Origins: From the Protosun to the First Steps of Life
Proceedings IAU Symposium No. 345, 2018
B. G. Elmegreen, L. Viktor Tóth & M. Güdel, eds.

doi:10.1017/S1743921319003028

The dense galactic environments of the Milky Way

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Abstract. Star formation takes place in the dense gas phase, and therefore a simple dense gas and star formation rate relation has been proposed. With the advent of multi-beam receivers, new observations show that the deviation from linear relations is possible. In addition, different dense gas tracers might also change significantly the measurement of dense gas mass and subsequently the relation between star formation rate and dense gas mass. We report the preliminary results the DEnse GAs in MAssive star-forming regions in the Milky Way (DEGAMA) survey that observed the dense gas toward a suite of well-characterized massive star-forming regions in the Milky Way. Using the resulting maps of HCO^+ 1–0, HCN 1–0, CS 2–1, we discuss the current understanding of the dense gas phase where star formation takes place.

Keywords. stars: formation, ISM: clouds, ISM: structure, ISM: evolution, Galaxy: evolution

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1. Introduction

We perform a survey of DEnse GAs in MAssive star-forming regions in the Milky Way (DEGAMA) survey to study the distribution of dense gas in molecular clouds and its role in forming stars. DEGAMA focusses on a larger sample that is sensitive to all gas above a column density threshold of $10^{22}\,\mathrm{cm}^{-2}$ with the goal of improving the understanding of how dense gas is formed and the relation between dense gas and star formation. The threshold column density of $N_{\mathrm{H}_2} \sim 10^{22}\,\mathrm{cm}^{-2}$, which might correspond to a volume density of $1 \times 10^4\,\mathrm{cm}^{-3}$, is chosen because this gas directly builds massive star-forming regions and forms lower mass stars (i.e., Onishi *et al.* 1998, André *et al.* 2010).

At sub-galactic scales, we want to understand how massive star-forming regions can accrete a large amount of mass on a short timescale of 10^5 yr (Peretto *et al.* 2013, Schneider *et al.* 2010) while being inhibited by different types of feedback. Current observations favour the dynamic scenario since it reproduces many aspects of the observational appearance of massive star-forming regions. These regions often show filamentary structure with dense ridges at the centre (Hennemann *et al.* 2010, Hill *et al.* 2011), i.e. the junctions of filamentary networks (Schneider *et al.* 2012), or ridge/hub structures where mass accretion continuously occurs (Liu *et al.* 2015). These locations are very dense with column density $\geqslant 3 \times 10^{22}\,\mathrm{cm}^{-2}$ (Hill *et al.* 2011, Nguyen Luong *et al.* 2011), and often show strong and wide-spread SiO 2–1 emission which is evidence of strong turbulent dissipation (Nguyen-Luong *et al.* 2013).

At the extragalactic scale, we seek to understand the relationship between stellar density and gas density that was put forward by Thackeray (1948) and van den Bergh (1957), and crystallized in a relationship between the observable surface density of SFR, Σ_{SFR}, and the surface density of gas, Σ_{gas}, as: $\Sigma_{SFR} = A\,\Sigma_{gas}^{N}$ by Schmidt (1959) and Kennicutt (1998). However, this relation is not scale-invariant, the power-law indexes depend on the size scales of the objects, as pointed out using the diffuse cloud tracer CO 1–0 and radio continuum luminosity (Nguyen-Luong *et al.* 2016). These relationships may behave differently if one considers only dense gas tracers, as was suggested for extragalactic environment (Wu *et al.* 2010, Liu *et al.* 2016). The linear relationship manifests in the extragalactic environments (Gao & Solomon 2004) and in the Milky Way environments (Lada *et al.* 2012), but significant gaps remain between extragalactic and galactic star formation laws (Heiderman *et al.* 2010). Nevertheless, the linear relationship between dense gas and SFR shows real scatter in excess of observational uncertainties (Usero *et al.* 2015), so additional factors are at work beyond a simple "more dense gas gives more star formation" model.

