Resolving the Rise and Fall of Star Formation in Galaxies
Proceedings IAU Symposium No. 373, 2023
T. Wong & W.-T. Kim, eds.
doi:10.1017/S1743921322003799

Sub kpc-scale gas density histogram: a new statistical method to characterize galactic-scale gas structures

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Abstract. To understand the physical properties of the interstellar medium (ISM) in various scales, we should investigate it with pc-scale resolution over kpc scale coverage. Here, we report the sub-kpc scale Gas Density Histogram (GDH) of the Milky Way. GDH is a histogram of averaged density and corresponds to the probability density distribution (PDF) of gas volume density. We use galactic plain survey data ($l = 10° - 50°$) at ^{12}CO and ^{13}CO ($J = 1 - 0$) obtained as a part of the FOREST Unbiased Galactic plane Imaging survey with the Nobeyama 45m telescope (FUGIN). With this method and data, we are free from spatial structure and molecular cloud identification. GDH can be well fitted with single or double log-normal distribution; which we call as the low-density log-normal (L-LN) and high-density log-normal (H-LN) components. We found both the H-LN fraction ($f_{\rm H}$) and L-LN width ($\sigma_{\rm L}$) along the gas density axis show a coherent structure on the longitude-velocity diagram. It suggests that there is a relationship between the ISM property and kpc scale structure in the Milky Way.

Keywords. ISM: clouds - ISM: structure - ISM: molecules - Galaxy: structure

1. Introduction

Star formation is not a single stage process, although stars are formed from the interstellar medium (ISM) by gravitational collapse. Many investigations have been made on the last two stages in star formation process in these decades; they are the sages from a dense core to a star and from an inhomogeneous molecular cloud to dense cores. This progress is mainly due to improvement of high-resolution millimetre observations and computer simulations since 1980s. Now we, therefore, should address stages before them; what makes density fluctuation in a molecular cloud and how molecular clouds are made from diffuse gas. It is closely related to the star formation scenario in a galaxy.

To address the density structure of ISM, many previous investigations are focused on its geometry and statistics based on geometry; such as dendrogram analysis and core mass function. They are focused on dense ISM. So, another approach is required to address the diffuse ISM. The characteristics of the density structure of diffuse ISM should be appeared in its statistics. It is primarily independent of morphology. So, we made a histogram of diffuse ISM for an assigned volume and call it as 'gas density histogram

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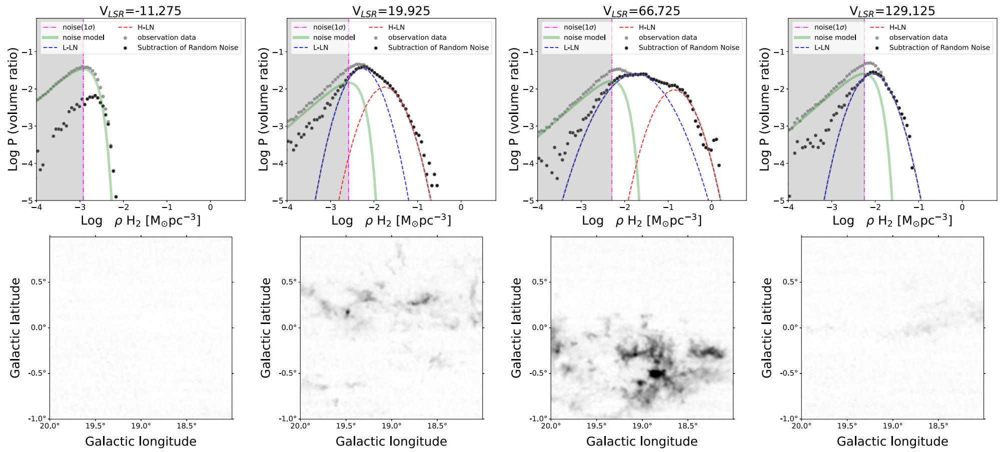

Figure 1. The GDHs and the intensity distribution on the sky of our unit area. Each area shown here is centered $(l, b) = (19°, 0°)$ in different velocities. The vertical dashed lines correspond to 1σ. The thick green solid line is the random noise model, and the black dots are the GDH after subtraction of the noise component. The red and blue dashed lines show the LN fitting results, respectively.

(GDH)'. GDHs from molecular lines can be made for each velocity channel on the same line of sight. For the velocity deconvolution we cannot use dust continuum data. In the case of ISM in the galactic disk of the Milky Way, we can estimate histograms not of the column density but of the volume density using the difference of kinetic distance (see Figure 1).

The star formation activity in kpc-scale concentrates to the spiral arms by many observational investigations in galactic astronomy. Theoretical studies suggest some relation between kpc-scale ISM structure and the pc-scale star formation. At the classical galactic shock scenario, Fujimoto (1968) says ISM compression due to spiral arm potential makes triggered star formation. It may be valid but proposed mechanisms consistent with detail observations, such as the internal structure of a spiral arm, has not been successfully developed. The variety of GDH at each position in the Milky Way should give a breakthrough to address the problem.

