Structural Model of Molecular Cloud Complexes: Mass, Size, and External Pressure

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Abstract

We investigate the structure of the molecular cloud complexes (MCCs) as a group of several giant molecular clouds (GMCs) in the Galaxy. Then, we find that the mass–size relation which has been reported for the GMCs establishes well even for the very large MCCs whose size is about 1 kpc. Since the horizontal size of the MCCs is more than the thickness of the Galactic disk, we can no longer consider the MCCs to be a sphere. Thus, we construct a structural model of the MCCs, adopting a rectangular-solid geometry. As a result, our model explains the observed mass–size relation of the MCCs very well. From the estimated external pressure around the MCCs, we find that they are in a rough pressure balance with the interstellar medium. Moreover, we find there is observational deficiency of the MCCs with a large size and surface density. Then, we suggest that the external pressure has a significant effect on the structure and evolution of the MCCs. We also discuss the effect of H II regions in the MCCs.

Key words: hydrodynamics — ISM : clouds — ISM : structure — Galaxy: ISM — stars : formation

1. Introduction

The star forming regions of the galaxies have a kind of the hierarchical structure; individual stars, H II regions, OB associations, aggregates, giant molecular clouds (GMCs), and complexes (Elmegreen, Salzer 1999). The star-forming complexes are the regions containing the smaller structures, and their typical size is more than several hundreds parsecs. For example, in our Galaxy, there are star complexes whose averaged diameter is about 600 pc (Efremov 1978). Also, there are H i superclouds which include a group of the GMCs (Elmegreen, Elmegreen 1987). In M51, the existence of the giant molecular associations, whose mass is more than \(10^7M_\odot\), are reported by Vogel, Kulkarni, Scoville (1988) and Rand, Kulkarni (1990). In this Letter, we concern such star-forming complexes, especially, the molecular cloud complexes (MCCs) as a group of several GMCs in order to understand the star formation activity over a galactic wide scale. Such MCCs have been observed in our Galaxy (Myers et al. 1986), although they are smaller than the giant molecular associations in M51.

By the way, from many observations of the GMCs, it has reported that there are famous correlations; the size–velocity dispersion relation and the size–mass (or density) relation (e.g., Larson 1981; Myers 1983; Sanders et al. 1985; Dame et al. 1986; Solomon et al. 1987). The former relation implies that the interstellar medium (ISM) is in a turbulent condition. The latter is that the mass of the GMCs is proportional to the square of their size. However, for the MCCs, these empirical correlations mentioned above have not discussed sufficiently to date. Hence, we discuss the mass-size relation (and also surface density-size relation) for the MCCs in this Letter.

On the other hand, the famous observational paper by Myers (1978) shows clearly that there is a global pressure balance among the variety components of the ISM. Although Bowyer et al. (1995) shows an evidence for a pressure imbalance in the local \((< 40 \text{ pc})\) ISM, such a pressure balance can be still acceptable in a galactic scale. Thus, a kind of the pressure equilibrium is often adopted to examine the structure and evolution of any component of the ISM. Indeed, the criterion of the gravitational contraction of the self-gravitating clouds is affected by the external pressure around them (e.g., Ebert 1955; Bonnor 1956; Nakano 1998). Thus, we should always pay a part of our attention to the importance of this external pressure.

Assuming such an pressure equilibrium and a spherical geometry, the structure and the empirical correlations among mass, size, and velocity dispersion of the GMCs are studied very well (e.g., Chèze 1987; Maloney 1988; Elmegreen 1989; Mecke, Holliman 1999). The assumption of the spherical structure for each GMC is not so crucial statistically if the number of sample clouds is sufficient. However, it is not good for the MCCs. Indeed, the MCCs are not spherical (see, for example, Figure 3 of Myers et al. 1986), and their horizontal size is about...
or above the thickness of the disk of the host galaxies. In this Letter, therefore, we investigate the structure of the MCCs, adopting not spherical geometry model.

In the next section, we summarize the property of the data adopted in our discussions. Our model is described in section 3. The results and discussions are presented in section 4, and the summary is presented in the final section.

2. Data Properties

We need a large sample of the MCCs, to obtain their clear and convincing property as a general picture. Furthermore, it is better that the sample MCCs are relatively similar each other. Then, we choose the MCCs in the Galaxy as the sample for our analysis. The suitable data of the MCCs are compiled in Myers et al. (1986).

