THE ELONGATIONS AND SUPersonic MOTIONS OF MOLECULAR CLOUDS

JIN KODA\textsuperscript{1,2,3}, TSUYOSHI SAWADA\textsuperscript{4}, TETSUO HASEGAWA\textsuperscript{3}, NICK Z. SCOVILLE\textsuperscript{2}

Manuscript in Preparation

ABSTRACT

New $^{13}$CO data from the BU-FCRAO Milky Way Galactic Ring Survey (GRS) are analyzed to understand the shape and internal motions of molecular clouds. For a sample of more than five hundred molecular clouds, we find that they are preferentially elongated along the Galactic plane. On the other hand, their spin axes are randomly oriented. We therefore conclude that the elongation is not supported by internal spin but by internal velocity anisotropy. It has been known that some driving mechanisms are necessary to sustain the supersonic velocity dispersion within molecular clouds. The mechanism for generating the velocity dispersion must also account for the preferred elongation. This excludes some driving mechanisms, such as stellar winds and supernovae, because they do not produce the systemic elongation along the Galactic plane. Driving energy is more likely to come from large scale motions, such as the Galactic rotation.

Subject headings: ISM: clouds — ISM: kinematics and dynamics — Galaxy: disk — Galaxy: kinematics and dynamics

1. INTRODUCTION

The nature, origin, and maintenance of the supersonic motions or turbulence in molecular clouds remain unresolved. These motions must be 'continuously' driven, since otherwise they decay on a cloud crossing timescale $\sim 3 \times 10^6$ yr. In fact, the free-fall collapse timescale of dense molecular clouds and presumably the timescale for the decay of supersonic motions are substantially shorter than the likely cloud lifetimes. Such driving mechanisms must exert influence on the shape of molecular clouds.

There is an argument that molecular clouds are only converging regions in interstellar turbulence, and thus, transient structures [Larson 1981; Fleck & Clark 1983]. Even in this case, the shape of structures on scales similar to the cloud sizes will reflect the mechanisms inputting energy at the top of the turbulent cascade. Using new data from the BU-FCRAO survey, we statistically investigate the shape of molecular clouds in the inner Galaxy.

Possible energy sources for the interstellar turbulence have recently been discussed on a theoretical basis (see Elmegreen & Scalo 2004; Mac Low & Klessen 2004). The sources may include stellar feedback (i.e. local events) and galactic rotation (i.e. large-scale motions). The physical mechanism converting these energies into turbulence has not been well understood. We expect that it affects the morphology of the gas structure as well as the turbulent motions. In particular, the shape of molecular clouds might indicate the possible energy source and physical mechanism. We will discuss the origin of the velocity dispersions as well as the shape of molecular clouds.

2. $^{13}$CO MOLECULAR CLOUDS

We use $^{13}$CO ($J = 1 \rightarrow 0$) line emission data from the BU-FCRAO Milky Way Galactic Ring Survey (GRS; see Simon et al. 2001). The data were downloaded from the GRS webpage in April 2004. They cover almost the entire region in the Galactic longitude $l \sim 16^\circ$ to $51^\circ$, latitude $b \sim -1.0^\circ$ to $+0.5^\circ$, and velocity $-10$ to $130$ km s$^{-1}$. The three-dimensional $(l, b, v)$ data cube has a fully sampled $22''$ grid in space and $0.22$ km s$^{-1}$ grid in velocity; the resolutions are $46''$ (FWHM beam size) and 0.25 km s$^{-1}$.

Molecular clouds are defined as topologically closed surfaces with the peak main-beam brightness temperature $T_{mb}$ above 4 K and the boundary temperature 2 K in the $^{13}$CO data cube. The 1-$\sigma$ noise level is $\Delta T_{mb} = 0.48$ K [Simon et al. 2001], and thus, emission features above 2 K (4$\sigma$) are all significant. The peak and boundary temperatures may be higher than those adopted in past CO studies (see Scoville et al. 1987; Solomon et al. 1987).

The kinematic distances are used to estimate cloud sizes and hence construct samples of small and large clouds. Distance ambiguities are solved by utilizing the virial- and LTE-mass relation as a distance indicator; we choose the distances so that the virial- and LTE-masses become the most similar. The relation is confirmed for the clouds at terminal velocities, which do not suffer from the distance ambiguity. The existence of the relation at terminal velocities justifies the assumption that virtually all clouds are gravitationally bound.

