H_3^+ IN DARK CLOUDS

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ABSTRACT

H_3^+, long thought to be the instigator of most interstellar gas phase chemistry, is now detected in about ten dark clouds, in all cases in absorption toward embedded young stellar objects. Analysis yields abundances consistent with predictions from known cloud parameters, thus providing a basic confirmation of the theory of cosmic ray-induced ion-molecule interstellar chemistry. The special characteristics of H_3^+ allow it to serve as a yardstick for measuring cloud dimensions and as a cosmic ray fluxmeter, in addition to being a simple thermometer in star forming regions. We present and discuss observational results in the light of recent models of dark clouds.

Key words: ISM: molecules – ISM: structure – ISM: clouds

1. INTRODUCTION

The existence of H_3^+ in the interstellar medium was predicted over forty years ago. About thirty years ago Herbst and Klemperer's (1973) and Watson's (1973) proposal that ion-molecule reaction networks result in production of many of the interstellar molecules that had then been discovered placed H_3^+ at the starting point of these networks.

Since then the importance of ion-molecule reactions in interstellar chemistry has been verified by countless observational and theoretical results. However, it was only after the detection of H_3^+ in two dark clouds (Geballe & Oka 1996), and subsequent detections in other dark clouds (McCall et al. 1999), that there was direct confirmation of the most fundamental premise of the hypothesis, that H_3^+ is the starting point of interstellar ion-molecule chemistry. A basic understanding is now developing of how observations of H_3^+ can be used in combination with observations of other molecules to learn more about the physical characteristics of dark clouds. In this paper we review the properties of H_3^+ and the unique ways in which it gives information about dark clouds, and then discuss recent observations of H_3^+ and their use.

2. THE SIGNIFICANCE OF H_3^+ MEASUREMENTS

There are two reasons why H_3^+ is fundamentally important in interstellar gas phase chemistry. First, it is generally true that in cold dark clouds ion-neutral chemistry is much faster than neutral chemistry. Second, the rate at which H_3^+ is produced from neutral material in dark clouds is far higher than the production rate of any other ionic species. This is because the origin of H_3^+ is the interaction between cosmic rays, which enter the cloud, and hydrogen molecules, which are by far the most abundant species in dark clouds and are the species with which cosmic rays interact most frequently. The cosmic rays readily ionize H_2 to H_2^+, which subsequently and quickly reacts with H_2 to form H_3^+. While the lifetime of a neutral H_2 molecule in a typical dark cloud is a billion years before it is ionized, in a typical molecular cloud the conversion to H_3^+ of that H_2^+ ion by interaction with H_2 requires only about a day. Hence, the production rate of H_3^+ may be written simply as $\zeta n(H_2)$, where ζ, the cosmic ray ionization rate, is generally thought to be $\sim 3\times10^{-17}$ sec^{-1}.

The destruction of H_3^+ in the cloud takes place whenever it interacts either with neutrals (other than H, H_2, He, N, and a few additional species), or with negatively charged species. The destruction rate can be written as:

$$R_d(H_3^+) = k_{CO}n(CO) + k_O n(O) + \ldots + k_e n(e) + \ldots .$$

This sum is dominated by the first term if CO is not heavily depleted. All of the other terms except that of atomic oxygen are 1–2 orders of magnitude smaller. Some have large reaction constants but small abundances, such as electrons; others, such as atomic oxygen, have more comparable abundances but lower reaction rates (see McCall 2001). When CO dominates, its constant abundance relative to H_2 over a wide range of conditions (Lee et al. 1996) results in a constant H_3^+ density of about 1×10^{-4} cm^{-3}, independent of the density of the cloud. Thus, the column

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density of H_3^+ in a dark cloud directly yields the dimension of the cloud along the line of sight. That information cannot be obtained from other molecules so clearly; in combination with other molecular tracers it can yield accurate information about cloud densities.

