Detection of H_3^+ in interstellar space

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THE H_3^+ ion is widely believed to play an important role in interstellar chemistry, by initiating the chains of reactions that lead to the production of many of the complex molecular species observed in the interstellar medium[1-5]. The presence of H_3^+ in the interstellar medium was first suggested[6] in 1961, and its infrared spectrum was measured[7] in the laboratory in 1980. But attempts[8-11] to detect it in interstellar space have hitherto proved unsuccessful. Here we report the detection of H_3^+ absorption in the spectra of two molecular clouds. Although the present results do not permit an accurate determination of the H_3^+ abundances, these ions appear nevertheless to be present in sufficient quantities to drive much of the chemistry in molecular clouds. It should soon be possible to obtain more accurate measurements, and thus better quantify the role of ion–neutral reactions in the chemical evolution of molecular clouds.

In H_2-dominated plasmas, H_3^+ is produced easily by the rapid ion–neutral reaction $H_2 + H_2^+ \rightarrow H_3^+ + H$. Although previously sought unsuccessfully in interstellar space, the emission spectrum of H_3^+ has been observed in the ionospheres of Jupiter[12], Uranus[13] and Saturn[14], and possibly also in SN1987A[15]. These detections attest to the high efficiency of production of H_3^+ by this reaction and, therefore, to its likely presence in interstellar molecular clouds. In the giant outer planets the ionization of H_2 is performed by accelerated charged particles in the magnetospheres and by solar radiation[16]. In the interiors of molecular clouds it is expected to be produced by cosmic-ray particles[1-4]. However, the small concentration of ions (10^{-6}–10^{-8} of neutrals) and the practical difficulties in observing weak and narrow infrared absorption lines make detection of interstellar H_3^+ difficult.

The present observations of H_3^+ in molecular clouds utilized the deeply embedded young stellar objects GL2136 and W33A, sources of infrared continua, in front of which absorptions in the molecular gas may be studied. These were chosen because the infrared sources are bright and because the large column densities of foreground gas improve the prospects of detecting H_3^+. In addition, in these clouds some of the gas-phase interstellar molecules which destroy H_3^+ through proton-hop reactions are known to be depleted by freezing on dust grains[17,18], although the depletions are probably small[19].

Measurements of GL2136 and W33A were made using the CGS4 spectrometer at a resolving power of ~15,000 at the United Kingdom Infrared Telescope (UKIRT) on the nights of 29 April, 10 June and 15 July 1996 (UT). Three vibration-rotation transitions of the ν_2 fundamental band near 3.7 μm (2,700 cm^{-1}) were used for the observations. These start from the lowest H_3^+ *para* level ($J = 1$, $K = 1$) and *ortho* level ($J = 1$, $K = 0$), which lies 22.84 cm^{-1} higher. In April all three absorption lines were detected in the spectrum of GL2136 and were marginally present in the spectrum of W33A, for which the signal-to-noise ratio was lower. In both objects the key *ortho–para* doublet at rest wavelengths 3.6681 and 3.6685 μm (2,726.22 and 2,725.90 cm^{-1}, respectively) was partially masked by a strong telluric absorption line of CH_4 at 3.6675 μm (2,726.7 cm^{-1}). However, at the times of the subsequent observations the Earth's orbital motion had shifted the doublet further away from the telluric line, making detection easier. Figure 1 shows the spectra of this doublet that were obtained in July, in which the absorption lines are clearly present in both objects. The lines, which are only ~2% deep, have observed widths equal to or slightly greater than the instrumental spectral resolution, indicating that their intrinsic full widths at half maxima are considerably less than 15 km s^{-1}. We derive velocities (with respect to the local standard of rest) for the H_3^+ absorption lines of 25 ± 5 km s^{-1} for GL2136 and 29 ± 5 km s^{-1} for W33A, in good agreement with velocities of the infrared absorption lines of quiescent cold CO towards these objects, 26.5 ± 2.8 km s^{-1} and 32.6 ± 1.7 km s^{-1}, respectively[9].

The observed absorptions, derived column densities of H_3^+ in each rotational level, and the total column densities derived from each transition are listed in Table 1. In calculating column densities N we used the standard formula for the equivalent width of an optically thin absorption line

$$W_\nu = \int [\Delta I(\nu)/I(\nu)] \mathrm{d}\nu = (8\pi^3\nu/3hc)N|\mu|^2 \qquad (1)$$

where $|\mu|^2$ is the square of the transition dipole moment, the values of which were provided to us by J. K. G. Watson.

To calculate the total column density, we assumed thermal equilibrium between *ortho* and *para* H_3^+ at the temperatures of 34 ± 4K and 35 ± 7K for GL2136 and W33A, respectively. These temperatures were obtained from the observed intensity ratios of the close doublet of the $R(1,1)^+$ and R(1,0) spectral lines and are significantly higher than the temperatures, 17 K and 23 K, respectively, derived from the infrared spectra of the quiescent CO in those clouds[19]. This suggests that the average distances of (gaseous) CO and H_3^+ with respect to the young stellar object may be

