Resolving the Rise and Fall of Star Formation in Galaxies
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The first detection of deuterated water toward extragalactic hot cores with ALMA

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Abstract. We discuss the first detection of deuterated water (HDO) in extragalactic hot cores. The HDO 2_{11}–2_{12} line has been detected with the Atacama Large Millimeter/submillimeter Array (ALMA) toward hot cores N 105–2 A and 2 B in the N 105 star-forming region in the low-metallicity Large Magellanic Cloud (LMC), the nearest star-forming galaxy. We compared the HDO line luminosity (L_{HDO}) measured toward two hot cores in N 105 to those observed toward a sample of 17 Galactic hot cores and found that the observed values of L_{HDO} for the LMC hot cores fit very well into the L_{HDO} trends with L_{bol} and metallicity observed toward the Galactic hot cores. Our results indicate that L_{HDO} seems to be largely dependent on the source luminosity, but metallicity also plays a role. We provide a rough estimate of the H_2O column density and abundance ranges toward N 105–2 A and 2 B by assuming that HDO/H_2O toward the LMC hot cores is the same as that observed in the Milky Way; the obtained values are systematically lower than those measured in the Galactic hot cores. The spatial distribution and velocity structure of the HDO emission in N 105–2 A is consistent with HDO being the product of the low-temperature dust grain chemistry.

Keywords. Astrochemistry, Magellanic Clouds, Star Formation, Protostars

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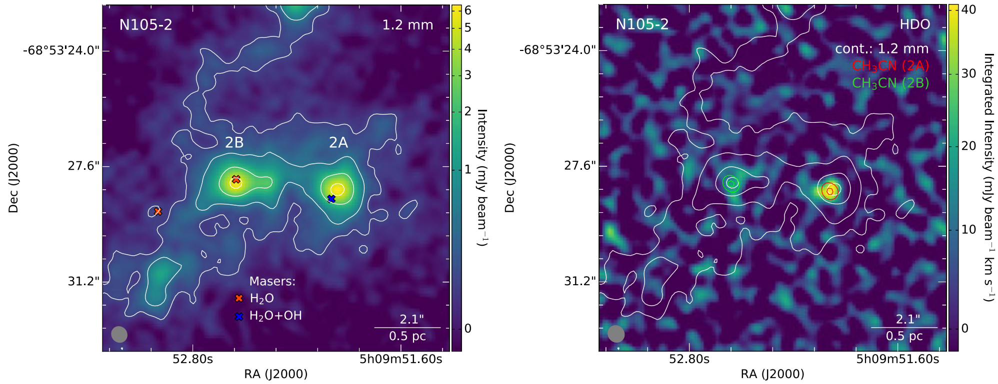

Figure 1. *Left*: The 1.2 mm continuum image of N 105–2 with the positions of hot cores 2 A and 2 B, and H_2O and OH masers indicated. *Right*: The HDO 2_{11}–2_{12} integrated intensity image. Red/green contours correspond to (50, 90)% of the CH_3CN integrated intensity peak of 0.38/0.19 Jy beam^{-1} km s^{-1} for 2 A/2 B. White contours in both panels represent the 1.2 mm continuum emission with contour levels of (3, 10, 40, 100) × the image rms noise level (σ) of 5.1×10^{-5} Jy beam^{-1}.