In cool portions of dark clouds, where temperatures are below 20 K, gaseous CO will freeze onto grains. In those regions other predator molecules and atoms dominate the destruction, and the density of H_3^+ is expected to increase to well above 1×10^{-4} cm^{-3}, until the sum of their rates equalizes the production rate of H_3^+. Whether such regions dominate the H_3^+ column densities of some dark clouds depends on the relative column lengths of the warmer and cooler regions.

Finally, we note the ease, in principle, both of using H_3^+ to determine the cloud temperature and of measuring the column density of this molecular ion. The two lowest rotational levels of H_3^+, (J,K) = (1,1) and (1,0), are at much lower energy than all other levels (note that (0,0) is forbidden by the Pauli principle). That means that they are the only significantly populated levels in dark clouds, unless the cloud temperature is above 100 K. The only clouds observed to date where levels other than these two are significantly populated are in the galactic center (Goto et al. 2002). The lower lying (1,1) level corresponds to para-H_3^+, the other to ortho-H_3^+. Unlike molecules (such as NH_3) where ortho and para populations have independent existences, collisions of H_3^+ with H_2 result in proton hops or exchanges, both of which are opportunities for changes in nuclear spin modifications. Hence the two levels are in LTE, and measurements of the strengths of a single line from each level results in determinations of both the temperature and the total H_3^+ column density. The energy separation of these low-lying ortho and para levels is 33 K, comparable to typical cloud temperatures, making the relative strengths of lines from these levels an ideal thermometer. Fortuitously, a vibration-rotation doublet consisting of one line from each level is located near 3.67 μm and both lines have been observed with the echelle spectrographs built for UKIRT and for NOAO telescopes.

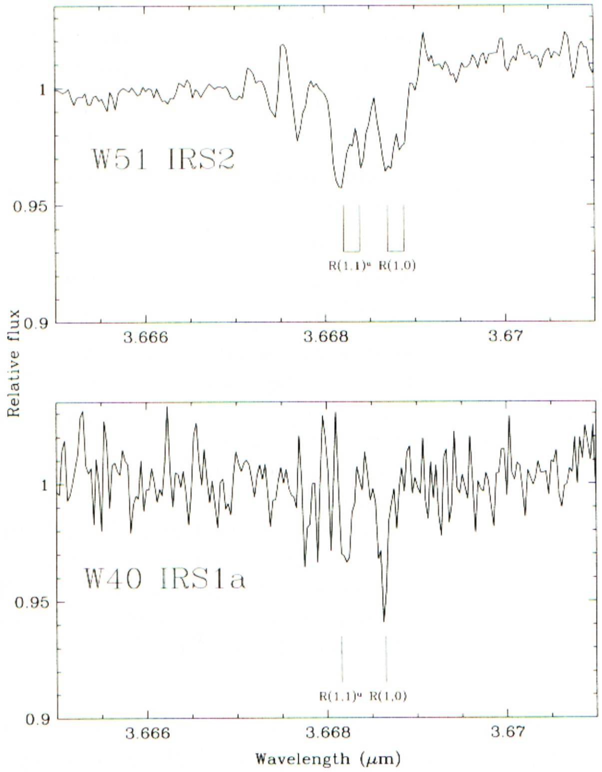

Figure 1. CGS4 (UKIRT) spectra of W51 IRS2 and W40 IRS1a at the wavelength of the H_3^+ ortho-para doublet, observed at UKIRT on 2001 May 25-26 UT.

3. Basic Observational Results

H_3^+ was first detected in dark clouds by Geballe & Oka (1996) using the above doublet, toward the embedded sources W33A and AFGL 2136. Their spectra illustrate the difficulty of detecting H_3^+; the absorption lines are usually very weak, and careful attention must be given to correcting for nearby strong telluric absorption lines and instrumental effects. Recent detections of the doublet toward W51 IRS2 and W40 IRS1a are shown in Figure 1. Toward W51 IRS2 two velocity components are seen in each line. Table 1 lists all detections reported in the literature.

