is $3.4 \pm 0.6$ km s$^{-1}$, whereas the median $|\Delta v|$ for the small clouds is $5.5 \pm 0.2$ km s$^{-1}$. The errors in the medians are estimated by the bootstrap method (Efron & Gong 1983).

We will compare these results with the concentration statistics of objects that have the same radial distribution and velocity dispersion as molecular clouds but are azimuthally symmetric and therefore have no concentration toward spiral arms. The radial distribution can be parameterized by

$$\rho \propto R^\alpha \exp \left(-\frac{R}{R_p}\right),$$

where $\rho$ is the surface density of objects, $R$ is radius from the Galactic center, and $\alpha$ and $R_p$ are parameters. The Galactic rotation curve is taken to be flat, at a velocity $\Theta_\odot$. The velocity dispersion is Gaussian, with a one-dimensional rms of $\sigma_r$ (e.g., Stark & Brand 1989). A set of Monte Carlo objects were generated by the following steps: (1) Choose a set of parameters, $\alpha$, $R_p$, $\Theta_\odot$, and $\sigma_r$. (2) Use a random number generator to create a set of objects in two dimensions that have a radial distribution given by equation (1). (3) Calculate the $l$ and $v$ of each object as seen from the Sun at $R_p = 8$ kpc. (4) Generate a random Gaussian deviate for each object from a distribution with $\sigma = \sigma_r$ and zero mean, and add it to each $v$. (5) Compare the resulting set of random $(l, v)$-values to the catalog of actual molecular clouds, using a two-dimensional Kolmogorov-Smirnov test (Press et al. 1992). (6) Go back to step 1, varying parameters to maximize the similarity between the random set of objects and the observed catalog.

This procedure results in the parameters $\Theta_\odot = 215$ km s$^{-1}$, $R_p = 1.7$ kpc, $\alpha = 2.3$, and $\sigma_r = 7.7$ km s$^{-1}$. This value of $\Theta_\odot$ should not be taken to be a measure of the Sun’s rotational velocity. If the rotation curve were parameterized as $\Theta(R) \approx \Theta_\odot + (R/R_p)\Theta_1 + \ldots$, then $\Theta_1$ cannot be constrained by fitting to objects in the inner Galaxy: Galactic kinematics looks the same with a solid-body term added to the rotation curve. These data do not constrain $\alpha$ very well either, since our cutoff at $l = 20^\circ$ eliminates much of the molecular hole at $R \approx 3.5$ kpc. The shape of the inner edge of this hole is parameterized by $\alpha$, and almost all values of $\alpha$ between 2 and 3 fit well. The quick drop-off of the molecular ring to larger radii, $R_p = 1.7$ kpc, is typical of fits to first quadrant molecular line surveys (Burton & Gordon 1978; Solomon et al. 1979). The value of $\sigma_r = 7.7$ km s$^{-1}$ is consistent with the value $\sigma_r = 7.8 \pm 0.6$ km s$^{-1}$ determined for moderately large clouds near the Sun by Stark & Brand (1989).

The distribution of $|\Delta v|$-values for the Monte Carlo objects is plotted in green in Figure 2, and their median value of $|\Delta v|$ is $7.81 \pm 0.05$ km s$^{-1}$. This value is robust, in the sense that essentially any azimuthally symmetric distribution of random objects in the Galactic plane that we have tried will produce a median value of $|\Delta v|$ greater than $7$ km s$^{-1}$. The small molecular clouds are more concentrated toward spiral arms than random objects, and the GMCs are even more concentrated than the small clouds.

5. DISCUSSION

It is unfortunate that we cannot observe the Milky Way from the outside or see the spatial relationship between the molecular clouds and the spiral arms directly. Interferometric observations of CO in other galaxies having well-defined spiral structure show that the CO emission is concentrated toward the spiral arms (Guélin et al. 2000; Engargiola et al. 2003; Murgia et al. 2005). In the Milky Way, most of the CO emission is from GMCs. This is illustrated in Figure 3. Here we have taken the catalog subset discussed in Stark & Lee (2005), where the clouds were selected to have well-determined distances, and further restricted that subset to clouds with $l > 20^\circ$. Figure 3 shows the distribution of virial mass estimates for these clouds. The vast majority of the CO-emitting material, over 85%, is in the GMCs. Since the CO luminosity per molecule is approximately constant (Liszt 1984), the majority of the CO luminosity will also arise in GMCs. It seems likely that this is true of all spiral galaxies and that the concentration of CO toward spiral arms is principally a concentration of GMCs toward the spiral arms.

Given the median velocity separations derived in § 4, we can estimate the typical size of the spatial deviations from the spiral arms. The distributions of $\Delta v$-values are approximately Gaussian for small values, ignoring the long tails. For purposes of this estimate, we assume that the spatial deviations from the arms are also Gaussian. Let $\sigma_\Delta$ be the standard deviation of the $\Delta v$ distribution; in the Gaussian approximation, it is proportional to the observed median, $m$: $\sigma_\Delta = m/(\sqrt{2}) = 1.48m$, where $\text{erf}(b) \approx 1/2$. So $\sigma_\Delta \approx 8.2$ km s$^{-1}$ for the small clouds and $\sigma_\Delta \approx 5.0$ km s$^{-1}$ for the GMCs. We know that the one-dimensional rms velocity dispersions of clouds are $\sigma_r \approx 7.8$ km s$^{-1}$ for moderate-sized clouds ($M \approx 10^5 M_\odot$; Stark & Brand 1989) and $\sigma_r \approx 4$ km s$^{-1}$ for GMCs ($M > 10^{5.5} M_\odot$), given the reduced scale
where $\langle |dv/dr| \rangle \sim 11.3 \text{ km s}^{-1} \text{ kpc}^{-1}$ is the absolute value of the change in radial velocity with distance due to Galactic rotation, evaluated at the $(l, v)$-position of each cloud using a flat rotation curve with $\Theta = 215 \text{ km s}^{-1}$ and averaged over all clouds. The value of $\langle |dv/dr| \rangle$ ranges from 29.1 $\text{ km s}^{-1}$ kpc$^{-1}$ for the cloud at $l = 20^\circ 52', v = 76.5 \text{ km s}^{-1}$ to zero for clouds at the tangent velocity; most clouds in the sample have values of $|dv/dr|$ that lie near the middle of this range. The estimated separation, $\Delta r \sim 220 \text{ pc}$, which applies to both the small clouds and the GMCs, is comparable to the scale of a spiral arm. This estimate is crude, but we can say that, aside from the long tails in the distribution of $\Delta r$-values that are a clear indication of interarm clouds, the data are consistent with the hypothesis that most molecular clouds are spatially coincident with the spiral arms. In other words, it is possible that most molecular clouds are located within a spiral arm and that their apparent separation from the arm in the $(l, v)$-diagram simply reflects their velocity dispersion.

The interaction of molecular clouds with spiral arms is a dynamical process in six-dimensional phase space that can be modeled by computer. The Bell Laboratories $^{13}$CO survey provides us with statistical information about two spatial dimensions and one velocity dimension. We have seen in Stark & Lee (2005) that, on average, the GMCs are tightly concentrated toward the Galactic plane, with an FWHM scale height about 30 pc. We now see that these same GMCs are concentrated toward the spiral arms as well. Most clouds are associated with spiral arms, with the exception of some outliers located in interarm regions. Among the clouds near the arms, the GMCs are significantly more concentrated toward the arms in the velocity dimension of phase space than are the small clouds.

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