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# New Views of Molecular Gas Distribution and Star Formation of the Southern Sky with NANTEN

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## 1 Introduction

Star formation is a fundamental process that dominates the cycling of various matters in galaxies. Stars are formed in molecular clouds, and the formed stars often affect the parent body of the molecular gas strongly via their UV photons, stellar winds, and supernova explosions. It is therefore of vital importance to reveal the distribution of molecular gas in a galaxy in order to investigate the galaxy history. Recent progress in developing (sub-)millimeter wave receiver systems has enabled us to rapidly increase our knowledge on molecular clouds. The “NANTEN” telescope has an angular resolution of  $2''.6$  at 115 GHz and has rapidly revealed the molecular view of the Galaxy, LMC, and SMC with its relatively high spatial resolution. The spatial coverage of the NANTEN is comparable or larger than that by CfA 1.2m telescopes[1] in the southern sky. In this presentation, I shall introduce some of the results obtained from the NANTEN CO surveys in the Galaxy. I will also mention the “NANTEN2” project, which is an upgrade of NANTEN to achieve an extensive survey in sub-mm wavelength at Atacama.

## 2 NANTEN Telescope

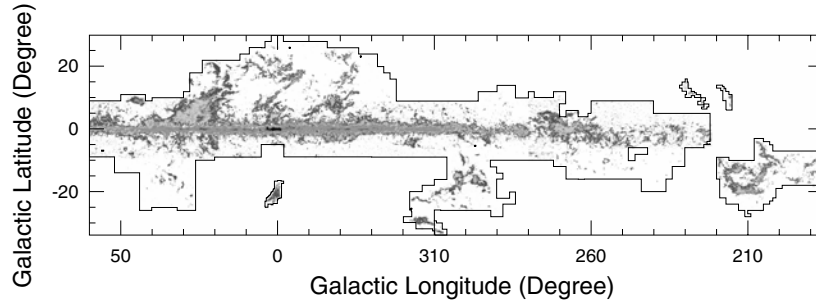
The 4-m radio telescope of Nagoya University equipped with the highest sensitivity SIS receiver at 115 GHz allowed us to cover a large area within a reasonable time at an angular resolution high enough to resolve dense cores in nearby (within 1 kpc) dark clouds and also to resolve distant (up to 30kpc from the sun) giant molecular clouds. In 1996, the 4-m telescope “NANTEN” was installed at Las Campanas observatory in Chile under mutual collaboration with the Carnegie Institution of Washington, and we started a CO survey toward the southern sky. Two major works with the NANTEN telescope were

the Galactic plane CO survey and the Magellanic Clouds molecular cloud survey (see Kawamura et al. in this conference). The other projects are to observe various objects including high mass star forming regions (Carina, Centaurus, Orion, Bright-Rimmed Clouds), SNRs/Supershells (Vela SNR, Gum Nebula, Carina Flare), Galactic center, Low-mass star forming regions (Ophiuchus, Lupus, Chamaeleon, Pipe nebula), Galactic high-latitude molecular clouds (Aquila, infrared-excess clouds), and so on. Many of the results are presented in two special issues of **PASJ 1999 vol. 51 No. 6** and **2001 vol. 53 No. 6**.