Each cloud is inspected by eye in $l-b$, $l-v$, and $b-v$ maps; possibly-blended clouds (about 10%) were removed from the sample (note that this operation does not change the following results; and the blending affected very few clouds as discussed in §5. We also remove small clouds with diameter $D < 5$ pc in order to select molecular clouds rather than small clumps and to have clouds which were well-resolved. Past CO surveys had similar cut-off for cloud identification because of their survey spacing (3$'$; Scoville et al. 1987; Solomon et al. 1987). The diameter is calculated as $D = (\Delta l \Delta b)^{1/2}$ by using the maximum linear extents in the $l$ and $b$ directions (Scoville et al. 1987). Incompletely sampled clouds

\textsuperscript{1} JSPS Research Fellow: koda@astro.caltech.edu
\textsuperscript{2} California Institute of Technology, MS105-24, Pasadena, CA 91125
\textsuperscript{3} National Astronomical Observatory, Mitaka, Tokyo, 181-8588, Japan
\textsuperscript{4} Nobeyama Radio Observatory, Minamisaku, Nagano, 384-1305, Japan
at the edge of the cube are also removed. The final catalog contains 552 clouds, most of which occupy more than 300 pixels each in the original data cube.

The data covers Galactic longitude $l = 16 - 51^\circ$. Its enclosed area is about $6.0 \times 10^7$ pc$^2$, assuming 8.5 kpc for the Galactocentric radius to the Sun. The average surface number density of our $^{13}$CO clouds is therefore $N_{MC} \sim 10$ kpc$^{-2}$ in the inner Galaxy ($R_{GC} \sim 4 - 8$ kpc). The number density is $n_{MC} \sim 100$ kpc$^{-3}$ assuming 100 pc for the thickness of the Galactic molecular disk (Sanders et al. 1984). These are slightly smaller than the values of CO molecular clouds (15 kpc$^{-2}$ i.e. 1427 clouds within $9 \times 10^7$ pc$^2$; Scoville et al. 1987).

Figure 4 shows the distribution of molecular clouds in $v - l$ diagram. Four thick lines indicate the Perseus arm, Sagittarius arm, Scutum arm, and 4 kpc arm (see Sanders et al. 1985). The other areas correspond to interarm regions. These spiral arms are identified entirely from the distribution of HI regions observed in radio recombination lines, and not from the molecular gas distribution. Most of massive $^{13}$CO molecular clouds ($> 10^5 M_\odot$) are associated with spiral arms, but many less-massive clouds exist in interarm regions. This indicates either that the most massive molecular clouds are broken up after passing spiral arms or that they cool down quickly so that $^{13}$CO emission becomes undetectable. On the contrary, the less-massive clouds survive across the spiral arms.

3. COMPARISON WITH $^{12}$CO MOLECULAR CLOUDS

Table 1 summarizes the average properties of $^{13}$CO molecular clouds. We adopted two definitions of characteristic size and velocity. The $D$ and $\Delta V$ are the diameter and full velocity width of the clouds (Scoville & Sanders 1987). The $S$ and $\sigma_v$ are the intensity-weighted dispersions of size and velocity (Solomon et al. 1987). The virial mass was calculated with the equation in Solomon et al. 1987.

The diameter $D$ is consistent with the CO values both on the average (18.1 pc in Scoville et al. 1987) and on the mass-weighted average (40 pc in Scoville et al. 1987). Therefore, the extensions of $^{13}$CO molecular clouds are almost the same as those of CO clouds. The velocity dispersion $\sigma_v$, however, is 1.4 times smaller than the one in past CO studies (1.4 km s$^{-1}$ in Scoville & Sanders 1987). The $\sigma_v$-$D$ relation is $\sigma_v = 0.23 D^{0.54}$, whose coefficient is $\sim 1.4$ times smaller than the one in the CO studies ($\sigma_v = 0.31 D^{0.55}$ in Scoville et al. 1987). A natural interpretation may be that the central dense regions of molecular clouds were saturated in the past CO studies. The $S$, i.e. dispersion, is also smaller by a factor of several than the one in CO studies (Solomon et al. 1985; see their Figure 1). Further discussion of the size and mass distributions will be presented in Sawada et al. (in preparation).