Myers et al. (1986) examined 54 molecular clouds and cloud complexes in the Galactic disk. These clouds and complexes locate in \(-1^{\circ} \leq b \leq 1^{\circ}, 12^{\circ} \leq l \leq 60^{\circ}\). The MCCs contain typically five local maxima of the observed CO intensity in themselves. Solomon et al. (1987) observed the same region and detected 273 GMCs. These two observations are supplemented each other because of their different spatial resolution. For example, Solomon’s No.45, 48, 49, and 56 objects seem to correspond to Myers’ 17,58 objects. Also, Myers et al. (1986) examine whether individual clouds and MCCs are associated with H i regions. Some properties of their sample are tabulated in their Table 2.

The mass of each MCC was estimated from the integrated CO intensity over its observed area by using a standard CO–H$_2$ conversion factor \((2 \times 10^{20} \text{ cm}^{-2} \text{ [K km s}^{-2}\text{]}^{-1})\text{ of Lebrun et al. 1983}\). The derived observational masses distribute over the range of \(10^{4} - 7 M_{\odot}\), and the median value is \(6.3 \times 10^{5} M_{\odot}\).

We can observe the projected size of the MCCs perpendicular to the line of sight. In this Letter, we define a horizontal size of each MCC, \(l\), by the following equation,

\[ l = D \tan \delta l \text{ [pc]}, \]

where \(D\) denotes the distance in kpc from the Sun to the MCCs given by the column (4) of Table 2 in Myers et al. (1986) and \(\delta l\) is defined in degree by \(l_{\text{max}} - l_{\text{min}}\), which are the maximum and minimum Galactic longitude of the location of samples also given by the columns (2) and (3), respectively. One of the sample clouds of Myers et al. (1986) has a very small size \((l = 7.9 \text{ pc})\). Since we focus on the MCCs, we exclude it from the sample in our analysis. The determined \(l\) of the sample MCCs distributes over the range from 40 pc to more than 1 kpc. The mean value of \(l\) is about 300 pc. Here, we must note that the vertical size of the sample complexes is not available from Myers et al. (1986). Then, it is determined via a structural model presented in section 3.

A typical cloud complex has \(6 \times 10^{5} M_{\odot}\) as its mass and 300 pc as its size. Then, the escape velocity against its gravitational potential is about 3 km/s. This is almost same with the typical velocity dispersion of the internal GMCs (Solomon et al. 1987) and the stellar populations in the Galactic disk. Thus, we cannot insist that the MCCs are self-gravitating, and the MCCs may be the coincident aggregates of the GMCs. Indeed, the MCCs in the inter-arm regions may be unbound, but it is shown that the superclouds in the arm regions cannot be reproduced by a simple random superposition of the GMCs (Rand, Kulkarni 1990). Moreover, our sample MCCs are the internal structure of the H i superclouds which are approximately virialized objects (Elmegreen, Elmegreen 1987). Therefore, we assume the MCCs to be bounded objects.

In this sample of the MCCs, there is a good correlation between the mass estimated from the integrated CO intensity and the size of the perpendicular to the line of sight, that is, their masses are proportional to the square of their sizes. This is shown in figure 1. This relation is the same with that of the GMCs, although the both relations differ in the range of size. That is, the well known mass–size relation of the GMCs is established up to the MCCs whose size is about 1 kpc.

Moreover, according to Elmegreen, Salzer (1999), the blue luminosity of the star-forming complexes in spiral and irregular galaxies, whose mass and size are equivalent to that of the MCCs of this Letter, is also proportional to the square of their size. If we consider the blue luminosity to be proportional to the mass of the region, the result of Elmegreen, Salzer (1999) is consistent with our figure 1. Thus, the mass–size relation may be universal over large dynamic range of the size and mass.

3. Model Description

In this Letter, we focus on the MCCs in the Galaxy. As mentioned in section 2, a typical size along the Galactic plane of the sample complexes is more than 100 pc which is the thickness of the Galactic disk. Thus, the horizontal size of the MCCs is too large for us to consider the MCCs to be a sphere, unfortunately. In addition, the mechanism to determine a typical horizontal size of the MCCs should be different from that of the vertical direction. That is, the shear of the Galactic rotation must affect the determination of the horizontal size because of their large “Galactic scale” size, while the vertical scale is little affected by the rotation. Therefore, we assume a rectangular-solid geometry for the MCCs. This is the most simple geometry, except for the spherical one.

Let us consider below the mass of the MCCs with the rectangular-solid geometry. Since the physical length of the MCCs parallel to the line of sight is never observed in the Galaxy, this length is assumed to be the same with
the size of perpendicular to the line of sight, \( l \), defined in section 2. First, using this \( l \), we define the expected mass of a MCC as

\[
M = \rho_m h^2, \tag{2}
\]

where \( \rho_m \) and \( h \) are a mean density and a vertical thickness of a MCC, respectively.

