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A NEW SEARCH FOR INTERSTELLAR C_3

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ABSTRACT

A new, very sensitive search for interstellar triatomic carbon has resulted in upper limits for a few diffuse clouds of order 10^{10} cm^{-2}, or about 10^{-11} with respect to hydrogen. These limits are consistent with recent cold diffuse cloud chemistry models, but may be in conflict with shocked cloud models such as those invoked to explain CH^+ abundances. Our results may also argue against linear carbon-chain molecules as carriers of the diffuse interstellar bands.

Subject headings: interstellar: abundances — interstellar: molecules — molecular processes

I. INTRODUCTION

The question of molecular abundances in diffuse interstellar clouds was opened in the 1930s, with the identification of the diatomic carbon-bearing species, CH, CH^+, and CN. Since that time, substantial progress has been made in the theoretical understanding of chemical processes in the diffuse interstellar medium (e.g., van Dishoeck and Black 1986 and references cited therein), but few additional species have been detected observationally. In dark clouds, on the contrary, millimeter-wave radio observations have revealed a myriad (~ 70) of molecular species, through rotational emission transitions (Irvine, Goldsmith, and Hjalmarson 1987).

Despite the fact that dark clouds are obviously more "productive" in the chemical sense, there is still substantial interest in the chemistry of diffuse clouds. One reason is that the complex molecular processes that occur in dark clouds are probably triggered by simple, rapid reactions that occur in less dense regions; another is the assorted evidence that molecules are important constituents of diffuse clouds. In the latter regard, it is known that H_2 is prevalent in the denser portions of diffuse clouds (Spitzer *et al.* 1973; Shull and Beckwith 1985), that CO is quite abundant in these regions (see, e.g., Jenkins *et al.* 1973; Smith, Krishna Swamy, and Stecher 1976), and that the numerous diffuse interstellar bands are as yet unexplained and may have a molecular origin (see, e.g. Danks and Lambert 1976; Smith, Snow, and York 1977; Crawford, Tielens, and Allamandola 1985).

The purpose of this brief paper is to report on a refined search for one of the few triatomic species expected to be reasonably abundant in diffuse clouds. The molecule C_3 has been predicted to be reasonably abundant (e.g., Black and Dalgarno 1977; Mitchell, Ginsburg, and Kuntz 1977; Mitchell and Watt 1985) and would be a precursor to more complex species observed in dark clouds (e.g., HC_7N, Kroto *et al.* 1978; HC_9N, Broten *et al.* 1978; and $HC_{11}N$, Bell and Matthews 1985) and to the linear carbon-chain molecules suggested to be the carriers of the diffuse bands (Douglas 1977; Smith, Snow, and York 1977; Thaddeus 1979). Very recently C_3 has been detected in the circumstellar gas of a carbon-rich star (Hinkle, Keady, and Bernath 1988) through infrared vibration-rotation transitions near 5 μm.

The present observations are described in the next section; their implications for column density limits are discussed in § III, and the significance of the new upper limits are discussed in § IV.

II. OBSERVATIONS

The data described in this paper were obtained with the coudé spectrograph in the Canada-France-Hawaii Telescope (CFHT) in 1987 early February. The dispersion was 1.48 Å per mm, which yields a resolution (2 pixel) of 0.074 Å, at 4050 Å, corresponding to a velocity resolution (2 pixel) of 5.5 km s^{-1}. The detector was an 1872-element Reticon array, with 25 μm pixels.

The detector is read-out noise-limited when good exposure levels are achieved, which was the case for all our C_3 observations. In that regime, the signal-to-noise (S/N) ratio is a logarithmic function of the total charge per pixel. The observations covering the 4050 Å band of C_3 are summarized in Table 1, which includes the nominal S/N ratios in the data (based on CFHT calibrations). We have compared the nominal S/N levels with those derived empirically from the observed scatter in the spectra, and we find good agreement. Thus we are confident that the tabulated S/N ratios are realistic.

