Enigma of H_3^+ in diffuse interstellar clouds

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1. INTRODUCTION

H_3^+ is of fundamental importance to interstellar chemistry both because it is a hydrogenic species (and >90% of all nuclei in the universe are hydrogen nuclei; see Figure 1) and because it serves as the universal protonator, initiating a chain of ion-neutral reactions that is responsible for the formation of most interstellar molecules.

The chemistry of H_3^+ in dense (molecular) clouds is now well understood,[1] and observations of H_3^+ in these environments now permit measurements of the path lengths, number densities, and kinetic temperatures of dense clouds. However, as discussed in more detail in a separate paper[2] in this volume, the situation in diffuse clouds is much less clear. H_3^+ has now been observed[3,4] in several diffuse cloud sources with unexpectedly large absorption strength. This enigma requires at least one of the model parameters (cosmic ray ionization rate, electron fraction, and the rate constant for dissociative recombination of H_3^+) to be changed by at least one to two orders of magnitude!

In this paper we describe in more detail the observations of H_3^+ in diffuse interstellar clouds, and the simple chemical model which is so obviously in error. We appeal to the specialists of dissociative recombination to resolve the current order-of-magnitude controversy in the rate constant for dissociative recombination of H_3^+, which is hindering further progress in the use of H_3^+ as an astronomical probe of the diffuse interstellar medium.

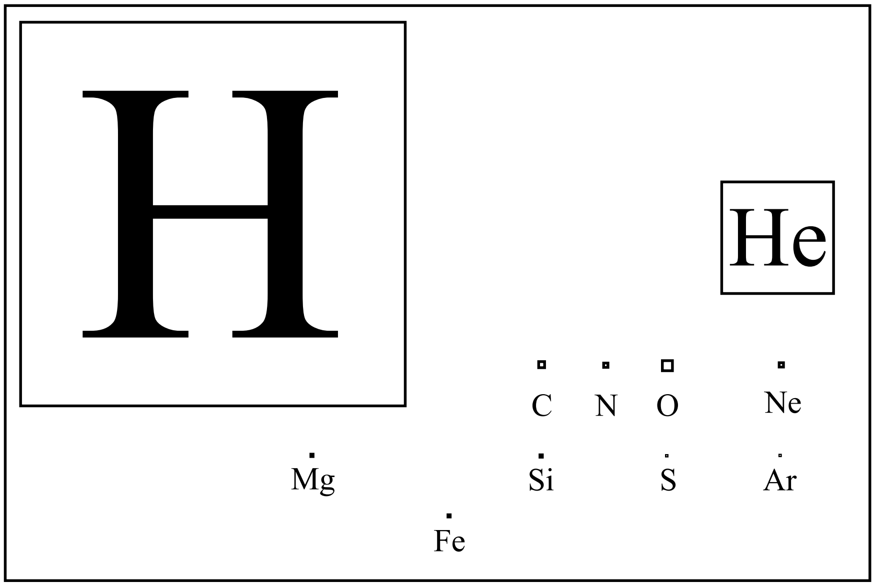

Figure 1. "The Astronomer's Periodic Table". The area of each element is proportional to its cosmic abundance.

2. OBSERVATIONAL TECHNIQUE

Because H_3^+ has no permanent dipole moment (its equilibrium structure is an equilateral triangle), it possesses no allowed rotational spectrum. This means that the sensitive techniques of radioastronomy cannot be brought to bear on the study of this key molecule. Furthermore, H_3^+ does not have any allowed electronic transitions, so visible spectroscopy (the most well-established form of spectroscopy in astronomy) is also useless. Thus our only tool for studying interstellar H_3^+ is its infrared rotation-vibration spectrum, first detected in the laboratory by Oka.[5]

