論文内容の要旨

論 文 題 目

The AMANOGAWA-2SB Galactic Plane Survey:
Large Scale Structure of Molecular Gas in the Milky Way Galaxy

あまのがわ望遠鏡による銀河面掃天観測：
天の川銀河における星間分子ガスの大局的構造

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In order to investigate physical condition of molecular gas in the Milky Way Galaxy (MWG) and to link the distribution of molecular gas with the star formation, we carried out a large scale survey over the northern MWG in ^{12}CO (2-1) and ^{13}CO (2-1). We presented the data in the first Galactic quadrant; i.e., l = 5 °－90 °, b = -6 °－+6 °, in this thesis. The spatial resolution is about 9' and the sampling grid is 7'.5. Hence, all Galactic disk gas in the area is covered without omission, and it is the largest coverage in the ^{12}CO (2-1) and the ^{13}CO (2-1) surveys. The velocity resolution after the data reduction is 1.3 km s^{-1}. The typical rms noise level is about 0.05 K, which exceed any other CO (2-1) surveys.

The observations were done using a new type receiver "2SB receiver" installed on the AMANOGAWA telescope, which was firstly operated for the scientific observations. Hence, some evaluations of telescope's characteristics and calibrations of the data were originally devised. The telescope's beam was measured using the attenuation grid in order to avoid the saturation of the receiver. The intensity scale was made uniform beyond the receiver tuning in order to absorb the variation of Image Rejection Ratio (IRR). We finally obtained well calibrated data of which intensity stability and velocity stability to be 7 % and 0.3 km s^{-1}, respectively.

Together with the ^{12}CO (1-0) data compiled by Dame et al. (2001), we exhibited overall views of the line intensities and the line intensity ratios in the integrated intensity maps, the longitude velocity maps and the channel maps. In these maps, most of data shows the ^{12}CO (2-1)/(1-0) ratio of about 0.6 and the ^{13}CO/^{12}CO (2-1) ratio of 0.2. However, we found three major systematic variations in the ^{12}CO (2-1)/(1-0) ratio. One is that compact features with the very high ^{12}CO (2-1)/(1-0) ratio, over 0.85, are studded over the Galactic plane. Some of them are spatially close to HII regions or Super Nova Remnants (SNRs), while the others have no associated objects. There are the velocity difference about 5－10 km s^{-1} between the very high ratio features and their associated HII regions. Another one is that some areas extended over a few square degrees have fairly high ^{12}CO (2-1)/(1-0) ratio, about 0.7. The areas include three tangent directions of the spiral arms; Scutum arm, Sagittarius arm and the local arm. The other one is that the ^{12}CO (2-1)/(1-0) ratio is low in the area of ($l = 10^\circ - 20^\circ$, $v_{LSR} >$ 60 km s^{-1}) and in the direction of $l = 20^\circ - 22^\circ$. In the former area, so small amount of molecular gas is contained. In the latter direction, fewer HII regions than other direction are distributed.

For the analysis using these data, we selected three topics in this thesis. The first topic is the global physical condition of the molecular gas in the MWG. In order to investigate it, statistical properties shown by large majority of the data are useful. Therefore, we made the two intensity correlation plots. In these plots, we found that a curved correlation between ^{12}CO (2-1) and ^{13}CO (2-1), and a linear correlation between ^{12}CO (1-0) and ^{12}CO (2-1). In order to discover the actual physical condition hidden in these correlations, we made an analysis using a simple radiative transfer equation. As a result, from the correlation between ^{13}CO (2-1) and ^{12}CO (2-1), we concluded that the optical depth in ^{12}CO (2-1) is much larger than that in ^{13}CO (2-1), and most of molecular gas follow the two relations. Simple descriptions of the two relations are that the ratio between the ^{12}CO (2-1) excitation temperature and the ^{13}CO (2-1) excitation temperature is roughly constant, and that the apparent sizes of molecular clouds in the CO lines are roughly proportional to the optical depth in ^{13}CO (2-1). From the correlation between ^{12}CO (1-0) and ^{12}CO (2-1), we concluded that ^{12}CO (2-1) is subthermally excited, and the excitation temperatures in ^{12}CO (1-0) and ^{12}CO (2-1) are higher than 19 K and 13 K, respectively. Using the quantities estimated in this analysis, we obtained typical values of physical condition of molecular gas in the MWG; (1) the gas kinematic temperature is higher than 19 K, (2) the H_2 volume density in a cloud is more than 100 cm^{-3}, and (3) The beam filling factor in the resolution of 9' is typically less than 0.15. The results (1) and (2) are consistent with the standard values in previous studies. The result (3) is applicable to observations with the same resolution.

The second topic is difference of physical condition in the MWG. We showed the radial distribution of the line intensity ratios, for one of two expected factors which cause the variation of the physical condition. As a result, we found the decreasing ^{12}CO (2-1)/(1-0) ratio from the peak at the Galactic disk radius of 4.0 kpc towards both ends of the observed radial span. In the radius of 4.0−8.5 kpc, Sakamoto et al. (1997) found the decreasing gradient outward the MWG in the observation area of ($l = 20^\circ - 60^\circ$, $|b| \leqq 1^\circ$). We showed it is valid for almost entire area of the northern MWG. Since Handa et al. (2002) showed the same trend in this radial span also in the southern MWG, we concluded it is a global property of the MWG. The decreasing gradient to the opposite direction in the radius of 2.0−4.0 kpc is the first observed result. The data which show the lower ^{12}CO (2-1)/(1-0) ratio locate in the area aside of the barred structure of the MWG, and they have weak CO intensity. We suppose the barred structure affects physical condition of molecular gas. Although Handa et al. (2002) showed a different trend in this radial span in the southern MWG, their data do not have high enough sensitivity to detect the same intensity level with our data. Therefore, it is required to conduct the high sensitive observations to the southern MWG. We also investigated the difference between the arm region and the interarm region for the other factor. Although it is difficult to distinguish the spiral arms in the MWG being a edge-on galaxy, we did it using three criterions. As a result, we showed that the ^{12}CO (2-1)/(1-0) ratio is higher in the arm region than in the interarm region. In addition, we showed that the amplitude of the radial variation is smaller in the arm region than in the interarm regions. We showed that the gas density and/or temperature of molecular gas are higher and more homogeneous in the spiral arm.

The third topic is the Probability Distribution Function (PDF) of the molecular gas density. It should be a clue to figure out the formation of dense molecular core, which is the first step of the star formation. We derived it using the conversion factor and the typical kinematic model. The derived PDFs above the noise level show a log-normal like shape which slightly deviates toward the less dense side near the denser end of the gas density. We confirmed this shape is less affected by the model used in deriving PDF, although the peak density and width of the fitted function are quantitatively changed. After the correction of the optical depth using the empirical relation between the optical depth and the intensity in ^{13}CO (2-1) (Yoda et al., 2010), the PDF derived from ^{13}CO (2-1) is well fitted by a log-normal function even for the denser end. In addition, we also showed the PDF for external galaxies using the ^{12}CO (1-0) data compiled by Kuno et al. (2007). The results indicated that about 2/3 of the sample galaxies have the log-normal like PDF. These results observationally support simulation studies which suggest the density structure of interstellar gas in a galaxy is governed by the turbulence rather than by systematic events such as self-gravity and shock wave (e.g., Vazquez-Semadeni, 1994). However, we found that 1/3 of the sampled external galaxies have the PDF which cannot be described by a log-normal function. We confirmed it is not due to several uncertainties in the observations and it is an intrinsic property of some galaxies. We could not found the common morphological property in these galaxies. It is required to investigate the origin of the non-log-normal PDF.