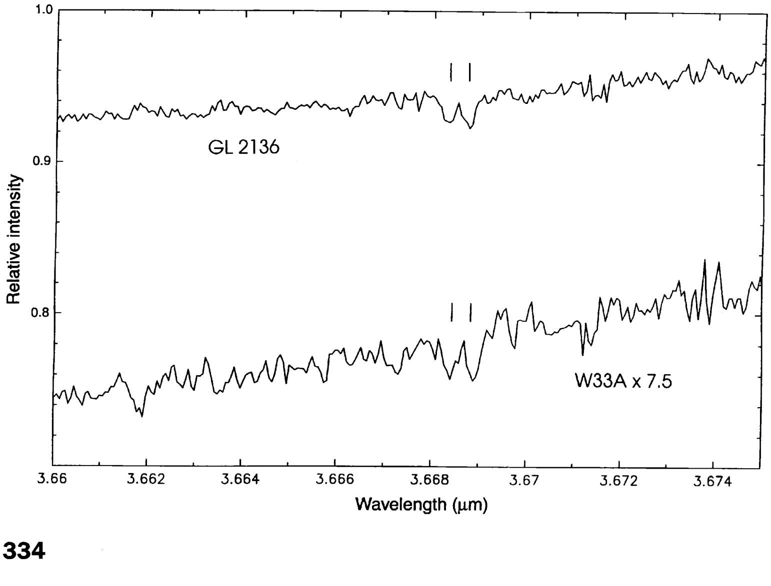

FIG. 1 Spectra of GL2136 and W33A ratioed by BS6378 (A2V), in the vicinity of the H_3^+ *ortho–para* doublet at 3.668 μm. The doublet, indicated by vertical lines, consists of the R(1,0) transition of *ortho* H_3^+ at 2,725.898 cm^{-1} (3.66852 μm, right-hand line of doublet) and the $R(1,1)^+$ transition of *para* H_3^+ at 2,726.219 cm^{-1} (3.66808 μm, left-hand line of doublet).

different, with most of the H_3^+ existing in a somewhat warmer environment than does most of the CO. Higher-quality measurements of these and other lines of H_3^+ are required to confirm this.

The total H_3^+ column densities, $N(H_3^+)$, are $4.0 \times 10^{14}\,cm^{-2}$ and $6.0 \times 10^{14}\,cm^{-2}$ for GL2136 and W33A, respectively (Table 1). Assuming H_2 column densities of $1.8 \times 10^{23}\,cm^{-2}$ and $2.8 \times 10^{23}\,cm^{2}$, respectively, determined from the silicate optical depths using the standard gas to dust conversion factor[20], we obtain H_3^+ to H_2 concentration ratios of 2.2×10^{-9} and 2.1×10^{-9} for GL2136 and W33A, respectively, which agree approximately with the results of theoretical model calculations[21] based on an assumed H_2 density of $10^4\,cm^{-3}$.

TABLE 1 Observed lines and derived column densities of H_3^+

Transition	Frequency* (cm^{-1})	$\|\mu\|^2$ (D^2)	Source	W_ν (cm^{-1})	N_{level}† ($10^{14}\,cm^{-2}$)	N_{total} ($10^{14}\,cm^{-2}$)
$R(1,1)^+$	2,726.219	0.0158	GL2136	0.0040 ± 0.0011	2.3 ± 0.5	4.0 ± 0.9
			W33A	0.0063 ± 0.0023	3.5 ± 1.3	6.0 ± 2.2
R(1,0)	2,725.898	0.0259	GL2136	0.0049 ± 0.0011	1.7 ± 0.4	4.0 ± 0.9
			W33A	0.0072 ± 0.0028	2.5 ± 1.0	6.0 ± 2.4
$R(1,1)^-$	2,691.444	0.0140	GL2136	0.0023 ± 0.0014	1.7 ± 1.0	3.0 ± 1.7
			W33A	0.0033 ± 0.0032	2.5 ± 2.4	4.3 ± 4.1

* Laboratory values[7].
† In lower vibration-rotation level.

These results mark the beginning of direct observations of H_3^+ in molecular clouds. The significance of such measurements is as follows.

First, they provide the most direct evidence supporting the ion–neutral scheme of interstellar chemistry initially proposed by Herbst and Klemperer[1] and by Watson[2].

Second, the column density of H_3^+ provides a variety of fundamental information, not only about the specific molecular cloud, but also about more universal physical conditions in the interstellar medium. This is because of the approximate equation[22] relating the number densities of H_2, H_3^+ and CO,

$$\zeta[H_2] \approx k[H_3^+][CO] \quad (2)$$

which is obtained by equating the production and destruction rates of H_3^+. The cosmic-ray ionization flux, ζ, usually is assumed to be $\sim 10^{-17}\,s^{-1}$. The rate constant, k, for the proton-hop reaction from H_3^+ to CO, expected to be the dominant destruction mechanism of interstellar H_3^+ (we neglect slower destruction by the oxygen atoms and other neutrals), has been measured[23] to be $\sim 2 \times 10^{-9}\,cm^3\,s^{-1}$. Equation (2) is valid in this approximation if the fractional abundance of electrons is less than $\sim 10^{-6}$ and thus dissociative recombination[24] of H_3^+ does not compete with proton-hop reactions. As the ratio $[CO]/[H_2]$ is approximately constant (at 1.5×10^{-4}) over a wide range of conditions[21], $[H_3^+] \sim 3 \times 10^{-5}\,cm^{-3}$ also is approximately constant.

Applying this last result, the concentration ratios of H_3^+ to H_2 derived above for GL2136 and W33A imply that the mean number density of H_2 in each of these clouds is approximately $1.4 \times 10^4\,cm^{-3}$. The effective length, L, of the cloud in front of the infrared continuum source, derived from $N(H_3^+)/[H_3^+]$, is 4 pc for GL2136 and 6 pc for W33A. When equation (2) is written in the form

$$\zeta L = kN(H_3^+)[CO]/[H_2] \quad (3)$$

the observed $N(H_3^+)$ gives values for ζL of $120\,cm\,s^{-1}$ and $180\,cm\,s^{-1}$, respectively. Independent estimates of L from other observations, such as mapping, can be compared to and combined with the observed values of $N(H_3^+)$ and $[CO]/[H_2]$ to yield a more accurate value for ζ, a parameter which is believed to have the same interstellar value everywhere in the Universe, but for which there are few observational data[25]. □

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