Next, we discuss the vertical scale of the MCCs. The Galactic rotation does not affect the determination of the size in the vertical direction. Thus, we estimate that the vertical size of the MCCs is the simple Jeans length. That is, \( h = \sqrt{\pi c_{s,\text{eff}}^2 / G \rho} \), where \( c_{s,\text{eff}} \) represents an effective sound speed in a complex which contains the effects of thermal motions, turbulence, and magnetic fields, and \( \rho \) is a mean density of the Galactic disk. If we represent the mean stellar density as \( \rho_\ast \), then \( \rho = \rho_m + \rho_\ast \). \( c_{s,\text{eff}} \) is given by \( \sqrt{p_{\text{eff}} / \rho} \), where \( p_{\text{eff}} \) denotes an internal effective pressure inside a MCC (e.g., Kamaya, Shchekinov 1998; Kamaya 1999). In this Letter, we approximate \( p_{\text{eff}} = a p_{\text{ex}} \) (\( a > 1 \)), where \( p_{\text{ex}} \) is an external pressure and \( a \) is a factor of order of unity, because the internal pressure connects to the external one continuously, so both pressures are same order. Also, we approximate \( \rho = b \rho_m \), i.e., \( \rho_\ast = (b - 1) \rho_m \) (\( b > 1 \)). Since \( \rho_\ast \sim 0.1 \sim 1 M_\odot \text{pc}^{-3} \) (Binney, Merrifield 1998), and \( \rho_m \sim 0.7 M_\odot \text{pc}^{-3} \) for the typical MCC (where we remember the scale height, \( h \), is about 100 pc), we consider \( b \sim 1 - 2 \). Therefore, we obtain the vertical thickness of a MCC as the following equation:

\[
h = \frac{p_{\text{ex}}^{1/2}}{\rho_m} \sqrt{\frac{\pi}{G}}, \tag{3}
\]

where we set \( \sqrt{\pi} / b \sim 1.0 \). From this equation, we find that the vertical thickness multiplied by the density of the MCCs, that is, \( h \rho_m \) which is considered to be a kind of the face-on surface density, depends only on the external pressure, \( p_{\text{ex}} \) (see also Inoue et al. 2000).

Finally, we eliminate \( \rho_m \) and \( h \) from equation (2) by equation (3), then, we obtain the expected mass of the MCCs;

\[
\log \left( \frac{M}{M_\odot} \right) = 2 \log \left( \frac{l}{\text{pc}} \right) + \frac{1}{2} \log \left( \frac{p_{\text{ex}}}{k_B \text{ K cm}^{-3}} \right) - 0.413, \tag{4}
\]

where \( k_B \) is the Boltzmann’s constant. We compare this expected mass with the observational mass of the MCCs in the next section.

4. Results and Discussions

4.1. Mass vs Size

In figure 1, we compare the observational mass of the sample of Myers et al. (1986) (excluded one very small cloud) with the theoretical lines calculated by utilizing equation (4). The filled points represent the observed data of the MCCs associating with H II regions and the open points are those of the MCCs without H II regions. The solid, dotted, dashed, and dash-dotted lines are calculated via equation (4) by adopting \( p_{\text{ex}} / k_B = 10^2, 10^3, 10^4, \) and \( 10^5 \text{ K cm}^{-3} \), respectively.

In this figure, we find that our model lines reproduce the observational correlation of the mass with the size of the MCCs. We also find from this figure that the external pressure around the cloud complexes is expected to be about \( 10^{2-4} \text{ K cm}^{-3} \). The average value is \( \langle \log (p_{\text{ex}} / k_B \text{ K cm}^{-3}) \rangle = 3.4 \pm 0.7 \), where we also show the standard-deviation. This pressure is consistent with the pressure roughly balancing among various components of the ISM reported by Myers (1978). This indicates that the MCCs are in an equilibrium state along the rough pressure balance of Myers (1978), while the GMCs, whose size is about 10-50 pc, are not generally in such an equilibrium.

The average pressure of the MCCs estimated here is less than the turbulent pressure of their parent H I clouds determined by Elmegreen, Elmegreen (1987). This can be understood naturally if we consider that the regions with low turbulent motion in the parent H I clouds evolve into the molecular clouds. In fact, the cold and quiescent (i.e., low velocity dispersion or narrow emission line width) H I clouds in dwarf irregulars associate with the star-forming regions (Young, Lo 1996). Since the star-forming regions are considered to be within the molecular clouds, it indicates that the turbulent motion around the molecular clouds are relatively low. Therefore, such low external pressure of the MCCs is reasonable.

