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DETECTION OF H_3^+ IN THE DIFFUSE INTERSTELLAR MEDIUM: THE GALACTIC CENTER AND CYGNUS OB2 NUMBER 12

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ABSTRACT

Absorption lines of H_3^+ have been detected in the spectra of two infrared sources in the Galactic center and also toward the heavily reddened star Cygnus OB2 No. 12, whose line of sight is believed to include only diffuse interstellar gas. The absorptions toward the Galactic center sources (IRS 3 and GCS 3-2) probably are due to H_3^+ both in diffuse gas and in molecular clouds. The ratios of H_3^+ line equivalent width to extinction toward these three sources are much greater than those toward dense clouds where H_3^+ has been detected previously. Analysis of the spectra coupled with a simple model for the abundance of H_3^+ in the diffuse interstellar medium implies that the observed H_3^+ is present at low densities along long path lengths. These are the first detections of H_3^+ in the diffuse interstellar medium.

Subject headings: Galaxy: center — infrared: ISM: lines and bands — ISM: clouds — ISM: molecules — molecular processes — stars: individual (Cygnus OB2 No. 12)

1. INTRODUCTION

The triatomic molecular ion H_3^+ is widely regarded as a cornerstone of chemistry in the gaseous interstellar medium. Ion-molecule reactions involving it are the starting point of reaction chains that lead to the production of many of the molecules that have been detected in dense molecular clouds (Herbst & Klemperer 1973; Watson 1973). H_3^+ does not have a conventional pure rotational spectrum, and astronomical searches for it had to await the measurement of its fundamental vibration-rotation band in the laboratory (Oka 1980) and the advent of sensitive high-resolution infrared array spectrometers for astronomy.

The first detections of H_3^+ outside the solar system, via two absorption lines near 3.67 μm, were reported in two dense molecular cloud cores along the lines of sight to the embedded young stellar objects W33A and GL 2136 (Geballe & Oka 1996). Since then a small survey at this wavelength has resulted in the detection of H_3^+ in several additional molecular clouds containing bright embedded young stellar objects (McCall, Geballe, & Oka 1999). In all of these cases the observed line strengths, which are very small, are consistent with the expected abundance of H_3^+ as determined by its predicted rates of production (following ionization of H_2 by cosmic rays) and destruction (by its reactions with other molecules, principally CO).

In the course of carrying out the above survey, we observed the Galactic center nuclear source IRS 3 (Becklin et al. 1978) and detected the 3.67 μm H_3^+ doublet in absorption. The absorption is unusually strong compared to those that have been measured in dense clouds, with a ratio of equivalent width to total extinction an order of magnitude larger than what is typical for dense clouds. We also detected absorption by H_3^+ with similar strength in the Galactic center "quintuplet" source GCS 3-2 (Nagata et al. 1990) located a quarter of a degree from the nucleus, which implies that the IRS 3 result is not anomalous.

The long lines of sight to the infrared sources in the Galactic center include molecular clouds near the Galactic center and in intervening spiral arms (Geballe, Baas, & Wade 1989), as well as considerable diffuse interstellar material, evidenced by the presence of a strong 3.4 μm absorption feature (Butchart et al. 1986; Okuda at al. 1990; Pendleton et al. 1994; Whittet et al. 1997). In order to better understand the origin of the large column density of H_3^+ toward the Galactic center, we obtained a spectrum near 3.67 μm of the heavily reddened star Cygnus OB2 No. 12, which is believed to be obscured almost entirely by diffuse, low-density material (and toward which the 3.4 μm absorption feature also is present; Adamson, Whittet, & Duley 1990; Pendleton et al. 1994). The H_3^+ doublet was detected in absorption there as well, and its equivalent width, while not approaching that of the Galactic center sources, is comparable to that seen toward sources embedded in dense molecular clouds despite the much lower extinction.

These observations clearly demonstrate that H_3^+ exists in detectable quantities in the diffuse interstellar medium as well as in molecular clouds. Much of the H_3^+ seen toward the Galactic center and Cygnus OB2 No. 12 thus exists in an environment completely different from that of the dense clouds studied to date. Few, if any, polyatomic molecules have been reported in diffuse clouds. In the following sections we describe these new observations and several follow-up measurements in more detail and discuss the physical conditions and processes affecting the abundance of H_3^+ in the diffuse interstellar medium.

