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H_3^+ in diffuse interstellar gas

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ABSTRACT

A model is constructed of the material in front of the star Cygnus OB2 no. 12 in which dense cores are embedded in diffuse clumps of gas. The model reproduces the measured abundances of H_3^+, C_2 and CO, and predicts a column density of $9 \times 10^{10}\,cm^{-2}$ for HCO^+.

Key words: molecular processes – ISM: clouds – ISM: molecules.

1 INTRODUCTION

The successful detection of the molecular ion H_3^+ in the interstellar medium (Geballe & Oka 1996; McCall et al. 1998) confirms the importance of cosmic-ray induced ion–molecule chemistry in the determination of the molecular composition in interstellar clouds. The abundance of H_3^+ observed along the line of sight to the star Cygnus OB2 no. 12 is $3.8 \times 10^{14}\,cm^{-2}$ (Geballe et al. 1999).

This value, comparable to that measured in dense clouds (Geballe & Oka 1996), is unexpectedly high, because the absence of the 3.0- and 4.27-μm features of H_2O and CO_2 ices and the presence of the 3.4-μm hydrocarbon feature (Whittet et al. 1997) strongly suggest that the intervening medium is a low-density diffuse gas (McCall et al. 1998).

An initial interpretation of the data by McCall et al. (1998), made by adopting a model of a gas of uniform density, used a total hydrogen number density of $10\,cm^{-3}$ and a column path length between 400 and 1200 pc. As McCall et al. (1998) pointed out, the suggested path length is apparently inconsistent with observations of CH, C_2 and CO. Further, at a density of $10\,cm^{-3}$, photodissociation will limit the abundance of molecular hydrogen that is needed to form H_3^+.

We propose an alternative model of the gas in which clumps of matter exist with a mean visual extinction of 1.6 mag embedded in a tenuous interclump medium. The mean clump hydrogen density is $100\,cm^{-3}$. The clumps contain dense cores with densities ranging from 10^3 to $10^6\,cm^{-3}$. The model is consistent with the presence of the 3.4-μm feature (Whittet et al. 1997) and the absence of ices (Whittet 1992).

2 THE MODEL FOR H_3^+

We adopt a chemical network constructed from 36 species consisting of the elements H, He, C and O. We select from the UMIST data file (Millar et al. 1997) all the reactions that couple the species. We terminate the hydrocarbon chemistry at $C_2H_2^+$. We modified the UMIST data file by incorporating the branching ratios for dissociative recombination of Andersen et al. (1996), Vejby-Christensen et al. (1997), Larson et al. (1998) and Derkatch et al. (1999). We describe the depth-dependent H_2 and CO photodissociation rates by self-shielding functions (van Dishoeck & Black 1988; Sternberg & Dalgarno 1995). From a consideration of the thermal balance we obtained a mean temperature of 35 K.

The chemical structure and ionization balance depend on the element depletion. A gas phase abundance for carbon atoms to hydrogen of $1.4(\pm 0.2) \times 10^{-4}$ has been derived by Cardelli et al. (1996) for five lines of sight, a ratio that agrees with the value of 1.3×10^{-4} found for ζ Ophiuchi (Snow & Witt 1996). For oxygen we adopt 3.3×10^{-4} (Snow & Witt 1996).

The H_3^+ ions are produced by the reaction of H_2 with the H_2^+ ions resulting from the cosmic-ray ionization of H_2. In diffuse gas with a visual extinction less than $A_V = 2$ mag, the fractional ionization $x = n_e/n_H$ is nearly constant and H_3^+ is removed largely by dissociative recombination with electrons at a rate αn_e, where $\alpha = 1.2 \times 10^{-7} \sqrt{300/T}\,cm^3\,s^{-1}$ (Sundström et al. 1998). Hence if $\zeta\,s^{-1}$ is the cosmic-ray ionization rate, the steady state abundance of H_3^+ is approximately

$$n(H_3^+) = \frac{\zeta n(H_2)}{\alpha x n_H} \approx 4\zeta \frac{n(H_2)}{n_H} \times 10^{10}\,cm^{-3}. \qquad (1)$$

The abundance of H_3^+ follows the increase in the fraction of hydrogen that is converted to molecular form with increasing depth into the individual clumps and tends to a constant value independent of density. At larger visual extinction, atomic ions are converted to molecular ions and the fractional ionization decreases. Removal of H_3^+ then occurs preferentially by proton transfer in reactions with neutral species, and the density of H_3^+ is constant at about $2 \times 10^{12}(\zeta/\delta)\,cm^{-3}$, where δ is the depletion factor.

