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Warm and Diffuse Gas in the Central Molecular Zone Revealed by Infrared H_3^+ Spectrum

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Abstract. Infrared spectroscopic observations of H_3^+ has revealed warm ($T \sim$ 250 K) and diffuse ($n \sim 100$ cm^{-3}) gas with long path lengths toward many stars from the center to 30 pc east of Sgr A*, indicating its ubiquity and high volume filling factor in the Central Molecular Zone (CMZ). This is a new category of gas in addition to the previously reported three, i. e., dense molecular clouds, the hot highly ionized HII region, and the ultra-hot X-ray emitting plasmas. Last year we extended our observations to wider regions of the CMZ and found two remarkable sightlines which show very strong H_3^+ spectra giving further evidence that the newly found gas occupy large volume of the CMZ.

1 H_3^+, the New Probe of the Central Molecular Zone

The infrared spectrum of H_3^+ at 3.5 - 4.0 μm is a new astrophysical probe (Geballe & Oka 1996). H_3^+ is particularly abundant (Geballe et al. 1999) and ubiquitous (Goto et al. 2008) in the CMZ. The simple physics and chemistry of H_3^+ allow us to study definitive properties of the gas in the CMZ.

Ionization Rate ζ and Column Length L

H_3^+ in the CMZ is produced via ionization of H_2 by cosmic rays or photoionization followed by a much faster reaction $H_2 + H_2^+ \rightarrow H_3^+ + H$, and destroyed by electron recombination $H_3^+ + e \rightarrow H + H + H$. Assuming that gaseous carbon atoms are singly ionized, we have (Oka et al. 2005, Oka 2006)

$$\zeta \cdot L = 2k_e N(H_3^+)(n_C/n_H)_{cv} R_X/f. \qquad (1)$$

If we use the recombination rate constant at 250 K of $k_e = 7.7 \times 10^{-8}$ cm^3 s^{-1} (McCall et al. 2004), the gaseous carbon to hydrogen ratio in the solar vicinity $(n_C/n_H)_{cv} = 1.6 \times 10^{-4}$ (Sofia et al. 2004), the increase of the C/H ratio from

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the solar vicinity to the GC of $R_{\rm X} = 3.6$ (Afflerbach et al. 1997, Rolleston et al. 2000), and fraction of molecular hydrogen $f = 1$, we have a numerical relation,

$$\zeta{\cdot}L = (7.8 \times 10^{-11}\ {\rm cm}^3\ {\rm s}^{-1}) N({\rm H}_3^+) \qquad (2)$$

Temperature T and Density n

The rotational energy levels of H_3^+ in Fig. 1 is ideally suited for measuring T and n of the gas in the CMZ. The population of H_3^+ in the $(J,K) = (3,3)$ metastable level 361 K above the ground level gives temperature. H_3^+ in the (2,2) unstable level decays to the ground state in 27 days, corresponding to the critical density of 200 cm^{-3}. Thus the population in the (2,2) level gives measure density in diffuse clouds. This division of labor, (3,3) as thermometer and (2,2) as densitometer leads to reliable T and n (Oka & Epp 2004, Oka et al. 2005).

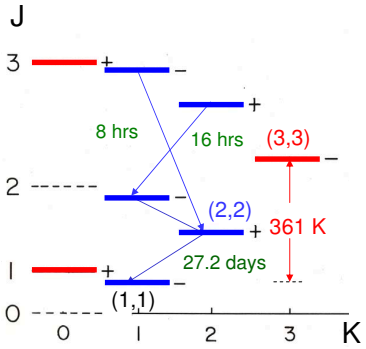

Figure 1. Rotational energy levels of H_3^+

2 H_3^+ Toward Bright Stars from the Center to 30 pc East

2.1 Observed Spectra

We have observed 15 bright dust embedded objects distributed from the Center to 30 pc to the East. High column densities on the order of (3×10^{15} cm^{-2}) of H_3^+ have been observed in all sightlines demonstrating the ubiquity of H_3^+ and large volume filling factor of the warm and diffuse environment. They all show strong $R(3,3)^l$ absorption indicating high temperature and missing or very weak $R(2,2)^l$ absorption indicating low density. The $R(3,3)^l$ absorption is unique to the CMZ.

