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EVIDENCE FOR INTERSTELLAR H_2O IN THE ORION MOLECULAR CLOUD

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ABSTRACT

We report a search for interstellar gas phase H_2O in the infrared spectrum of the BN object in Orion. There is absorption ($S/N = 2$–4) at the position of the ν_3 1_{01}–2_{02} line of H_2O at 3801.42 cm^{-1}, the strongest expected H_2O line. Statistical analysis of the spectrum provides corroborating evidence for other H_2O lines. With an assumed H_2O excitation temperature of 150 K, we derive $N(H_2O) \leq 2.3 \times 10^{17}$ cm^{-2} toward the BN object. The H_2O column density implies abundance ratios of $[H_2O]/[CO] \leq 0.01$–0.08 and $[HDO]/[H_2O] \geq 0.8$–3.0×10^{-3}. The gas-to-ice ratio is $[H_2O \text{ gas}]/[H_2O \text{ ice}] \leq 0.06$ with an estimated uncertainty of a factor of 5.

Subject headings: interstellar: abundances — interstellar: molecules — nebulae: Orion Nebula

I. INTRODUCTION

Water in molecular clouds is a vexing problem in interstellar chemistry. Water should be significant in chemical processes (cf. Leung, Herbst, and Heubner 1984; Prasad and Huntress 1980) and as a reservoir contributing to the total oxygen abundance. It is a difficult molecule to observe with radio techniques because terrestrial H_2O vapor totally blocks lines originating between low-lying rotational levels. In the few cases where H_2O has been detected in extended molecular clouds, the excitation is complicated, and the transitions may be masing (Waters *et al.* 1980).

Deuterated water (HDO) is easier to detect, but the HDO/H_2O abundance ratio depends on strong and uncertain fractionation processes (Blake *et al.* 1987; Moore, Langer, and Huebner 1986; Olofsson 1984). One would much prefer to use measured HDO/H_2O abundance ratios to study fractionation mechanisms, rather than to use estimates of fractionation to infer abundances.

Water ice is observationally accessible through its infrared (IR) bands in spectra of sources embedded in molecular clouds. However, in many molecular clouds, H_2O ice accounts for only 5%–15% of the cosmic abundance of oxygen (Irvine and Knacke 1988). Where then is the rest of the oxygen in molecular clouds, and what fraction of it is in H_2O gas?

To address these issues, we are exploring a new observational approach: a search for IR lines of neutral gaseous H_2O in the vibration-rotation band near 3800 cm^{-1} (2.63 μm). The lines would appear in absorption in spectra of bright IR sources embedded in molecular clouds. So far, CO is the only gas-phase interstellar molecule detected by this method (Scoville *et al.* 1983; Black and Willner 1984). Upper limits were established for H_2 by Black and Willner and for CH_4 by Knacke *et al.* (1985).

Observation of interstellar water is impossible at ground-based telescopes because atmospheric H_2O lines are deeply saturated, but the atmospheric lines are weaker and narrower at the 12.5 km altitude reached by the NASA Kuiper Airborne Observatory. We scheduled observations when Doppler shifts moved interstellar H_2O lines away from the deepest parts of the telluric line profiles, an approach used to observe gaseous H_2O in comets (cf. Larson *et al.* 1989). We report the first results from airborne IR observations of H_2O in the interstellar medium.

II. THE IR SPECTRUM OF INTERSTELLAR WATER

The ν_3 vibration-rotation transitions near 3800 cm^{-1} (2.63 μm) form the strongest H_2O band in the near-IR spectral region. In the limit of low temperature and density where H_2O molecules would be completely relaxed, there would be only three lines: 0_{00}–1_{01} (3779.49 cm^{-1}), 1_{01}–0_{00} (3732.13 cm^{-1}), and 1_{01}–2_{02} (3801.42 cm^{-1}) with relative intensities of 1.00 : 1.04 : 1.92 (from Gates *et al.* 1964).

The transition of a thermal spectrum should take place at densities of 10^6–10^7 cm^{-3} (A values of the low-rotation lines are of order 10^{-3} to 1 s^{-1}; de Jong 1973). Radiative excitation can contribute or dominate in clouds with strong grain emission.