### 3 Results from Surveys by NANTEN

#### 3.1 Galactic Plane Survey

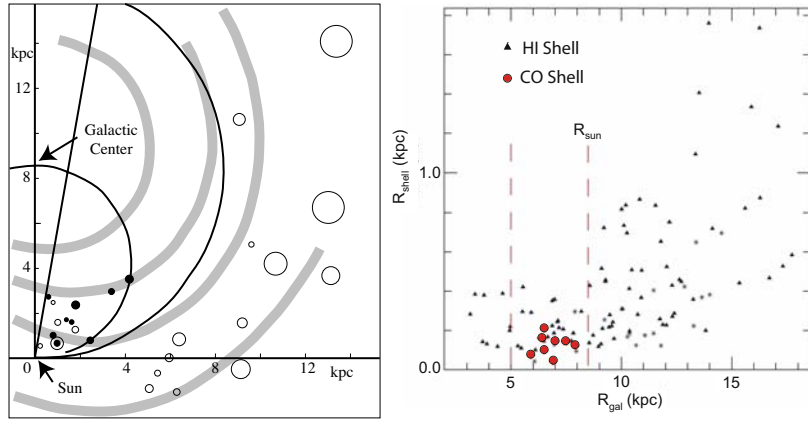
Figure 1 shows the CO total intensity map of a part of the southern Galactic plane obtained with the NANTEN telescope. This map consists of more than 1,100,000 spectra. The observing grid spacings are  $4'$  between  $5^\circ$  from the galactic plane and  $8'$  for the area above  $5^\circ$  in the galactic latitude with a  $2'.6$  beam. In the longitudinal direction almost  $200^\circ$  degrees, i.e.,  $L=220^\circ$  to  $60^\circ$  have been covered. The velocity resolution and coverage are  $0.65 \text{ km s}^{-1}$  and  $\sim 500 \text{ km s}^{-1}$ , respectively. Typical rms noise fluctuations are  $\sim 0.4 \text{ K}$  at a velocity resolution of  $0.65 \text{ km s}^{-1}$ . We are trying to re-identify Giant Molecular Clouds in the Galaxy by using this new data set. One of the notable features seen especially in this survey is the existence of a number of vertical features perpendicular to the galactic plane. I will focus here on two of such features, CO supershells and high galactic latitude clouds.



**Fig. 1.** A grayscale map of the  $^{12}\text{CO}$  ( $J=1-0$ ) velocity integrated intensity shown in galactic coordinate for the galactic plane survey with NANTEN.

### 3.2 Molecular Supershells

Supershells are large cavities created by multiple supernovae, having a size greater than  $\sim 100$  pc in the interstellar space mostly identified in the HI emission in the past. Some of the supershells exhibit expansion at a velocity greater than  $10 \text{ km s}^{-1}$ , and their kinetic energies are more than  $10^{52}$  erg. So far, more than a few hundred HI shells including galactic worms have been identified in the galaxy (e.g., [5, 6]). On the other hand, the number of CO supershells, large shell structure identified in CO emission, are quite few because of the lack of systematic CO searches out of the plane to date.



**Fig. 2.** (Left) Distribution of the CO shells (filled circles, [9]) and the HI shells (open circles, [10]) in the 4th quadrant. The gray thick lines indicate the location of spiral arms. (Right) Galacto-centric radius vs. size distribution of the CO and HI shells.

We discovered a CO supershell in the Carina region, named “Carina flare”, from sensitive observations with NANTEN [2], demonstrating that there actually exist molecular clouds associated with supershells. More detailed analysis is carrying out by using high resolution HI data toward the Carina flare (Dawson et al. in preparation). Subsequently, we started a systematic search for CO supershells with NANTEN. [9] completed the search for CO supershells in the 4th galactic quadrant between  $300^\circ$  and  $350^\circ$  in the galactic longitude. Eight CO supershell candidates have been additionally identified by them. In Figure 2a, we show the face-on view of the distribution of CO [9] and HI [10] supershells. It is notable that the coincidence between the CO and HI shells is fairly poor. Only one shell is detected in both CO and HI.