Fig. 1 shows the calculated densities of H, H_2 and H_3^+ for an isolated clump of visual extinction $A_V = 1.6$ mag and a density of $100\,cm^{-3}$ as a function of distance from the centre of the clump outwards to radius r_c. The abundance of H_3^+ follows the decrease

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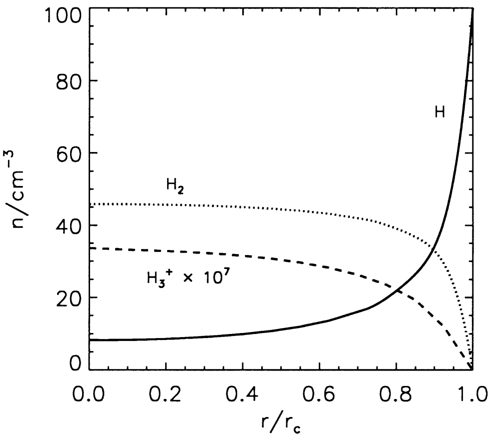

Figure 1. Volume density of H, H_2 and H_3^+ as a function of clump radius. The density of the clump is taken as $100\,\mathrm{cm}^{-3}$ and the ionization rate is $4 \times 10^{-17}\,\mathrm{s}^{-1}$.

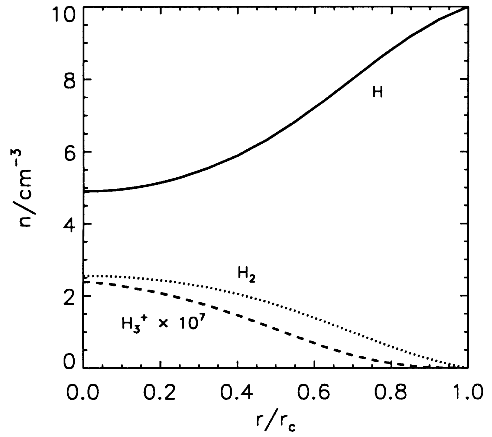

Figure 2. Same as Fig. 1 for a clump density of $10\,\mathrm{cm}^{-3}$.

in the H_2 molecular fraction. Fig. 2 is similar to Fig. 1 but for a density of $10\,\mathrm{cm}^{-3}$. There is little conversion of H into H_2 and the density of H_3^+ is very small.

The integrated column densities of H_3^+ for clumps with A_V between 0.6 and 2 mag expressed as fractions of the total H column densities are shown in Fig. 3 as functions of the cloud density for an ionizing frequency of $4 \times 10^{-17}\,\mathrm{s}^{-1}$. Significant amounts of H_3^+ are produced for volume densities exceeding about $25\,\mathrm{cm}^{-3}$. The volume density of H_3^+ tends to a constant value for clump densities larger than about $100\,\mathrm{cm}^{-3}$. As a consequence, the integrated column densities of H_3^+ decrease with increasing clump density.

Low densities are not conducive to the formation of H_3^+, and they require anomalously large values for the clump mass and dimension if the correct visual magnitude is to be obtained. We show in Fig. 4 the dependence of fractional abundances on clump mass for $A_V = 1.6$ mag.

We solved the H_3^+ radiative transfer problem with 9 spherical clumps along the line of sight with a mean chord length of 6.7 pc, equal to two-thirds of the diameter, and a hydrogen density of $100\,\mathrm{cm}^{-3}$. We assume that the background gas has a small density such that it does not contribute to the extinction. The total visual extinction is 10.2 mag. If we choose $\zeta = 6 \times 10^{-17}\,\mathrm{s}^{-1}$, we predict a column density of H_3^+ of $3.8 \times 10^{14}\,\mathrm{cm}^{-2}$, in agreement with the value observed by Geballe et al. (1999).

