Dwarf Galaxies: From the Deep Universe to the Present
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Molecular Composition of Local Dwarf Galaxies: Astrochemistry in Low-metallicity Environments

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Abstract. To investigate molecular composition of low-metallicity environments, we conducted spectral line survey observations in the 3 mm band toward three dwarf galaxies, the Large Magellanic Cloud, IC 10, and NGC 6822 with the Mopra 22 m, the Nobeyama 45 m and the IRAM 30 m, respectively. The rotational transitions of CCH, HCN, HCO^+, HNC, CS, SO, ^{13}CO, and ^{12}CO were detected in all three galaxies. We found that the spectral intensity patterns are similar to one another regardless of star formation activities. Compared with Solar-metallicity environments, the molecular compositions of dwarf galaxies are characterized by (1) deficient nitrogen-bearing molecules and (2) enhanced CCH and suppressed CH_3OH. These are interpreted (1) as a direct consequence of the lower elemental abundance of nitrogen, and (2) as a consequence of extended photon dominated regions in cloud peripheries due to the lower abundance of dust grains, respectively.

Keywords. galaxies: dwarf, galaxies: ISM, ISM: clouds, radio lines: galaxies, astrochemistry

1. Introduction

In the Local Group, there are more than 50 galaxies, most of which are low-metallicity dwarf ones. Observations of such low-metallicity galaxies provide us with clues to understanding the chemical characteristics of faint galaxies in the early universe, which are also in a metal-poor environment. Metallicity is an important parameter which has a significant impact on atomic and molecular composition of molecular clouds via change in the gas phase and grain surface chemistry. The abundances of metal-bearing molecules are not only scaled down by metal abundances, but also affected by, for example, photodissociation and photoionization because of the small amount of dust grains and intense UV radiation. Thus, detailed characterization of the chemical features in low-metallicity dwarfs is of fundamental importance in astrochemistry and astrophysics. Motivated by

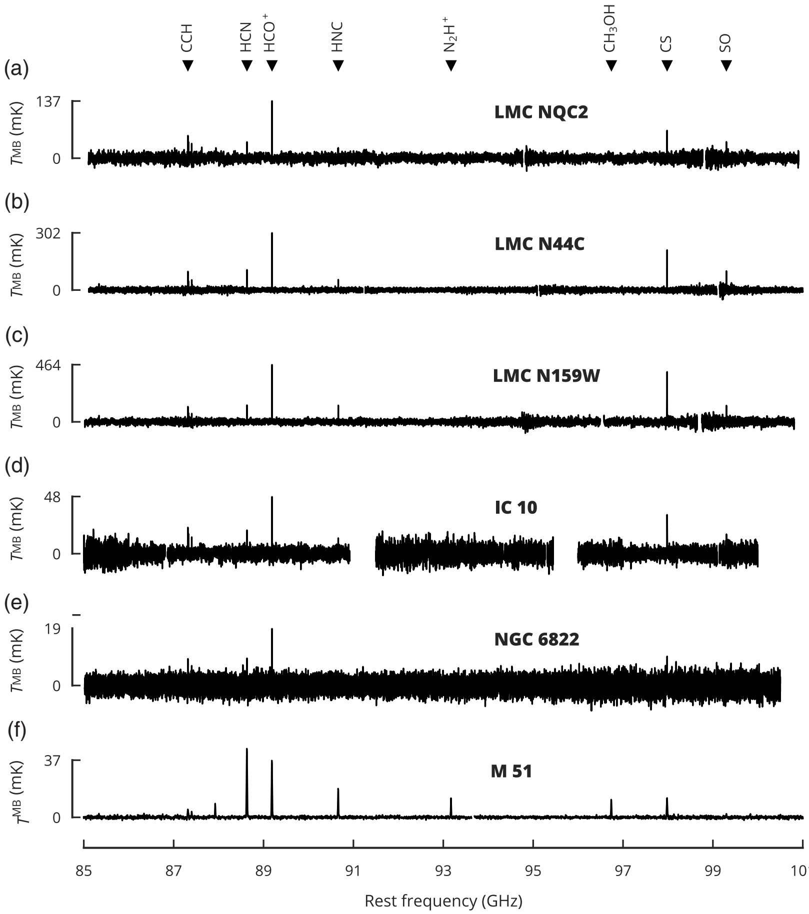

Figure 1. The 3 mm-band spectra observed toward (a) a quiescent molecular cloud NQC2 in the LMC, (b) a star-forming cloud without H II region N44C in the LMC, (c) a star-forming cloud with H II region N113 in the LMC, (d) a star-forming clouds in IC 10, and (e) Hubble V in NGC 6822, For Solar-metallicity reference, the spectra observed toward (f) a spiral arm of M 51 (Watanabe *et al.* 2014) is also shown. The representative molecular lines are indicated on top.

this, we conducted spectral line survey observations in the 3 mm band toward three Local Group dwarfs, the Large Magellanic Cloud (LMC), IC 10, and NGC 6822.

