The Ubiquitous H_3^+

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1 Ubiquitous H_3^+

Although it took many years from the discovery of the laboratory spectrum of H_3^+ (Oka 1980) and its first astronomical search (Oka 1981) to its detection in interstellar space (Geballe & Oka 1996), subsequent observations have revealed ubiquity of this fundamental molecular ion in a wide variety of astronomical objects. H_3^+ with column densities on the order of $\sim 10^{14}$ cm^{-2} has been detected not only in many dense clouds (McCall et al. 1998^a, 1999, Geballe et al. 2002, Kulesa et al. 2002), where its presence had been anticipated from chemical model calculations (Herbst & Klemperer 1973, Watson, 1973), but also in many diffuse clouds (McCall et al. 1998^b, Geballe et al. 1999, McCall et al. 2002) where its abundance was not anticipated and introduced an enigma in the chemistry of the diffuse interstellar medium. Many astronomers, physicists and chemists are currently attempting to understand this problem (Oka 2000, McCall & Oka, 2000).

In this contribution I would like to summarize our H_3^+ observations toward stars with a wide range of extinctions (Sect. 2), special characteristics of the chemistry of H_3^+ (Sect. 3), H_3^+ toward the Galactic center (Sect. 4), H_3^+ in metastable rotational level (Sect. 5) and some recent highlights (Sect. 6).

2 From Dense to Diffuse Clouds

The initial detections of interstellar H_3^+ (Geballe & Oka 1996) were toward young stellar objects W33A and AFGL 2136 that are deeply embedded in molecular clouds and have high magnitude of extinction ($A_v \sim 100$). Subsequently, H_3^+ have been found in many dense clouds and the observed column densities are approximately proportional to the extinction.

It was a big surprise when nearly equal column density of H_3^+ was discovered in the diffuse interstellar medium toward a faint visible star Cygnus OB2 No. 12 whose extinction is much smaller ($A_v \sim 10$, V=11.98) (McCall et al. 1998b, Geballe et al. 1999). It had been thought that the number density of H_3^+ in diffuse clouds was two to three orders of magnitude lower than that in dense clouds since the H_3^+ destruction mechanism in the former (dissociative recombination with an electron) is much more rapid than that in the latter (proton hop reaction from H_3^+ to CO) as discussed in the next section.

Subsequently, however, H_3^+ has been observed toward even brighter stars with lower extinction such as the classic translucent sightline HD183143 with $A_v \sim 4.0$ and V=6.86 (McCall et al. 2002). The recent observations of H_3^+ toward the bright star ζ Per with $A_v \sim 1$ and V=2.88 is particularly noteworthy (McCall et al. 2003). This universal abundance of H_3^+ in sightlines with a wide range of extinction makes it a general astrophysical probe to study a wide variety of objects.

The observed H_3^+ column densities, $N(H_3^+)$, in many dense and diffuse clouds are plotted against their extinction A_v in Fig. 1.

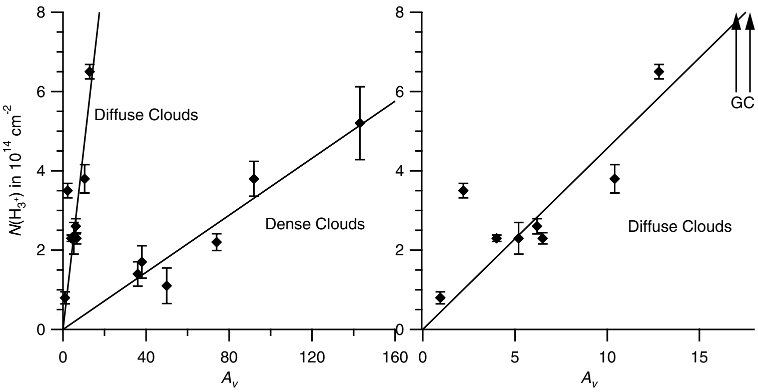

Fig. 1. Observed H_3^+ column density versus A_v for dense and diffuse clouds. $N(H_3^+)$ toward GC are higher than what the slope indicates by a factor of 3$\sim$ 5

We note two surprises in this figure. The first is the huge difference between the slopes of $N(H_3^+)$ versus A_v for dense and diffuse clouds. This is clearly due to the very different chemistry and physics of H_3^+ in the two categories of clouds as discussed in the next section. We are now attempting to fill this singularity of slopes by observing high A_v translucent clouds such as those toward the Stephenson objects (Rawlings et al. 2000).

