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Star-formation efficiency in the outer Galaxy

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Abstract. We report the results of new survey of star-forming regions in the outer Galaxy at Galactocentric radius of more than 13.5 kpc, where the environment is significantly different from that in the solar neighborhood.

Keywords. stars: formation, infrared:stars, ISM:clouds

1. Introduction

The environment of the outer Galaxy is significantly different from the environment around the solar neighbourhood with lower gas density (e.g., Wolfire *et al.* 2003) and lower metallicity (e.g., Smartt & Rolleston 1997). Therefore, the outer Galaxy serves as an excellent laboratory for studying the star-forming processes in an environment with characteristics similar to dwarf galaxies as well as the early phase of the formation of our Galaxy (Ferguson *et al.* 1998; Kobayashi *et al.* 2008). It is known that the star-formation rate (SFR) or constant star-formation efficiency (cSFE), for converting HI gas to stars, decreases significantly at under low surface gas density (e.g., Kennicutt & Evans 2012). A similar trend is also observed in our Galaxy up to Galactocentric radius ($R_{\rm G}$) of about 15 kpc (Kennicutt & Evans 2012). Both SFR and cSFE start decreasing significantly at $R_{\rm G} \sim 13.5$ kpc, then decrease to about 1/8 and 1/4 of that of the solar neighborhood, respectively, at $R_{\rm G} \sim 15$ kpc. Thus, in the outer Galaxy, we may examine the causes of such trends in much greater detail than in extra-galactic objects. This study is a part of Izumi (2016).

2. New survey of star-forming regions in the outer Galaxy

To clarify the global nature of star-formation activity in the outer Galaxy, we need a statistical sample of star-forming regions. However, the outer Galaxy has never been comprehensively surveyed because of lack of infrared (IR) survey data deep enough for the large distances, and only about 30 star-forming regions are known so far (e.g., Snell *et al.* 2002; Brand & Wouterloot, 2007). Therefore, we have examined the Wide-Field Infrared

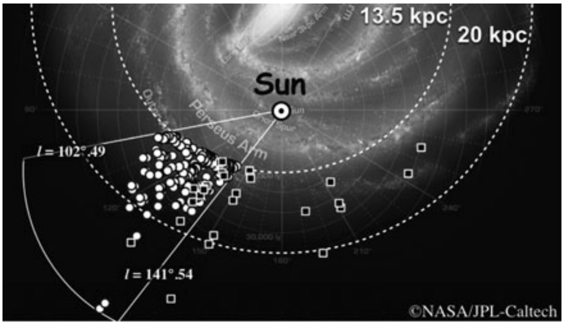

Figure 1. Distribution of star-forming regions in the second and third quadrants (adapted from the image of Milky Way Galaxy from NASA's Spitzer Space Telescope by NASA/JPL-Caltech). The white circles and black squares show newly identified star-forming regions and known star–forming regions, respectively. The white fan-shaped region shows the survey area of FCRAO CO outer Galaxy survey ($102°.49 \leqslant l \leqslant 141°.54$, $-3°.03 \leqslant b \leqslant 5°.41$) , and thus also that of the present survey.

Survey Explorer (WISE) mid infrared (MIR) all sky survey data (Wright *et al.* 2010), which has a high potential for detecting distant star-forming regions in the outer Galaxy. *WISE* has achieved a great increase in sensitivity, and is about a hundred times more sensitive than *IRAS* (Wright *et al.* 2010). We developed a simple criteria for identifying star-forming regions with *WISE* colors, which is effective when used with available CO survey data in the outer Galaxy. We employed FCRAO CO outer Galaxy survey data (Heyer *et al.* 1998; Brunt *et al.* 2003) to search for star-forming regions within an area of 320 $\deg^2$. As a result, we identified 711 new candidate of star-forming regions (Figure 1), which enables a statistical study of star-formation activity in the outer Galaxy for the first time.