With a critical density of $\sim 10^4\,\mathrm{cm}^{-3}$, HCO^+ 1–0 (89.188 MHz) and HCN 1–0 (88.631 GHz), and CS 2–1 (97.980 GHz) is suitable to trace the total dense gas component in star-forming regions. We observed these lines with the Taeduk Radio Astronomy Observatory (TRAO) telescope† in the DEGAMA survey and report its first results in this paper.

2. Observations

TRAO was established in October 1986 with the 13.7 meter Radio Telescope and recently equipped with the 16 pixels 4x4 SEQUOIA receiver. The 2nd IF modules with the narrow band and the 8 channels with 4 FFT spectrometers allow to observe 2 frequencies simultaneously within the 85–100 or 100–115 GHz bands for all 16 pixels of the receiver. We carried out the DEGAMA mapping observations between December 2016 and December 2017. Observations were done in OTF mode and the native velocity resolution is less than 0.1 km s^{-1} (15 kHz) per channel, and their full spectra bandwidth is 60 MHz. The telescope beam size is $\sim 50''$ at 100 GHz, and the main-beam efficiency η_{MB} is $\sim 50\%$ at 100 GHz.

Our target is a sample of massive star-forming cloud complexes in the Galaxy that present the entire massive star-forming sequences from quiescent to active and evolved regions. This sample includes the massive star-forming regions that are rather nearby ($\mathrm{d} < 5\,\mathrm{kpc}$), so known star formation rate measurements from direct YSOs counting with Spitzer/WISE or Herschel. The sample includes the following sources that can be categorized in evolutionary stages, from quiescient to more active states.

3. Results

From a global perspective, dense gas tracers such as $L_{\mathrm{HCO^+}}$ or L_{HCN} and SFR tracers such as L_{IR} or $L_{\mathrm{H_\alpha}}$ are believed to correlate well with each other in log-log space (Gao & Solomon 2004, Bussmann *et al.* 2008, Wu *et al.* 2010). The relations, however, are not identical for different transitions nor for different dense gas tracers (Krumholz & Tan 2007, Narayanan 2008, Juneau *et al.* 2009). Moreover, intrinsic variation in this relationship suggests that simple correlations are inadequate for capturing the full range of star formation behavior (Usero *et al.* 2015).

We calculate the integrated line luminosity using an equation developed in Solomon & Vanden Bout (2005) where

$$\frac{L'_{\mathrm{line}}}{\mathrm{K\ km/s\ pc^2}} = 23.5 \times 10^{-6} \times \frac{D}{\mathrm{kpc}}^{2} \times \frac{A}{''^2} \times \frac{I_{\mathrm{line}}}{\mathrm{K\ km/s}}\,. \tag{3.1}$$

In DEGAMA survey, integrated line luminosity was derived from a collection of integrated maps of HCO^+ 1–0, HCN 1–0 and CS 2–1. Figure 1 shows an example of

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† https://radio.kasi.re.kr/trao/main_trao.php

