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First Results of a CO Survey of the Large Magellanic Cloud with NANTEN; Giant Molecular Clouds as Formation Sites of Populous Clusters

Yasuo FUKUI,[1] Norikazu MIZUNO,[1] Reiko YAMAGUCHI,[1] Akira MIZUNO,[1] Toshikazu ONISHI,[1]
Hideo OGAWA,[1,*] Yoshinori YONEKURA,[2] Akiko KAWAMURA,[1,†] Kengo TACHIHARA,[1]
Kecheng XIAO,[1] Nobuyuki YAMAGUCHI,[1] Atsushi HARA,[1] Takahiro HAYAKAWA,[1] Shigeo KATO,[1]
Rihei ABE,[1] Hiro SAITO,[1] Satoru MANO,[1] Ken'ichi MATSUNAGA,[1] Yoshihiro MINE,[1]
Yoshiaki MORIGUCHI,[1] Hiroko AOYAMA,[1] Shin-ichiro ASAYAMA,[1]
Nao YOSHIKAWA,[1] and Monica RUBIO[3]

[1]*Department of Astrophysics, Nagoya University, Chikusa-ku, Nagoya 464-8602*
E-mail (YF): fukui@a.phys.nagoya-u.ac.jp
[2]*Department of Earth and Life Sciences, Osaka Prefecture University, Sakai, Osaka 599-8531*
[3]*Departamento de Astronomía, Universidad de Chile, Casilla 36-D, Santiago, Chile*

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Abstract

A new survey of the LMC has been completed in 2.6 mm carbon monoxide emission with NANTEN. This survey has revealed 107 giant molecular clouds, the first complete sample of giant molecular clouds in a single galaxy at a linear resolution of $\sim$ 40 pc. The cloud mass ranges from $\sim 6 \times 10^4$ to $2 \times 10^6\ M_{\odot}$, and the total molecular mass has been estimated to be $4\text{–}7 \times 10^7\ M_{\odot}$ for a molecular column density of $\gtrsim 1.0 \times 10^{21}$ cm^{-2}, corresponding to 5–10% of the atomic mass. The molecular clouds exhibit a good spatial correlation with the youngest stellar clusters whose ages are $\lesssim 10$ Myr, demonstrating that cluster formation is on-going in these clouds. On the other hand, they show little correlation with older clusters or with supernova remnants, suggesting that the molecular clouds are being rapidly dissipated in several Myrs, probably due to the UV photons of massive stars in clusters.

Key words: galaxies: Magellanic Clouds — galaxies: star clusters — ISM: clouds — radio lines: ISM — stars: formation

1. Introduction

The Large Magellanic Cloud (LMC), classified as a barred sub-type of Hubble's irregular class, is the nearest neighbor to our own. Studies of this galaxy have provided invaluable information on the structure and evolution of galaxies in various aspects, including stellar clusters and interstellar medium, owing to its unrivaled closeness to the solar system ($D \sim 50$ kpc). Compared to the optical/ properties of advanced evolutionary phase of stars, the process of star formation in the LMC has been only poorly understood, mainly due to a lack of complete, high-resolution observations of giant molecular clouds where stars are formed. Previous observations of molecular gas in the LMC are either of low angular resolution or of small spatial coverage (e.g., Cohen et al. 1988; Israel et al. 1993; Caldwell, Kutner 1996; Kutner et al. 1997; Johansson et al. 1998), not allowing us to identify the formation sites of stellar clusters.

One of the unique properties of the LMC is that there are gravitationally bound rich clusters including $\sim 10^4$ stars. These clusters, called "populous clusters," apparently resemble globular clusters in the galactic halo, although the number of stars in a populous cluster is 10-times smaller than in a globular cluster (e.g., Hodge 1961). These bound clusters, showing marked contrast with unbound open clusters in the galactic disk, may be used as unique fossil records of star formation as long as destruction by tidal interactions etc. is not significant (van den Bergh, McClure 1980).

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 the detailed molecular gas distribution at a linear resolution of $\sim$ 40 pc. In this paper, we present the first results of the study with particular emphasis on the rela-

* Present address: Department of Earth and Life Sciences, Osaka Prefecture University, Sakai, Osaka 599-8531.
† Present address: Institute of Astronomy, School of Science, The University of Tokyo, Mitaka, Tokyo 181-8588.

tionship between stellar clusters and CO clouds. Further accounts of the survey will be published separately in a future issue of PASJ.