The temperatures derived from the H_3^+ lines generally are well above the CO freezing point of about 20 K. Thus, although solid CO has been detected along the line of sight to some of these clouds, one can safely conclude that the bulk of the H_3^+ in each cloud is located in regions where CO is predominantly gaseous. The high temperatures indicate that if ζ is 3×10^{-17} s^{-1}, the densities of H_3^+ should be close to the canonical dark cloud value of 1×10^{-4} cm^{-3}. Using this value and the measured column densities, cloud dimensions of typically 1 parsec are derived (although there is considerable variation), roughly similar to the dimensions of the cloud cores on the plane of the sky. Moreover cloud densities, estimated from the above column lengths and the column densities of CO translated into H_2 column densities, are mostly in the

Table 1. Detections of H_3^+ in molecular clouds

Name	$N_{tot}(H_3^+)$	ζL^a	L^b	$N(H_2)^c$	$<n(H_2)>$	T^d
	$10^{14} cm^{-2}$	$cm\ s^{-1}$	pc	$10^{22} cm^{-2}$	$10^4 cm^{-3}$	K
AFGL 2136	3.8	110	1.3	22	6	47
W33A	5.2	150	1.7	27	5	36
MonR2 IRS3	1.4	41	0.5	1.3	9	31
AFGL 961E	1.7	49	0.6	3.2	2	25
AFGL 490	1.1	32	0.4	7.6	6	26
AFGL 2591	2.2	64	0.7	13	6	38
NGC 2024 IRS2[e]	0.4	12	0.13	3.5	7	32
W51 IRS2 (46 km s^{-1})	5.3	155	1.7	–	–	32
W51 IRS2 (62 km s^{-1})	2.4	70	0.8	–	–	39
W40 IRS1a	3.3	99	1.1	0.7	0.2	64

[a] Assumes $n(H_3^+) = 1 \times 10^{-4}$ cm^{-3}.

[b] Assumes $\zeta = 3 \times 10^{-17}$ s^{-1}.

[c] Derived from measured CO column densities (see McCall et al. 1999 for references for first seven sources and Shuping et al. 1999 for W40 IRS1a), using $n(CO)/n(H_2) = 1.5 \times 10^{-4}$ (Lee et al. 1996).

[d] From ratio of ortho and para H_3^+ line intensities.

[e] H_3^+ and H_2 data from Kulesa & Black (2000).

range 10^4–10^5 cm^{-3}, as expected based on other data. Both suggest that the abundance of H_3^+ is roughly as predicted for cosmic ray-induced ion–molecule chemistry, confirming the fundamental importance of H_3^+ in molecular cloud gas phase chemistry.

4. H_3^+ AND CLOUD MODELS

A measurement of N(H_3^+) gives the absorption path length times the cosmic ray ionization rate and, if the latter is assumed, then the former can be determined. In the hypothetical case of a cloud of constant density $n(H_2)$, the strength of an optically thin H_2 or CO absorption line is proportional to $n(H_2)L$, and one can determine the density accurately since L is determined from H_3^+. In reality of course, clouds are not of constant density, cloud chemistry is density-dependent, and the information provided by H_3^+ is only one piece of a complex puzzle.

Recently the Leiden University group has begun to develop thermal and chemical models of the envelopes of some of the same star forming regions that have been observed in H_3^+. In these models they constrain the density structure from measurements of the submillimeter continuum and a variety of lines. To date they have published one paper (Doty et al. 2002), modeling the envelope around AFGL 2591, and fitting a number of observations of the cloud using a cloud density decreasing as r^{-1}, with the cloud truncated at $n = 5 \times 10^4$ cm^{-3}. For H_3^+ they calculate about a factor of five less H_3^+ than is observed, using a cosmic ray ionization rate (i.e., an H_3^+ production rate) of almost twice the value adopted here. As the dark cloud would still be dark at much lower densities than 5×10^4 cm^{-3}, a lower truncation density would result in a considerably longer column and an H_3^+ column density closer to that observed. However, in their model of AFGL 2591 an extended lower density envelope would have a lower temperature, leading to a cooler average temperature than found for this cloud using the H_3^+ thermometer.