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2. OBSERVATIONS AND DATA REDUCTION

A log of the observations is provided in Table 1. The first detections of absorption by H_3^+ in the Galactic center sources IRS 3 and GCS 3-2, and in Cygnus OB2 No. 12, were of the $R(1, 0)$ and $R(1, 1)^+$ ortho-para doublet at 3.67 μm (see Oka & Jagod 1993 for an explanation of the spectroscopic notation). They were obtained on UT 1997 July 11 at the 3.8 m United Kingdom Infrared Telescope (UKIRT) on Mauna Kea with the facility spectrometer CGS4, and its echelle was used, which provided a resolution of 15 km s^{-1}. The observing techniques were standard and similar to those described in Geballe & Oka (1996). The identification of the rather broad 3.67 μm absorption in the Galactic center as owing to H_3^+ was supported by detection of a broad isolated line of H_3^+ at 3.953 μm.

A spectrum of the 3.715 μm $R(1, 1)^-$ line of H_3^+ was obtained toward Cygnus OB2 No. 12 on 1997 September 5 using the echelle spectrometer, Phoenix, at the 4.0 m Mayall Telescope on Kitt Peak. The resolution achieved by Phoenix was approximately 9 km s^{-1}, somewhat higher than that by CGS4. To test for molecular material along the line of sight to Cygnus OB2 No. 12, CGS4 was used again on 1997 August 2 to obtain a spectrum of $v = 1$–0 lines of the fundamental vibration rotation band of CO near 4.65 μm at a resolution of 20 km s^{-1}. Several narrow absorption lines from low-lying J levels were detected. Finally, spectra of the pure rotational $J = 2$–1 emission lines of ^{12}CO and ^{13}CO in the direction of the star were secured on 1997 August 5 and November 13 at the James Clerk Maxwell Telescope (JCMT) on Mauna Kea using the heterodyne receiver A2. A background sky position 30′ north of the star was used for the ^{13}CO spectrum, and a combination of sky positions was used for the ^{12}CO spectrum.

Each of the spectra obtained with CGS4 was sampled every $\frac{1}{3}$ resolution element; those obtained by Phoenix were sampled every 0.18 resolution element. Data reduction consisted of small wavelength shifts of the spectra to bring atmospheric features in the source and calibration star spectra into coincidence, dividing the spectra of the sources by those of the comparison stars (adjusted for air mass using Beer's law), and wavelength calibration (using telluric absorption lines). The comparison stars are expected to be featureless in the wavelength regions observed except for the presence of the H I Pfβ line at 4.654 μm. Wavelength calibration is accurate to ± 3 km s^{-1} for the CGS4 spectra, and ± 2 km s^{-1} for the Phoenix spectra.

Two of the three H_3^+ lines observed near 3.7 μm are clear of strong telluric absorption lines; however, the shorter wavelength component of the 3.67 μm doublet is in near coincidence with a strong telluric absorption of methane centered at 3.6675 μm. Two telluric lines of HDO lie just longward in wavelength of the methane feature. For the Galactic center sources, which have broad absorption profiles, the wavelengths of these telluric lines lie within the blended H_3^+ profile. On the date that the doublet was measured toward Cygnus OB2 No. 12, the methane absorption coincided with the short-wavelength edge of the $R(1, 1)^+$ (shorter wavelength) line. Care was taken to observe each source and its calibration star close to the same air mass, and in fact the air masses of the pairs of observations were equal to within 4% in the case of the Galactic center, and to within 2% in the case of Cygnus OB2 No. 12 (for both the H_3^+ and the CO spectra). Nevertheless, proper correction of the methane line is problematic. In both the Galactic center and Cygnus 3.67 μm spectra it is likely that the divided spectra are distorted near the $R(1, 1)^+$ line. Consequently, the parameters derived from this line have relatively large uncertainties. At Kitt Peak, measurement of the doublet was virtually impossible because of the much stronger telluric absorption lines, and hence the single line at 3.715 μm was observed.

3. RESULTS

The observed H_3^+ lines originate from the lowest lying ortho and para states of the molecular ion. The $R(1, 1)$ absorptions are from the ground $(J, K) = (1, 1)$ para state, and the $R(1, 0)$ absorptions are from the lowest ortho level 33 K above the ground state. The lowest lying $J = 2$ level (2, 2) is 151 K above ground. Because of this and the low temperatures of dark clouds and the interiors of diffuse clouds (van Dishoeck 1990), $J = 1$ levels are the only ones significantly populated in interstellar clouds (Oka & Jagod 1993). Although no radiative transitions are permitted between ortho and para states of H_3^+ (Pan & Oka 1986), collisions of H_3^+ with H_2 exchange protons and thereby maintain the relative populations of the two types of H_3^+ in thermal equilibrium (Uy, Cordonnier, & Oka 1997).