2. Spectral intensity patterns of molecular clouds in dwarf galaxies

The observations of the LMC, IC 10, and NGC 6822 were conducted with the Mopra 22 m, the Nobeyama 45 m, and the IRAM 30 m, respectively. For the LMC, we selected seven targets with different star-formation activities (quiescent clouds: CO Peak 1, NQC2, star-forming clouds: N79, N44C, N11B, star-forming clouds *with* H II regions: N113, N159W). For IC 10 and NGC 6822, we selected the CO-brightest cloud in each of the galaxies. As a result, we detected the lines of CCH $(1-0)$, HCN $(1-0)$, HCO^+ $(1-0)$, HNC $(1-0)$, CS $(2-1)$, and SO (2_3-1_2) toward all of the targets (Fig. 1; with exceptions of the HNC and SO lines in NGC 6822 because of the insufficient sensitivity). On the other hand, CH_3OH was not detected in any galaxies. Interestingly, spectral intensity patterns are similar to one another regardless of star formation activities. The spectra averaged over the entire molecular cloud do not seem to reflect the local star formation

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Table 1. Elemental abundance and column density ratio

Galaxy		NGC 6822	IC 10	LMC	"Solar"	M 51
Metallicity	$Z/Z_{\odot}$	$\sim 1/3$	$\sim 1/3$	$\sim 1/2$	1	~ 1
Elemental abundance ratio	N/O	0.039	0.04	0.036	0.12	~ 0.25
	C/O	0.50	0.30	0.33	0.60	~ 0.6
Molecular column density ratio	$N[\mathrm{HCN}]/N[\mathrm{HCO^+}]$	$1.2^{+0.6}_{-0.7}$	$2.5^{+1.3}_{-1.4}$	$3.4^{+1.3}_{-1.8}$	$8.0^{+2.9}_{-4.6}$	$8.4^{+4.0}_{-4.6}$
	$N[\mathrm{HNC}]/N[\mathrm{HCO^+}]$	< 0.3	$0.4^{+0.2}_{-0.2}$	$0.8^{+0.3}_{-0.3}$	$3.4^{+1.3}_{-1.2}$	$1.6^{+0.6}_{-0.6}$
	$N[\mathrm{CCH}]/N[\mathrm{HCO^+}]$	$16.7^{+6.9}_{-5.3}$	$17.5^{+7.6}_{-5.8}$	$13.9^{+7.2}_{-5.3}$	$5.3^{+3.9}_{-2.4}$	$9.1^{+3.8}_{-2.9}$

Notes: Elemental abundances are based on Esteban *et al.* (2014) for NGC 6822, Lequeux *et al.* (1979), Bolatto *et al.* (2000), and Magrini & Gonçalves (2009) for IC 10, Dufour *et al.* (1982) for the LMC and "Solar", Bresolin *et al.* (2004) and Garnett *et al.* (2004) for M51. The molecular column densities are calculated for each combination of the H_2 density of 3×10^3, 1×10^4, 3×10^4, and 1×10^5 cm^{-3} and the gas kinetic temperature of 10, 20, 30, 40, and 50 K, using the publicly available RADEX code (van der Tak *et al.* 2007). For "Solar" and M 51, we used the data of Galactic translucent clouds (Turner 1995; Turner *et al.* 1997, 2000) and giant molecular clouds in a spiral arm of M 51 (Watanabe *et al.* 2014), respectively. The errors are estimated from the variation due to the assumed H_2 density and gas kinetic temperature.