In Figure 1 we summarize H_2O line strengths, evaluated from National Bureau of Standards compilations (Gates *et al.* 1964), for temperatures relevant to molecular clouds. The spectral bandwidth used in these calculations, 3730–3840 cm^{-2} (2.60–2.68 μm), contains the most important interstellar H_2O lines accessible from the KAO. The strongest line is 1_{01}–2_{02} at 3801.42 cm^{-1}. It is very prominent at low temperatures but becomes relatively weaker as more levels are populated at higher temperature.

III. OBSERVATIONS

We searched for H_2O in the clouds in front of the BN object in Orion, the brightest near-IR source in a dense molecular region. BN was observed on 1988 February 17 UT with the University of Arizona Fourier transform spectrometer (Davis *et al.* 1980). The beam diameter was 20″. The unapodized spectral resolution was 0.09 cm^{-1} (7.1 km s^{-1}), a compromise between requirements for high spectral line contrast (radio linewidths are 3–10 km s^{-1}) and acceptable signal-to-noise ratio in the continuum spectrum. Useful observing time on the source was 140 minutes.

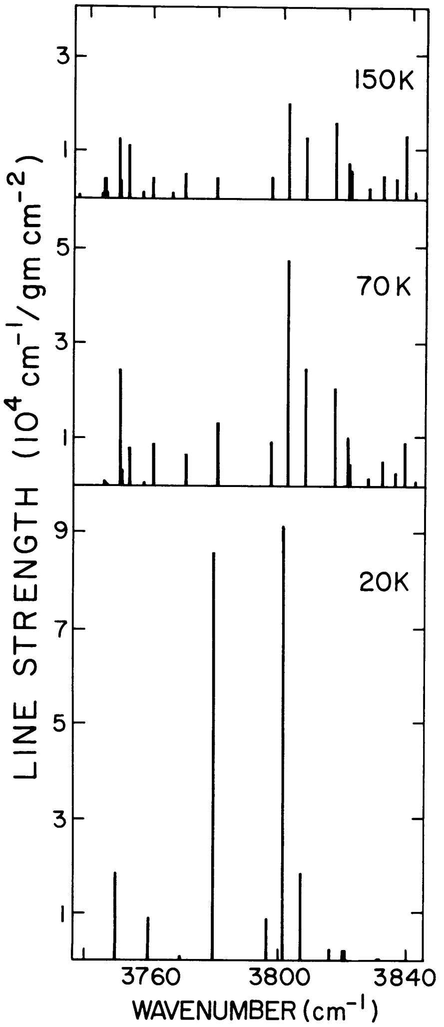

FIG. 1.—H_2O line strengths for three temperatures

Blocking filters in the spectrometer established a spectral passband from 3730 cm^{-1}, where atmospheric CO_2 absorbs, to 3850 cm^{-1}, where excitation of the ν_3 band of H_2O becomes unimportant. In Figure 2 we include portions of the spectra of BN and a comparison star (α UMa) in the 3790–3820 cm^{-1} region where the strongest interstellar H_2O lines in our passband would occur (see Fig. 1). The spectrum of BN is dominated by strong nebular lines: HBr β ($n = 6$–4) at 3808.3 cm^{-1} and H_2 (1–0) O(2) at 3806.8 cm^{-1}. The weaker emission feature at 3810.3 cm^{-1} is unassigned. The identification of individual interstellar absorption lines is limited by the low S/N (≈ 10) in the continuum spectra of BN. Expected features in the BN spectrum, such as the stronger telluric H_2O lines marked in Figure 2, appear with strengths, widths, and positions consistent with the indicated rms noise level. This agreement suggests that absorption features of similar strengths can be assigned to interstellar species.