3.1. *Galactic Center Sources*

Figure 1 shows the spectrum of the Galactic center nuclear source IRS 3 and the quintuplet source GCS 3-2 near the 3.67 μm H_3^+ doublet. A broad absorption, which extends over at least 0.003 μm (250 km s^{-1}) is seen in each spectrum. The rest wavelengths of the components of the doublet are separated by only 0.00043 μm (35 km s^{-1}). Thus toward these objects a significant part of the line absorption extends over a wide range of velocities, and the individual profiles of the lines in the doublet considerably overlap one

TABLE 1

LOG OF OBSERVATIONS

UT Date (1997)	Telescope	Instrument	Object	Molecule	Wavelength/Frequency	Integration Time (minutes)	Standard Star	Resolution (km s^{-1})
Jul 11	UKIRT	CGS4	GC IRS 3	H_3^+	3.668 μm	29	HR 6486	15
			GCS 3-2	H_3^+	3.668 μm	7	HR 6486	15
			GC IRS 3	H_3^+	3.953 μm	16	HR 6486	16
			Cyg OB2 12	H_3^+	3.668 μm	10	HR 7924	15
Aug 2	UKIRT	CGS4	Cyg OB2 12	CO	4.65 μm	3	HR 7924	20
Aug 5	JCMT	A2	Cyg OB2 12	^{12}CO	230 GHz	4	...	0.3
Sep 5	Mayall	Phoenix	Cyg OB2 12	H_3^+	3.715 μm	60	HR 7924	9
Nov 13......	JCMT	A2	Cyg OB2 12	^{13}CO	220 GHz	30	...	0.3

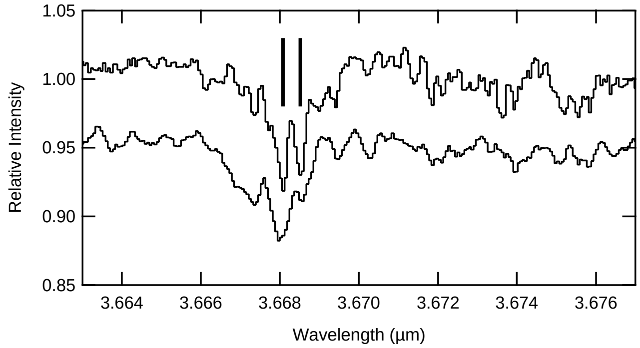

FIG. 1.—Spectrum of the Galactic nuclear source IRS 3 (*upper line*) and the "quintuplet" source GCS 3-2 (*lower line*, shifted down by 0.05 units), near the $R(1, 1)^+$ and $R(1, 0)$ doublet of H_3^+. The rest wavelengths of the lines are indicated by vertical bars. The noise levels are indicated by the point-to-point variations.

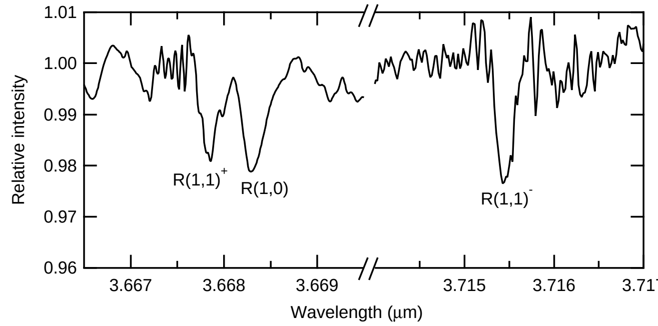

FIG. 2.—Spectrum of Cygnus OB2 No. 12 in two wavelength intervals near 3.7 μm. Lines of H_3^+ are indicated. The high-frequency noise near 3.6675 μm is a result of the correction for a strong telluric CH_4 line.

another. A narrow doublet is observed toward IRS 3 at $v_{LSR} = 0$ km s^{-1} with the correct (4.3 Å) spacing, and it also may be present toward GCS 3-2, but it is less obvious there. The measured equivalent widths of the observed lines toward both Galactic center sources are given in Table 2. The equivalent width toward IRS 3 has been separated into a broad component and a narrow component (the latter defined as absorption below 0.97, which corresponds to the $v_{LSR} = 0$ component). Also listed in Table 2 are the estimated column densities of H_3^+ that were obtained using the standard formula for an optically thin line, $W_\lambda = (8\pi^3\lambda/3hc)N|\mu|^2$, where N is the column density in the lower state of the transition and μ is the dipole moment of the transition (values have been provided by J. K. G. Watson and are listed by Geballe & Oka 1996).

