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SEARCH FOR MICROWAVE H_2O EMISSION IN COMET BENNETT (1969i)

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ABSTRACT

The 85-foot radio telescope of the Naval Research Laboratory was used in an attempt to detect the 22,235 MHz transition ($6_{16} \rightarrow 5_{23}$) of H_2O during the recent appearance of Comet Bennett (1969i). No H_2O emission of antenna temperature greater than 2.5 K was observed. We have derived upper limits to the H_2O column density ($\sim 2 \times 10^{17}$ molec/cm^2) for various temperatures of the cometary gas. These limits have been compared with H_2O column densities calculated from two different cometary models. We find that on one of these models, our sensitivity was just at the threshold for detection of H_2O.

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Water is assumed to be the most abundant parent molecule in most proposed cometary models (Delsemme and Miller 1970). There is no direct observational evidence for H_2O, but optical observations of the OH radical strongly imply the existence of a large quantity of H_2O molecules near the comet nucleus. The recent detection of the $6_{16} \rightarrow 5_{23}$ rotational transition of H_2O (Cheung et al. 1969) at a frequency of 22235.08 MHz (wavelength of 1.35 cm) in interstellar space provides a new impetus for searches for H_2O in other astronomical objects. Comet Bennett (1969i) was a bright, young comet which reached its perihelion distance of 0.5 a.u. on 20 March 1970 at which time its geocentric distance was 0.7 a.u. An attempt was made to detect the 1.35-cm line or continuum emission from the head of this comet on 25 March, 28 March, 30 March, and 1 April 1970.

The 85-foot (26-m) reflector at the Maryland Point Observatory of the Naval Research Laboratory was used. This antenna has a main-beam efficiency of 0.6 and a half-power beamwidth of 2.3 arcmin at a wavelength of 1.35 cm. An antenna temperature of 1 K for a point source is equivalent to a flux density of 13×10^{-26} W m^{-2} Hz^{-1}. The beam-switched receiver employed a backward-wave oscillator which was phase-locked to a tunable reference oscillator at 350 MHz, which in turn was phase-locked to a quartz crystal standard for further frequency stability. The single-sideband system temperature was about 2500 K. The receiver gain was calibrated with an argon discharge tube of 200 K equivalent noise power and the receiver baseline was determined using "off-source" runs. Data were taken using both a bank of 10 contiguous 100-kHz filters and a bank of 50 contiguous 4-kHz filters. The 4-kHz profiles were averaged to an effective resolution of 12 kHz. A Doppler shift of 74.2 kHz is equivalent to a radial velocity of 1.0 km/sec.

The primary limitation of this experiment was the fact that available ephemerides for the comet at the time of our observations were not of sufficient accuracy (within 2 arcmin) for us to know the precise coordinates of the comet. The proximity of the comet to the sun precluded any attempts at alignment using an optical telescope. Thus we could only observe a grid of points centered on the "most likely" position of the comet and *ex post facto* determine which of those runs were taken while indeed observing the comet head. In this way we were able to obtain useful data, but our integration times on the comet head were severely limited.

The results of our observations are summarized in Table I. Zone 1 is defined as a run in which the center of the beam was $\leq$ 0.6 arcmin from the comet head and Zone 2 is a separation of 0.6-1.2 arcmin. We can also place an upper limit of 10 K for the antenna temperature of any 1.35-cm continuum radiation from the comet.

TABLE I

1.35-CM H_2O LINE SEARCH IN COMET BENNETT (1969i)

Date	Resolution (kHz)	Zone	Integration Time (min)	Peak-to-Peak T_A(K)	Velocity Range (km/sec) About V_{comet}
26 March 1970	100	1	5	2.5	-8 → +5
1 April 1970	12	1	20	10	-2 → +2
1 April 1970	12	2	15	10	-1 → +4

The data in Table 1 may be used to estimate an upper limit for the column density of H_2O in Comet Bennett. The observed antenna temperature T_A may be expressed as

$$T_A = F\eta_B T (1 - e^{-\tau}) \tag{1}$$

where F is the beam dilution factor, η_B the main-beam efficiency (0.6), T the temperature of the cometary gas, and τ the optical depth of the water vapor. Since the rotational levels corresponding to the 1.35-cm line of H_2O are 447 cm^{-1} above the ground rotational level, the water vapor is optically thin for the cometary models considered in this paper ($T \leq 500$ K). Equation 1 then reduces to

$$T_A = \eta_B \, T \, \bar{\tau} \qquad (\bar{\tau} << 1). \tag{2}$$

where $\bar{\tau}$ is the optical depth of the water vapor averaged over the radio beam; for a rotational transition of an asymmetric molecule such as H_2O, frequency-averaged over the width at half-amplitude, $\bar{\tau}$ is given by (Townes and Schawlow 1955)

$$\bar{\tau} = \frac{8\pi^{3/2} h^{3/2}}{3c\ k^{5/2}} \sqrt{ABC} \ \frac{e^{-\epsilon/kT}}{T^{5/2}} \ \frac{\mu^2 S \nu^2}{\Delta\nu} \langle N \rangle \tag{3}$$

where $\langle N \rangle$ is the mean column density of H_2O in any state averaged over the beam response of the telescope, ϵ the energy of the 6_{16} state, A, B, and C the rotational constants of the molecule, μ the dipole moment, S the strength of the transition, ν the frequency of the transition, and $\Delta\nu$ the half-width at half-intensity of the line. Substituting into Eqs. (2) and (3) the values A = 836 GHz, B = 435 GHz, C = 278 GHz, $\mu = 1.83 \times 10^{-18}$ esu cm, S = 0.06, $\epsilon = 0.0554$ eV, $\nu = 22235.08$ MHz, and $\Delta\nu = (\nu/c) \sqrt{\frac{2kT \ \ln 2}{m}}$, where m is the mass of the H_2O molecule, we find

$$T_A = 1.2 \times 10^{-11} \langle N \rangle \frac{e^{-643/T}}{T^2} \tag{4}$$

The minimum detectable antenna temperature was 2.5 K. The implied upper limits for mean H_2O column densities are given in column 2 of Table II for comet gas temperatures ranging from 100 K to 500 K.

