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A ^{12}CO Survey of the LMC with NANTEN

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Abstract. We have made a ^{12}CO($J = 1$–0) survey of the LMC with NANTEN. A sample of 55 giant molecular clouds has been identified and comparisons with stellar clusters, HII regions and SNRs are presented. The connection between the clouds and cluster formation is discussed.

1. Introduction

The Large Magellanic Cloud (LMC) classified as the barred sub-type of Hubble's irregular class is the nearest neighbor to our own. Studies of this galaxy have provided invaluable information for our understanding of the universe and galaxies in various aspects including evolution of stars and stellar clusters, owing to its proximity to the solar system ($D \sim 50$ kpc). Compared to the advanced evolutionary phase of stars, the process of star formation in the LMC has been only poorly understood, mainly due to the lack of comprehensive observations of giant molecular clouds where stars form. Previous observations of molecular gas in the LMC are either of low angular resolution or of small spatial coverage (Cohen et al. 1988; Israel et al. 1993; Kutner et al. 1997; Johansson et al. 1998). We have performed new observations of the LMC in the $J = 1$–0 rotational transition of interstellar carbon monoxide (CO) at 2.6 mm wavelength in order to reveal detailed molecular gas distribution at a linear resolution of $\sim$ 30 pc. These observations were made with NANTEN newly installed at Las Campanas Observatory, Chile in 1996 (Fig. 1) and should allow us to have a complete view of the giant molecular clouds in the LMC for the first time. Four related contributions included in these proceedings are complementary to this paper, describing more details of these CO observations and comparisons with other astronomical objects (Abe et al.; Mizuno et al.; Saito et al.; Yamaguchi et al.).

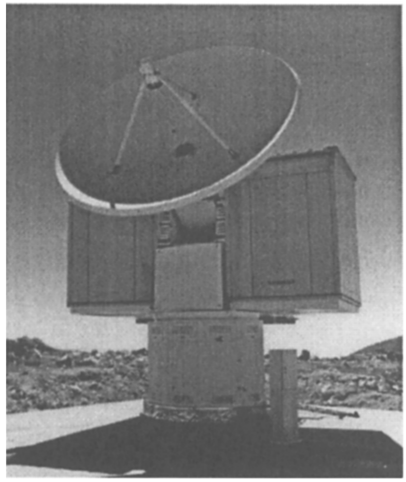

Figure 1. 4m millimeter-wave telescope, NANTEN, of Nagoya University located at Las Campanas Observatory, Chile.

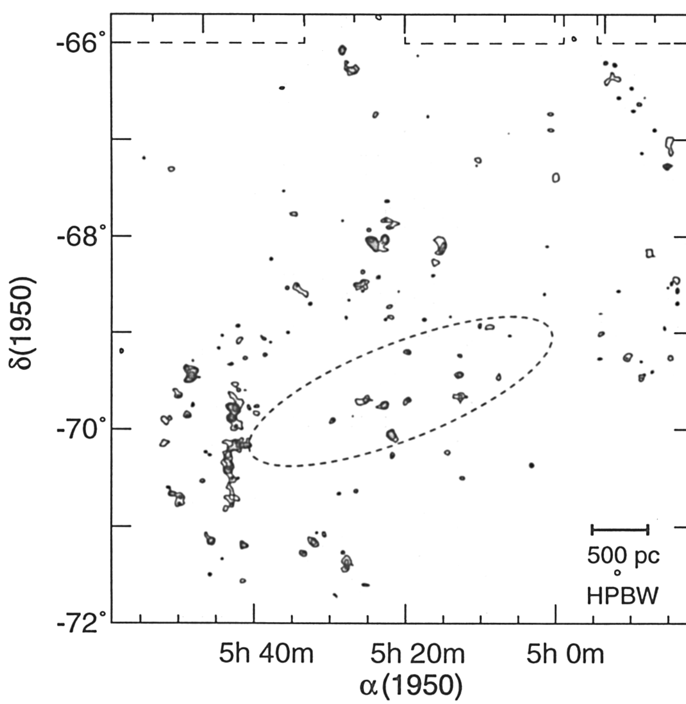

Figure 2. Velocity-integrated intensity of CO ($J = 1$–0) emission obtained with NANTEN. The lowest contour and the separations between contours are 3.0 K km s^{-1} for each. The dotted line shows the optical boundary of the Bar.