In view of the detection of H_3^+ toward Cygnus OB2 No. 12, the H_3^+ absorptions toward the Galactic center sources are expected to include both diffuse and dark cloud components, each of which should contribute to the overall line profile. Infrared absorption lines of the fundamental vibration-rotation band of carbon monoxide previously have been observed toward both IRS 3 and GCS 3-2 (Geballe et al. 1989; Okuda et al. 1990). The velocity profiles of these CO lines are complex and contain a number of discrete components, several of which are identified with specific dense clouds known from radio and millimeter spectral mapping. In the case of IRS 3, the CO absorption lines, which are heavily saturated at low-J levels, have strong components at $v_{LSR} = 0$ km s^{-1}, similar to H_3^+. Their centroids, however, are at $v_{LSR} \sim 30$ km s^{-1}, and weak blueshifted absorption extending to -150 km s^{-1} is present (Geballe et al. 1989). For GCS 3-2, strong absorption by CO is centered roughly at -70 km s^{-1}. The observed H_3^+ profiles and source-to-source differences are crudely similar to those of the CO observations. This suggests that some of the H_3^+ observed toward the Galactic center indeed is found in molecular clouds.

3.2. *Cygnus OB2 No. 12*

The spectral lines of H_3^+ toward Cygnus OB2 No. 12 (initially reported by McCall et al. 1998) are shown in Figure 2. Parameters derived from each line in Figure 2 are listed in Table 3. In contrast to the Galactic center, the components of the 3.67 μm doublet are well resolved from one another, and no broad component is observed. The individual lines of the doublet were partially resolved by CGS4, and the $R(1, 1)^-$ transition was more fully resolved by Phoenix. Each $R(1, 1)$ line arises from the lowest lying para level and hence should yield the same column density; however, as pointed out above, possible noncancellation of the telluric CH_4 line leads to large uncertainties in the column density and velocity width derived for the $R(1, 1)^+$ line. Hence we rely on the measurement of the $R(1, 1)^-$ line to determine the column density of para-H_3^+. We calculate a total H_3^+ column density of 3.8×10^{14} cm^{-2} toward Cygnus OB2 No. 12 and derive an intrinsic line width of ~ 14 km s^{-1} (FWHM).

The infrared spectrum of CO toward Cygnus OB2 No. 12, which also was presented by McCall et al. (1998), is

TABLE 2

H_3^+ LINE PARAMETERS TOWARD THE GALACTIC CENTER

Source	Line(s)	λ (μm)	W_λ (10^{-6} μm)[a]	$N_{level}(H_3^+)$ (10^{14} cm^{-2})[a]	Level
Narrow component:[b]					
GC IRS 3	$R(1, 1)^+$	3.66808	12(4)	5.1(1.7)	para
GC IRS 3	$R(1, 0)$	3.66852	9(4)	2.4(1.1)	ortho
Broad component:[c]					
GC IRS 3	$R(1, 1)^+ + R(1, 0)$	3.668	53(12)	17.5(3.9)	Total
GCS 3-2	$R(1, 1)^+ + R(1, 0)$	3.668	83(8)	27.7(2.4)	Total

[a] Statistical uncertainties (3 σ) are given in parentheses. Systematic errors are difficult to estimate and may be larger.

[b] The narrow component at $v_{LSR} \approx 0$, defined as the absorption below 0.97.

[c] Column densities for broad components are estimated assuming equal amounts of para- and ortho-H_3^+ and using an average value of $|\mu|^2 = 0.0209$ D^2.

TABLE 3

H_3^+ LINE PARAMETERS TOWARD CYGNUS OB2 No. 12

Line	λ (μm)	W_λ (10^{-6} μm)[a]	N_{level} (10^{14} cm^{-2})[a]	v_{LSR} (km s^{-1})[a]	FWHM$_{obs}$ (km s^{-1})[a]	FWHM$_{deconv}$ (km s^{-1})
$R(1, 1)^+$	3.66808	3.9(9)	1.6(4)	8(5)	17(5)	8
$R(1, 0)$	3.66852	5.4(9)	1.4(2)	11(5)	22(5)	16
$R(1, 1)^-$	3.71548	5.2(7)	2.4(3)	8(3)	16(3)	13

[a] Statistical uncertainties (3 σ) are given in parentheses.

shown in Figure 3, and the millimeter-wave spectra of the $J = 2$–1 lines of ^{12}CO and ^{13}CO are shown in Figure 4. Six narrow absorption lines of ^{12}CO can be seen in the infrared spectrum. Of these, the weaker ones are unresolved and therefore have widths much less than the resolution of 20 km s^{-1}. The stronger lines appear to be partially resolved, although their profiles may be contaminated by incomplete removal of telluric CO lines. If they are composed of a few very narrow components, the stronger lines may be saturated. The CO absorption profiles are centered at $v_{LSR} \sim 15 \pm 4$ km s^{-1}. The millimeter CO spectra, obtained at a much higher spectral resolution but with an angular resolution of 21″, much lower than the pencil beam of the infrared absorption spectra, show narrow emission lines at three velocities, -21, 7, and 12 km s^{-1}. This suggests that the CO absorption lines are produced largely by the 7 and 12 km s^{-1} clouds.