2. Observations

Observations of the $J = 1$–0 CO emission at 2.6 mm wavelength were made with the 4-m radio telescope NANTEN (Fukui et al. 1991; Fukui, Sakakibara 1992; Fukui, Yonekura 1998) installed at Las Campanas Observatory in Chile during the period from 1997 February to November. The front end was a superconductor mixer receiver cryogenically cooled at 4.2 K (Ogawa et al. 1990), followed by an acousto-optical spectrometer (AOS) which provided a velocity resolution and coverage of 0.1 km s^{-1} and 100 km s^{-1}, respectively. The system temperature during the observations was typically 210 K in the single side band toward the zenith, including the atmosphere. The telescope beam size was $2\overset{'}{.}6$, and the observations were made every $2'$ spacing in position switching over a $6° \times 6°$ area including the whole optical extent of the LMC. In a typical integration time of $\sim$ 60 s, rms noise fluctuations of $\sim$ 0.35 K were achieved at 0.1 km s^{-1} velocity resolution. The telescope pointing was measured to be accurate within $20''$ by observing Jupiter. The total number of the observed positions was 32800.

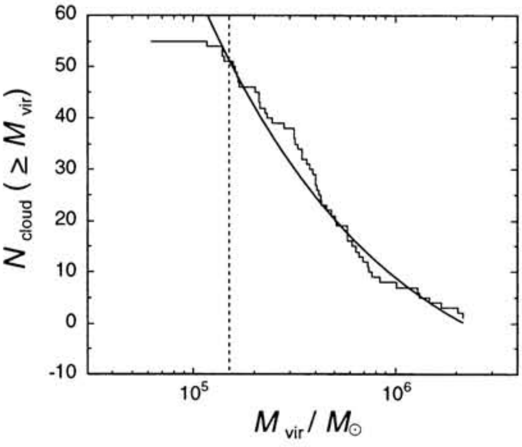

Fig. 2. Cumulative mass spectrum of the 55 giant molecular clouds. The number of clouds, N_{cloud} ($\geq M_{vir}$) with mass greater than M_{vir} is plotted against the cloud mass, M_{vir} along with the best-fitting power law (solid line). The power law $N_{cloud}(\geq M_{vir}) = 3 \times 10^4\ M_{vir}^{-0.5} - 18$ is derived by using the maximum-likelihood method of Crawford et al. (1970) for a completeness limit of $1.5 \times 10^5\ M_\odot$. The completeness limit is indicated by the broken line in the figure.

3. Results

Figures 1a (Plate 25) and b (Plate 26) show the total integrated intensity of the ^{12}CO emission. The ^{12}CO emission was significantly detected at 464 positions within a velocity range from 218 km s^{-1} to 295 km s^{-1} in V_{LSR}. The grid spacing $2'$, corresponding to $\sim$ 30 pc at 50 kpc, allowed us to resolve giant molecular clouds. The ^{12}CO distribution is found to be remarkably clumpy, and their area filling factor is small, $\sim$ 1.4%. We have identified 107 ^{12}CO clouds in figure 1, where the lowest contour (5σ noise level) corresponds to 3 K km s^{-1}.

The most prominent ^{12}CO emission is seen at $\alpha \sim 5^h40^m$ and $\delta \sim -71°$–$-69\overset{\circ}{.}5$ (B1950.0) as a straight feature to the south of 30 Dor, and the second prominent one is toward N 44 at $\alpha \sim 5^h22^m$ and $\delta \sim -68°$. There are also several clouds within the optical bar shown in figure 1b (Plate 26). Another notable feature is an arc-like distribution whose radius is $\sim$ 1 kpc centered at $\alpha \sim 5^h35^m$ and $\delta \sim -70°20'$ [see figure 1a (Plate 25)]. It is notable that this arc well delineates the shape of the faint optical outskirts of the LMC.

Among the 107 clouds, we have selected 55 that are detected at more than 3 observing positions for a detailed analysis of the physical properties. The radius of a cloud is estimated to be $R = (A/\pi)^{0.5}$, where A stands for the cloud area above 3 K km s^{-1}. The virial mass of a cloud is then calculated as $M_{vir} = kR\Delta V^2$, where k is taken as 190 based on the assumption of a spherical density distribution of $\sim r^{-1}$ (MacLaren et al. 1988), and ΔV is the half-power line width. The virial mass of the present 55 ^{12}CO clouds ranges from $\sim 6 \times 10^4\ M_\odot$ to $\sim 2 \times 10^6\ M_\odot$. The mass spectrum shown in figure 2 is well represented by a power-law distribution as $dN/dM_{vir} \propto (M_{vir}/M_\odot)^{-1.5\pm0.1}$. This spectrum as well as the highest cloud mass is fairly similar to that of our own Galaxy (see Solomon et al. 1987).