The discrepancy might be due to incomplete modeling of the outer envelope of the cloud, but it could also be due to significant additional contributions to the H_3^+ absorption from other material along the line of sight. It is possible that the observed H_3^+ absorption lines, which are fairly broad, arise in more than one discrete dark cloud. Indeed millimeter CO measurements (van der Tak et al. 1999) reveal more than one cloud along the line of sight. In addition, absorption may arise partly in the outflow, a considerable part of which lies along the line of sight to the young stellar object, judging from the relatively small displacement of the red- and blue-shifted wings of millimeter CO lines (e.g., Mitchell, Hasegawa & Schella 1992) and the extreme breadth of the infrared CO profiles (Geballe & Wade 1985; Mitchell et al. 1989). Correcting

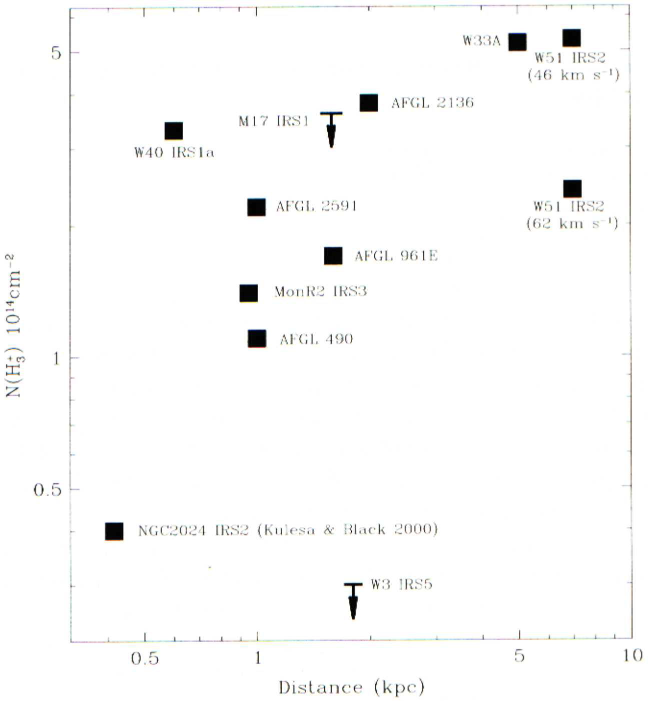

Figure 2. Column densities of H_3^+ in molecular clouds versus distances of sources. H_3^+ data are from McCall et al. (1999) or this paper, except where noted.

for these contributions could bring the observed H_3^+ column density and the model value into somewhat better agreement.

It also has been suggested by van der Tak & van Dishoeck (2000) that a diffuse or translucent cloud component could be responsible for a significant fraction of the H_3^+ absorption column density toward distant galactic sources. They noted a trend of increasing H_3^+ column density with increasing source distance. In Figure 2 we have updated their Fig. 3, adding the latest detections and removing their galactic center and Cyg OB2 No. 12 data points (as the former is a special case and the latter is not a dark cloud). A trend may still exist but it is much less apparent, particularly for the sources within 2 kpc (which include AFGL 2591). We also note that selection effects probably are important, as the number of sources at large distances is small and some of them were chosen because there were reasons to believe that they were particularly excellent possibilities for detecting H_3^+. That was not necessarily the case for the nearby sources, which often were selected because of their brightness as opposed to their being the very best H_3^+ candidates. The more distant sources tend to be more luminous objects, and could be more massive young stellar objects located in larger molecular clouds or cloud complexes, with longer path lengths within the cloud or complex, and thus stronger H_3^+ lines. In conclusion, we believe that it is premature to argue based on the present data for large foreground cloud components to the H_3^+ absorptions observed toward the more distant embedded sources.

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