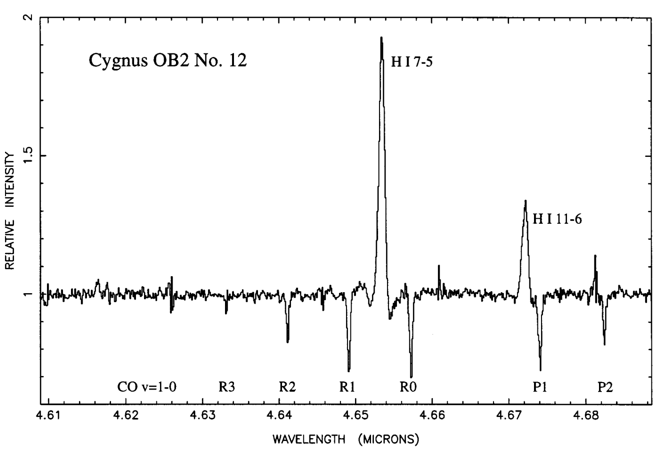

FIG. 3.—Spectrum of Cygnus OB2 No. 12 near 4.65 μm, which shows absorption lines of ^{12}CO and emission lines of atomic hydrogen.

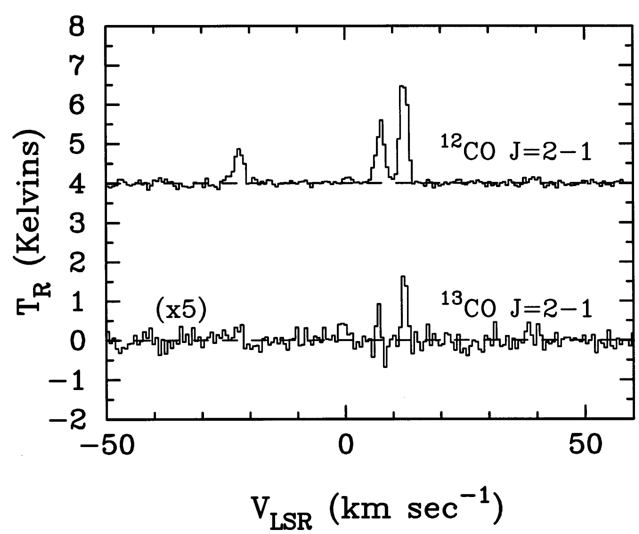

FIG. 4.—Spectra of pure rotational 2–1 lines of ^{12}CO and ^{13}CO. The original data have been binned into 0.6 km s^{-1} intervals, and a 4 K offset has been given to the ^{12}CO spectrum. The vertical axis is detected antenna temperature corrected for the telescope efficiency.

Additional information on the molecular gas along the line of sight to Cygnus OB2 No. 12 is available from high-resolution near-infrared spectra of C_2 obtained by Gredel & Münch (1994). Their spectra reveal four absorption components at LSR velocities of 7, 12, 15, and 31 km s^{-1}, with the last of these very weak compared to the first three. As in the case of the infrared CO lines, absorption at -21 km s^{-1} was not detected and therefore the -21 km s^{-1} cloud seen in emission in the millimeter-wave spectra either does not fill the millimeter beam or lies beyond Cygnus OB2 No. 12.

As pointed out earlier, the relative populations of ortho- and para-H_3^+ are in LTE. The mean temperature of the H_3^+ may be derived from the column densities of the lowest lying ortho and para levels, according to the formula

$$N_{ortho}/N_{para} = (g_{ortho}/g_{para})e^{-32.87/T} . \quad (1)$$

Using the measured column densities derived from the $R(1, 0)$ and $R(1, 1)^-$ lines (Table 3), we estimate the mean temperature of the H_3^+ to be $\sim$30 K. Gas temperatures of 35 and 50 K were derived from the C_2 spectra of Souza & Lutz (1977) and Gredel & Münch (1994), respectively. Assuming LTE, the relative strengths of the infrared CO lines (see Table 4) suggest a temperature of 5–10 K; however, the gas temperatures derived from C_2 are more realistic than those from CO because the long radiative relaxation time of C_2 guarantees that C_2 level populations are governed by collisions. Indeed the difference in these derived temperatures indicates that the rotational levels of

TABLE 4

CO INFRARED LINES TOWARD CYGNUS OB2 No. 12

Line	λ_{obs} (μm)	W_λ (10^{-6} μm)[a]	v_{LSR} (km s^{-1})[a]
$R(3)$......	4.63308	19(4)	13(4)
$R(2)$......	4.64112	62(6)	19(4)
$R(1)$......	4.64913	121(7)	15(4)
$R(0)$......	4.65727	134(7)	12(4)
$P(1)$......	4.67401	132(7)	18(4)
$P(2)$......	4.68243	69(6)	13(4)

[a] Statistical uncertainties (3 σ) are given in parentheses. Systematic errors due to incomplete cancellation of telluric CO lines are difficult to estimate and may be larger.