Fig. 2 shows H_3^+ and CO spectra toward the brightest Quintuplet star GCS 3-2 (Oka et al. 2005). The three sharp absorptions at the velocities of -52, -32, and -5 km s^{-1} conspicuous in the top H_3^+ $R(1,1)$ line and the bottom CO $R(1)$ line are due to relatively cold and dense

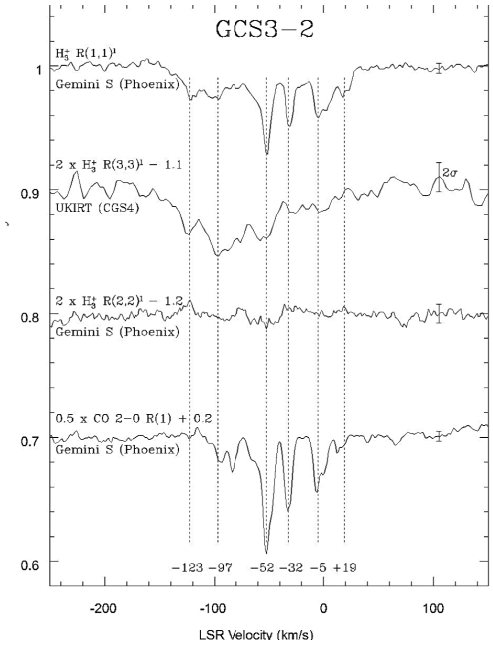

Figure 2. H_3^+ and CO spectra toward GCS 3-2

gas in the foreground three spiral
arms. These three absorptions dominate the CO spectrum indicating little CO in the diffuse gas in the front side of the CMZ. In contrast the three sharp absorptions are sitting on top of a broad trough in the H_3^+ spectrum which we ascribe to diffuse gas with high velocity dispersion in the CMZ.

The broad $R(3,3)^l$ absorption due to metastable H_3^+ in the second trace of Fig. 2 is interpreted to be all in the CMZ. Its strength shows high temperature of the environment. The non-detection of the $R(2,2)^l$ absorption third from the to in Fig. 2 demonstrates dramatically non-thermal distribution between the (2,2) and (3,3) levels and thus the low density of the environment.

The 15 stars so far observed from the center to 30 pc to the east show different velocity profiles but roughly similar patterns.

2.2 High ζ and L

The analysis of the H_3^+ column densities in rotational levels $J,K) = (1,1)$, (1,0), (2,2), and (3,3) obtained from intensities of absorption based on the model calculation of thermalization by Oka and Epp (2004) show the temperature of the environment of $T \sim 250$ K and density of $n \sim 100$ cm^{-3} for all sightlines toward the observed stars from the center to 30 pc to the east. The observed total H_3^+ column densities of $\sim 3.1 \times 10^{15}$ cm^{-2} give $\zeta \cdot L \sim 2.4 \times 10^5$ cm s^{-1} which is larger than the values for dense and diffuse clouds outside of GC by factor of more than 1000 and 10, respectively indicating high values of both ζ and L (Goto et al. 2008). We cannot separate ζ and L easily. If we assume $\zeta \sim 4 \times 10^{-16}$ s^{-1}, the typical value for diffuse clouds in the Galactic disk (Indriolo et al. 2007), we have $L = 200$ pc which is clearly too high. Even if we assume a very high value of $\zeta \sim 10^{-16}$ s^{-1}, we have very long path lengths of ~ 80 pc. This plus the very high velocity dispersion from -140 to 0 km s^{-1} strongly indicate ling path length of the newly found warm and diffuse gas.

3 The Observation Drastically Changes the Concept of Gas in the CMZ

Acknowledgments.

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