III. INTERPRETATION OF THE DATA

Because C_3 has many closely spaced rotational levels, the interpretation of equivalent width observations necessarily must take into account rotational excitation. A detailed rotational analysis was carried out by Clegg and Lambert (1981), which we adopt in the present study. These authors point out that the rotational lines in 4050 Å band of C_3 are closely blended, so that the composite equivalent width of the band must be interpreted as a blend of the rotational lines arising from those levels that are populated. This is in principle a

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TABLE 1

C_3 DATA

Star	HD	$E(B-V)$	log N_H[a]	S/N	m.e. (2 σ)	$N(C_3)(T < 40$ K)
ω Per	23180	0.32	21.21	1400	0.15 mÅ	$\leq 5.7 \times 10^{10}$ cm^{-2}
ζ Per	24938	0.32	21.20	1350	0.16	$\leq 6.1 \times 10^{10}$
	27778	0.40	...	1100	0.19	$\leq 7.3 \times 10^{10}$
HR 4049	89353	$\leq$0.10	...	580	0.36	$\leq 1.4 \times 10^{11}$
δ Sco	143275	0.16	21.16	1550	0.14	$\leq 5.4 \times 10^{10}$
σ Sco	147165	0.40	21.37	1260	0.17	$\leq 6.5 \times 10^{10}$
ρ Oph	147933	0.48	21.86	330	0.64	$\leq 2.4 \times 10^{11}$
ζ Oph	149757	0.32	21.15	1500	0.14	$\leq 5.4 \times 10^{10}$

[a] Hydrogen column densities are from Bohlin, Savage, and Drake 1978.

complex undertaking, but fortunately, as shown by Clegg and Lambert, only the even J-states are populated, with the result that the expected absorption band at low temperatures is relatively invariant with temperature. Rather than reproduce the detailed rotational excitation calculations of Clegg and Lambert, we have adopted their bandwidth calculation for cold diffuse clouds, and interpreted our equivalent width limits accordingly.

Table 1 lists equivalent width limits (2 σ) for the C_3 4050 band, assuming $T_{\rm rot} \leq 40$ K and a bandwidth of 0.3 Å. These limits are much lower than those cited by Clegg and Lambert, by as much as a factor of 30. The corresponding column density limits, again adopting molecular parameters derived by Clegg and Lambert, are also given in Table 1. For the best S/N achieved, these limits are of order 10^{10} cm^{-2}.

IV. DISCUSSION

Diffuse cloud chemistry models extant at the time of the Clegg and Lambert study indicated an expected C_3 column density toward moderately reddened stars such as ζ Per and ζ Oph of order 10^{12-13} cm^{-2}. The Clegg and Lambert upper limits mildly violated these theoretical predictions, and our new results severely violate them, amounting to nearly a factor of 100 underabundance in the most stringent cases.

Fortunately, diffuse cloud chemical models have been improved in the years between the Clegg and Lambert search and our own, and more detailed, models (e.g., van Dishoeck and Black 1986) show that C_3 should be much less abundant than expected under the other models. The new predictions call for $N(C_3)$ of order 10^7 cm^{-2} in the diffuse clouds we have searched, so that our new limits are some three orders of magnitude higher than the expected abundance of C_3. This means that our observations, while strongly ruling out the earlier theory, are easily consistent with the new predictions.

A new class of models, suggested by Elitzur and Watson (1978), postulates enhanced molecular abundances in shocked gas. The motivation for these models was the difficulty in explaining the observed abundance of the molecular ion CH^+, for which the most straightforward formation reaction ($C^+ + H_2 \rightarrow CH^+ + H$) is endothermic. Elitzur and Watson proposed that the required energy could come from shock heating, and they were able to demonstrate general feasibility of this picture for CH^+ formation (Elitzur and Watson 1978, 1980).

More recently, shock models have been developed which address the expected abundances of species other than CH^+ (Mitchell and Watt 1985; Pineau des Forêts *et al.* 1986; Draine and Katz 1986*a*, *b*). While the more recently published models are perhaps the most physically realistic, the only one that includes predicted C_3 abundances is the study by Mitchell and Watt (1985). Their model shows a significant enhancement of C_3 over the cold diffuse cloud models. For initial densities in the range $n_H = 5$–50 cm^{-3} and shock velocities between 5 and 20 km s^{-1}, Mitchell and Watt find C_3 to be enhanced by factors ranging from 10^3 to 10^6 over those expected for cold, unshocked gas. Such enhancements could easily raise the expected C_3 column densities in our observed sightlines to values greater than our limits. Thus our results may place significant constraints on the shock models.