Figure 3 shows the relation between the virial mass (M_{vir}) and the CO luminosity (L_{CO}) for the 55 clouds. The CO luminosities in the LMC (filled circles) appear to be smaller than those in the Galaxy (open circles) by a factor of $\sim$ 3, and the factor $X \equiv N(H_2)/I_{CO}$ is estimated to be $\sim 9 \times 10^{20}$ cm^{-2}/(K km s^{-1}). This is about half of the value derived by Israel (1997); he estimated the overall X factor by including H_2 outside of the CO boundaries on the basis of the IRAS emission. The total molecular mass was then estimated to be $\sim 4 \times 10^7\ M_\odot$ by applying the X factor to the ^{12}CO total intensity for the 107 clouds, where the detection limit is $\sim 5 \times 10^4\ M_\odot$ in cloud mass, or $\sim 2.7 \times 10^{21}$ cm^{-2} in the molecular column density. The 55 clouds occupy $\sim$ 90% of the total mass. CO emission weaker than $\sim$ 3 K km s^{-1} would have been missed with the present sensitivity, resulting in an underestimate of the total molecular mass. In order to test how this affects the total mass, we performed deeper observations toward 21% of the present field, and

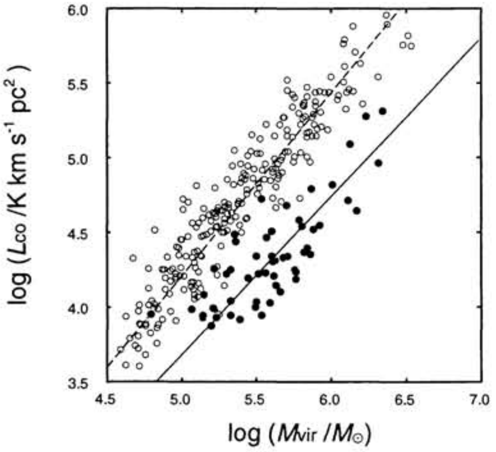

Fig. 3. CO luminosity, L_{CO}, plotted against the virial mass, M_{vir}. The filled circles show the 55 giant molecular clouds in the LMC and open circles are those in the Galaxy (Solomon et al. 1987). The straight line represents the least-squares fit for the 55 giant molecular clouds. The dashed line indicates the same relation, but derived for the galactic molecular clouds.

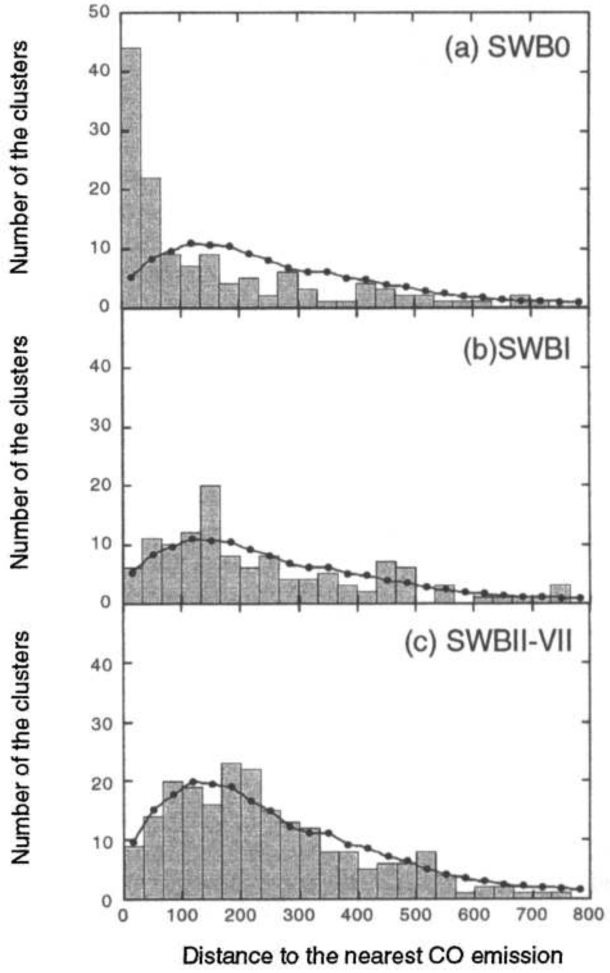

Fig. 4. Histograms of projected separation from the clusters cataloged by Bica et al. (1996) to the nearest CO emission; (a) clusters with $\tau < 10$ Myr (SWB 0), (b) those with $10 < \tau < 30$ Myr (SWB I), and (c) those with $\tau > 30$ Myr (SWB II–VII). The lines represent the frequency distribution expected if the same number of the clusters are distributed at random in the observed area.