IV. INTERSTELLAR H_2O

An absorption feature with optical depth of about 0.50 ± 0.25 appears in the red wing of the terrestrial 1_{01}–2_{02} H_2O line at 3801.42 cm^{-1}. The Doppler shift is 0.6 ± 0.1 cm^{-1} (47 ± 8 km s^{-1}) from the line center of the telluric feature. At the time of the observation, the Doppler shift of the Orion molecular cloud ("Ridge Source") was 43 (Earth with respect to LSR) + 8.5 (BN with respect to LSR) = 51.5 km s^{-1}, in good agreement with the observed position of the feature in the spectrum of BN.

This feature is coincident with the strongest predicted H_2O line (Fig. 1). Lines weaker than this transition would be at or below the noise level in our observed spectrum, but suggestions of their presence can be discerned in the red wings of telluric H_2O lines at 3749.6, 3769.8, 3779.5 (not shown), 3796.4, and 3816.1 cm^{-1}. In addition, the absorption on the high-frequency side of the H_2 line profile at 3806.3 cm^{-1} in Figure 2 may be interstellar H_2O in the wing of the terrestrial H_2O line at 3807.0 cm^{-1}.

The collective assignment of these weak features to interstellar H_2O is supported with a correlation analysis. The autocorrelation of the comparison star spectrum (Fig. 3*a*) has a strong, symmetric extremum at 0 cm^{-1} due primarily to telluric H_2O lines. The cross-correlation of spectra of BN and the comparison star (Fig. 3*a*) also displays the prominent telluric H_2O signature, but it is asymmetrically broadened by redshifted components in the BN spectrum (the irrelevant H and H_2 lines were excluded from the cross-correlation calculation). The difference between these two correlograms (Fig. 3*b*) reveals more clearly the BN feature at a redshift of approximately 0.5 cm^{-1} (40 km s^{-1}). We assign this correlation to numerous interstellar H_2O lines with $S/N \leq 1$ distributed across the recorded spectrum of BN.

In summary, our evidence for the detection of H_2O in the Orion molecular cloud includes (1) absorption at the redshifted position of the strongest predicted interstellar H_2O line; and (2) statistical evidence for additional, weaker absorptions at the expected Dopper-shifted position on the red wings of telluric H_2O lines.

There are possible lines not associated with water at 3798.4, 3805.2, and between 3810–3815 cm^{-1}. Interpretations of these features are still under investigation.

V. H_2O ABUNDANCE

The Orion region is complex with clouds at different temperatures, densities, and, almost certainly, different water abundances. The effective H_2O excitation temperature toward BN cannot be determined from direct observation of just one interstellar line. However, the temperature must be high to populate enough levels for excitation of several lines as indicated by the statistical analysis.

To first approximation, it seems reasonable to infer the H_2O temperature from IR CO observations of BN. Scoville *et al.* (1983) found the CO rotational temperature to be 150 ± 10 K in the strongest lines, which come from the "Quiescent Molecular Cloud OMC-1" at a $v_{\rm LSR}$ of 8.5–9.0 km s^{-1}, also called the "Compact Source" or "Ridge Source." This is higher than typical CO radio brightness temperatures of 60–115 K (Blake *et al.* 1987; Ulich and Haas 1976). The CO rotational temperature is also higher than the 70–100 K dust temperatures (Houck, Schaak, and Reed 1974).

The column density of H_2O is given by

$$N(H_2O) = {\rm EW}/mS(T)\,,$$

where EW is the equivalent width, m is the mass of the H_2O molecule, and $S(T)$ is the line strength (cm^{-1}/g cm^{-2}). The measured equivalent width of the 3801 cm^{-1} line is 0.14 cm^{-1}. For an assumed temperature of 150 K, the derived column abundance of H_2O is $N(H_2O) \leq 2.3 \times 10^{17}$ cm^{-2}. Table 1