The averaged masses are different by an order of magnitude between the mass-weighted average and normal average (Table 1). This indicates that most molecular gas is in giant molecular clouds ($> 10^5 M_\odot$), however, the majority of molecular clouds has only $\sim 10^4 M_\odot$. These averaged masses are consistent with the ones derived in the past CO studies (Scoville et al. 1987; Scoville & Sanders 1987), if the 1.4 times difference of $\sigma_v$ is taken into account. The sound speed corresponding to the molecular gas temperature of 10 K is $\sim 0.2$ km s$^{-1}$. The much larger velocity widths ($\Delta V$ and $\sigma_v$) indicate that the internal gas motions are supersonic.

4. ELONGATION

The position angles and axis ratios of molecular clouds are calculated by diagonalizing the moment of inertia matrix as,

$$R_{-\theta} = \begin{pmatrix}
T_{ij} & -T_{ij} & 0 \\
-T_{ij} & T_{ij} & 0 \\
0 & 0 & 1
\end{pmatrix} = \begin{pmatrix}
I_{xx} & 0 & 0 \\
0 & 0 & 1
\end{pmatrix}$$

where $T_{ij}$ is the brightness temperature at a pixel $(i,j)$, and $\alpha_{ij}$ and $\beta_{ij}$ are the distances from the emission centroid to the pixel in the $l$- and $b$-directions. $R_\theta$ is a rotation matrix with the rotation angle $\theta$. The axis ratio and position angle of clouds correspond to $(I_{xx}/I_{yy})^{1/2}$ and $\theta$, respectively. The position angle is defined from the positive $b$-direction going counterclockwise to the positive $l$. The direction along the Galactic plane is $\theta = 90^\circ$.

Figure 2 shows the histograms of axis ratio and position angle. The axis ratio has the peak at about 1.8, indicating that the molecular clouds are significantly elongated. The population of round clouds, having the axis ratio of 1, is small. The position angle peaks at $\theta \sim 90^\circ$ (i.e. along the Galactic plane). Clouds with $\theta \sim 90^\circ$ is about two times more populated than those with $\theta \sim 0^\circ$ or $180^\circ$. Therefore, molecular clouds are elongated predominantly in the direction of the Galactic plane. We separate small clouds ($D < 15$ pc) from large clouds ($D > 15$ pc) in Figure 2. As well as the large clouds, the small clouds are predominantly elongated along the Galactic plane. These clouds are much smaller than the width of the gas disk (about 100 pc) and stellar disk (about 600 pc).

5. SPIN

It is possible that the elongation is supported by the spin of molecular clouds. In order to evaluate this, we measured the velocity gradient in molecular clouds (projection on the sky) and the position angle perpendicular to the maximum velocity gradient, i.e. parallel to the axis of possible spin (Figure 3). The velocity gradient is estimated from the observed velocity field by fitting a plane. The position angle $\psi$ is oriented with $0^\circ$ at $+b$, increasing toward $+l$. Typical velocity gradients $dv/dr$ projected on the sky are about 0.15 km s$^{-1}$ pc$^{-1}$. We did not correct for the apparent velocity gradient due to the projected LSR velocity over the diameter of the clouds, since this gradient is at most $\sim 0.04$ km s$^{-1}$ pc$^{-1}$, assuming a rotation velocity of 220 km s$^{-1}$. Prograde and retrograde spins with respect to the Galactic rotation are indicated with different patterns, and are equally populated.

Figure 3 right can be directly compared to Figure 2 right. If spin supports the elongation, the $\psi$ should be distributed similarly to the $\theta$; their peaks should be related as $\theta \sim \psi \sim \theta_{peak} \sim 90^\circ$. The figures, however, show that the spin is randomly oriented and has no dominant peak. Figure 4 shows the difference of the position angles of the elongation axis and spin axis. This figure shows no significant peak at $90^\circ$, compared with Figure 2 right and considering the statistical error $\sim N^{1/2}$. Therefore,
the cloud elongations are not supported by internal spins, but should be related to the internal velocity dispersions (supersonic motions).

It is noteworthy that confusion (blending) in cloud identification is likely to align the apparent spin axis perpendicular to an elongation – it is most likely that two clouds are slightly offset in space and velocity. The opposing result strongly indicates that the blending is not important in our sample.

6. DISCUSSION

The supersonic motions within molecular clouds must be regenerated continuously; otherwise they decay rapidly within a cloud crossing time. Mechanisms for driving the supersonic motion must also account for the cloud elongation along the Galactic plane. In light of the new results, we discuss a possible energy source and mechanism for driving supersonic motions and cloud elongations.