detected weaker emission down to ~ 1.2 K km s^{-1} (details will be presented by N. Mizuno et al. 2000). By comparing the present data with these additional observations, we find that the possible increase of the total molecular mass is less than $\sim 80\%$ at a detection limit of ~ 1.2 K km s^{-1}, or $\sim 1.0 \times 10^{21}$ cm^{-2} in molecular column density. Accordingly, we estimate the total molecular mass of the LMC as $\sim (4–7)\times 10^7 M_\odot$ for a molecular column density of $\gtrsim 1.0 \times 10^{21}$ cm^{-2}. This corresponds to 5–10% of the atomic mass, including helium, which corresponds to 36% of H I in mass $\sim 7 \times 10^8 M_\odot$ (McGee, Milton 1966), smaller than that of the Galaxy, $\sim 25\%$ (Bloemen et al. 1990).

4. Discussion

4.1. Formation Sites of Stellar Clusters

In order to study star formation in the LMC, a detailed comparison of the CO clouds with *stellar clusters* and *OB associations* (hereafter, *clusters*) along with H II regions and supernova remnants has been made over the whole cloud.

Figures 4a–c show histograms for the apparent separation of stellar clusters from their nearest CO clouds, where 502 clusters are taken from Bica et al. (1996). It is found that $\sim 1/3$ of the youngest clusters (SWB 0) are located within ~ 130 pc of the CO clouds (figure 4a). This correlation cannot be due to chance coincidence, because the histogram is significantly different from what is expected for a purely random distribution. We conclude that these youngest clusters, $\sim 30\%$ of the SWB 0 clusters (Bica et al. 1996), show significant physical association with the CO clouds. On the other hand, the older clusters (SWB I and others) show little sign of a correlation with CO, and only a few SWB I are found to be close to CO clouds within ~ 130 pc. This comparison strongly suggests that the associated clusters are recently formed ones in the individual CO clouds. According to the estimated age of the clusters from *UBV* color indices (Bica et al. 1996), $\sim 90\%$ of the clusters associated with the CO clouds should be younger than 10 Myr. H II regions also show a fairly good correlation with CO; among the 244 H II regions cataloged (Kennicutt, Hodge 1986), $\sim 1/4$ are located within ~ 130 pc of the CO clouds, suggesting their physical association. On the other hand, a comparison with SNRs (Mathewson et al. 1983) indicates no spatial correlation between SNRs and CO.

Cohen et al. (1988) also compared their low-resolution CO map with H II regions and SNRs, and reached the conclusion that they both show good spatial correlations with CO. On the other hand, the present CO data have demonstrated that the CO clouds show a good correlation with H II regions, but not with SNRs. This difference is ascribed to the low resolution of Cohen et al. data, which caused a significant instrumental increase in cloud size, by a factor of ~ 20 in the lowest contours compared to the present work.

Figure 5 (Plate 27) illustrates a field including 30 Dor, where related objects, including H II regions and clusters (SWB 0 and SWB I) are overlaid. It is found that the youngest clusters associated with massive CO clouds tend to be in a compact group of young stellar clusters, e.g., N 159 ($\alpha \sim 5^{\rm h}40^{\rm m}20^{\rm s}$ and $\delta \sim -69°47'$) and N 44 ($\alpha \sim 5^{\rm h}22^{\rm m}8^{\rm s}$ and $\delta \sim -68°2'$). These groups of clusters are located at or near the peaks of the CO clouds, indicating that they have just been formed in massive CO clouds. Particularly impressive in figure 5 (Plate 27) are the five clusters concentrated toward the CO peak at $\alpha \sim 5^{\rm h}40^{\rm m}20^{\rm s}$ and $\delta \sim -69°47'$. It is also seen that a significant fraction of H II regions are well correlated with CO, although there are some CO clouds associated with no clusters or no H II regions (see e.g., $\alpha \sim 5^{\rm h}48^{\rm m}35^{\rm s}$ and $\delta \sim -70°40'$). On the other hand, there are several regions where stellar clusters (SWB 0 and SWB I) are coexistent with large H II regions, but associated with only small CO clouds. Such an example is seen toward 30 Dor at $\alpha \sim 5^{\rm h}40^{\rm m}$ and $\delta \sim -69°$ and N 11 at $\alpha \sim 4^{\rm h}56^{\rm m}$ and $\delta \sim -66°30'$.