The band origin of the ν_2 fundmanental vibration of H_3^+ lies at 2521.31 cm^{-1}, around 4 μm. Fortunately for us, few other molecules have strong vibrational transitions in this frequency range, and as a result the atmosphere is fairly transparent there – hence we can study interstellar H_3^+ from the ground rather than needing space-based telescopes. Because of the large rotational constant of H_3^+ the individual ro-vibrational transitions are generally well-separated in frequency. Another consequence of the large rotational constant is that at the low temperatures of the interstellar medium, only the lowest two allowed rotational states (in the vibrational ground state) are populated. A diagram of the energy levels and transitions of H_3^+ is shown in Figure 2. A detailed explanation of the notation for H_3^+ transitions is given elsewhere.[6]

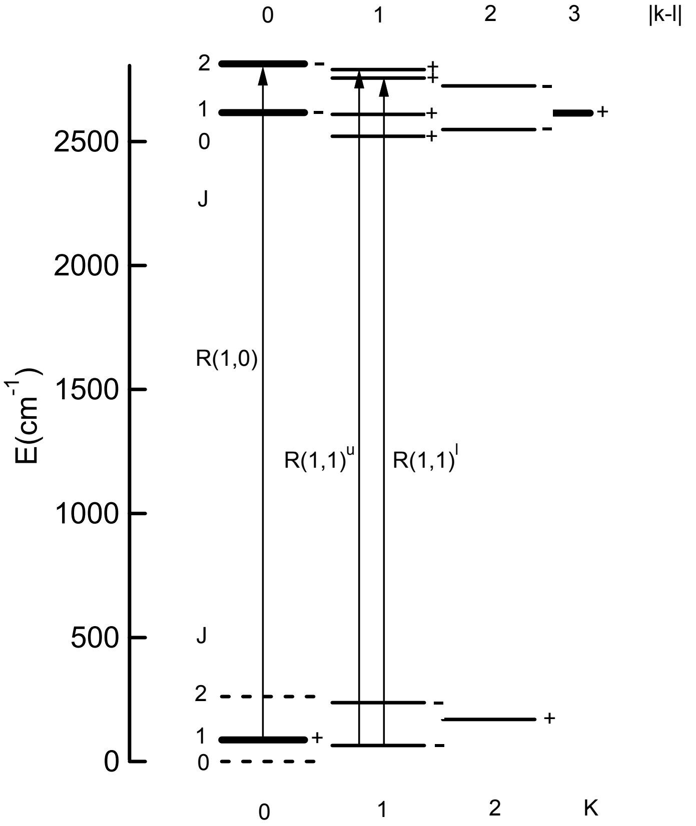

Figure 2. Energy level diagram and transitions used to study interstellar H_3^+. Since the J=K=0 level is forbidden by the Pauli principle, the two J=1 levels are the lowest allowed levels and are the only ones populated at interstellar temperatures.

Conveniently, it happens that the two transitions R(1,0) and $R(1,1)^u$ are only 0.321 cm^{-1} apart, and can thus be observed together in a single observation. This "doublet" is convenient for recognizing the spectral signature of H_3^+ in low signal-to-noise spectra, and also provides measurements of both the *ortho* and *para* spin configurations of H_3^+. The downside of this doublet is that it lies near a fairly strong (~30% deep) line of atmospheric methane, so it can only be observed from high mountains such as Mauna Kea in Hawaii. Elsewhere (for example, at Kitt Peak in Arizona) we use the $R(1,1)^l$ transition, which is less affected by atmospheric absorption lines.

We study H_3^+ using absorption spectroscopy, with a hot star (which is essentially a blackbody lamp with T>10,000 K) as the continuum source. The light from the star passes through the interstellar cloud, is collected by a large telescope (such as the United Kingdom Infrared Telescope in Hawaii or the Mayall Telescope at Kitt Peak), dispersed by a cryogenically cooled echelle spectrometer (such as CGS4 at UKIRT or Phoenix at Kitt Peak), and finally detected (in two-dimensional form) by a cooled InSb array. Image processing techniques then yield a one-dimensional absorption spectrum of the interstellar cloud.