1. Background

Water (H_2O) is a key molecule tracing the chemical and physical processes associated with the formation of stars and planets. Deuterated water (HDO) has recently been detected for the first time toward an extragalactic star-forming region, providing us an excellent opportunity to study water chemistry in a significantly different environment than in today's Galaxy. The HDO 2_{11}–2_{12} transition at 241,561.550 MHz has been detected with ALMA toward hot cores N 105–2 A and 2 B in the star-forming region N 105 in the low-metallicity LMC (see Fig. 1; Sewiło et al. 2022a,b). Hot cores are compact ($\lesssim$0.1 pc), warm ($\gtrsim$100 K), and dense ($\gtrsim 10^{6-7}$ cm^{-3}) regions surrounding high-mass protostars very early in their evolution; a typical Galactic hot core is chemically rich, containing the products of the interstellar grain-surface chemistry (including complex organics and water). Hot cores N 105–2 A and 2 B are two of only a handful of extragalactic sources with hot core complex organic chemistry (Sewiło et al. 2022a and references therein). The metallicity of the LMC ($Z_{\rm LMC}$~0.3–0.5 $Z_\odot$; e.g., Russell & Dopita 1992) is similar to galaxies around the peak of star formation in the Universe (redshift~1.5), making it an ideal template for studying star formation and water chemistry in low-metallicity systems at earlier cosmological epochs where direct observations are impossible.

There are several factors that can directly impact the formation and destruction of H_2O and HDO molecules in a low-metallicity environment. The abundance of atomic O in the LMC is more than a factor of 2 lower when compared with the Galaxy (i.e., fewer O atoms are available for water chemistry). The dust-to-gas ratio in the LMC is lower, resulting in fewer dust grains for surface chemistry and less shielding than in the Galaxy. The deficiency of dust combined with the harsher UV radiation field in the LMC leads to warmer dust temperatures and consequently, less efficient grain-surface reactions. The LMC's cosmic-ray density is about 25% of that measured in the solar neighborhood, resulting in less effective cosmic-ray-induced UV radiation.

2. Results and Conclusions

The HDO data indicate that there are some minor differences (in comparison to expected) in the HDO chemistry between the LMC and the Galaxy. The HDO line luminosities ($L_{\rm HDO}$) measured toward the LMC hot cores (directly from the observed

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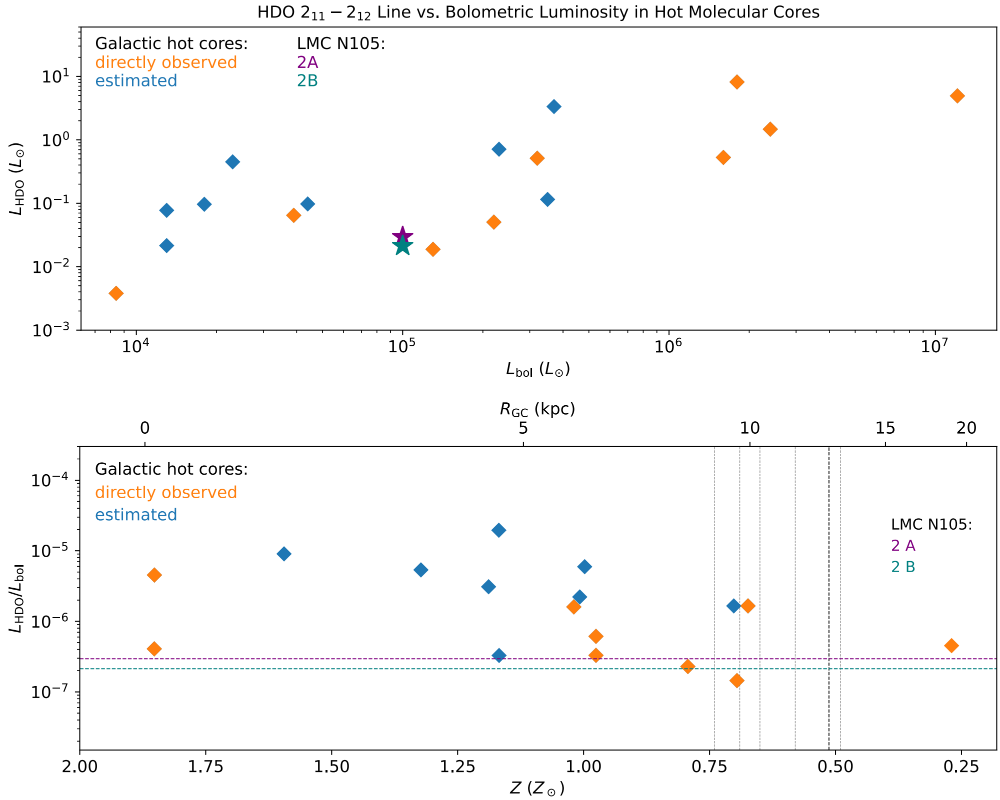