We caution, however, that in the shock model the kinetic temperature of the postshock gas is high, and this would populate a wide range of rotational states, greatly broadening the expected absorption feature. For example, if the kinetic temperature is ~ 1000 K and C_3 is thermalized, the band would be some 10 Å broad instead of 0.3 Å as it is for $T < 40$ K (this is based on line wavelengths from Gausset *et al.* [1966] and the small rotational constant $B = 0.43$ cm^{-1} given by Clegg and Lambert 1982). The formal equivalent width sensitivity of the data scales as the square root of the line width, so for $T_{\rm rot} \simeq 1000$ K our limits increase by a factor of 5–6 (this can be counteracted by smoothing the data, but further uncertainty is introduced by the difficulty in defining the continuum over the width of a broad feature). As discussed below, however, this still may place significant constraints on the shock model.

While direct comparison of our results with the predictions of Mitchell and Watt would be difficult (we would have to adopt specific parameters for shocked gas in each cloud), it is easier and at least as useful to compare observed and predicted C_3/CH^+ ratios. The CH^+ column densities for our target stars, where known, all lie in the range 2×10^{12} cm^{-2} to 2×10^{13} cm^{-2}. The case from Mitchell and Watt that most closely reproduces these CH^+ abundances has initial density $n_H = 10$ cm^{-3} and $H_2/H = 0.05$, and shock velocity 20 km s^{-1} with a total shocked column density of 3×10^{19} cm^{-2} (thought to be appropriate for such well-studied cases as ζ Oph). This model yields an expected C_3 column density of 1.9×10^{10} cm^{-2}, very close to our observed limits for cold C_3 but below those for hot C_3. Mitchell and Watt point out, however, that an enhanced value of H_2/H would very significantly enhance $N(C_3)$ while having little effect on CH^+; the predicted column density reaches $N(C_3) = 7.5 \times 10^{12}$ cm^{-2} for $H_2/H = 1$. For our lines of sight where $N(H_2)$ is available, H_2/H values up to 1 are found (although this refers to the integrated line of sight, not specifically the shocked portion). Thus, our results *may* contradict the shock model of Mitchell and Watt. It is worth noting that if C_3 is eventually detected, the width of the feature will provide a good measurement of the cloud kinetic temperature, thus tightly constraining the shock model.

The upper limits on C_3 implied by our data may argue against linear carbon molecules as the carriers of the diffuse interstellar bands, as suggested by Douglas (1977) and Thaddeus (1979). In these suggestions, moderately long (C_5 and longer) carbon chains are invoked as the band carriers, because such molecules are known to have rich optical spectra, and because even longer carbon-chain molecules (cited in § I), had been identified in dark clouds. While C_3 itself is not invoked as the diffuse band carrier, the presence of large column densities ($N = 10^{13-15}$ cm^{-2}) of longer carbon chains would imply a substantial abundance of shorter ones, either as precursors to the long ones or as fragments thereof. It is indeed difficult to believe in sufficient quantities of long carbon chains to produce the diffuse bands if C_3 is as rare as is apparently the case, although it is possible that the longer chains are more stable against destruction than is C_3.

Our results do not rule out other possible precursors to long carbon chains (e.g., C_2H), nor do they rule out other classes of carbon-bearing molecules as the source of the diffuse bands (e.g., polycyclic aromatic hydrocarbons; Crawford, Tielens, and Allamandola 1985). They surely place stringent limits on diffuse cloud chemistry models that invoke abundant C_3, and they reduce the credibility of diffuse band origins in long carbon-chain molecules.

One of our target stars, HR 4049, deserves special mention. This is a high-latitude star with a very carbon-rich circumstellar dust shell (Lamers *et al.* 1986; Waters *et al.* 1988). This dust produces steep far-ultraviolet extinction, but no 2175 Å bump and no diffuse bands. There is mass outflow that consists entirely of carbon and hydrogen, and in the wind the density is far higher than in ordinary diffuse clouds. Thus the absence of C_3 is striking (but may be explained entirely by the radiation field of the central star, whose effective temperature is roughly 10,000 K).

Finally, it is worth noting that it may be profitable to push the search for C_3 into somewhat denser clouds, having higher molecular abundances while still being sufficiently transparent for optical absorption-line studies. An observational and theoretical study of one such cloud has led recently to the prediction that C_3 should have a column density of order $0.6\text{–}1.5 \times 10^{10}$ cm^{-2} (Jannuzi *et al.* 1988). The star in question is sufficiently bright to be studied with the CFHT, and we plan to do so in the near future.

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