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Recent Observations of H_3^+ in Molecular Clouds

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Abstract. The molecular ion H_3^+, which is a cornerstone of interstellar chemistry, now has been detected spectroscopically in several dark clouds. This paper reviews the detections and discusses the information that H_3^+ measurements can provide on important physical characteristics of the interstellar medium.

1. Introduction

Almost a quarter century ago Herbst & Klemperer (1973) and Watson (1973) proposed that many of the molecules that had been detected in by observations at millimeter wavelengths were produced as the result of reactions between molecular ions and atomic and molecular neutrals. In their models the molecular ion H_3^+ is the cornerstone of this ion-neutral chemistry. H_3^+ is produced readily in the interstellar medium by the reaction of H_2 and H_2^+, following the creation of H_2^+ via interaction of H_2 and cosmic rays Martin *et al.* 1961). Physically H_3^+ is as stable against dissociation as H_2, but chemically it is highly reactive, even at the lowest temperatures, with almost every neutral atom and molecule. Although not present in the earth's atmosphere, H_3^+ is observed in the hydrogen-rich ionospheres and aurorae of several of the giant outer planets of our solar system, most abundantly in Jupiter where it is produced largely by the bombardment by the solar wind. In dense clouds according to ion-neutral models, reactions involving H_3^+ are the starting point in reaction chains which produce most of the molecules and molecular ions that have been discovered.

2. Observations

The first detections of H_3^+ in molecular clouds have been made at the United Kingdom 3.8 m Infrared Telescope (UKIRT) during 1996 and 1997, using the facility instrument, CGS4. The observations utilized the 31 l/mm echelle in CGS4 which, together with CGS4's 150 mm focal length camera optics and 1.2" wide slit, provided a resolving power of 20,000 (corresponding to a FWHM of 15 km s^{-1}. The observations concentrated on a single spectral region near

3.67 μm which includes two transtititons of H_3^+, one from each of the lowest lying ortho and para states.

Figure 1 shows the discovery spectra of these two lines toward the deeply embedded young stellar object, AFGL 2136. This source and others were chosen for their high IR brightnesses (necessary because of both the high spectral resolution and the expected weaknesses of the lines) and high extinctions (implying considerable molecular cloud material along the line of sight). In each of the two spectra, obtained in 1996 April and 1996 July, the H_3^+ lines are clearly seen; their observed wavelengths shifted due to the earth's orbital motion. Their absorption depths are approximately one percent. However the lines are unresolved by CGS4; thus it is likely that intrinsically they are both considerably narrower and considerably deeper than they appear in these spectra.