2. Data

We used the ^{12}CO and ^{13}CO $(J = 1 - 0)$ datasets from the FUGIN project (Umemoto et al. 2017). In this study, we focus on the region of $10° \leq l \leq 50°$, $|b| \leq 1.0°$. FUGIN data is released by Japanese Virtual Observatory (JVO). Its angular and velocity resolutions are $20''$ and 0.65 km s^{-1}), respectively. To improve the sensitivity, we smoothed the $l - b - v$ data cube with a Gaussian Kernel that has a width of 5.2 km s^{-1}), or 8 channels of the spectrometer and two-dimensional spatial smoothing with a Gaussian function to be the resultant angular resolution of $1'$.

3. Results & Discussion

In this section, we present two major results of GDH from FUGIN data. One is the shape of the GDH in different regions and the other is a relationship between the GDH property and kpc scale structure in the Milky Way.

Figure 1 suggests a correlation sample between the morphology of intense emission, shape of GDH and results of the multi log normal (LN) fitting. GDH of a channel map only with diffuse less-bright gas, such as at $v = 129.125$ shows the sharp peak close to

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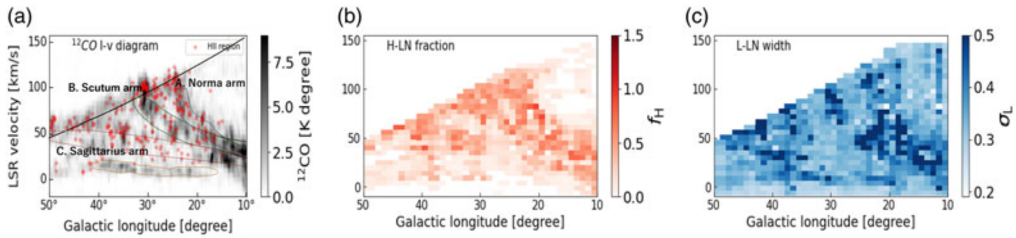

Figure 2. (a) The l-v diagram of the FUGIN ^{12}CO ($J = 1-0$) data. The integration range is from -1° to $+1^\circ$. The thick black line shows the curve of the terminal velocities. The coloured lines show the loci of the Galactic arms constructed by Reid M. J. et al. (2016) and the HII regions (red points: Anderson et al. 2009. (b) The l-v distribution of $f_{\rm H}$ in each $\Delta l \times \Delta b = 2^\circ \times 2^\circ$. The region where the H-LN cannot be defined (i.e., only diffuse gas, see section 3 is shown as $f_{\rm H} = 0$). (c) Same as (b) but the distribution of $\sigma_{\rm L}$.

the sensitivity limit and steep declining at the dense side. In contrast, GDH of a map with compact bright features, such as 66.725 km s^{-1}, GDH has a flat top structure and most likely has another peak or excess component in the dense side. At -11.275 km s^{-1}, correspond to the far outside of the Milky Way. GDH shows close shape of gaussian noise on the blank sky (see Figure 1, left). At 19.925 km s^{-1}, GDH have real features at the densest tail, which corresponds to features seen in the channel map.

Each GDH shows a straight line under the sensitivity limit. This is quantitatively consistent to the noise estimation from the data. We can easily estimate its contribution of the Gaussian noise estimated using the observed rms noise level (Figure 1, noise model). This may allows us to approach the actual GDH in the lower density side even beyond the "*completeness limit*" defined by previous N-PDF works on a molecular cloud (e.g. Alves et al. 2017).

We found every GDH of our data is well described by one or two log-normal components (Figure 1). Based on a simulation of turbulent ISM, interprets the LN GDH will be made through many random walk processes modifying ISM density by a factor at each step. It means the peak and width of GDH are the initial value and the number of steps or the modification factor by each step, respectively.our results suggest any process of modification of gas density in the sub-kpc scale, such as streaming motion, spiral arm shocks, star-forming feedback, etc., can make a LN GDH.

Figure 2 show the distribution of ^{12}CO integrated intensity, H-LN fraction ($f_{\rm H}$) and L-LN width ($\sigma_{\rm L}$) on the $l - v$ plane. In both parameters we found three ridges of high $f_{\rm L}$ and $\sigma_{\rm H}$; ridges A, B, and C are connecting from $(l, v) \simeq (15^\circ, 25$ km s$^{-1})$ to $(27^\circ, 100$ km s$^{-1})$, from $(l, v) \simeq (15^\circ, 25$ km s$^{-1})$ to $(32^\circ, 80$ km s$^{-1})$, and from $(20^\circ, 40$ km s$^{-1})$ to $(40^\circ, 80$ km s$^{-1})$, respectively. These ridges correspond to the spiral arms identified in the CO intensity distribution (Figure 2(a)). Ridges A, B, and C are Norma, Scutum, and Sagittarius arms, respectively (Dame et al. 2001). This indicates that molecular gas changes its density structure as it flows in the spiral arms. It suggests that uniform, diffuse gas should have a structured at encounter with the spiral arms.

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