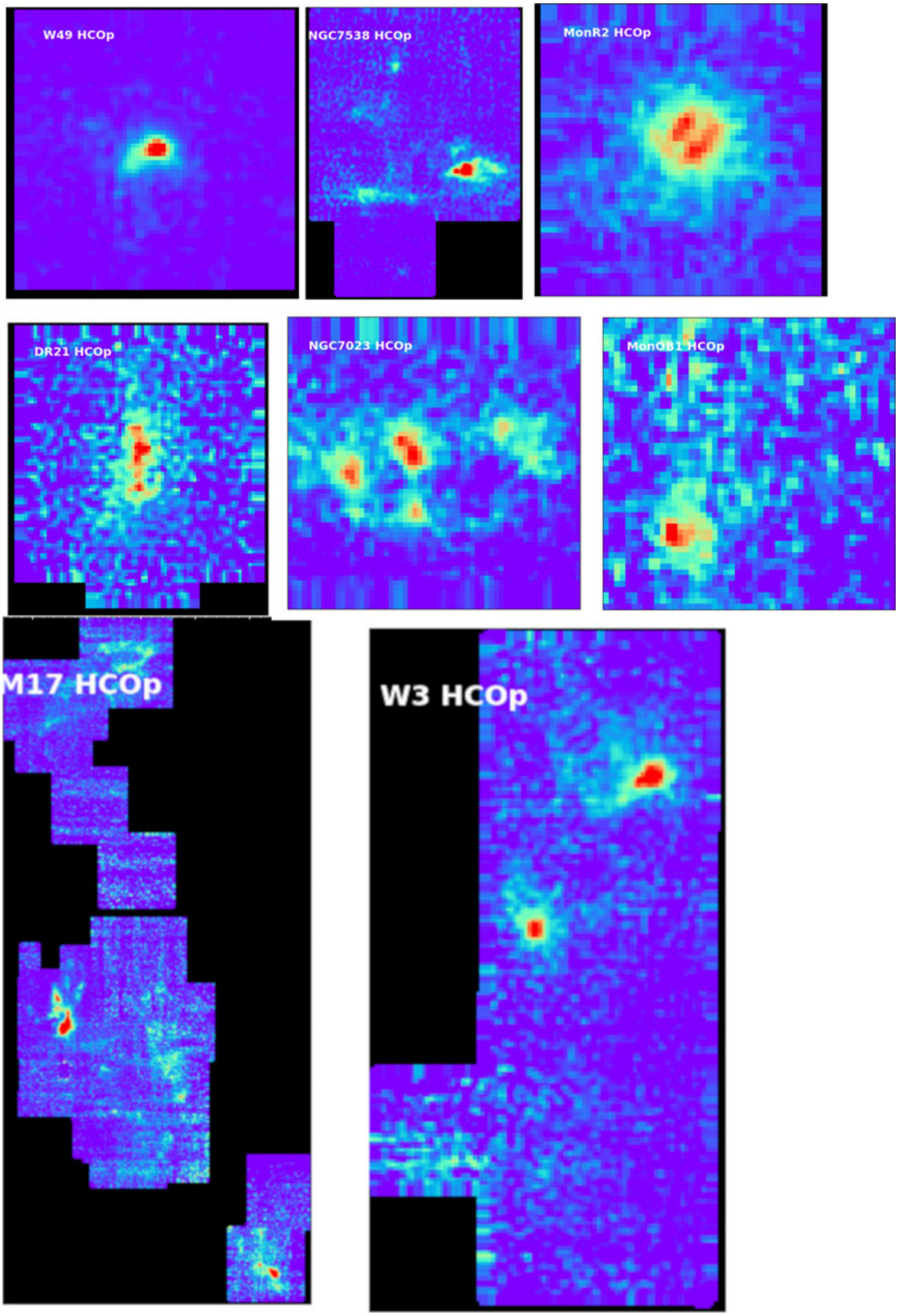

Figure 1. An overview of HCO^+ 1–0 integrated maps of DEGAMA targets.

only HCO^+ 1–0 maps. The ratio of L_{HCO^+}/L_{HCN} from DEGAMA survey shows that HCO^+ varies from cloud-to-cloud and varies around the average extragalactic ratio of 2 (Figure 2a). It might show that although having similar critical density, HCO^+ and HCN might trace quite different types of dense gas. When plotting on the L_{TIR}-L_{HCN}

