Weak CS Emission in an Extremely Metal-poor Galaxy

DDO 70

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ABSTRACT

In most galaxies like the Milky Way, stars form in clouds of molecular gas. Unlike the CO emission that traces the bulk of molecular gas, the rotational transitions of HCN and CS molecules mainly probe the dense phase of molecular gas, which has a tight and almost linear relation with the far-infrared luminosity and star formation rate. However, it is unclear if dense molecular gas exists at very low metallicity, and if it is related to star formation. In this work, we report ALMA observations of the CS J=5→4 emission line of DDO 70, a nearby gas-rich dwarf galaxy with ~7% solar metallicity. We did not detect CS emission from all regions with strong CO emission. After stacking all CS spectra from CO-bright clumps, we find no more than a marginal detection of CS J=5→4 transition, at a signal-to-noise ratio of ~ 3.3. This 3-σ upper limit deviates from the L_{CS}^{IR}-L_{IR} and L_{CS}-SFR relationships found in local star forming galaxies and dense clumps in the Milky Way, implying weaker CS emission at given IR luminosity and SFR. We discuss the possible mechanisms that suppress CS emission at low metallicity.

Key words: galaxies: dwarf - galaxies: ISM - submillimeter: ISM

1 INTRODUCTION

Molecular clouds are the main sites of star formation in most galaxies. Studies of Galactic star formation indicate that stars, especially the massive stars, mainly form in the dense cores of giant molecular clouds (McKee & Ostriker 2007; Zinnecker & Yorke 2007). The raw material reservoir of star formation is provided by molecular gas (Bolatto et al. 2013), except the uncertainty of the very first generations of stars.

Low-J CO lines are the best tracer of the bulk of molecular gas because of its small dipole moment, low upper energy levels, and high abundance. CO lines serve as a powerful tool to understand the role of gas in driving star formation across the Universe (Kennicutt 1989; Genzel et al. 2010; Shi et al. 2018). However, CO lines are not suitable probes of regions with gas densities ten times higher than the average conditions in giant molecular clouds (Gao & Solomon 2004a), where the star-forming gas locates.

Molecules with high dipole moments, e.g., HCN, CS, HCO+, require much higher H₂ volume densities to excite, therefore their rotational transitions can trace H₂ gas at densities n_H₂ \geq 3 \times 10^4 \text{cm}^{-3} (Gao & Solomon 2004a; Bergin & Tafalla 2007). Studies have found tight and linear correlations between luminosities of HCN J=1→0 and IR emission (Gao & Solomon 2004a; Gao et al. 2007; Krips et al. 2008; Chen et al. 2015; Privon et al. 2015). Wu et al. (2010) and Wang et al. (2011) show linear correlations between the IR luminosity and that of CS J=5→4 in massive Galactic dense cores and spiral galaxies, respectively. Zhang et al. (2014) found linear correlations between the IR luminosity and the dense gas tracers including CS J=7→6 and HCN J=4→3, and a slightly super-linear correlation for HCO+ J=4→3.

On the other hand, some studies (Kauffmann et al. 2017; Shingirji et al. 2017) found that those so-called dense gas tracers, e.g. HCN, HCO+, do not particularly trace dense gas regions. Recent studies, Nguyen-Luong et al. (2020) and Evans et al. (2020), also found the a large fraction of the total luminosity of HCN J=1→0 and HCO+ J=1→0 emission arises in less dense molecular gas regions in inner Galactic molecular clouds and M17 clouds. At this point, the CS emission may also arises from more extended and less dense regions. Observations with high resolution can
provide samples for studying the complex cases of excitation of CS molecules in interstellar medium.

Few studies have extended the study of dense gas tracers to galaxies at very low metallicities, where even CO emission is very faint (Taylor et al. 1998; Leroy et al. 2005, 2007; Cormier et al. 2014; Shi et al. 2013, 2016). Extremely metal-poor galaxies, with $Z < 10\%Z_\odot$, are chemically unevolved, providing the best local analogues for primordial galaxies in the early Universe (Shi et al. 2014; Hunt et al. 2014). The quest for dense gas emission in these galaxies thus offer insights into star formation in the nascent galaxies.