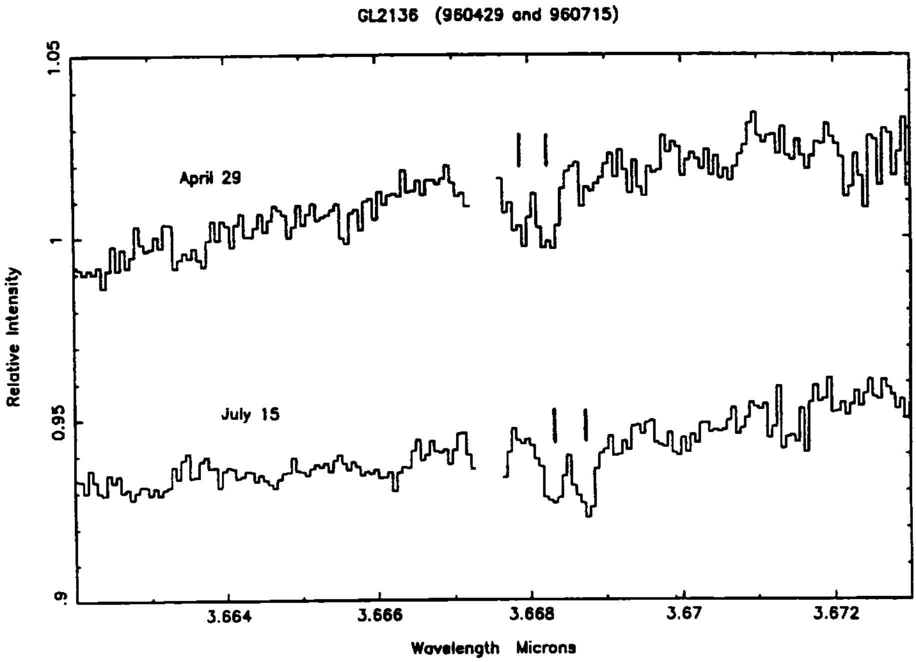

Figure 1. Spectra of AFGL 2136 obtained in 1996 April and July. A pair of H_3^+ lines from the lowest lying ortho and para levels, are indicated by vertical lines. The wavelengths of the lines in the two spectra are shifted due to the earth's orbital motion. The gaps in the spectra are at the location of a strong telluric absorption feature.

In 1996 H_3^+ was detected both in AFGL 2136 and in W33A (Geballe and Oka 1996). During 1997 a larger survey of bright highly extinguished infrared sources is being carried out at UKIRT. Seven additional sources were observed in 1996 February and two additional detections were made (McCall *et al.* 1997), so that of the nine sources measured, at least four have detectable H_3^+ along their lines of sight.

3. Analysis and Discussion

In all of the dense molecular clouds in which H_3^+ is detected, equivalent widths of each of the detected lines are 2-3 x 10^{-6} μm (~0.001 cm^{-1}. At the low temperatures in dense molecular clouds the only populated energy levels are the two from which the detected absorption lines are seen. Using values of the H_3^+ transition dipole moments kindly provided by J.K.G. Watson, the measured optical depths of the silicate features toward the infrared sources, and assuming the standard dust-to-gas ratio, the abundance ratio $[H_3^+]$ / $[H_2]$ is estimated to be ~ 2 x 10^{-9} (e.g., Geballe & Oka 1996). Values of this magnitude are expected for molecular clouds with densities of 10^4 cm^{-3} if the cosmic ray ionization rate for H_2 is 10^{-17} sec^{-1} mol^{-1} (Spitzer & Jenkins 1975). Thus the abundances of H_3^+ are roughly consistent with those predicted by ion-neutral chemistry.

Analysis more detailed than the above requires observations of absorption strengths of CO and H_2. This is because of the approximate equation (Lepp *et al.* 1987) relating the number densities of H_2, H_3^+, and CO,

$$\zeta[H_2] \sim k[H_3^+][CO], \qquad (1)$$

which can be rewritten as

$$\zeta L = kN(H_3^+)[CO]/[H_2]. \qquad (2)$$

These relations are obtained by equating the production and destruction rates of H_3^+. ζ is the cosmic ray ionization rate. The rate constant, k, for the proton-hop reaction from H_3^+ to CO, expected to be the dominant destruction mechanism for interstellar H_3^+ (destruction by the oxygen atoms and other neutrals is considerably slower), has been measured to be ~ 2 x 10^{-9} cm^3 s^{-1} (Anicich & Huntress 1986). The equation is valid in this approximation if the fractional abundance of electrons is less than ~10^{-6} so that dissociative recombination of H_3^+ does not compete with proton-hop reactions (Amano 1988). L is the length of the absorbing column of molecular cloud along the line of sight

The ratio $[CO]/[H_2]$ is predicted to be approximately constant at 1.5 x 10^{-4}) over a wide range of conditions (Lee *et al.* 1996). If ζ is constant through the bulk of the cloud, this implies that $[H_3^+]$ ~ 3 x 10^{-5} cm^{-3} also is approximately constant. This means that for two clouds with equal H_2 column densities, the column density of H_3^+ is greater in the cloud with lower volume density.

From the equation 2 it is evident that if lines of CO and H_2 can be detected as well as those of H_3^+, and if L can be either estimated (e.g., by by statistical methods), it will be possible to determine ζ, a parameter whose value is highly uncertain. Measurements of CO column densities have been made toward many embedded sources, and are relatively easy with current instrumentation. Measurements of (quiescent) H_2 absorption lines are much more problematical; to date they have succeeded only in the case of one source (Lacy *et al.* 1994). An improved success rate will require higher sensitivities, higher spectral resolution than currently available, and perhaps most importantly, better image quality so that extended H_2 line emission, which is common and often bright in the vicinities of young stellar objects can be better rejected.

4. References

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