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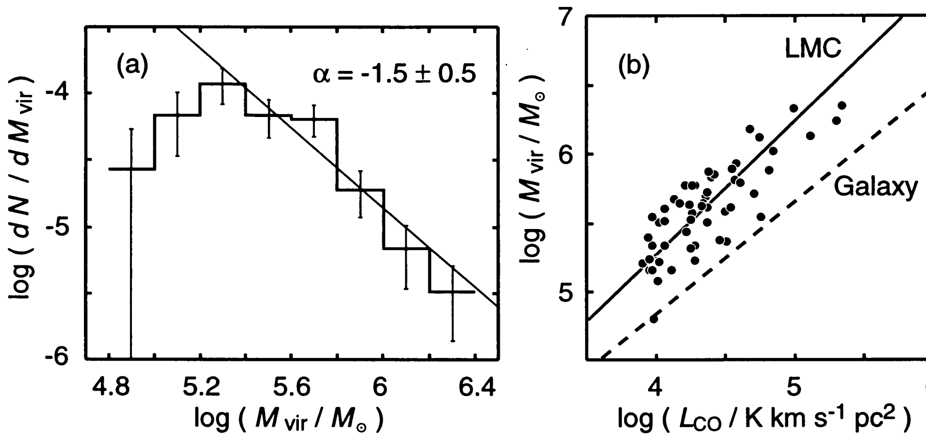

Figure 3. (a) Mass spectrum, $dN/dM_{\rm vir}$, of the 55 clouds. The error bars represent the $(dN)^{1/2}$ statistical errors. The straight line is the least-squares fit to the clouds with $M_{\rm vir} \geq 1.6 \times 10^5 M_\odot$ (by $[dN/dM_{\rm vir}] = 1.2 \times 10^4 \, [M_{\rm vir}/M_\odot \,]^{-1.5}$). (b) Virial mass, $M_{\rm vir}$, plotted against CO luminosity, $L_{\rm CO}$. The solid line represents the least-square fit and the dashed line indicates the same relation but derived for the Galactic molecular clouds (Solomon et al. 1987).

2. Properties of the Giant Molecular Clouds

Figure 2 shows the CO image obtained with NANTEN. This image consists of 32,800 spectra taken at every 2′, corresponding to $\sim$ 30 pc at a distance of 50 kpc, with a 2.′6 beam. The distribution is highly clumpy, extended over 36 square-degrees. Large CO complexes whose size is more than 100 pc are located at the southern part of 30 Dor and N44 regions. Smaller CO clouds are distributed over the observed area, with moderate concentration toward the Bar and toward several prominent HII regions. We note that an arclike semi-circular CO distribution whose diameter is $\sim$ 3 kpc is seen in the south-east boundary of the optical galaxy.

The number of the CO clouds in Figure 2 is more than 100. Among them, there are 55 CO clouds which are detected at more than three positions. The mass of these 55 clouds ranges from $\sim 10^5 M_\odot$ to $\sim 3 \times 10^6 M_\odot$, indicating that they are giant molecular clouds. In Figure 3a, we present the mass spectrum $dN/dM_{\rm vir}$ of the 55 clouds. It is fitted by a single power-law of an index of -1.5 in a cloud mass range 10^5–$10^6 M_\odot$, which is similar to that found in our Galaxy (Solomon et al. 1987). The lower boundary, $\simeq 10^5 M_\odot$, is the present detection limit in mass. Figure 3b shows the relation between the virial mass ($M_{\rm vir}$) and CO luminosity ($L_{\rm CO}$), for the 55 CO clouds. The CO luminosities in the LMC are weaker by a factor of $\sim$ 3 relative to those in the Galaxy. By using this factor, the total molecular cloud mass is estimated from the CO luminosities to be $\sim 4 \times 10^7 M_\odot$, 90% of which is included in the large 55 clouds whose H_2 column density is greater than 2×10^{21} cm^{-2}. According to the subsequent, more sensitive observations of selected regions, the cloud mass may increase up to $\sim 7 \times 10^7 M_\odot$ at the H_2 column density $\geq 1 \times 10^{21}$ cm^{-2} (see Mizuno et al. 1999 in these proceedings). We, therefore, estimate the molecular mass to be 4 – 7 $\times 10^7 M_\odot$, corresponding to 5 – 10% of the HI mass M(HI) $\sim 7 \times 10^8 M_\odot$ (McGee & Milton 1966).

The apparent weakness of CO relative to $M_{\rm vir}$ (Fig. 3b) is possibly caused by the lower metal abundance and by enhanced photodissociation due to relatively strong UV radiation fields under significantly smaller shielding. The conversion factor $X \equiv N(H_2) / I_{CO}$, the ratio of H_2 column density to CO line intensity, varies strongly with such physical conditions in clouds. The conversion factor, X, for clouds in the LMC, determined by assuming that they are virialized, is 9×10^{20} cm^{-2}/(K km s^{-1}). This is smaller than the value from Cohen et al. (1988) obtained with the 1.2 m radio telescope, but about 3 times higher than the value for our Galaxy (Solomon et al. 1987).

3. Formation of Star Clusters

In order to study star formation in the LMC, detailed comparisons of the CO clouds with stellar clusters, HII regions, and SNRs have been made over the whole Cloud as shown in Fig. 4.