With the IRAM 30-m telescope, Shi et al. (2016) detected CO $J=2\rightarrow1$ in an extremely metal-poor galaxy, DDO 70, and provided a direct evidence for the existence of molecular gas in galaxies of such low metallicity. Our follow-up ALMA observation further resolved the CO emission into a few clumpy structures at a spatial resolution of 1.4 pc (Shi et al. 2020). The same observation also covers the CS $J=5\rightarrow4$ transition, offering an opportunity to explore the complex cases of CS excitation at such extremely low metallicity.

2 DATA

DDO 70 is an extremely metal-poor galaxy with a gas-phase oxygen abundance of 12 + log(O/H) = 7.53 (Kniazev et al. 2005), ~7% of the Solar value (the Solar abundance is 12 + log(O/H) = 8.66 (Asplund et al. 2009)). This galaxy is at a distance of 1.38 Mpc (Tully et al. 2013) and a redshift of 0.001004 (Springob et al. 2005).

As detailed in Shi et al. (2020), our ALMA observations consist of two runs on 11 Nov. 2016 and 03 Aug. 2017, with the C40-4 and C40-7 array configurations at their best angular resolutions of 0.10$''$ and 0.35$''$, respectively. The on-source exposure times were 37 minutes and 63 minutes, respectively. After combining two data sets together, the final achieved r.m.s noise level is ~ 1.0 mJy/beam at a velocity resolution of 0.32 km/s. Natural weighting was adopted in the clean process to optimize sensitivity. The final synthesized beam is 0.22$''$ × 0.19$''$.

We used CASA 5.4.0 (McMullin et al. 2007) to extract the CS $J=5\rightarrow4$ spectra from five clumps with significant CO emission identified in Shi et al. (2020), which are shown in Figure 1. We did not detect CS $J=5\rightarrow4$ in any of the CO clumps. Therefore, to improve the signal-to-noise ratio level, we further stack the CS spectra from all CO-bright clumps.

To minimize noise contamination, we convolve the CO moment-0 map with twice the synthesized beam, make a mask of 3-$\sigma$ flux threshold, and then extract both CO and CS spectra from the data with original resolution. The total CO flux summed up from all five clumps accounts for ~ 80% of the emission seen by IRAM 30-m telescope (Shi et al. 2020), suggesting that the extended CO and CS emission is not systematically missed in our ALMA data.

Figure 2 shows the stacked spectra of CO $J=2\rightarrow1$ and CS $J=5\rightarrow4$ transition. The CO $J=2\rightarrow1$ emission is detected at very high signal-to-noise ratio, with a luminosity of $156.2 \ K\ km\ s^{-1} \ pc^2$, according to Equation 1 of Solomon & Vanden Bout (2005):

$$L' = 3.25 \times 10^7 (1 + z)^{-3} f_{\text{int}}^{-2} S_{\text{CO}} D_L^2,$$

where $S_{\text{CO}}$ is the velocity-integrated flux density, $L'$ (measured in Jy km s$^{-1}$), to luminosity in units of K km s$^{-1}$ pc$^2$. We adopt the Full Width Zero Intensity (FWZI) line width for CO $J=2\rightarrow1$. $D_L$ is the luminosity distance at redshift z and $f_{\text{int}}$ is the observing frequency in GHz. As shown in Figure 2, the stacked CS $J=5\rightarrow4$ emission line shows a marginal detection feature with a signal to noise ratio (S/N) of ~ 3.3 in the integrated flux. This marginal feature is within the velocity range of the CO $J=2\rightarrow1$ line, and shows a much narrower line width.

Similar to what was found in Lapinov et al. (1998), the line width of CS $J=5\rightarrow4$ emission line is much narrower than that of CO $J=1\rightarrow0$. Since the line widths of CO $J=2\rightarrow1$ and CO $J=1\rightarrow0$ are nearly the same, it seems reasonable that CS $J=5\rightarrow4$ emission of DDO 70 has such narrow line width. Because the detection is no more than marginal, we used the 3-$\sigma$ upper limit of CS $J=5\rightarrow4$ luminosity in the study, which is ~ $10.9 \ K\ km\ s^{-1} \ pc^2$.