Finally, we comment on the method for estimating the mass of the MCCs or the star-forming regions. Once an external pressure is given, we can determine the mass of the MCCs from the observation of their size, by using equation (4). Moreover, if a MCC is the parent cloud of a star-forming region, and the sizes of the both objects are nearly the same, we can determine the mass of the star-forming region from only its size and a proper external pressure. Therefore, equation (4) may be very useful.

4.2. Face-On Surface Density vs Size relation

To discuss the relation between the surface density and size, we define a face-on surface density, \( \Sigma \), by the observational mass and size of the sample MCCs as being \( \Sigma \equiv M / l^2 \). In figure 2, we show the relation between this surface density and the size. The lines are calculated by the following equation;

\[
\log \left( \frac{\Sigma}{M_\odot \text{pc}^{-2}} \right) = \frac{1}{2} \log \left( \frac{p_{\text{ex}}}{k_B \text{ K cm}^{-3}} \right) - 0.413, \tag{5}
\]

which is derived from equation (3). The filled and open points stand for the same mean as figure 1.

We find evidently the void region of observational points at the region of a large surface density and a large
size in figure 2. In other words, the large MCCs are not observed under a high pressure condition along the context of our rectangular-solid model. If the deficiency is real, we suggest that a higher external pressure makes the size of the MCCs smaller. It may mean that the MCCs in a high pressure evolve efficiently. Indeed, a higher external pressure is likely to compress the MCCs more easily than a lower pressure. Then, cloud components inside each MCC may collide each other and the MCCs evolve rather quickly. Inversely, under the condition of a low external pressure, even the large MCCs can survive and evolve slowly. Thus, we conclude that the external pressure is important to determine the structure of the MCCs.

Unfortunately, we must comment that the uncertainty of the size determination of sample MCCs is large. In fact, Myers et al. (1986) includes the uncertainty of a factor of ∼2 for their determination of the cloud's boundary. Then, we must note that our result also includes this observational uncertainty. Hence, it is possible to think that the upper-right void is a just observational bias.

4.3. Effect of H II Regions

Since H II regions may affect the structure of the MCCs, we divide the sample into two groups in order to examine this effect. One is the group of the MCCs associating with observed H II regions, and the other is that of the MCCs without these regions. In figures 1 and 2, we find the comparison between this divided data points and model lines.

If there are H II regions in the MCCs, the effective pressure in the MCCs should be larger than that of the MCCs without H II regions. This means that the suitable external pressure is rather high for the MCCs with H II regions. In fact, for the MCCs with H II regions, \((\log(p_{ex}/k_{B} \text{cm}^{-3})) = 3.5 \pm 0.8\) while for the sample without H II regions, \((\log(p_{ex}/k_{B} \text{cm}^{-3})) = 3.1 \pm 0.7\), where we also show the standard-deviation. Thus, we find this trend in figures 1 and 2, although it is rather weak. This indicates that the effect of H II regions on the entire structure of the MCCs dose not so significant. However, for the individual GMCs in each MCC, the effect may be critical. It is important to examine whether the pressure of the GMCs with H II regions is higher than those without the regions. Unfortunately, we cannot resolve the problem in the framework of this Letter. Thus, it is an interesting future work.

5. Summary

We examine the mass–size relation and the structure of the MCCs in the Galaxy. Here we summarize our findings. First, we find that the mass–size relation which has been reported for the GMCs establishes well even for the very large MCCs. This relation is reproduced by our rectangular-solid model of the structure of the MCCs. In our model, the typical external pressure of the MCCs is estimated to be \(2.5 \times 10^5 \text{ kPa cm}^{-3}\). Thus, the MCCs may be in rough pressure balance of Myers (1978). Also, we find the observational deficiency of the MCCs with a large size and a large face-on surface density. And, we find the existence of H II regions in the MCCs increases the expected pressure slightly.

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Fig. 1. Comparison between the observational mass of the Galactic MCCs and the lines expected theoretically. The points denote the observational data of the sample in Myers et al. (1986) excluded one very small cloud. The filled points denote the MCCs associated with H ii regions and the open points are without these regions. Each of the lines are calculated by equation (4). The solid, dotted, dashed, and dash-dotted lines correspond to $p_{ex}/k_B = 10^2$, $10^3$, $10^4$, and $10^5$ K cm$^{-3}$, respectively.

Fig. 2. The estimated face-on surface density vs the observational size for the Galactic MCCs. The filled and open points mean the same as figure 1. The lines which are also the same as figure 1 are calculated by equation (5).

Figure Captions