6.1. Energy Source

Among several suggested energy sources (see Elmegreen & Scalo 2004), two sources, i.e. stellar feedback and galactic rotation, are most often considered. Most other sources extract their intrinsic energies from these two.

Stellar feedback includes protostellar outflows, stellar winds, ionizing radiation, and supernova explosions. These feedback mechanisms, however, release energy isotropically or in random directions. Such processes are unlikely to cause the preferential orientation of molecular clouds. They would cause a random orientation.

Supernovae are the most energetic feedback mechanism (Norman & Ferrara 1996; Mac Low & Klessen 2004). There are some arguments for supernovae-induced dense gas formation and supersonic turbulence. If supernova blastwaves, however, compress surrounding material and induce molecular cloud formation, their round expansion will produce no preferential orientation. The blastwaves would escape from the Galactic disk predominantly in the direction normal to the Galactic plane. Then, most molecular clouds would be elongated perpendicular to the plane. The stellar feedback is unlikely to be the dominant cause of the elongation of molecular clouds.

Evidence has been accumulated for the presence of molecular clouds without star formation activity (Mooney & Solomon 1988; Scoville & Good 1983; Williams & Blitz 1998). Stellar feedback cannot supply energy to such clouds. High mass star-forming regions are localized around spiral arms in the Galaxy (Downes et al. 1983; Sanders et al. 1985) and in external galaxies (Scoville et al. 2001). It is also unlikely that the energy supply from stellar feedback suffices to maintain supersonic motions in interarm molecular clouds.

Since the cloud elongation has the preferential direction, the energy source is likely to have a similar preferred direction. Galactic rotation has an rotation axis, and is a likely energy source. Galactic rotation provides an enormous reservoir of energy; it can maintain the elongations and supersonic motions over the Galactic age.

Even if molecular clouds are only transient structures in large-scale interstellar turbulence, the anisotropic shapes should indicate the origin of the turbulence. It is still likely that the Galactic rotation is the main source of the turbulent energy.

6.2. Driving Mechanism

How might the rotation energy be transferred to random motion in molecular clouds? Energy transfer from rotation to random motions generally occurs in a differentially rotating disk, if mass elements orbiting at slightly different radii pull on each other (Sellwood & Balbus 1999). Sellwood & Balbus pointed out that many types of viscous stress, including Reynolds, Maxwell, and gravitational stresses, can cause the energy transfer from rotation to random motion.

For example, Jog & Ostriker (1988) found with an analytic calculation that cloud-cloud gravitational interactions (gravitational stress) can transfer the orbital energy of clouds into random motions between clouds (but they did not discuss internal motions). Wada, Meurer & Norman (2002) used hydrodynamical simulations and showed that the rotational energy could cascade into smaller scales (down to their resolution limit, i.e. the size of giant molecular clouds), owing to local tidal force among clouds, filaments, and voids. Perhaps, this cascade proceeds down to the internal motions of the clouds.

If tidal gravitational torques exerted by passing clouds is the cause of the velocity dispersions, the preferred elongation of molecular clouds would be produced naturally. The mean separation of molecular clouds is about 3 pc. This is larger than the thickness of the Galactic molecular disk 100 pc. Tidal radius of molecular clouds should be at least a few times larger than their diameter, and thus is not negligible compared with the disk thickness. Tidal interaction should occur predominantly in the Galactic plane; it may generate asymmetric velocity dispersions which cause the elongation along the Galactic disk.

A slight exchange of angular momentum may occur during tidal interaction and spin up clouds. The spin axis might become perpendicular to the elongation, however, this effect should be little. In case that two clouds pass by at the distance $d = 100$ pc and velocity $v \sim 6$ km s$^{-1}$ (typical cloud-cloud velocity dispersion), the tidal interaction would increase the velocity gradient within a cloud by at most $v/2\pi d \sim 0.01$ km s$^{-1}$ pc$^{-1}$ if the two clouds are strongly coupled. This is negligible compared with the observed velocity gradient. In addition, random encounters would suppress the increase of angular momentum. The spin-up is not significant even if the tidal interaction is the cause of supersonic motions.