The above comparisons are in turn summarized with respect to the CO clouds as follows:

(1) 12 CO clouds show no sign of star formation; i.e., they are associated with no H II regions nor stellar clusters (e.g., the cloud at $\alpha \sim 5^{\rm h}48^{\rm m}35^{\rm s}$ and $\delta \sim -70°40'$).

(2) 17 CO clouds are associated with small H II regions only, but with no stellar clusters, where small H II regions correspond to those of Hα luminosity, $L_{\rm H\alpha} \sim 10^{36-37}$ erg s^{-1} (e.g., the cloud at $\alpha \sim 5^{\rm h}44^{\rm m}40^{\rm s}$ and $\delta \sim -69°28'$).

(3) 26 CO clouds are associated with stellar clusters and large H II regions with $L_{\rm H\alpha} \gtrsim 10^{37}$ erg s^{-1}, suggesting active, on-going formation of massive clusters (e.g., N 44 at $\alpha \sim 5^{\rm h}22^{\rm m}8^{\rm s}$ and $\delta \sim -68°2'$).

If we assume that the CO clouds in the LMC are being formed nearly steadily (e.g., van den Bergh 1998), we may try to understand the evolution of the CO clouds based on the above-mentioned. The fact that about half of the CO clouds are associated with the youngest stellar clusters, SWB 0, suggests that stellar clusters are actively formed over $\sim 50\%$ of a cloud lifetime. This lifetime is roughly estimated to be ~ 3 Myr, since $\sim 1/3$ of the SWB 0 clusters, whose ages are younger than 10 Myr, are associated with the CO clouds. By including the period prior to cluster formation, the typical lifetime of a CO cloud may be estimated as ~ 6 Myr in the LMC. On the other hand, the absence of a massive CO cloud near the rest of the SWB 0 clusters suggests that cloud dissipation is fairly rapid, possibly due to the stellar UV photons. The strong effect of stellar photons in cloud disruption is, in fact, demonstrated by a recent HST image toward R 136 (e.g., Scowen et al. 1998). Also, the effect of the radiation field on molecular clouds in N 159 and N 160 is discussed by Israel et al. (1996) on the basis of C II observations. A comparison with the 1500 Å UV image of the LMC (Smith et al. 1987) also indicates an apparent anticorrelation between UV and CO, lending a further support to this interpretation.

To summarize, a complete sample of the giant molecular clouds in a single galaxy, the LMC, has allowed us to infer the evolution of clouds and the formation of stellar clusters. The present results suggest that a giant molecular cloud forms massive stellar clusters fairly quickly in a few Myrs after cloud formation, leading to rapid dissipation of the cloud on a time scale of some 6 Myr. A natural consequence of such a rapid dissipation is a short lifetime of a cloud. This is consistent with the fact that SNRs show little spatial correlation with CO, suggesting that the time scale of the stellar progenitor of Type-II SNR is longer than the cloud dissipation time, perhaps, $\gtrsim 10$ Myr. It may also be relevant to note that a qualitatively similar destruction of clouds by young open clusters is also shown by Leisawitz, Bash, and Thaddeus (1989) in the Galaxy, although their masses are by an order of magnitude smaller than those in the LMC.

4.2. Formation and Destruction of Populous Clusters

The past history of cluster formation has been extensively discussed by van den Bergh (1998) and Hodge (1988). According to these authors, the most recent burst of cluster formation started 3–4 Gyr ago, following the "dark age" from ~ 13 to ~ 6 Gyr ago during which only a single cluster is known to have been formed. This means that the present epoch is most active in cluster formation in the LMC.

An important remaining question is what are the physical conditions required for formation of populous clusters. The present study has shown that the mass and size of the giant molecular clouds are quite similar between the two galaxies, the LMC and the Galaxy. The star-formation efficiency in a giant molecular cloud is roughly estimated to be $\sim 1\%$ in the LMC, also similar to that in the Galaxy. Nevertheless, the LMC is forming populous clusters, although the present-day Galaxy is forming exclusively unbound open clusters. It is at this moment not clear what is most importantly affecting the richness of the stellar clusters.