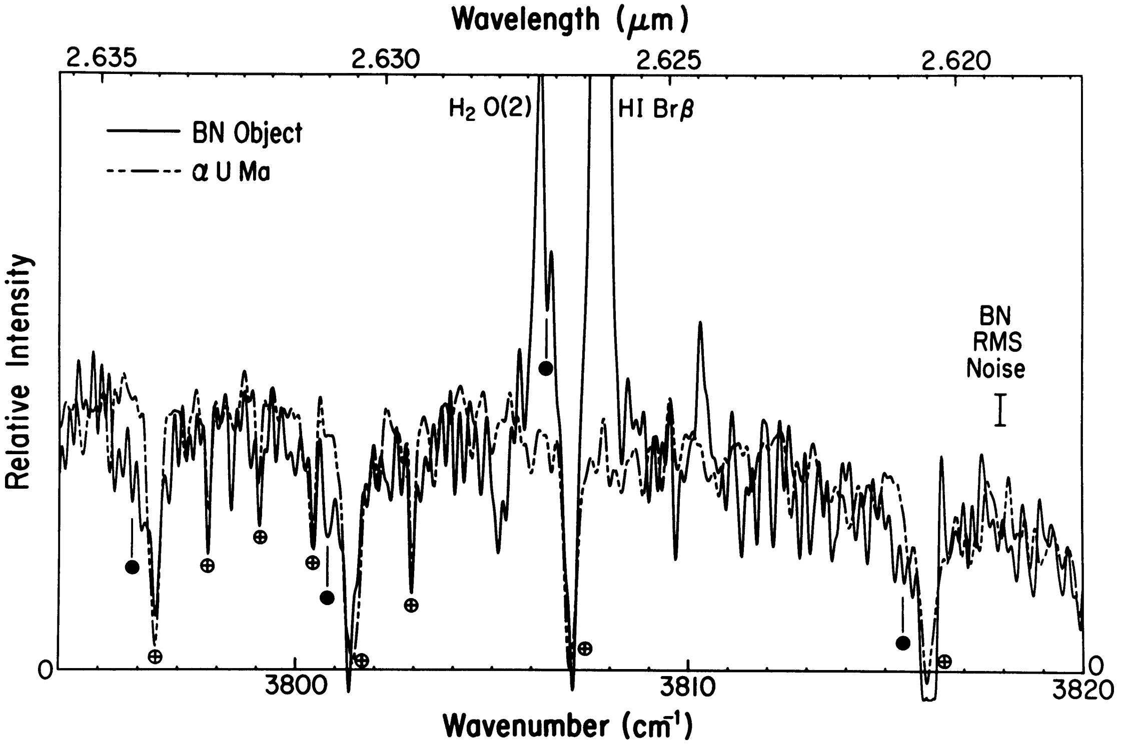

FIG. 2.—A portion of the normalized spectra of BN and a comparison star. The (apodized) spectral resolution is 0.11 cm^{-1} (8.7 km s^{-1}). The symbol ⊕ represents telluric H_2O lines; filled circles are Doppler-shifted positions of predicted interstellar H_2O lines.

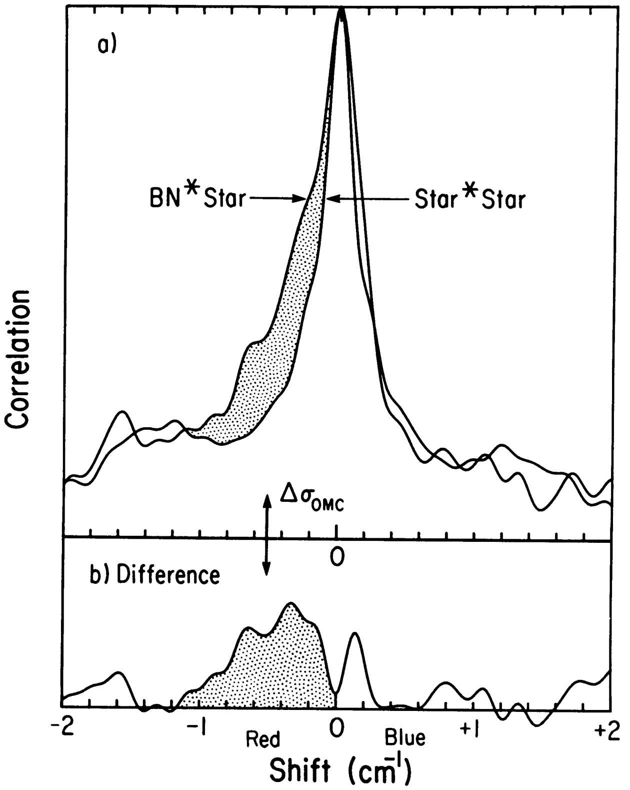

FIG. 3.—(*a*) Auto- and cross-correlation plots of the spectra in Fig. 2. The asymmetrically broadened peak in the BN-star cross-correlation implies that there is a shifted H_2O signature in BN. (*b*) The difference of the two correlograms in (*a*). The shaded feature is consistent with interstellar H_2O absorption toward the BN object.