CO are not in LTE, which is not surprising for diffuse clouds. From strengths of the absorption lines of CO we estimate a total column density of CO of 3×10^{16} cm^{-2} toward Cygnus OB2 No. 12.

4. DISCUSSION

4.1. *Abundances of* H_3^+ *in Molecular Clouds and Diffuse Clouds*

In interstellar clouds most H_3^+ is thought to be formed following cosmic-ray ionization of H_2 via the rapid reaction of the newly formed H_2^+ with H_2 (Martin, McDaniel, & Meeks 1961). It is destroyed by recombination with free electrons or via reactions with any number of neutral atoms or molecules. In diffuse clouds the former destruction process should dominate; in dark molecular clouds, it is reactions with neutrals and molecules (in particular with CO) that are dominant. McCall et al. (1998) have given a general treatment for determining the density of H_3^+ where both of the destructive processes are included. Here we separate the two cases of dark and diffuse clouds, which allows simple approximate expressions for the density of H_3^+ to be derived for both. We then apply these to the observations in hand: those of Cygnus OB2 No. 12 where only the diffuse component is present, and those of the Galactic center in which both environments exist along the line of sight.

The analysis for molecular clouds has been given elsewhere (see, e.g., Geballe & Oka 1989, 1996). To summarize, the concentration of H_3^+, derived from the approximate equation equating its rates of creation and destruction, is

$$n(H_3^+) = (\zeta/k_{CO})n(H_2)/n(CO) , \qquad (2)$$

where ζ is the cosmic-ray ionization rate per H_2 molecule, and k_{CO} is the reaction rate constant of H_3^+ with CO. This simple equation arises because the proton hop from H_3^+ to CO dominates the destruction of H_3^+. To evaluate the equation we use $\zeta = 3 \times 10^{-17}$ s^{-1}, which is an average of recently used values (van Dishoeck & Black 1986; Lee, Bettens, & Herbst 1996), and $k_{CO} = 2 \times 10^{-9}$ cm^3 s^{-1} (Anicich & Huntress 1986), and the result from Lee, Bettens, & Herbst (1996) that in dark clouds with gas phase C/H $= 7.3 \times 10^{-5}$, $n(CO)/n(H_2) = 1.5 \times 10^{-4}$ is constant over a wide range of conditions. [Note that Lacy et al. 1994 have measured $N(CO)/N(H_2) = 2.8 \times 10^{-4}$ in one cloud, with a large uncertainty.] Then $n(H_3^+) \sim 1 \times 10^{-4}$ cm^{-3} is independent of cloud density, and from the measured H_3^+ column density one can estimate the distance through the dark cloud to the source. An interesting consequence of this result is that the column density of H_3^+ is simply proportional to the column length of the cloud rather than the column density of all molecules in the cloud. For example, for two molecular clouds of equal masses but one with twice the linear dimensions of the other [i.e., with 8 times lower density $n(H_2)$], $N(H_3^+)$ in the larger cloud is twice as high even though the column density $N(H_2)$ is 4 times less.

In diffuse clouds H_3^+ is formed in the same way as in dense clouds, but its destruction is dominated by recombination with electrons (van Dishoeck & Black 1986). Thus, the steady state rate equation for H_3^+ is

$$\zeta n(H_2) = k_e n(e) n(H_3^+) . \qquad (3)$$

Both atomic and molecular hydrogen are abundant in diffuse clouds, and very little H is ionized; thus $n(H_2)$ may be expressed as $(f/2)n(\Sigma H)$, where f is the fraction of hydrogen in molecular form, $f = 2n(H_2)/[n(H) + 2n(H_2)]$, and $n(\Sigma H) = n(H) + 2n(H_2)$ is the density of H atoms in atomic and molecular form. Essentially all of the electrons in the diffuse interstellar medium are from carbon, which is almost fully singly ionized, and hence $n(e)$ may be expressed as $z_C n(\Sigma H)$, where z_C is the fractional abundance of *free* carbon. We thus obtain

$$n(H_3^+) = \zeta f/(2k_e z_C) . \qquad (4)$$

To estimate $n(H_3^+)$ we use the same value for ζ as we used for dark clouds. If H_2-dissociating UV radiation is shielded from the regions where H_3^+ is observed (which requires boundary column densities of $\sim 10^{20}$ cm^{-2}; Glassgold & Langer 1974), $f \sim \frac{1}{2}$ (see also van Dishoeck & Black 1986). Cardelli et al. (1996) and Sofia et al. (1997) have measured z_C to be 1.4×10^{-4} in diffuse clouds.