H_3^+ is not very abundant in interstellar clouds, because it is formed slowly by cosmic-ray ionization of H_2 and destroyed quickly by chemical reactions (to form new molecules) or by dissociative recombination. As a result, the H_3^+ column densities (column density is essentially the number density times the path length) in interstellar clouds are only $\sim 10^{14}$ cm^{-2}, which yield absorptions of order 1% deep. Measuring such weak absorption signals from interstellar clouds requires long integration times and careful data reduction techniques. On the other hand, the fact that the lines are weak means that they are not saturated, so that measurement of the integrated area of the absorption lines (what the astronomers call "equivalent width") directly yields the column density of H_3^+. Figure 3 shows a few representative spectra of H_3^+ in diffuse clouds.

3. THE H_3^+ PROBLEM IN DIFFUSE CLOUDS

The chemistry of H_3^+ in diffuse clouds is described elsewhere[2] in this volume in detail, so here we give only a brief summary. H_3^+ is produced by cosmic-ray ionization of H_2 to form H_2^+, followed by a fast ion-neutral reaction with another H_2 to form H_3^+. The cosmic-ray ionization is the rate limiting step, so the rate of H_3^+ formation can be given as ζ [H_2], where $\zeta \sim 10^{-17}$ s^{-1} is the cosmic-ray ionization rate. In diffuse clouds, all carbon atoms (which are about 10^{-4} as abundant as hydrogen atoms) are ionized to form C^+ and e^-, so electron recombination is the dominant destruction mechanism for H_3^+. Consquently, the H_3^+ destruction rate can be expressed as $k_e[e^-][H_3^+]$. The steady state number density of H_3^+ can then be found by equating the formation and destruction rates: $[H_3^+] = (\zeta/k_e)\ ([H_2]/[e^-])$.

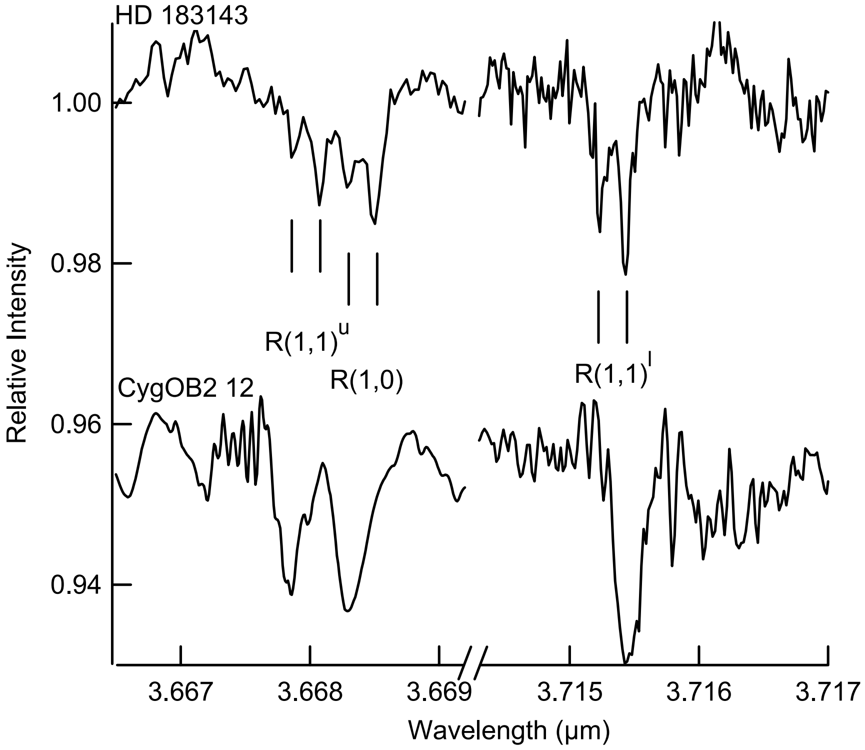

Figure 3. Spectra of H_3^+ in two diffuse cloud sightlines HD 183143 and CygOB2 12. HD 183143 has two velocity components, so each transition appears as a doublet.