We discussed only gravitational interactions between molecular clouds. Some other density fluctuations, such as filamentary structure in gas, would also strengthen the tidal field around clouds. There, of course, some other possible mechanisms introduced by magnetic field, surrounding diffuse gas (HI and H$_2$), and gradients in stellar potential. Further discussions would require theoretical researches.

7. SUMMARY

We showed that $^{13}$CO molecular clouds are elongated predominantly along the Galactic plane. The elongations are not supported by the spins of molecular clouds, but should be supported by supersonic velocity dispersions in molecular clouds. In order to avoid a rapid decay of the
supersonic motions, there must be some mechanisms to
drive them continuously. The driving mechanisms must
also account for the elongations of molecular clouds. The
driving energy is likely to come from large-scale motions,
such as the Galactic rotation, and not from stellar feed-
back.

The Boston University-FCRAO Milky Way Galactic
Ring Survey (GRS) is a joint project of Boston University
and Five College Radio Astronomy Observatory, funded
by the National Science Foundation under grants AST-
9800334, AST-0098562, & AST-0100793. We thank Kei-
ichi Wada, Masahiro Sugimoto, and Toshihiro Handa for
useful discussions. JK was financially supported by the
Japan Society for the Promotion of Science (JSPS) for
Young Scientists. This work has been partially supported
by National Science Foundation under grant 9981546.

REFERENCES

Mac Low, M. -M., Klessen, R. S., Burkert, A. & Smith, M. D. 1998,
Phys. Rev. Lett., 80, 2754
Mac Low, M. -M. & Klessen, R. S. 2004, Reviews of Modern
Physics, 76, 125
Scoville, N. Z., Yun, M. S., Clemens, D. P., Sanders, D. B. & Waller,
Hollenbach and H. Thronson (Dordrecht: Reidel).
Scoville, N. Z., Polletta, M., Ewald, S, Stolovy, S. R., Thompson,
Simon, R., Jackson, J. M., Clemens, D. P. & Bania, T. M. 2001,

Koda et al
TABLE 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>mass-weighted</th>
<th>mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D$ (pc)$^a$</td>
<td>38</td>
<td>15</td>
</tr>
<tr>
<td>$S$ (pc)$^b$</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>$\Delta V$ (km s$^{-1}$)$^c$</td>
<td>11.5</td>
<td>5.1</td>
</tr>
<tr>
<td>$\sigma_v$ (km s$^{-1}$)$^d$</td>
<td>2.2</td>
<td>1.0</td>
</tr>
<tr>
<td>$T_{\text{peak}}$ (K)$^e$</td>
<td>11</td>
<td>8.9</td>
</tr>
<tr>
<td>$M_{\text{VT}}$ (M$\odot$)$^f$</td>
<td>$1.2 \times 10^5$</td>
<td>$1.3 \times 10^4$</td>
</tr>
</tbody>
</table>

Note. — Mean parameters are calculated among molecular clouds with $D > 5$ pc.

$^a$ Diameter of molecular cloud
$^b$ Intensity-weighted size
$^c$ Velocity width at the 2 K level
$^d$ Intensity-weighted velocity dispersion
$^e$ Excitation temperature (calculated from main beam temperature and cosmic microwave background temperature (2.7 K))
$^f$ Virial mass

Fig. 1.— $v - l$ diagram of the distribution of all identified molecular clouds. Thick grey lines indicate four major spiral arms, i.e., Perseus arm, Sagittarius arm, Scutum arms, and 4 kpc arm (from left to right). These spiral arms are identified entirely from radio recombination observations, and not from CO observations (Downes et al. 1980; see also Sanders et al. 1985).
Fig. 2.— Distribution of axis ratios (left) and position angles (right) of molecular clouds. The values are calculated using the moments of inertia. Position angle $\theta$ is defined from the $+b$ direction going to positive $l$. Hence $\theta = 90^\circ$ is the direction along the Galactic plane. Large ($D > 15$ pc) and small ($D < 15$ pc) clouds are indicated with different patterns and illustrated accumulatively.

Fig. 3.— Distribution of velocity gradients (left) and position angles of spin (right) of molecular clouds. Position angle $\psi$ is defined as in Figure 2 (right), but ranges between $-90^\circ$ and $90^\circ$. Hence, $\psi = 0^\circ$ is the direction perpendicular to the Galactic plane. The right figure can be compared directly with Figure 2 (right). Prograde and retrograde spins are indicated with different patterns.
Fig. 4.— Difference between the position angles of elongation and spin.