The final parameter needed to estimate $n(H_3^+)$ is the rate constant k_e for electron recombination of H_3^+. Experimental values of this constant have varied widely, but recent results seem to be converging to a value of $k_e \sim 10^{-7}$ cm^3 s^{-1} at room temperature. Using Amano's (1988) value of 1.8×10^{-7}, we obtain $n(H_3^+) \sim 3 \times 10^{-7}$ cm^{-3}. Using the expression derived from storage ring experiments, $k_e = 4.6 \times 10^{-6}\, T^{-0.65}$ cm^3 s^{-1} (Sundström et al. 1994), and using an assumed electron temperature of 30 K, we obtain $n(H_3^+) \sim 1 \times 10^{-7}$ cm^{-3}. The uncertainty in k_e, along with that of ζ, is the greatest uncertainty in the determination of $n(H_3^+)$. Further experimental and theoretical results for k_e are eagerly awaited.

Thus under the above conditions, the volume density of H_3^+ in diffuse clouds also is approximately independent of cloud density, but its value is roughly 3 orders of magnitude less than in dark clouds. Only if the path length through diffuse clouds is vastly greater than that through an individual dark cloud can the column density of H_3^+ be comparable to its value through the dark cloud.

4.2. H_3^+ *toward Cygnus OB2 No. 12*

From the visual extinction of 10.2 magnitudes to Cygnus OB2 No. 12 (Humphreys 1978), its distance of 1.7 kpc (Torres-Dodgen, Tapia, & Carroll 1991) and the standard gas-to-dust conversion factor (Bohlin, Savage, & Drake 1978), the column density of hydrogen atoms, $N(\Sigma H) = N(H) + 2N(H_2)$, along the line of sight is roughly 2×10^{22} cm^{-2}. The analysis of the infrared CO absorption lines indicates that along the line of sight $N(CO)/N(\Sigma H) \sim 1.5 \times 10^{-6}$, which is much less than C/H. Thus at most a few percent of the carbon is in molecular form. This is consistent with the clouds in front of Cygnus OB2 No. 12 being diffuse.

Using the measured value of $N(H_3^+)$ and the values of $n(H_3^+)$ calculated in § 4.1, the length of the absorbing column of H_3^+ is roughly $L = N(H_3^+)/n(H_3^+) \sim$ 400–1200 pc. This path length seems unreasonably large (although it does not exceed the total distance to the star). The mean gas density over the path would be $N(\Sigma H)/L \sim 10$ cm^{-3}. Carbon monoxide at such low densities is virtually completely confined to the lowest rotational level (Zuckerman & Palmer 1974) and could not produce the observed CO and ^{13}CO $J = 2$–1 line emission. The derived path length also is not in agreement with observations of rotational lines of CH (E. F. van Dishoeck 1997, private communication) and the near-infrared spectra of C_2 (Souza

& Lutz 1977; Gredel & Münch 1994). Those observations suggest that the bulk of the intervening molecular material exists in clouds with typical densities of a few hundred cm^{-3}. The total gas column density then implies that these clouds have an aggregate length of ~ 30 pc. If the H_3^+ at densities of (1–3) $\times 10^{-7}$ cm^{-3} were confined to such diffuse clouds it would have a column density more than an order of magnitude less than observed. Taken together these results suggest that most of the H_3^+ is found where the other molecules do not exist. It is, of course, possible that the H_3^+ does not trace the presence of other molecules, but there is no a priori reason to assume that it should not.

On the other hand, if the observed H_3^+ is confined solely to clouds containing CH and C_2 along a path length of ~ 30 pc, the density of H_3^+ in them is $\sim 4 \times 10^{-6}$ cm^{-3}. This is more than an order of magnitude higher than the estimated density of H_3^+ in diffuse clouds (see § 4.1). This density would imply either that the value of ζ/k_e is at least 1 order of magnitude larger than that used here (suggesting that one or both of these assumed constants needs to be revised), or that one or more processes in addition to the interaction of cosmic rays with H_2 governs the production of H_3^+ in diffuse clouds.

Galactic rotation along the line of sight to Cygnus OB2 No. 12 produces a range of radial velocities of approximately 3.3 km s^{-1}, assuming a flat rotation curve with $v_c = 220$ km s^{-1}, $R_0 = 8$ kpc, and $l = 80\overset{\circ}{.}10$. The velocity dispersion of the interstellar medium ($\sigma \sim 6.6$ km s^{-1}, which implies FWHM = 15.6 km s^{-1}; Welty, Hobbs, & Kulkarni 1994) is considerably greater than this. The presence of H_3^+ along a large fraction of the line of sight to Cygnus OB2 No. 12 thus is not ruled out by the observed line width and is consistent with typical velocity dispersions observed in the interstellar medium. If the path length over which H_3^+ absorption occurs is indeed very long compared to those of other molecular absorption lines, the profiles of H_3^+ lines should differ from those of the other molecules, probably in the sense of being more complex. Higher resolution spectroscopy of the H_3^+ infrared absorption lines will test this possibility and will facilitate important comparisons with the C_2 near-infrared and CO radio spectra, both of which show a few well-defined velocity components.