3 RESULTS

As shown in Figure 3(a), we compiled both extra-galactic and Galactic measurements of CS $J=5\rightarrow4$ from Wang et al. (2011) and Wu et al. (2010). The combined data show a correlation between the luminosities of CS $J=5\rightarrow4$ and IR emission. We refit all data points with a straight line, excluding upper limits. The derived best-fit line is consistent with the empirical logarithmic relationship found in previous studies. The 3-$\sigma$ upper limit of CS $J=5\rightarrow4$ of DDO 70 is located above the 1-$\sigma$ upper bound of the linear correlation, which may imply a deficit of CS molecules at such low metallicity. Assuming that the IR luminosities represent the star-formation rates (SFR) in galaxies, we converted the IR luminosities of the sample in Wang et al. (2011) and Wu et al. (2010) to luminosities in units of $10^4\ L_\odot$. The combined data show a correlation between the CS and IR emission, which is given in Equation 2 of Solomon & Vanden Bout (2005):
et al. (2010) into the SFR using the following equation in Kennicutt (1998):

\[
SFR(M_\odot/yr) = 2.8 \times 10^{-44} L(\text{IR})(\text{erg} \cdot s^{-1}),
\]

(2)

where the initial mass function (IMF) is adapted from Chabrier (2003).

The amount of dust in DDO 70 is expected to be much less than that of normal galaxies, and the SFR calculated only with IR emission would underestimate the total SFR (Hayward et al. 2014). Therefore, we adopted the UV and IR combined SFR of $1.6 \times 10^{-3} M_\odot/yr$ within the ALMA aperture of DDO 70, as detailed in Shi et al. (2020). Figure 3(b) shows the correlation between $L'_{\text{CS}}$ and the updated SFR, where DDO 70 also shows a larger offset from this relationship.

We also calculated the ratio of the line integrated luminosity of CO $J=1\rightarrow0$ and CS $J=5\rightarrow4$ of DDO 70. Molecular clouds in Milky Way have an average CO $J=2\rightarrow1$/CO $J=1\rightarrow0$ line ratio from 0.89 for galactic nuclei (Braine & Combes 1992) to 0.6 in the Solar neighborhood (Hasegawa 1997). The average CO $J=2\rightarrow1$/CO $J=1\rightarrow0$ ratios are $\sim 0.7$ and $\sim 0.89$ in nearby early-type galaxies (Baldi et al. 2015) and spiral galaxies (Braine & Combes 1992), respectively. Because dwarf galaxies have warm interstellar medium (ISM) indicated by their relatively higher dust temperature (Shi et al. 2014; Zhou et al. 2016), we assumed that CO $J=2\rightarrow1$/CO $J=1\rightarrow0$ line ratio is $\sim 1$, under optically thick and local thermodynamic equilibrium conditions. Figure 4 shows the ratio between CO $J=1\rightarrow0$ and CS $J=5\rightarrow4$ against the IR luminosity of DDO 70 along with data from Wang et al. (2011) and Gao & Solomon (2004b). The lower limit of CO $J=1\rightarrow0$/CS $J=5\rightarrow4$ of DDO 70 is consistent with IR bright galaxies.

![Figure 2. Stacked spectra of CO $J=2\rightarrow1$ and CS $J=5\rightarrow4$ in DDO 70. The spectra are extracted from five individual CO-bright clumps detected with ALMA. The red line presents the stacked spectrum of CO $J=2\rightarrow1$, and the blue line shows the stacked spectrum of CS $J=5\rightarrow4$. The CS emission has an S/N $\sim 3$ and a much narrower line width compared to the CO spectrum.](image-url)

![Figure 3. (a) $L_{\text{IR}}$ as a function of $L'_{\text{CSJ}=5-4}$ of galaxies in Wang et al. (2011) (open blue circles) and Galactic dense cores in Wu et al. (2010) (open red circles). We fit a correlation (black dashed line) between the luminosities of CS $J=5-4$ and IR from the two sample, with upper limits excluded (Wang et al. 2011). The grey region shows the 1-σ scatter bounds of this best-fit model. The upper limit luminosity of CS $J=5-4$ of DDO 70 lies above the 1-σ scatter upper bound. (b) SFR as a function of $L'_{\text{CSJ}=5-4}$ in the same sample. The black dashed line shows the fitted correlation. The grey region shows the 1-σ scatter bounds of the best fit.](image-url)
metallicity declines, meaning a much smaller fraction of metals depleted onto dust grain surface at low metallicity than at high metallicity. Therefore, the IR luminosity may decrease more rapidly than that of CS $J=5\rightarrow 4$ toward the low end of the range of metallicity. DDO 70 is expected to be below the relationship, which is inconsistent with the observation.