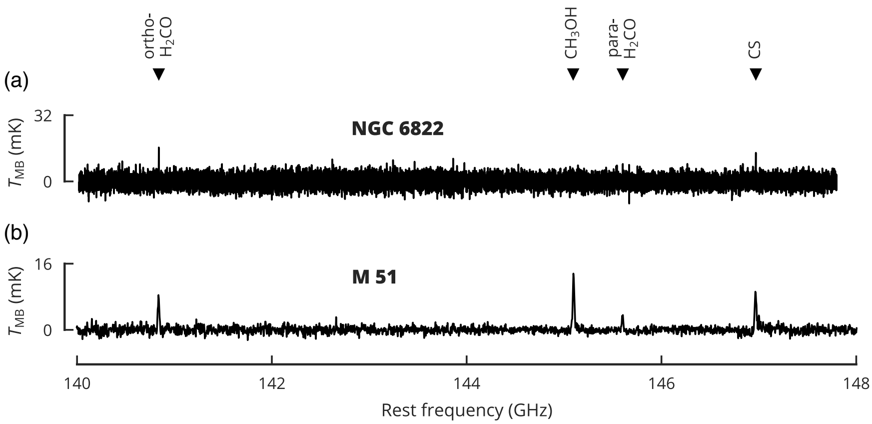

Figure 2. The 2 mm-band spectra observed toward (a) Hubble V in NGC 6822. For Solar-metallicity reference, the spectra observed toward (b) a spiral arm of M 51 (Watanabe *et al.* 2014) is also shown. The representative molecular lines are indicated on top.

activities. Toward NGC 6822, we could obtain the 2 mm-band spectrum simultaneously. The lines of H_2CO ($2_{12} - 1_{11}$ and $2_{02} - 1_{01}$) and CS ($3 - 2$) were detected (Fig. 2).

3. Characteristics of the molecular composition of dwarf galaxies

Deficient nitrogen-bearing species: HCN and HCO^+ are the most commonly observed dense gas tracers (e.g., Gao & Solomon 2004). As shown in Table 1, the HCN/HCO^+ and HNC/HCO^+ ratios are lower in the three dwarfs than in the Solar-metallicity spirals. Other nitrogen-bearing species N_2H^+ is not detected in the spectra of any dwarfs, while these species are seen in the M 51 spectrum. The deficiency of the nitrogen-bearing species most likely reflects a lower N/O ratio by a factor of 2–3 in the dwarfs.

Enhanced CCH and suppressed CH_3OH: CCH is enhanced in the dwarfs, as shown in Table 1. Unlike nitrogen-bearing species, this feature cannot be interpreted as the consequence of the elemental abundance ratio. Considering the elemental C/O ratio is lower in the dwarfs, the enhancement of the CCH/HCO^+ ratio is striking. In low-metallicity environments, the abundance of dust grains are low, and hence, the extinction for a given H_2 column density becomes lower. This effects extends photon dominated regions (PDRs) in cloud peripheries. Since CCH is efficiently produced in PDRs, the high abundance of CCH in the dwarfs is likely due to the extension of PDRs.

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Moreover, non-detection of CH_3OH can also be explained in the same picture. CH_3OH is formed on dust grain by successive hydrogenation of CO. In addition to the lower abundance of dust grains, higher temperature owing to the intense UV radiation decrease the CH_3OH formation because of a fall of sticking probability of hydrogen atoms (Watanabe & Kouch 2002). Hence, CH_3OH is suppressed in low-metallicity environments.

H_2CO formation in low-metallicity environments: In general, H_2CO is considered to be formed both on dust grains and in the gas phase. The grain-surface formation of H_2CO is, however, not likely the case in low-metallicity dwarfs, considering the lower abundance of CH_3OH (note that CH_3OH is formed on dust grains by further hydrogenation of H_2CO: $H_2CO \rightarrow CH_3O \rightarrow CH_3OH$). The detection of H_2CO in NGC 6822 suggests that the gas-phase formation pathways of H_2CO is essential in low-metallicity environments.

4. Concluding remarks

The 3 mm-band line survey observations toward the LMC, IC 10, and NGC 6822 revealed the characteristic molecular composition of the low-metallicity dwarfs. Deficiency of nitrogen-bearing molecular species indicates importance of the elemental abundance in interpretation of molecular abundances in external galaxies. The enhanced CCH and suppressed CH_3OH represent a crucial role of the UV radiation in low-metallicity environments. These results can be used as a benchmark of the molecular composition of low-metallicity galaxies, which will be useful to understand molecular composition of external galaxies, especially those in the early universe.

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Discussion

Q: Would you not expect CCH to be enhanced in star-forming clouds with respect to quiescent ones (if it is a by-product of photodissociation)? Why doesn't this show as a chemical difference between clouds with different levels of activity?

A: The distribution of CCH is not localized to star-forming cores, but rather widespread over the entire molecular clouds. Hence, the abundance of CCH is not very sensitive to the star-formation activities. The enhancement of CCH is considered to be the consequence of the extension of PDR caused by less-attenuated interstellar radiation field.