Table II

COMPARISON OF OBSERVATIONS AND MODEL CALCULATIONS FOR <N>

	Mean Column Density $\langle N \rangle$ Molec/cm^2		
T(K)	Min. Detectable (T_A = 2.5K)	Fluid Dynamic Model	Malaise Model
100	13.0×10^{17}	0.6×10^{17}	8×10^{17}
200	2.1	0.6	8
300	1.6	0.6	8
400	1.7	0.6	8
500	1.9	0.6	8

In order to interpret this lack of microwave emission, we compare our results with two cometary models: (i) the fluid dynamic model which predicts an r^{-2} density distribution of molecules, and (ii) the model of Malaise (1970) derived from the observed behavior of the CN rotational distribution in several comets.

In the fluid dynamic model, the density n_F as a function of distance R from the nucleus is

$$n_F \ (R) = \frac{bER_c^{\ 2}}{vR^2} \tag{5}$$

where E is the evaporation rate of the icy nucleus, R_c the radius of the icy nucleus, v the flow velocity of the gas, and b the number fraction of H_2O molecules in the gas and is set equal to unity in the calculations which follow. It is assumed that H_2O molecules only exist out to a radius R_m defined by the product of v and the lifetime t_m of the H_2O against photo-ionization. The expressions for integrating $n_F(R)$ along the line-of-sight and averaging over the radio beam have been derived by Huebner and Snyder (1970) for the fluid dynamic model. Column 3 of Table II gives the value of $\langle N \rangle_F$ using the parameters $b = 1$, $E = 10^{18}$ molec/(cm^{2}sec), $R_c = 5 \times 10^6$ cm, $v = 10^5$ cm/sec, and $t_m = 1 \times 10^4$ sec (therefore $R_M = 10^9$cm). The value for R_c is an upper limit based upon the absence of gravitational perturbations due to comets on other bodies in the solar system.

The empirical density distribution of Malaise, on the other hand, is given by

$$n_M(R) = \frac{n_o R_o^{\,2}}{R^2} \left[\frac{1 - e^{-R/R_e}}{1 - e^{-R_o/R_e}} \right] \tag{6}$$

where n_o is the gas density at the arbitrary distance R_o (taken as 10^9 cm) and R_e is the effective radius of the molecule cloud, is a parameter fitted to observations which varies between 5×10^8 and 2×10^9 cm, depending on the comet and its solar distance. The Malaise distribution does not strongly depend on the value of R_e, however, and we adopt a value of 1×10^9 cm for our calculations. There are no reported observations of Comet Bennett that can be used to determine n_o, but Malaise reports values of 5×10^9 and 3×10^9 molec/cm^3 for Comet Seki-Lines (1962c) and Comet Ikeya (1963a) respectively. We adopt a value for n_o of 4×10^9 cm^{-3} for Comet Bennett since, although it was some $2^m.5$ brighter than either Comet Seki-Lines or Comet Ikeya, its dust continuum was very strong relative to its gas emission.

No simple exact analytic expression for $\langle N \rangle_M$, the integral of $n_M(R)$ over the line-of-sight and the telescope beam response, exists; however an examination of Eq. (6) shows that at worst a 30% error is introduced in the calculation of $\langle N \rangle_M$ if $(1-e^{-R/R_e})$ is approximated as (R/R_e). Making this approximation, the column density $N_M(\rho)$ at a projected distance ρ from the nucleus is

$$N_M(\rho) = \frac{2 n_o R_o^2 \cosh^{-1}(R_o/\rho)}{R_e\left[1-e^{-R_o/R_e}\right]} \tag{7}$$

Finally $\langle N \rangle_M$ is obtained by integrating $N_M(\rho)$ over the H_2O cloud and averaging this value over the area of the radio beam of radius R_B ($R_B = 4 \times 10^9$ cm for these observations). The final expression is

$$\langle N\rangle_M = \frac{2n_o R_o^4}{R_B^2 R_e (1-e^{-R_o/R_e})} \tag{8}$$

The calculated mean column density $\langle N\rangle_M$ is 8×10^{17} molec/cm^2 as compared with 0.6×10^{17} for the fluid dynamic model (Table II).

If all of the assumptions inherent is these calculations are correct, on the Malaise model our threshold of detection was almost adequate for a positive result. Column densities predicted on the fluid dynamic model, however, are an order of magnitude less. With only slightly improved sensitivity, a good radio test of the Malaise model may be possible for the next suitable comet. If these observations could be coupled with simultaneous optical observations, then the various model parameters would be more precisely known and more definitve statements concerning the mole fraction of H_2O could be made.

The negative results of this and the formaldehyde search (Heubner and Snyder, 1970) both suggest however that under somewhat more favorable conditions i.e. smaller geocentric distance, larger telescope, higher sensitivity, longer observing times, the detection of parent molecules by radio observations could be possible, assuming present ideas an nuclear composition are correct. A concentrated effort by radio astronomers on future nearly, bright comets is called for.

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