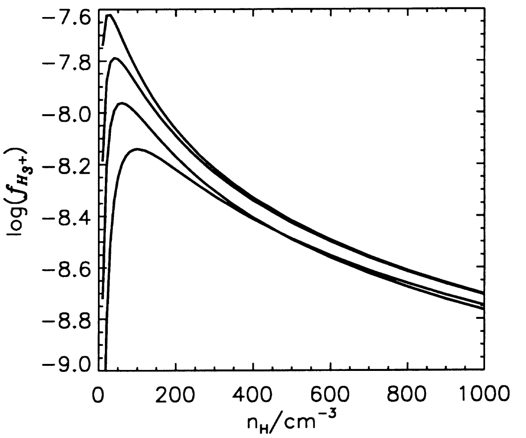

Figure 3. Fractional column densities of H_3^+ as functions of the clump density for clumps of total visual extinction $A_V = 2$, 1.4, 1 and 0.6 mag (top to bottom).

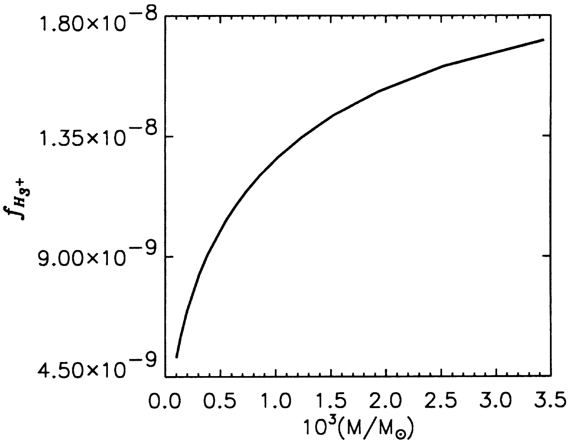

Figure 4. Fractional abundance of H_3^+ as a function of the clump mass.

Other than H_2, H_3^+ and OH, molecular species are nearly absent from the clump gas. To explain the measured abundances of C_2 (Gredel & Münch 1994) and CO (McCall et al. 1998), we postulate a nesting structure (Houlahan & Scalo 1992) in which the clumps of density $10^2\,\mathrm{cm}^{-3}$ contain cloudlets at a density of about $10^4\,\mathrm{cm}^{-3}$, embedded in which are high-density cores with a density of $10^5\,\mathrm{cm}^{-3}$ or greater. The aggregate contribution of the cloudlets to the visual extinction is 0.9 mag, and that of the high-density cores 0.1 mag. The major source of C_2 is the dissociative recombination of $C_2H_2^+$, the formation of which requires the presence of atomic carbon. It is produced in the cloudlets but not in the dense cores, where the carbon is largely taken up as CO. With a cosmic ray ionization rate of $6 \times 10^{-17}\,\mathrm{s}^{-1}$, we can accurately reproduce the measured abundance of $2 \times 10^{14}\,\mathrm{cm}^{-2}$ (Gredel and Münch 1994) for C_2 with a density in the cloudlet of $7 \times 10^3\,\mathrm{cm}^{-3}$, and we can reproduce the measured abundance of $2.6 \times 10^{16}\,\mathrm{cm}^{-2}$ (McCall et al 1998) for CO with a density of $10^5\,\mathrm{cm}^{-3}$ or greater in the core. The core contains a column density of no more than $10^{11}\,\mathrm{cm}^{-2}$ of H_3^+ and the cloudlet no more than $10^{12}\,\mathrm{cm}^{-2}$.

We predict a column density for OH of $6 \times 10^{13}\,\mathrm{cm}^{-2}$ produced mostly in the clump gas, a column density for C_2H of $2 \times 10^{13}\,\mathrm{cm}^{-2}$ produced mostly in the cloudlet, and a column density for HCO^+ of $9 \times 10^{10}\,\mathrm{cm}^{-2}$ produced mostly in the high-density core. The core has a density greater than the critical density for the 1–0 rotational transition of HCO^+, so that HCO^+ may be detectable in emission at the 1–0 frequency.

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