We summarize the characteristics of CO shells along with a comparison with those of HI shells: (1) CO shells are located along the galactic arms, but many HI shells are located in the inter-arm regions (see Figure 2a). (2) CO shells are smaller in size than most of the HI shells (see Figure 2b). (3) The

dynamical timescales ( $=R_{\text{shell}} / V_{\text{exp}}$ ) of CO shells ( $(0.2 - 1) \times 10^7$  yr) are smaller than those of HI shells ( $(0.5 - 3) \times 10^7$  yr). These three characteristics are interpreted in terms of the evolution of supershells as follows. It is likely that a supershell is formed in an OB association that is located in the spiral arm. In the spiral arm, the shell accumulates the ambient gas as it expands, and molecular clouds are formed in the shell. In this phase, the supershell tends to be observable as a CO shell rather than a HI shell because the cavity of the shell is embedded in and contaminated by the HI gas. After a typical crossing time, a few  $\times 10^7$  yr, the shell should gradually move to the inter-arm region due to the galactic rotation, and the galactic shear may distort the shell. Then the expanding shell cannot collect the ambient gas efficiently any longer. Separation between the CO clouds in the shell becomes sparse, and the CO clouds themselves may dissipate due to the expansion or by forming stars. Thus, the shell-like feature of CO clouds is not significant in this phase. In the inter-arm region, the HI contamination becomes less significant, and the shell becomes more obvious in HI than in CO. In this scenario, the HI and CO shell corresponds to different evolutionary stages of a single shell, and this may explain the cause for the poor coincidence between the CO and HI shells.

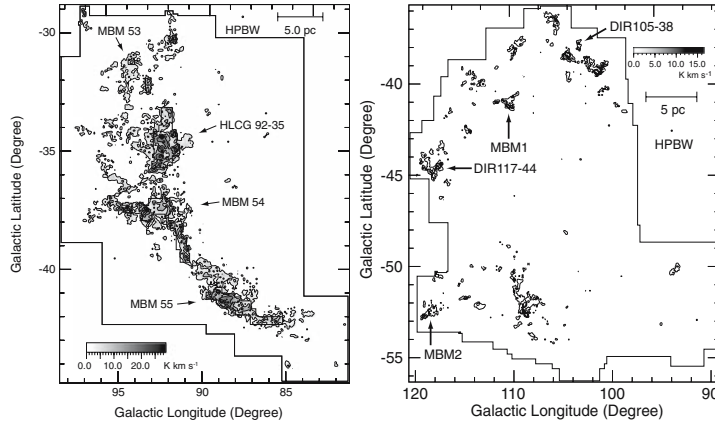
### 3.3 High Latitude Clouds

We have carried out high galactic latitude molecular clouds observations with the NANTEN telescope in order to reveal the molecular gas distribution around the solar system and the physical properties of low-density molecular clouds. Three types of observations have been made at the region.

A survey for high galactic latitude molecular clouds was carried out toward the 68 of far-infrared excess clouds of [12] by using  $^{12}\text{CO}$  ( $J=1-0$ ) line [11]. The CO emissions were detected in the 32 infrared excess clouds, corresponding to the detection rate of 47%. The CO detection rates for the cold and warm infrared excess clouds whose dust temperature are lower and higher than 17 K are 72% and 33%, respectively. This indicates that the cold clouds are well shielded from external UV radiation, resulting in a high CO abundance and a low temperature of the clouds. The infrared-excess clouds with no CO emission are most likely to be molecular hydrogen clouds because the temperature is similar to, or lower than, that of the surrounding HI gas. Even in far-infrared excess clouds with CO emission, molecular gas without CO emission seems to occupy more than 90% of the area of the clouds.

We then carried out a CO survey of high galactic latitude molecular clouds toward an HI filament including MBM 53, 54, and 55 [13]. We covered the whole area of the HI filament in  $^{12}\text{CO}$  ( $J=1-0$ ) with a  $4'$  grid spacing (Figure 3a). Many clumpy molecular clouds are found to form the filament. We identified 110  $^{12}\text{CO}$  clouds and the total mass is estimated to be  $\sim 1200 M_{\odot}$ .  $^{13}\text{CO}$  ( $J=1-0$ ) observations were carried out toward the region of strong  $^{12}\text{CO}$  intensities in order to measure the optical depth of molecular gas. There is