The second surprise is the extremely high H_3^+ column densities observed toward bright infrared sources GCS 3-2 and GC IRS3 near the Galactic center. These column densities are off from the slope of other diffuse clouds by a factor of $\sim$3. If we include H_3^+ in metastable levels discussed in Sect. 5, this factor is more likely $\sim$ 5. Based on the H_3^+ chemistry discussed in the next section, this indicates that the sightlines cross long paths of low density clouds. This has implications on metastable H_3^+ so far observed only toward the Galactic center as discussed in Sect. 5.

3 Special Characteristics of the H_3^+ Chemistry

H_3^+ is produced via ionization of H_2 to H_2^+ by the ubiquitous cosmic ray or local X-ray, followed by the efficient Langevin reaction, $H_2^+ + H_2 \rightarrow H_3^+ + H$.

Since the latter process ($\sim$ 1/day) is much faster than the former ($\sim 1/10^{7-9}$ years), the production rate is given by $\zeta n(H_2)$ where ζ ($10^{-17} \sim 10^{-15} s^{-1}$) is the H_2 ionization rate. H_3^+ is destroyed by the proton-hop reaction, $H_3^+ + X \rightarrow HX^+ + H_2$, with the rate $k_X n(H_3^+) n(X)$. Equating the production and destruction rates, we have the steady state H_3^+ number density of

$$N(H_3^+) = (\zeta/k_X)[n(H_2)/n(X)] \quad (1)$$

In dense clouds X=CO is the main destroyer and

$$N(H_3^+) = (\zeta/k_{CO})[n(H_2)/n(CO)] \quad (2)$$

$\sim 10^{-4} cm^{-3}$, where the canonical values of $\zeta = 3 \times 10^{-17}$ s^{-1}, $k_{CO} = 2 \times 10^{-9}$ cm^3 s^{-1} and $n(CO)/n(H_2) = 1.5 \times 10^{-4}$ are used.

In diffuse clouds, $X = e^-$ is the main destroyer and

$$N(H_3^+) = (\zeta/k_e)[n(H_2)/n(C^+)] \quad (3)$$

$\sim 10^{-6} cm^{-3}$ where $k_e = 2 \times 10^{-7} cm^3 s^{-1}$ is used.

Note that $n(H_3^+)$ is constant as long as the clouds are typically dense or diffuse. Note also that $n(H_3^+)$ in diffuse clouds is lower than in dense clouds by two orders of magnitude because the dissociative recombination rate k_e is that much faster than the proton hop reaction rate k_{CO}. These situations are schematically summarized in Fig. 2.

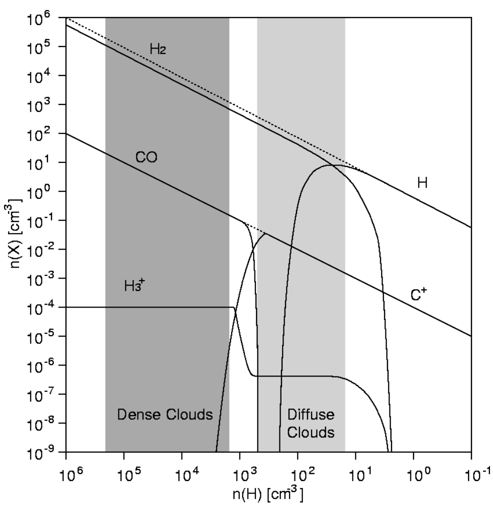

Fig. 2. Number densities of main chemical species n(X) versus cloud density n(H). Note that the H_2 and CO densities scale with the cloud density while that of H_3^+ is constant for typical dense and diffuse clouds. The ratio of the H_3^+ density in dense and diffuse clouds has been controversial. This figure shows results based on canonical values of ζ and k_e where $n(H_3^+)$ in dense cloud is higher than in diffuse cloud by two to tree orders of magnitude.

Since comparable H_3^+ column densities have been seen in dense and diffuse clouds, we need to assume a path in diffuse clouds which is 100 times longer than in dense clouds if we are to accept the above calculations. This contradicts to other astronomical evidences. An easy way out of this dilemma would be to assume smaller recombination rate k_e for which both laboratory data and theory have been highly controversial (Oka 2003). Recently McCall et al. (2003) measured k_e to be equal to the canonical value and claimed 40 times higher ζ in ζ Per than in dense clouds. This is highly controversial and further studies will be needed. Anyhow, observed values of $N(H_3^+)$ should provide crucial information on the ionization of clouds.