summarizes column densities for the range of probable temperatures in BN.

The last column in Table 1 gives abundance ratios of H_2O to CO (averaged along the line of sight). *Local* abundance ratios could differ significantly since they must depend on cloud conditions, particularly on temperature and the degree of grain disruption. Furthermore, the CO abundance toward BN seems to be unusually high (Scoville *et al.* 1983). However, the derived ratios are within the range of theoretical estimates. For example, Leung, Herbst, and Huebner (1984) find $[H_2O]/[CO]$ ratios of 0.014–0.072 in their low metal abundance models. Many factors enter these estimates in a complicated region like Orion; we defer detailed analysis of the $[H_2O]/[CO]$ ratio to a later study.

Using the HDO abundance in the Compact Region (Blake *et al.* 1987), we find $[HDO]/[H_2O] \geq 8 \times 10^{-4}$. Again this is an averaged value along the line of sight and combines radio and IR observations with different spatial resolutions. Our derived H_2O column abundance, combined with observations of HDO in the "Compact Ridge Cloud" (Olofsson 1984), gives $[HDO]/[H_2O] \geq 3 \times 10^{-3}$. Uncertainties in the H_2O mea-

TABLE 1

COLUMN DENSITIES OF GASEOUS WATER IN THE DIRECTION OF BN

T (K)	*S*(*T*) ($cm^{-1}/g\ cm^{-2}$)	*N*(H_2O) (cm^{-2})	$[H_2O]/[CO]$[a]
70..........	47,673	8.9×10^{16}	0.012
150..........	19,726	2.3×10^{17}	0.031
300..........	7,753	6.1×10^{17}	0.081

[a] *N*(CO) = 7.5×10^{18} cm^{-2}; Scoville *et al.* 1983.

surement are on the order of a factor of 3 (Table 1). The column density of HDO toward the Hot Core is 23 times greater than to the Ridge Sources (Blake *et al.*, 1987), which would give a very high HDO/H_2O ratio. All these estimates are far above the cosmic D/H ratio of $\sim 2 \times 10^{-5}$, supporting strong HDO enhancement in molecular clouds.

The intensity of the 3.07 μm ice band gives a column density of $N(H_2O \text{ ice}) = 4 \times 10^{18}$ cm^{-2}, with perhaps an uncertainty of a factor of 2–3 (Knacke *et al.* 1982). Therefore (again using the 150 K estimate), $N(H_2O \text{ gas})/N(H_2O \text{ ice}) \leq 0.06$ with uncertainty on the order of a factor of 5. Thus, most of the H_2O along the line of sight to BN is ice.

Only a small fraction of the oxygen (at cosmic abundance) toward BN can be in gaseous H_2O. CO column densities in the Orion Ridge source estimated by radio techniques (1.5×10^{19} cm^{-2}; Blake *et al.* 1987) and toward BN (1.4×10^{19} cm^{-2}; Scoville *et al.* 1983) agree well, but the H_2 column density estimates differ by a factor near 10. The Scoville *et al.* result seems more relevant here since it is based on extinction toward BN. Their values of $N(\mathrm{CO})/A_v \geq 5 \times 10^{17}$ cm^{-2} mag^{-1}, $A_v =$ 25 mag, and $N(H_2)/A_v = 0.94 \times 10^{21}$ cm^{-2} mag^{-1}, suggest that about 40% of the oxygen is in CO (with a factor of 2 uncertainty). Using this estimate, we find that less than 2% of the oxygen is in neutral, gaseous H_2O.

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