The physical properties of the LMC giant molecular clouds are characterized by (i) the lower CO luminosity (the present result), (ii) the higher gas–dust ratio (Koorneef 1982), and possibly, (iii) the higher ionization degree than in the Galaxy (Israel et al. 1996). These different conditions should certainly affect the cooling of the molecular gas, and thereby, possibly cloud contraction. In addition, it is notable that the stellar gravitational field is different between the two galaxies. The flattened stellar field of the Galaxy may favor a flattened distribution of individual clouds, leading to smaller cloud fragments to form open clusters. The gravitational field of the LMC is perhaps weaker, and less flattened than that of the Galaxy, favoring thus formation of more massive fragments that may lead to form populous clusters. It is also suggested that a galaxy–galaxy interaction may cause a rich globular cluster, as in the case of NGC 4038/39 Antennae (Whitmore, Schweizer 1995). In the LMC, a dynamical interaction with the Galaxy might also be playing a role. Possible consequences of these physical differences on cloud evolution should deserve further extensive studies.

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References

Bica E., Claria J.J., Dottori H., Santos J.F.C. Jr, Piatti A.E. 1996, ApJS 102, 57
Bloemen J.B.G.M., Deul E.R., Thaddeus P. 1990, A&A 233, 437
Caldwell D.A., Kutner M.L. 1996, ApJ 472, 611
Cohen R.S., Dame T.M., Garay G., Montani J., Rubio M., Thaddeus P. 1988, ApJ 331, L95
Crawford D.F., Jauncey D.L., Murdoch H.S. 1970, ApJ 162, 405
Davies R.D., Elliott K.H., Meaburn J. 1976, MmRAS 81, 89
Fukui Y., Ogawa H., Kawabata K., Mizuno A., Sugitani K. 1991, in the Magellanic Clouds, ed R. Haynes, D. Milne (Kluwer Academic Publishers, Dordrecht) p105
Fukui Y., Sakakibara O. 1992, Mitsubishi Electric Advance 60, 11
Fukui Y., Yonekura Y. 1998, in New Horizons from Multi-Wavelength Sky Surveys, ed B.J. McLean, D.A. Golombek, J.J.E. Hayes, H.E. Payne (Reidel, Dordrecht) p165
Hodge P.W. 1961, ApJ 133, 413
Hodge P.W. 1988, PASP 100, 576
Israel F.P. 1997, A&A 328, 471
Israel F.P., Johansson L.E.B., Lequeux J., Booth R.S., Nyman L.-A., Crane P., Rubio M., de Graauw Th. et al. 1993, A&A 276, 25
Israel F.P., Maloney P.R., Geis N., Herrmann F., Madden S.C., Poglitsch A., Stacey G.J. 1996, ApJ 465, 738
Johansson L.E.B., Greve A., Booth R.S., Boulanger F., Garay G., de Graauw Th., Israel F.P., Kutner M.L. et al. 1998, A&A 331, 857
Kennicutt R.C., Hodge P.W. 1986, ApJ 306, 130
Koornneef J. 1982, A&A 107, 247
Kutner M.L., Rubio M., Booth R.S., Boulanger F., de Graauw Th., Garay G., Israel F.P., Johansson L.E.B. et al. 1997, A&AS 122, 255
Leisawitz D., Bash F.N., Thaddeus P. 1989 ApJS, 70, 731
MacLaren I., Richardson K.M., Wolfendale A.W. 1988, ApJ 333, 821
Mathewson D.S., Ford V.L., Dopita M.A., Tuohy I.R., Long K.S., Helfand D.J. 1983, ApJS 51, 345
McGee R.X., Milton J.A. 1966, Aust. J. Phys. 19, 343
Ogawa H., Mizuno A., Hoko H., Ishikawa H., Fukui Y. 1990, Int. J. Infrared Millimeter Waves 11, 717
Scowen P.A., Hester J.J., Sankrit R., Gallagher J.S., Ballester G. E., Burrows C.J., Clarke J.T., Crisp D. et al. 1998, AJ 116, 163
Smith A.M., Cornett R.H., Hill R.S. 1987, ApJ 320, 609
Solomon P.M., Rivolo A.R., Barrett J., Yahil A. 1987, ApJ 319, 730
van den Bergh S. 1998, ApJ 507, L39
van den Bergh S., McClure R.D. 1980, A&A 88, 360
Whitmore B.C., Schweizer F. 1995, AJ 109 , 960

