SOFIA/FIFI-LS spectroscopy of Gy 3-7 cluster in the Outer Galaxy

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Star formation is ubiquitous in the Galaxy, but the physical and chemical conditions in star-forming sites might differ as a function of Galactocentric radius. For example, due to the negative metallicity gradient, the efficiency of gas cooling and dust shielding is expected to decrease in the outer Galaxy. Here, we present the SOFIA/FIFI-LS mapping observations toward the Gy 3-7 cluster in the Canis Major star-forming region covering highly excited CO lines from J=14-13 up to 30-29, [C II] at 158 μm, and [O I] at 63 and 145 μm. The CO rotational temperature of $\sim$ 200 K toward two dense cores is similar to other Galactic star-forming regions of similar masses. On the other hand, the ratio of total line emission in CO versus [O I], a tracer of metallicity, is comparable to star-forming regions in the Magellanic Clouds. Thus, Gy 3-7 is a suitable target to quantify the impact of low metallicity on star formation.

1 Introduction

Gy 3-7 is a deeply-embedded cluster located in the Canis Major star-forming region at the distance of $\sim$ 1 kpc (Tapia et al., 1997). It is associated with several young stellar objects (YSOs), two dense cores (Elia et al., 2013), and an extended 4.5 μm emission typically associated with H_2 outflows (Sewiło et al., 2019). With the expected gas metallicity as low as $\sim 0.6\ Z_\odot$ (e.g., Balser et al., 2011), Gy 3-7 provides an opportunity to study the energy balance of dense gas in the environment that is significantly different than the solar neighbourhood.

2 Observations

We used the Far Infrared Field-Imaging Line Spectrometer (FIFI-LS; Fischer et al., 2018) onboard SOFIA to map Gy 3-7 in key far-infrared (IR) gas cooling lines of CO, [O I], and [CII] (project 07_157, PI: M. Kaźmierczak-Barthel). FIFI-LS consists of two grating spectrometers with spectral coverage of 51-120 μm (blue channel) and

115-200 μm (red channel), that are operated simultaneously. The array of 5×5 spatial pixels (*spaxels*) covers a field-of-view of $\sim 1'$ (red channel) and $\sim 30''$ (blue channel). The observations were performed as 2×2 mosaics in the [O I] line at 63 μm and the [C II] line at 157 63 μm, and as single footprints in the CO 14-13 line at 186 μm. The data reduction was done following the FIFI-LS data reduction procedures (see Fischer et al., 2018).

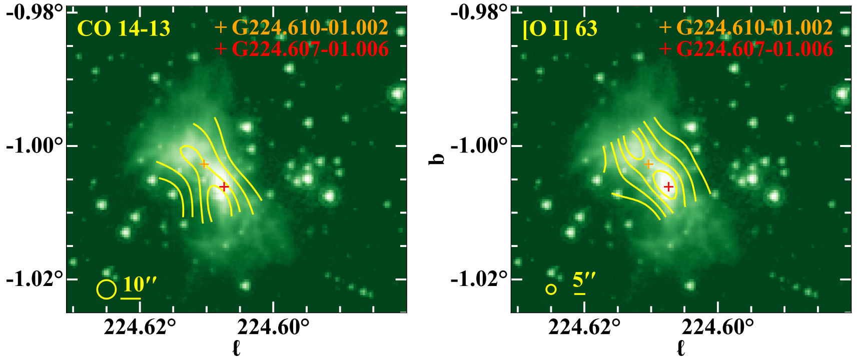

Fig. 1: *Spitzer*/IRAC 4.5 μm images of Gy 3-7 in the CMa-ℓ224 star-forming region. Orange and red plus signs show the positions of dense cores identified as part of the *Herschel* Hi-GAL survey. Yellow contours show the integrated intensity emission of CO 14-13 (*left*) and [O I] 63 μm (*right*). The contours correspond to 90%, 75%, 50%, and 25% of the line emission peak. Yellow circles show the beam sizes in the respective channels.

3 Results and analysis

Figure 1 shows the spatial distribution of the CO 14-13 and [O I] 63 μm line emission toward Gy 3-7. The emission clearly follows the "outflow-like" pattern seen in the 4.5 μm obtained with the *Spitzer*'s Infrared Array Camera (IRAC; Fazio et al., 2004). The emission in the [O I] line peaks in the position of G224.607-01.006, the dense core with a bolometric luminosity of 324.2 $L_\odot$, which is a factor of 4.3 more luminous than the core G224.610-01.002 located $16''$ away (Elia et al., 2013). The second peak of the [O I] emission corresponds to the other side of the mid-IR nebulosity (Fig. 1). The CO 14-13 emission peaks in the vicinity but not directly at the position of G224.607-01.006.

We consider the areas with a radius of $5''$ around the two cores to calculate gas rotational temperature and the ratios of CO-to-[O I] line cooling. Assuming the local thermodynamic equilibrium conditions (LTE), we obtain the temperatures of 230±50 K and 170±90 K toward G224.607-01.006 and G224.610-01.002, respectively, using a standard method involving the Boltzmann diagram. These gas rotational temperatures are within the range but at the low-end of those Class 0/I YSOs in nearby regions (Karska et al., 2013; Green et al., 2013; Manoj et al., 2013).

We quantify the total far-IR luminosity of [O I] ($L_{[\rm OI]}$) by directly adding fluxes of the two observed transitions, and of CO ($L_{\rm CO}$) by adding the interpolated fluxes of all CO lines in the range from ∼100 to ∼190 μm. Figure 2 shows the comparison of the CO and [O I] line luminosity ratios for the two cores in Gy 3-7 and for several intermediate/high-mass YSOs in the Milky Way and the Magellanic Clouds. The median $L_{\rm CO}/L_{[\rm OI]}$ is 3.7 for the Galactic massive YSOs, 0.4-0.5 for the dense cores of Gy 3-7, 0.6 and 0.1 for 9 YSOs in Large and 4 YSOs in Small Magellanic Clouds, respectively. Thus, Gy 3-7 shows the molecular-to-atomic fraction characteristic for low-metallicity environments.

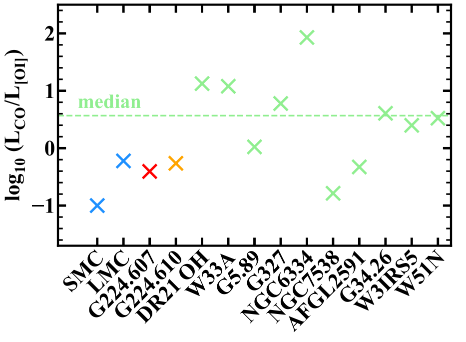

Fig. 2: The ratio of $L_{\rm CO}$ and $L_{\rm [OI]}$ toward dense cores in Gy 3-7 region (red and orange), intermediate- and high-mass YSOs in the nearby Galactic star-forming regions (green; Karska et al., 2014), and YSOs in the Magellanic Clouds (blue; Oliveira et al., 2019).

4 Conclusions and perspectives

Measurements of the CO rotational temperatures and the line cooling in CO and [O I] show that YSOs in Gy 3-7 share the characteristics with YSOs in the Magellanic Clouds representing low-metallicity environments. The low abundances of dust and molecules increase the role of atomic cooling in the energy budget of gas, which may become a useful probe of the impact of metallicity on star formation. The analysis of new APEX/PI230 spectra will constrain the gas kinematics in Gy 3-7, and better describe the physical processes responsible for the far-IR emission in the cluster.

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