4.3. H_3^+ *toward the Galactic Center*

The total column density of H_3^+ observed toward the Galactic center source IRS 3 is 25×10^{14} cm^{-2}, nearly an order of magnitude greater than those found in dense cloud cores (Geballe & Oka 1996; McCall, Geballe, & Oka 1999) and along the line of sight to Cygnus OB2 No. 12. The visual extinction toward the nuclear sources in the Galactic center is approximately 27 mag (Wade et al. 1987). Various lines of evidence suggest that roughly one-third of the extinction occurs in molecular clouds and that two-thirds arises in diffuse gas (see, e.g., Whittet et al. 1997). However, there is no a priori reason that the division of H_3^+ column density between the diffuse and molecular clouds should be the same as the division of visual extinctions. Neither can it be assumed that the column density of H_3^+ in the diffuse gas toward the Galactic center may be determined by scaling $N(H_3^+)$ toward Cygnus OB2 No. 12 by the ratio of visual extinctions in diffuse gas or by the ratio of optical depths of the 3.4 μm absorption feature.

It is likely that toward the Galactic center substantial column densities of H_3^+ are found in both dark and diffuse environments. For illustrative purposes we assume that the sharp H_3^+ doublet is due to diffuse gas in the bulk of the Galaxy. This assumption seems reasonable since gas on circular orbits at $l = 0°$ should appear near $v_{LSR} \sim 0$, which is where the doublet is seen. We assume that the remainder of the H_3^+ line profile occurs in denser gas nearer the Galactic center and presumably in noncircular orbits.

For the diffuse gas we employ the H_3^+ density estimates derived in § 4.1. For $N(H_3^+) \sim 7.5 \times 10^{14}$ cm^{-2} (Table 2), the H_3^+ absorption toward IRS 3 extends over $\sim$0.8–2.5 kpc. While this is a surprisingly extended path length, it is not completely unrealistic in view of the much larger distance to the Galactic center than toward Cygnus OB2; however, as also pointed out for Cygnus OB2 No. 12, if k_e is lower or ζ higher than our assumptions in § 4.1, the derived path length would decrease proportionately.

In molecular clouds, the number density of H_3^+ is roughly 3 orders of magnitude greater, and for a column density of $\sim 17.5 \times 10^{14}$ cm^{-2} we deduce a path length of ~ 6 pc. From the extinction produced by the molecular clouds (5–10 mag; see Whittet et al. 1997), the standard gas-to-dust ratio (Bohlin et al. 1978), and the above path length, a mean gas density of ~ 1000 cm^{-3} is derived. This is considerably less than the densities in the cloud cores in which H_3^+ has been detected. The difference is not surprising, however, because the line of sight to the Galactic center, which is known to pass through a number of massive clouds near the center as well as spiral arms, does not pass through or even very close to any cloud cores (see, e.g., Federman & Evans 1981).

Here we have discussed only the source IRS 3. These conclusions should in general also apply to the quintuplet source GCS 3-2, although in the case of this source it is difficult to separate the diffuse and dense cloud contributions to the H_3^+ profile.

5. CONCLUSIONS

H_3^+ has been detected in the diffuse interstellar medium toward two sources in the Galactic center and toward the highly reddened star Cygnus OB2 No. 12. The column density of H_3^+ observed toward the Galactic center is nearly an order of magnitude greater than that toward the dense cloud cores where interstellar H_3^+ has been found. Despite the relatively low extinction toward Cygnus OB2 No. 12, the column density of H_3^+ in front of it is comparable to those found toward cloud cores. Using the best values currently available for the rates of cosmic-ray ionization of H_2 in diffuse clouds and dissociative recombination of H_3^+, the density of H_3^+ in the diffuse interstellar medium is roughly 3 orders of magnitude less than in dark clouds, which implies that toward both the Galactic center and Cygnus OB2 No. 12 the observed H_3^+ exists along very long path lengths. Measurements of H_3^+ toward Cygnus OB2 No. 12 at higher spectral resolution coupled with more accurate values of the above two rates are required to understand the physical relation between H_3^+ and the other molecules observed along this line of sight.

These detections open the way for organized study of the diffuse interstellar medium via infrared spectroscopy. Both CO and H_3^+ are demonstrated here to have detectable infrared signatures for modest amounts of extinction by diffuse gas within the Galaxy. It is likely that soon there will be detections of these features in the diffuse interstellar media of external galaxies.

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