The following are the results of the comparison of CO clouds with *stellar clusters* and *OB associations* (hereafter, *clusters*). Out of the 55 CO clouds, 26 are associated with clusters. Using the age of the clusters estimated from their color indices, UBV (Bica et al. 1996), $\sim$ 90% of the clusters associated with the CO clouds are younger than 10 Myr (SWB0). The older clusters with $\tau > 10$ Myr (SWBII-VII) show little correlation with the CO clouds. The youngest clusters associated with massive CO clouds tend to be in a compact group of young stellar clusters, i.e., N159 and N44. These groups of clusters are located at or near the peak of the CO clouds, indicating that they have been just formed in massive CO clouds.

The youngest clusters show a significant correlation with the CO clouds; about $\sim$ 30% of them are associated with CO clouds. The remaining $\sim$ 70% of the youngest clusters tend to be scattered, away from the CO clouds. Though these clusters may be associated with clouds smaller than the present detection limit, this suggests that young stellar clusters can rapidly dissipate their surrounding CO clouds (see also Yamaguchi et al. in these proceedings.)

Comparisons of the 55 massive CO clouds with HII regions and with stellar clusters indicate the following:

1. 12 CO clouds show no sign of star formation; i.e., they are associated with no HII regions or stellar clusters.

2. 17 CO clouds are associated with small HII regions only, but with no stellar clusters.

3. 26 CO clouds are associated with stellar clusters and large HII regions, suggesting active, on-going formation of massive clusters (e.g., N44).

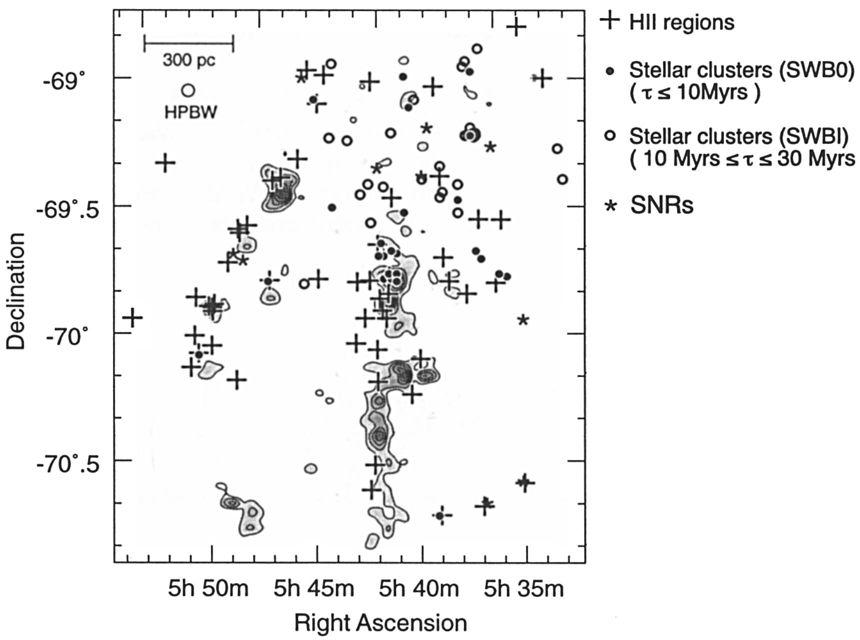

Figure 4. Distribution of the CO clouds, HII regions, stellar clusters and SNRs toward 30 Dor. The contours represent an intensity map of CO; the lowest contour and the separations are each 3.0 K km s^{-1} . The pluses indicate HII regions cataloged by Davies et al. (1976). The filled circles and squares are stellar clusters with $\tau \leq 10^6$ yr (SWB0) and 10^6 yr $\leq \tau \leq 3 \times 10^6$ yr (SWBI), respectively (Bica et al. 1996). The asterisks are SNRs (Mathewson et al. 1983).

On the other hand, there are several regions where stellar clusters (SWB0 and SWBI) are coexistent with large HII regions, but associated with only a small amount of CO clouds. Such an example is seen toward 30 Dor.

If we assume that the CO clouds in the LMC are being formed nearly steadily, the above comparisons may represent evolution of the CO clouds. The fact that about a half of the CO clouds are associated with the youngest clusters, SWB0, suggests that stellar clusters are activey formed over ~50% of a cloud's lifetime. This lifetime is roughly estimated to be ~ 3 Myr, since ~1/3 of the SWB0 clusters, which are younger than 10 Myr, are associated with CO clouds. By including the period prior to cluster formation, the typical lifetime of a CO cloud may be estimated as ~ 6 Myr the LMC. On the other hand, the absence of a massive CO cloud near the rest of the SWB0 clusters suggests that cloud dissipation is fairly rapid, possibly due to stellar UV photons (see Yamaguchi et al. in these proceedings).

To summarize, the complete sample of the giant molecular clouds in a single galaxy, the LMC, has allowed us to pursue how formation of stellar clusters takes place in them. The present results suggest that a giant molecular cloud forms *massive stellar clusters fairly quickly, leading to very rapid dissipation of itself* over a timescale of some 6 Myr.

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