no detection in  $\text{C}^{18}\text{O}$  ( $J=1-0$ ) line in the observed region. This indicates that there are no clouds dense enough to have star formation in the near future. These observations spatially resolved the entire gas distribution of MBM 53, 54, and 55 for the first time, and we have found a massive cloud, HLCG 92–35 whose mass is  $\sim 330 M_{\odot}$ , corresponding to 1/4 of the total mass. This CO cloud occupies the galactic western half of a circular HI cloud toward (L, B)  $\sim (92^{\circ}, -35^{\circ})$ , and the HI to CO mass ratio is estimated to be the largest in the observed region. Far-infrared excess clouds toward HLCG 92–35 are the largest in the observed region. The ratio of the luminosity of the infrared excess to CO mass is also significantly larger than those of the other clouds, by a factor of  $\sim 5$ . These facts indicate that HLCG 92–35 is a CO-forming molecular cloud, which is younger than the MBM clouds in terms of molecular cloud formation. A past explosive event has been suggested by [3] toward the HI filament. Toward HLCG 92–35, molecular gas is distributed along the western edge of the HI cloud, which implies that the molecular gas may be formed by a compression of expanding HI shell.



**Fig. 3.** (Left) a: Total velocity integrated intensity map of  $^{12}\text{CO}$  ( $J = 1-0$ ) toward MBM53, 54, and 55 region in the galactic coordinate[13]. The lowest contour is  $1.50 \text{ K km s}^{-1}$ , and the separation between the contours is  $6.0 \text{ K km s}^{-1}$ . The observed area of  $^{12}\text{CO}$  is denoted by a thin solid line and the one of  $^{13}\text{CO}$  is denoted by thick solid lines. (Right) b: Total velocity integrated intensity map of  $^{12}\text{CO}$  ( $J = 1-0$ ) shown in the galactic coordinate[14]. The lowest contour and the separation between contours are  $0.77$  and  $3.08 \text{ K km s}^{-1}$ , respectively. The solid line represents the observed area. The locations of DIR clouds in [12] and MBM clouds in [8] are shown in the figure.

Finally, we carried out large scale CO observations toward a loop-like structure in far infrared whose angular extent is about  $20 \times 20$  degrees around (L, B)  $\sim (109^{\circ}, -45^{\circ})$  in Pegasus whose diameter corresponds to  $\sim 26 \text{ pc}$  assuming a distance of  $100 \text{ pc}$ , which is a distance of a star HD886 (B2IV) at

the center of the loop. We covered the loop-like structure in the  $^{12}\text{CO}$  ( $J=1-0$ ) emission at  $4'-8'$  grid spacing and in the  $^{13}\text{CO}$  ( $J=1-0$ ) emission at  $2'$  grid spacing for the  $^{12}\text{CO}$  emitting regions [14]. The  $^{12}\text{CO}$  distribution is found to consist of 78 small clumpy clouds whose mass ranges from  $0.04 M_{\odot}$  to  $11 M_{\odot}$ . Interestingly, about 83% of the  $^{12}\text{CO}$  clouds have very small masses of less than  $1.0 M_{\odot}$ .  $^{13}\text{CO}$  observations revealed that 19 of the 78  $^{12}\text{CO}$  clouds show significant  $^{13}\text{CO}$  emission.  $^{13}\text{CO}$  emission was detected the region where the molecular column density of  $^{12}\text{CO}$  clouds is greater than  $5 \times 10^{20} \text{ cm}^{-2}$ , corresponding to  $A_v$  of  $\sim 1$  mag. We find no indication of star formation in these clouds in IRAS Point Source Catalog and 2MASS Point Source Catalog. The very low mass clouds identified are unusual in the sense that they have very weak  $^{12}\text{CO}$   $T_{\text{peak}}$  of 0.5 K–2.7 K and that they aggregate in a region of a few pc with no main massive clouds; contrarily to this, similar low mass clouds less than  $1 M_{\odot}$  previously observed in the other regions including at high galactic latitude region are all associated with more massive main clouds of  $\gtrsim 100 M_{\odot}$ . A comparison with a theoretical work on molecular cloud formation [7] suggests that such small clouds may have been formed in the shocked layer through the thermal instability. The star HD886 (B2IV) at the center of the shell may be the source of the mechanical luminosity via stellar winds to create shocks, forming the loop-like structure with very small clouds delineated.