4 H_3^+ Toward the Galactic Center

The sightlines toward infrared sources near the Galactic center are the treasure house of H_3^+. They cross several mostly diffuse clouds including local clouds near the solar-system, clouds in the intervening 3kpc and 4kpc spiral arms, and clouds near the Galactic center in the expanding molecular ring and the circumnuclear ring. Luckily, the different radial velocities of the clouds separate their H_3^+ spectrum. Examples of the observed H_3^+ and CO spectra are given in Fig. 3 (Goto et al. 2002).

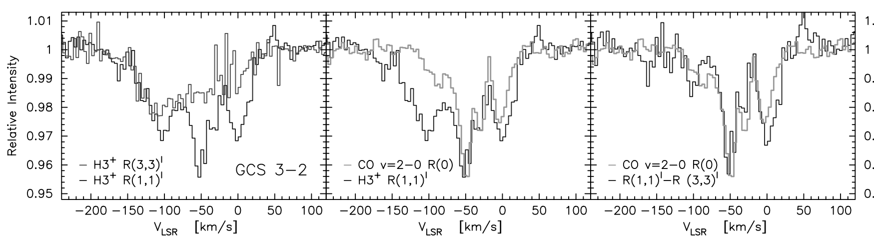

Fig. 3. H_3^+ and CO spectra observed toward the Galactic center

While the peak positions of the H_3^+ and CO absorption agree for each cloud component, their relative intensities differ greatly from cloud to cloud. For example, a strong H_3^+ absorption is noted in the expanding molecular ring at v$\sim$110 km/s, while almost no CO absorption is observed indicating the low density of the area. This difference in the H_3^+ and CO column densities resulting from the different chemical behavior of H_3^+ and CO shown in Fig. 2, make them nice complementary probes. H_3^+ gives a radial dimension of the cloud while CO gives the total amount of molecules on relatively dense clouds.

There are many infrared sources toward the Galactic center. We have observed quintuplets (Nagata et al. 1990) and some NHS stars (Nagata et al. 1993) using the Phoenix Spectrometer at Gemini South.

5 H_3^+ in Metastable Rotational Level

The most exciting observation toward the Galactic center has been our discovery of abundant H_3^+ in the (J,K)=(3,3) metastable rotational level which is 361 K above the lowest (1,1) level. The $R(3,3)^l$ line from the (3,3) level is strongly observed while the $R(2,2)^l$ line from the lower (2,2) level, only 151 K above the lowest level, is undetectable, demonstrating high temperature of the clouds and a very non-thermal rotational distribution of H_3^+. The metastability of the (3,3) level predicted from theory (Pan and Oka 1986) is clearly demonstrated by observations!

The intensity of the metastable $R(3,3)^l$ line is comparable to the ordinary $R(1,1)^l$ line demonstrating the comparable population in the 2 levels. This newly discovered population of H_3^+ amplifies the deviation of $N(H_3^+)$ from the slope of Fig. 1 and make the mystery of H_3^+ overabundance even more pronounced! A theoretical calculation shows that such distribution is only possible in a high temperature (> 200K) low density ($n < 50$) cm^{-3} medium. If we subtract the metastable $R(3,3)^l$ spectrum from the $R(1,1)^l$ spectrum, we obtain a velocity profile nearly identical to that of CO as shown in the right in Fig. 3. This suggests that the right figure give H_3^+ and CO in the ordinary clouds while the subtracted part which contain nearly equal amount of H_3^+ in the (3,3) and (1,1) level result from novel high temperature low density clouds which may not have previously been detected by any other means.

6 H_3^+ in Other Objects

The observed ubiquity of H_3^+ in interstellar clouds suggests that it is also observable in many other objects where molecules and ionization abound. The intense 3.7μm H_3^+ emission spectrum from, Jupiter (Oka & Geballe 1990), Saturn (Geballe et al. 1993) and Uranus (Trafton et al. 1993) has become a general tool to study planetary ionospheres (Connerney & Satoh 2000). Recently, Brittain and Rettig (2002) reported a detection of the H_3^+ emission from the Herbig AeBe star HD141569 and speculated that it is from a protoplanet in the preplanetary disk. The detection remains controversial (Oka 2002).

The high abundance of H_3^+ toward the galactic center suggests abundance of H_3^+ toward obscured active Galactic nuclei (AGN). A detection has been reported toward IRAS 08572 + 3815 with z = 0.05821 (Geballe 2001). With large diameter telescopes, observations of objects such as NGC 7172 (L=8.2) NGC 7479 (L=9.8) and UGC 5101 (L=10.1) are realistic. With low metallicity, Magellanic clouds may also be interesting objects to try H_3^+.

Planetary nebulae and proto-planetary nebulae are also interesting targets. The metastable H_3^+ spectrum may play a great role in such objects.

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