3. Spiral distribution of star-forming regions in the outer Galaxy

From the distribution of newly identified star-forming regions, we found a gap in the distribution at $R_{\rm G} \sim 15$ kpc between two separate groups at $R_{\rm G} \sim 14$ kpc and $R_{\rm G} = 16 - 17$ kpc. The former group is likely to be associated with the outer arm at $R_{\rm G} \sim 14$ kpc in the direction of the anticenter (e.g., Hachisuka *et al.* 2015) and the latter group appears to be a part of a new arm beyond the outer arm. This new arm has slightly smaller $R_{\rm G}$ than that of the newly suggested arm by Strasser *et al.* (2007) and Sun *et al.* (2015). Sun *et al.* (2015) proposed that their new arm is connected to the Scutum-Centaurus arm. While our data shows a number of star-forming regions on the trail of Sun *et al.* (2015)'s proposed new arm, our new arm appears to form another branch from the outer arm. Obviously, surveys of star-forming regions at $l = 60 \sim 100°$ will be very important for understanding these arm structures.

4. Star-formation efficiency in the outer Galaxy

Using the newly identified star-forming regions, we investigate SFE of each molecular cloud as opposed to global SFE used for constructing the Kennicutt-Schmidt law. We developed two empirical SFE-indices of molecular cloud, 1) the number ratio of clouds with star-forming region to all clouds, and 2) MIR luminosities per cloud mass, to examine the variation of SFE with $R_{\rm G}$. Although star-formation processes are predicted to change with environment, we could not find any clear trend in the range $R_{\rm G} = 13.5 - 20$ kpc. For

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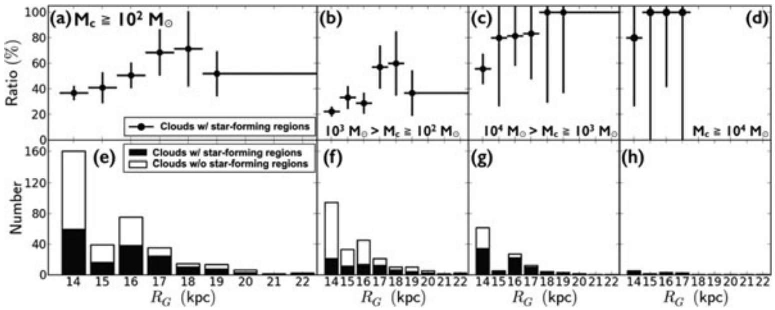

Figure 2. (a): Galactocentric variation of the ratio of clouds w/star-forming regions to the total number of clouds with cloud mass (M_c) of larger than 10^2 $M_\odot$ (SFE-index 1). (b)∼(d): Same as (a) plot but using clouds in three M_c ranges (b: 10^3 $M_\odot > M_c \geqslant 10^2$ $M_\odot$, c: 10^4 $M_\odot > M_c \geqslant 10^3$ $M_\odot$, d: $M_c \geqslant 10^4$ $M_\odot$). (e): Galactocentric variation of the number of clouds with $M_c \geqslant 10^2$ $M_\odot$. The black and white bars show the number of clouds w/ and w/o star-forming regions, respectively. (f)∼(h): Same as (e) plot but using clouds in three M_c ranges (f: 10^3 $M_\odot > M_c \geqslant 10^2$ $M_\odot$, g: 10^4 $M_\odot > M_c \geqslant 10^3$ $M_\odot$, h: $M_c \geqslant 10^4$ $M_\odot$).

example, Figure 2 shows the variation of SFE-index 1 with R_G. Although the index may appear to increase slightly with increasing R_G (in other words, decreasing gas density and metallicity), we could only safely say that the ratio does not decrease in view of the statistics at larger R_G. We note that such increasing trend is not shown in the variation of SFE-index 2 with R_G. This suggests that the star-formation processes *inside molecular cloud* do not heavily depend on the environmental parameters, such as metallicity. If this is the case, low SFE found in the outer regions of disk galaxies (e.g., Bigiel *et al.* 2010) simply reflects the smaller number of molecular clouds in such region. SFE in the inner regions of galaxies, where the interstellar medium (ISM) is dominated by H_2 molecular gas, is suggested to depend only on the amount of H_2 gas, but not that of HI gas (e.g., Schruba *et al.* 2011). The above results suggest that SFE in the outer Galaxy, where the ISM is dominated by HI gas, also depends simply on the amount of H_2 gas as in the inner region of galaxies.z We plan to expand the survey area to detect larger number of samples, in particular, at $R_G \geqslant 17$ kpc for improving the statistical reliability of our study in the near future.

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