One more possible explanation for the lack of CS emission is the difficulty for carbon and sulfur to stay in the form of CS molecules. The interstellar radiation field could destroy CS molecules efficiently at low metallicities. When the metallicity declines, the amount of dust decreases rapidly, and the dust extinction $A_V$ decreases. Lee et al. (2015, 2018) show that the dust shielding protects CO molecules from photodissociation efficiently within the extinction threshold, below which the CO molecules are largely destroyed. For typical molecular clouds in Milky Way, the dust extinction can reach a few or tens of magnitude (Lee et al. 2018). But for the extremely low-metallicity conditions like DDO 70, dust protection is much less. As studied in Shi et al. (2020), the extinctions for CO-bright clumps are between 1 and 2.5 mag, estimated from the $I_{12} - A_V$ relation for SMC (Lee et al. 2018). Heays et al. (2017) suggests that the photodissociation rate of molecules increases rapidly with decreasing extinction, when the extinction is below two magnitude. Thus, for DDO 70, few CS molecules can survive against the strong photodissociation effect, even within dense regions.

In the summary, the lack of carbon and sulfur elements, the decrease of dust, and the strong photodissociation field could all contribute to the deviation of DDO 70 from the $L_{CS} - L_{IR}$ and $L_{CS} - SFR$ correlations. In the end, it is still unknown that whether these two effects can fully contribute to such low luminosity and whether there exists other dominant physical mechanisms.

4 DISCUSSION

We found no more than marginal detection of CS $J=5\rightarrow 4$ in DDO 70. The 3-$\sigma$ upper limit of CS $J=5\rightarrow 4$ in DDO 70 locates at above the best fit of the $L_{CS} - L_{IR}$ and $L_{CS} - SFR$ relations. This suggests that the CS emission in DDO 70 is very weak for the given IR luminosity compared to spiral galaxies and the Milky Way molecular clouds, and DDO 70 deviates from the $L_{CS} - L_{IR}$ relation. One possibility is that the molecular gas in DDO 70 may not have sufficient density to efficiently excite the CS lines, which is consistent with the finding of Shi et al. (2020). Because of inefficient gas cooling and weak turbulence at very low metallicity, the large clumps cannot fragment into small ones and the average gas density of a clump is lower (see Figure 8 in Shi et al. (2020)), leading to inefficient star formation (Shi et al. 2014). As a result, a molecular cloud at low metallicity has on average lower densities, resulting in weaker CS emission.

Another explanation for weak CS emission in DDO 70 is that the abundances of gas-phase carbon and sulfur are too low due to the extremely low metallicity, leading to weak CS emission. Braine et al. (2017) found weak HCN emission in low-metallicity galaxies but with relatively normal CO and HCO$^+$ emission. This weak HCN emission is likely due to the relatively low N/O abundance ratio in a low oxygen abundance environment. However, the relative abundance of $\alpha$ elements, including sulfur, is roughly constant for different oxygen abundance (van Zee & Haynes 2006). So the dominant cause for the weak HCN line in Braine et al. (2017) may not apply to our CS study.

On the other hand, as the metallicity declines, the total amount of the dust decreases, which lowers the IR luminosity as well. Besides, as shown in Ledoux et al. (2003), Wolfe et al. (2005), Meirig et al. (2009), De Cia et al. (2013), and De Cia et al. (2016), the strength of dust depletion effect decreases when metallicity declines, meaning a much smaller fraction of metals depleted onto dust grain surface at low metallicity than at high metallicity. Therefore, the IR luminosity may decrease more rapidly than that of CS $J=5\rightarrow 4$ toward the low end of the range of metallicity. DDO 70 is expected to be below the relationship, which is inconsistent with the observation.

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![Figure 4. Ratios of line luminosities of CO $J=1\rightarrow 0$ to CS $J=5\rightarrow 4$ as a function of IR luminosity. Black circles show galaxies from Wang et al. (2011), for which the CO $J=1\rightarrow 0$ data are taken from Gao & Solomon (2004b). DDO 70 is plotted as the filled magenta circle.](image-url)
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