If we substitute the accepted values ($[H_2]/[e^-]$)~2000, $\zeta \sim 3\times10^{-17}$ s^{-1}, and $k_e \sim 5\times10^{-7}$ cm^3 s^{-1}, we find that $[H_3^+] \sim 10^{-7}$ cm^{-3}. Then we can estimate the path length of the cloud as the column density divided by the number density (from the definition of column density), so $L \sim (10^{14}$ $cm^{-2})/(10^{-7}$ $cm^{-3}) \sim 10^{21}$ cm. This is an enormous distance of about 1000 light-years, or ~300 parsecs, and is in fact a substantial fraction of the distance to the background stars! If true, this would imply that much of the volume of the galaxy is filled with H_3^+.

A simple calculation shows that this is unreasonable. Since we know the column density of H_2 is of order 10^{22} cm^{-2}, we can use our inferred length to estimate the average number density of hydrogen along the line of sight: $[H_2] \sim (10^{22}$ $cm^{-2})/(10^{21}$ cm$) \sim 10$ cm^{-3}. This is a ridiculously low hydrogen number density; at such low densities, hydrogen would not be predominantly in molecular form, as we have assumed in the model. In addition, observations of other molecular species suggest the density is much higher. This suggests that we can exclude the possibility that the path lengths are this large, so it must be the case that H_3^+ is much more abundant in diffuse clouds than our model suggests. Evidently the H_3^+ number density needs to be increased by one to two orders of magnitude to bring the cloud path lengths into accord with other observations.

4. POSSIBLE SOLUTIONS

Looking again at the equation for the H_3^+ number density, $[H_3^+] = (\zeta/k_e)([H_2]/[e^-])$, we see that there are really only three parameters: the cosmic-ray ionization rate ζ, the electron fraction $[e^-]/[H_2]$, and the H_3^+ dissociative recombination rate constant k_e.

The first parameter (ζ) is considered unlikely to be different in diffuse clouds than in dense clouds (where it is reasonably well-constrained), but there is a possibility that there could be a large flux of lower energy cosmic-rays that could penetrate into diffuse clouds but not dense clouds. If this were the case, it would be extremely interesting and have widespread ramifications. However, this parameter is very difficult to get a handle on observationally, so we hope it can be determined once the other parameters are nailed down.

The second parameter (the electron fraction) is governed largely by the form of carbon atoms. The conventional wisdom in the astronomy community is that in diffuse clouds all carbon is ionized, so the electron fraction is large. However, this has not been directly confirmed in any of the sightlines where H_3^+ has been observed – we are hoping to pin this down using the Hubble Space Telescope in the next year or so.

Finally we come to the biggest suspect of all, the dissociative recombination rate constant for H_3^+. This “constant” has varied by at least four order of magnitude over the past 20 years, and different experimental techniques continue to give different results, as reviewed elsewhere[2] in this volume. Complicating matters is that theoretical calculations do not yet provide any support for the large values of k_e currently being measured. The need for a “solid” value of k_e cannot be overemphasized!

5. CONCLUSIONS

H_3^+ has demonstrated its promise as a powerful probe of the physical conditions in dense (molecular) clouds. Because H_3^+ is now being routinely observed in the diffuse interstellar medium, one would naïvely expect that it should also serve as a useful probe of the conditions in diffuse clouds. Instead, due to the uncertainty in the value of the dissociative recombination rate constant k_e, we are at an impasse — at this stage, all we know for sure is that "something is wrong" with the chemical model for diffuse clouds. Perhaps k_e is wrong, in which case the cosmic-ray flux and electron fraction in diffuse clouds are what we expect them to be. But perhaps the current value of k_e is correct! Then there is exciting new astrophysics waiting to be explored…either carbon is mostly not ionized in diffuse clouds or the cosmic-ray flux is much higher than generally thought.

Once the dissociative recombination community is finally able to nail down the value of k_e, H_3^+ will assume its rightful place as a "barometer, thermometer, and ruler" for diffuse clouds. Until then, we are left groping in the darkness for an explanation of the observed H_3^+ column densities.

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