Figure 2. *Top:* The HDO 241.6 GHz line luminosities ($L_{\rm HDO}$) measured toward the LMC hot cores N 105–2 A and 2 B and those observed toward a sample of 17 Galactic hot cores as a function of the bolometric luminosity ($L_{\rm bol}$); Fig. 3 from Sewiło et al. (2022b). The values of $L_{\rm HDO}$ indicated with orange diamonds are based on the observations of the HDO $2_{11} - 2_{12}$ transition, while those indicated with blue diamonds were estimated using the observations of other HDO transitions as described in Sewiło et al. (2022b). *Bottom:* The $L_{\rm HDO}/L_{\rm bol}$ ratio as a function of the Galactocentric distance ($R_{\rm GC}$) and metallicity (Z); adapted from Fig. 4 in Sewiło et al. (2022b). Z at a given $R_{\rm GC}$ was calculated using the Balser et al. (2011)'s O/H radial gradient: $12 + \log({\rm O/H}) = -0.0446\, R_{\rm GC} + 8.962$; the vertical black line indicates $R_{\rm GC}$ where $[12 + \log({\rm O/H})]$ equals to the LMC value of 8.4 (e.g., Russell & Dopita 1992). The vertical gray lines indicate $R_{\rm GC}$ where $[12 + \log({\rm O/H})] = 8.4$ based on the O/H gradients found in other H II region studies.

integrated HDO line intensities) have been compared to those observed toward a sample of 17 Galactic hot cores covering three orders of magnitude in $L_{\rm HDO}$, four orders of magnitude in bolometric luminosity ($L_{\rm bol}$), and a wide range of Galactocentric distances (from ∼0.1 to 19 kpc), and thus metallicities (from ∼1.8 $Z_\odot$ toward the Galactic Center to ∼0.25 $Z_\odot$ in the outer Galaxy). The results are shown in Fig. 2. The Galactic hot cores shown in the plots are (in order of increasing $L_{\rm bol}$): WB 89–789 SMM1 (an extreme outer Galaxy source), NGC 7538 S, IRAS 18089−1732, G9.62+0.19, W43 MM1, W3(H_2O), W33A, NGC 7538 IRS1, AFGL 2591, G31.41+0.31, G34.26+0.15, G29.96−0.02, G10.47+0.03A, W51 e1/e2, Sgr B2(N), W51d, and Sgr B2(M).

Our results are providing first insights into the HDO chemistry in the LMC: (1) $L_{\rm HDO}$ for the LMC hot cores fit well into the $L_{\rm HDO}$ trends with $L_{\rm bol}$ and metallicity observed toward the Galactic hot cores; (2) $L_{\rm HDO}$ seems to be largely dependent on the source luminosity, but metallicity also plays a role. Moreover, the observations show that if

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HDO/H_2O in the LMC hot cores N 105–2 A and 2 B is within the range observed in the Galactic hot cores (typically $(2-8)\times10^{-4}$, van Dishoeck et al. 2021), then for the measured HDO abundances, the resulting H_2O abundance ranges toward N 105–2 A and 2 B would be systematically lower than Galactic values. The spatial distribution and velocity structure of the HDO emission in N 105–2 A is consistent with HDO being the product of the low-temperature dust grain chemistry.

Our results are in agreement with the astrochemical model predictions that HDO is abundant regardless of the extragalactic environment and should be detectable with ALMA in other external galaxies.

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