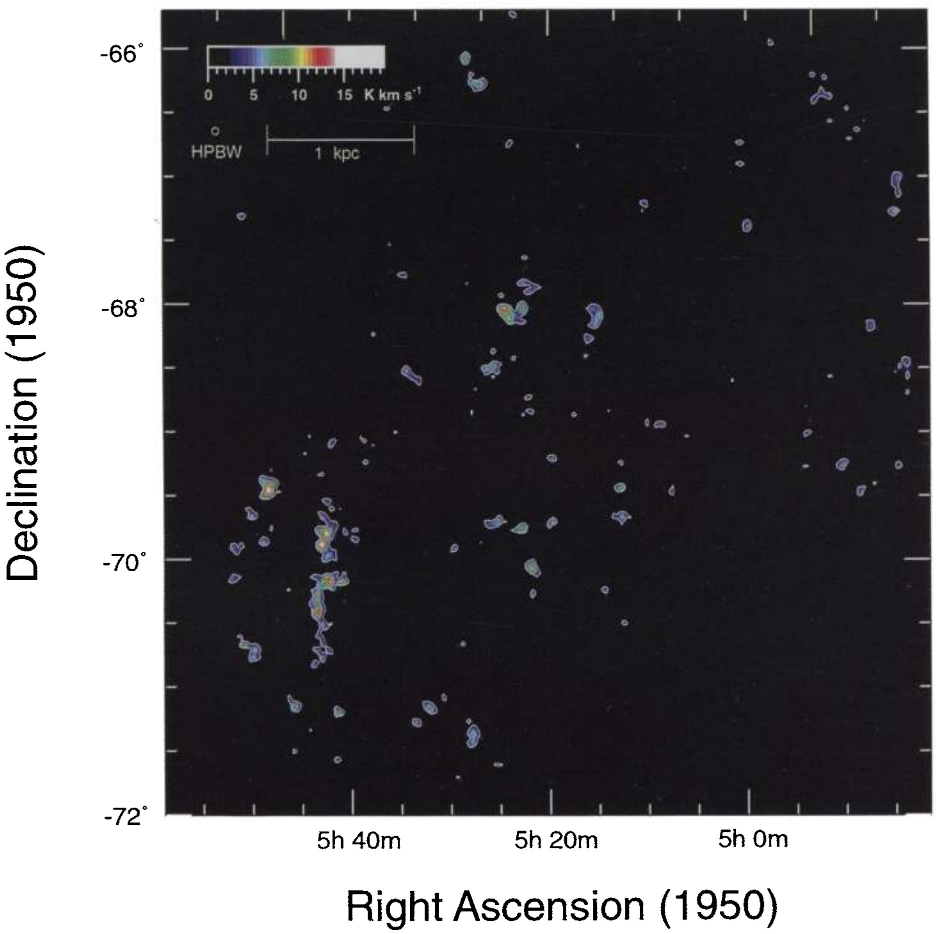

Fig. 1. (a) Velocity-integrated intensity map of CO(J = 1–0) emission. The white contours show 3 K km s^{-1}.

