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. The presence of H$_3^+$ in the interstellar medium was first suggested in 1961, and its infrared spectrum was measured in the laboratory in 1980. But attempts 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$_3^+ + H_2 \rightarrow H_3^+ + H$. Although previously sought unsuccessfully in interstellar space, the emission spectrum of H$_3^+$ has been observed in the ionospheres of Jupiter, Uranus, and Saturn, and possibly also in SN1987A. 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. In the interiors of molecular clouds it is expected to be produced by cosmic-ray particles. However, the small concentration of ions (10$^{-8}$–10$^{-9}$ 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, although the depletions are probably small. Measurements of GL2136 and W33A were made using the CDS 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 $v$ fundamental band near 3.7 μm (2.70 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 ~25% 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.

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

$$W = \int [\Delta f(v)/I(v)]dv = \frac{8\pi^3}{3hc^2}N|\mu|^2$$

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. This suggests that the average distances of (gaseous) CO and H$_3^+$ with respect to the young stellar object may be
different, with most of the H\(_2\) existing in a somewhat warmer environment than does most of the CO. Higher-quality measurements of these and other lines of H\(_2\) are required to confirm this.

The total H\(_2\) column densities, N(H\(_2\)), are 4.0 \times 10\(^4\) cm\(^{-2}\) and 6.0 \times 10\(^4\) cm\(^{-2}\) for GL2136 and W33A, respectively (Table 1). Assuming H\(_2\) column densities of 1.8 \times 10\(^3\) cm\(^{-2}\) and 2.8 \times 10\(^3\) cm\(^{-2}\), respectively, determined from the silicate optical depths using the standard gas to dust conversion factor\(^{20}\), we obtain H\(_2\) to H\(_3\) concentration ratios of 2.2 \times 10\(^{-9}\) and 2.1 \times 10\(^{-9}\) for GL2136 and W33A, respectively, which agree approximately with the results of theoretical model calculations based on an assumed H\(_2\) density of 10\(^4\) cm\(^{-3}\).

These results mark the beginning of direct observations of H\(_2\) 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\(^2\) and by Watson\(^3\).

Second, the column density of H\(_2\) 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\(^2\) relating the number densities of H\(_2\), H\(_3\), and CO,

\[
\left[\text{H}_2\right] \approx k \left[\text{H}_3\right] [\text{CO}]
\]

which is obtained by equating the production and destruction rates of H\(_2\). The cosmic-ray ionization flux, \(\zeta\), usually is assumed to be \(\sim 10^{-17}\) s\(^{-1}\). The rate constant, \(k\), for the proton-hopping 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\(^{20}\) to be \(\sim 2 \times 10^{-6}\) 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\(_2\) does not compete with proton-hopping reactions. As the ratio [CO]/[H\(_2\)] is approximately constant (at 1.5 \times 10\(^{-4}\)) over a wide range of conditions, [H\(_2\)] \(\sim 3 \times 10^{-3}\) cm\(^{-3}\) also is approximately constant.

Applying this last result, the concentration ratios of H\(_2\) to H\(_3\) derived above for GL2136 and W33A imply that the mean number density of H\(_3\) in each of these clouds is approximately 1.4 \times 10\(^3\) cm\(^{-3}\). The effective length, \(L\), of the cloud in front of the infrared continuum source, derived from N(H\(_3\))/N(H\(_2\)), is 4 pc for GL2136 and 6 pc for W33A. When equation (2) is written in the form

\[
\zeta L = k N(\text{H}_2) [\text{CO}] / N(\text{H}_3)
\]

the observed N(H\(_3\)) gives values for \(\zeta L\) 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 \(\zeta\), a parameter which is believed to have the same interstellar value everywhere in the Universe, but for which there are few observational data\(^2\).

**Table 1** Observed lines and derived column densities of H\(_2\)

<table>
<thead>
<tr>
<th>Transition</th>
<th>Frequency(^a) (cm(^{-1}))</th>
<th>(\mu_1^2) (D(_2))</th>
<th>Source</th>
<th>(W(_1)) (cm(^{-1}))</th>
<th>(N_{\text{rad}}) (10(^{14}) cm(^{-2}))</th>
<th>(N_{\text{tot}}) (10(^{17}) cm(^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(R(1,1)(^{-}))</td>
<td>2.726.219</td>
<td>0.0158</td>
<td>GL2136</td>
<td>0.0040 \pm 0.0011</td>
<td>2.3 \pm 0.5</td>
<td>4.0 \pm 0.9</td>
</tr>
<tr>
<td>W33A</td>
<td></td>
<td></td>
<td></td>
<td>0.0063 \pm 0.0023</td>
<td>3.5 \pm 1.3</td>
<td>6.0 \pm 2.2</td>
</tr>
<tr>
<td>(R(1,0)(^{+}))</td>
<td>2.725.898</td>
<td>0.0259</td>
<td>GL2136</td>
<td>0.0049 \pm 0.0011</td>
<td>1.7 \pm 0.4</td>
<td>4.0 \pm 0.9</td>
</tr>
<tr>
<td>W33A</td>
<td></td>
<td></td>
<td></td>
<td>0.0072 \pm 0.0028</td>
<td>2.5 \pm 1.0</td>
<td>6.0 \pm 2.4</td>
</tr>
<tr>
<td>(R(1,1)(^{-}))</td>
<td>2.691.444</td>
<td>0.0140</td>
<td>GL2136</td>
<td>0.0023 \pm 0.0014</td>
<td>1.7 \pm 1.0</td>
<td>3.0 \pm 1.7</td>
</tr>
<tr>
<td>W33A</td>
<td></td>
<td></td>
<td></td>
<td>0.0033 \pm 0.0032</td>
<td>2.5 \pm 2.4</td>
<td>4.3 \pm 4.1</td>
</tr>
</tbody>
</table>

\(\mu_1^2\) Laboratory values\(^3\).

\(^{+}\) In lower vibration-rotation level.


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