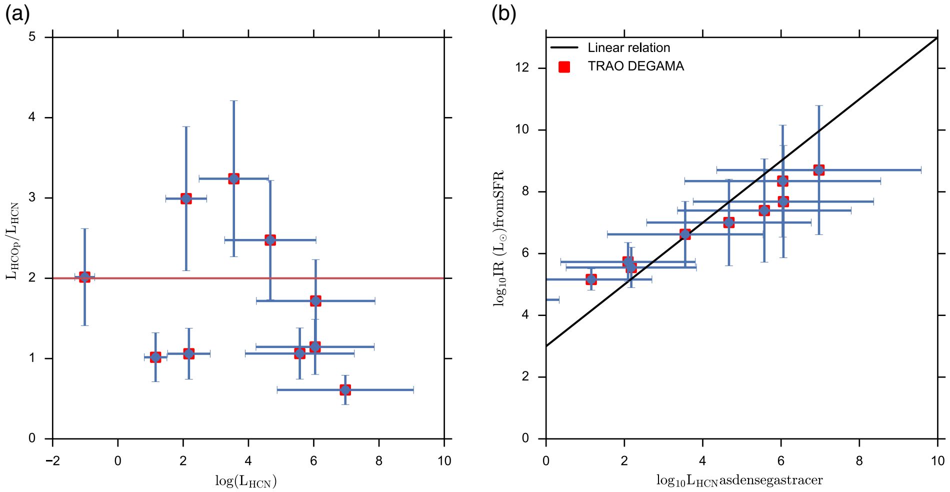

Figure 2. **a:** Ratio $L_{\mathrm{HCO+}}/L_{\mathrm{HCN}}$ as function of L_{HCN} luminosity, the horizontal line indicates where the average ratio $L_{\mathrm{HCO+}}/L_{\mathrm{HCN}}=2$. **b** L_{TIR} as function of L_{HCN} and the straightline is the linear function $\log(\mathrm{L_{TIR}}) = \log(\mathrm{L_{HCN}}) + 3$ (Gao & Solomon 2004, Wu *et al.* 2010).

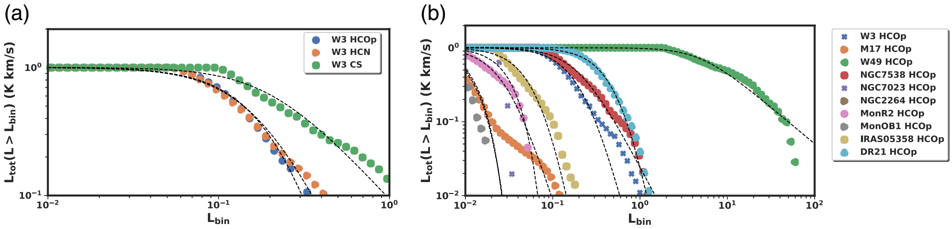

Figure 3. Normalized cumulative integrated line luminosity distributions of different tracers **(a)** and normalized cumulative integrated line luminosity distributions of HCO$^+$ for different DEGAMA targets **(b)**.

plane, there is evidence that Galactic clouds do not follow a simple linear relation as the extragalactic clouds or the scatter is very large (Figure 2b).

Then, we divide the integrated line luminosities into 100 bins and calculate the cumulative distributions (CDs) of the integrated line luminosities for each bin. The results are plotted as functions of luminosity bin in normalized forms (Figure 3). As the CD profiles are different for different sources and different tracers, we model them using a Plummer-like function that describes a flat plateaux and power law decreasing at higher column density as:

$$L(>L_{\mathrm{bin}}) = L_{\mathrm{tot}} \left(\frac{L_{\mathrm{cut}}}{\sqrt{L_{\mathrm{cut}}^2 + L_{\mathrm{bin}}^2}} \right)^p. \tag{3.2}$$

L_{bin} is the luminosity threshold of each bin, L_{tot} is the total luminosity of the cloud, L_{cut} is where the luminosity profile changes from power-law shape to flat plateau, and p is the power-law index of the profile's section at the high luminosity tail. Figures 3 shows that each cloud can be characterized by parameters L_{tot}, L_{cut}, p from the profile in Equation 3.2. This differentiation is potentially applicable to differentiate different types of clouds and also their behaviour in different dense gas tracers. We will explore this topic further in the next paper.

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Discussion

HACAR: You are comparing line luminosities but line tracers are subject to excitation, opacity and temperature effects. How do you take into account all these effects in your comparisons?

QUANG: The better way is to compare the column density distributions of different lines if we can have multiple transitions of multiple isotopologue observations of the same molecules. With only lines at single transitions, we can only compare them and examine how excitation, opacity and temperature affect the line luminosity distributions.

MAROV: In modern cosmology there are theories assuming dark matter properties with an existence of multiple galaxies around the Milky Way core. Could you associate dense clouds which you have been talking about with such faint observing features?

QUANG: I couldn't comment on that because there is no observational evidence to distinguish dark matter properties associated with multiple galaxies in the Milky Way vicinity.