## 4 NANTEN2 Projects

The “NANTEN2” is an upgrade of the 4-m mm telescope, NANTEN, which was operated at Las Campanas Observatory, Chile. The upgrade started by moving NANTEN from Las Campanas to Atacama in Northern Chile at an altitude of 4,800m in 2004 to realize a large-scale survey at sub-mm wavelengths. In this new project, we will make large-scale surveys toward the Galaxy and the nearby galaxies including the Magellanic Clouds. We will reveal the physical and chemical states of interstellar gas in various density regions with the highly excited CO (carbon-monoxide) and CI (neutral carbon) spectra in the millimeter to sub-millimeter wavelength (86–810 GHz). With thorough extensive surveys, we will make studies of star formation process in the Local Group and investigate the dynamical effects of energetic explosive events like supernovae and supershells on the interstellar matter.

We installed a new main dish to achieve the sub-mm observations for NANTEN2. It consists of 33 aluminum panels that are adjustable with actuators (3 for each panel), and a light-weight carbon fiber back structure. After adjustment of the main reflector using photogrammetry and holography, the expected surface accuracy is 15 micron rms. The new telescope is enclosed in a dome with a shiftable GoreTex membrane to prevent perturbations such as strong wind and sunlight. The installation started at the beginning of 2004. The highest observing frequencies will be covered by KOSMA SMART

(Sub-Millimeter Array Receivers for Two frequencies) receiver [4], a new multi-beam receiver capable of observing both 490 GHz and 810 GHz radiation simultaneously and effectively.



**Fig. 4.** NANTEN2 telescope

NANTEN2 is equipped with such low-noise superconducting receivers and the field of view of NANTEN2 is larger than those of ASTE, APEX, and ALMA. NANTEN2 will be suitable to cover a large sky area within a short observation time while the resolution is coarser than those of ASTE, APEX, and ALMA. In this sense NANTEN2 and other telescopes in Atacama are complementary relationship. The NANTEN2 observations provide a large database of interstellar matter in the Galaxy and the Magellanic Clouds. This database must be a useful guide for the future science with ALMA.

NANTEN2 Project is a collaboration between universities in Japan (Nagoya University and Osaka Prefecture University), in Germany (University of Cologne and University of Bonn), in South Korea (Seoul National University), and in Chile (University of Chile). Two groups are joining, University of New South Wales (Australia) and ETH Zurich (Switzerland), making a NANTEN2 Consortium with 8 Universities.

## 5 Summary

The NANTEN CO survey has provided a new view of the molecular distribution in the southern sky, from the galactic center to the outer edge of the galaxy. Its larger coverage in the galactic latitude than the previous surveys

and high sensitivity have allowed us to identify previously unknown weak features such as CO supershells. Detailed searches for weak CO emission toward the galactic center and the warp regions have revealed physical properties of CO clouds in peculiar environments in the galaxy. NANTEN telescope was moved to Atacama area in 2004 with an upgraded main reflector having three times better surface accuracy. This project, NANTEN2, is motivated to explore the large-scale molecular distribution for the first time in the sub-mm region.

#### *Acknowledgements*

The NANTEN project is based on the mutual agreement between Nagoya University and the Carnegie Institution of Washington. We acknowledge that this project was able to be realized by contributions from many Japanese public donators and companies. This work is financially supported in part by a Grant-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science and Technology of Japan (No. 15071203) and from JSPS (No. 14102003, core-to-core program 17004 and No. 18684003).

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<http://www.springer.com/978-0-387-72767-7>

Mapping the Galaxy and Nearby Galaxies

Wada, K.; COMBES, F. (Eds.)

2008, Hardcover

ISBN: 978-0-387-72767-7