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Plate 26

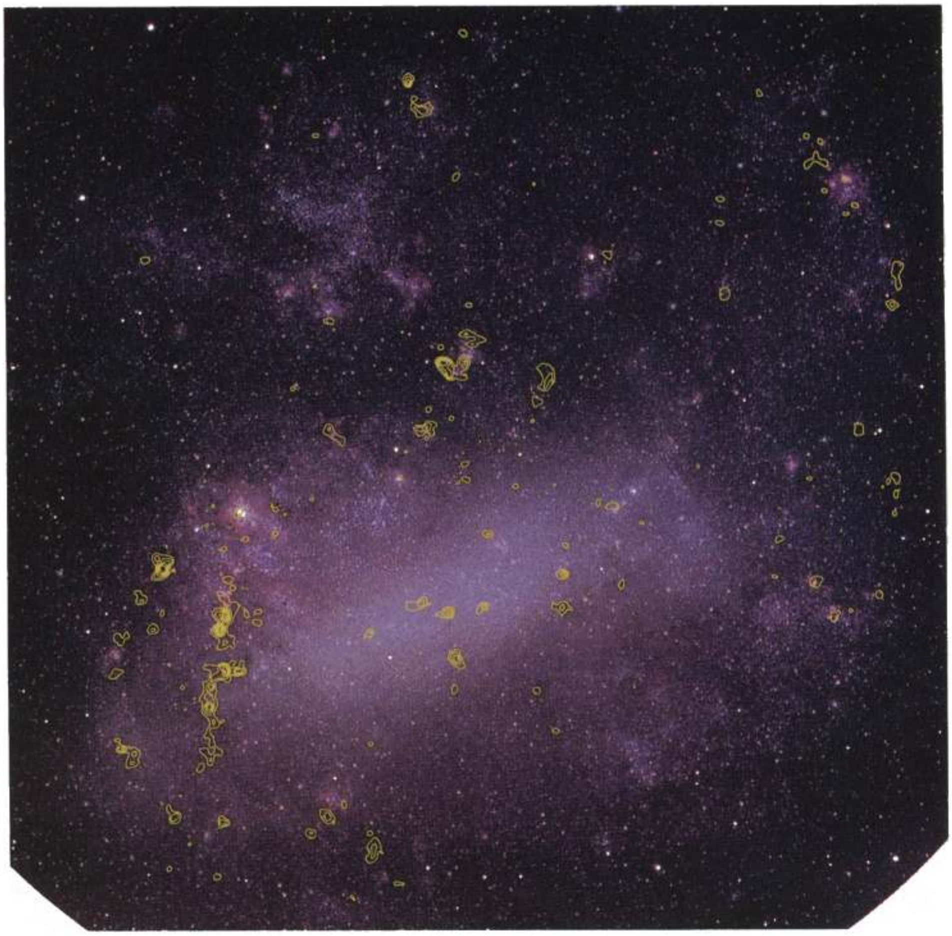

Fig. 1. (b) Velocity-integrated intensity map of CO(J = 1–0) emission superposed on the optical image. The lowest contours and separation between contours are 3 K km s^{-1} for each.

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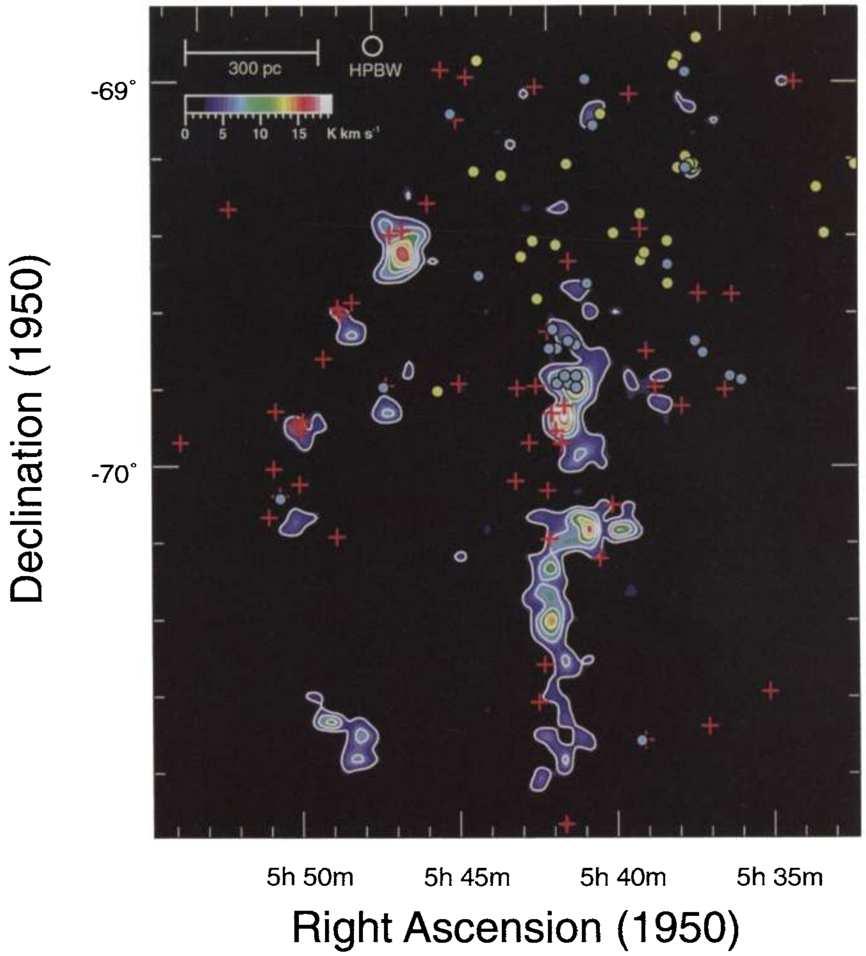

Fig. 5. Distribution of the giant molecular clouds, H II regions, and stellar clusters in the 30 Dor region. The contours represent an intensity map of CO; the lowest contours and separation between contours are each 3 K km s^{-1}. The red pluses indicate H II regions cataloged by Davies et al. (1976). The blue and yellow circles are stellar clusters with 10 Myr (SWB 0) and 10–30 Myr (SWB I), respectively (Bica et al. 1996).