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Radio Observations of OH in the Interstellar Medium

In this note we wish to report the detection of 18-cm absorption lines of the hydroxl (OH) radical in the radio absorption spectrum of Cassiopeia A, thereby providing positive evidence for the existence of OH in the interstellar medium. The microwave transitions of OH in the ground state, $^2\pi_{3/2}$, J = 3/2, arise from two Λ-type doublet levels, each of which is split by hyperfine interactions with the hydrogen nucleus, so that four transitions result. The two strongest lines have been previously measured in the laboratory at 1667.34 ± 0.03 Mc/sec (F = 2→2 and 1665.46 ± 0.10 Mc/sec (F = 1→1) with relative intensities of 9 and 5, respectively;[1] these results are in agreement with theory. The suggestion that these lines might be detected in the radio spectrum of the interstellar medium has been made by Shklovsky[2] and Townes.[3] A previous search by Barrett and Lilley,[4] in 1956, was unsuccessful, primarily because the laboratory measurements of the frequencies had not been made. A recent search for OH emission also yielded negative results.[5]

Our observations were conducted on 10 days between October 15, and October 29, 1963, using the 84-foot parabolic antenna of the Millstone Hill Observatory of Lincoln Laboratory, M.I.T. and the spectral-line autocorrelation radiometer designed by Weinreb.[6] The receiver uses digital techniques to determine the autocorrelation function of the received signal. The resulting autocorrelation function is then coupled directly into a digital computer that performs a Fourier transformation and displays the resulting spectrum on a cathode-ray tube or a precision x-y plotter. During one integration time interval of 2000 seconds, a 100-kc portion of the spectrum is determined with a frequency resolution of 7.5 kc. The ability to see immediately a calibrated visual display of the measured spectrum and average this result with others greatly facilitated the conduct of the experiment and eliminated almost all post observation data handling. The system noise temperature was $420^{o}K$, of which $110^{o}K$ was due to Cassiopeia A. System tests were performed by observing the hydrogen line.

The data taken during the first evening of our observations showed strong evidence of the 1667 Mc/sec line in Cassiopeia A; the signal is visible after 2000 seconds of integration. We decided that positive identification of OH absorption lines of Cassiopeia A would be secured before proceeding to observations of other regions. Our results indicate that two of the three clouds showing strong H absorption,[7] namely those at radial velocities of -0.8 and -48.2 km/sec also give rise to OH absorption lines that we have detected at both 1667 Mc/sec and 1665 Mc/sec. The strong H absorption line at -38.1 km/sec appears to be composed of two lines at -37.4 km/sec and -42.1 km/sec when observed at the OH frequency. It is to be expected that a one-to-one correspondence between OH absorption and H absorption will not be observed because of (a) greater thermal broadening of H lines, (b) larger optical depth of the H lines, and (c) possible OH/H abundance variations from cloud to cloud. A typical record showing the 1667-mc line in the -0.8 km/sec cloud is shown in Fig.1. A summary of all of our observations is presented in Table 1. The evidence that we are indeed detecting interstellar OH in these observations may be summarized as follows.

1. Lines at both 1667 Mc/sec and 1665 Mc/sec have been detected with frequencies and intensity ratios that are in good agreement with the expected values.

2. The OH absorption spectra at both frequencies show general agreement with the H absorption spectra.

3. The absorption lines disappear when the antenna is positioned off Cassiopeia A by one degree in both azimuth and elevation.

4. The lines shifted 20 kc/sec between October 17, and October 29; this is the shift expected from the orbital velocity of the earth during this time interval.

A quantity of immediate astrophysical interest which follows from our observations is the abundance ratio of OH to H. This can be obtained in the following way: The spectral change in antenna temperature ΔT_{OH} owing to the OH absorption is given by

$$\Delta T_{OH} = \tau_{OH} T_{AC},$$

where τ_{OH} is the OH optical depth in the direction of Cassiopeia A and T_{AC} is the antenna temperature attributable onto to Cassiopeia A. The maximum optical depth is given by

$$\tau_{OH} = \frac{hc^2 A\ N_{OH}}{8\pi k T_s \nu_o \Delta\nu} \ \frac{g_i}{\Sigma g_i},$$

where A is the spontaneous transition probability, T_s is the excitation temperature analagous to the H spin temperature, ν_o is the line frequency $\Delta\nu$ is the line width, g_i is the statistical weight of level i, and N_{OH} is the total number of OH radicals per unit cross section. The statistical weight g_1 of the upper level of the 1667-Mc/sec transition is 5, and for the 1665-Mc/sec transition it is 3; the sum of the statistical weights for all levels is 16. The spontaneous transition probability A must be evaluated by using the matrix element derived from a quantum-mechanical treatment of Λ-type doubling[8], and has the value of 2.86×10^{-11} sec^{-1} for the 1667-Mc/sec transition. The OH dipole moment used in these calculations[9] is $(1.60 \pm 0.12) \times 10^{-18}$ e.s.u.

The excitation temperature T_s is the subject of considerable uncertainty because it cannot be assumed that it will be the same as that for H. The excitation temperature is defined by the relation

$$\frac{n_i}{n_o} = \frac{g_i}{g_o} e^{(-h\nu)/(kT_s)},$$

where n_i and n_o are the densities of radicals in the upper and lower states of the transition, respectively. For H it has been shown that T_s equals the kinetic temperature in a typical galactic gas cloud[10] because radiative transitions are relatively rare as compared with collisional transitions. For OH, however, the spontaneous transition probability is 10^4 times larger than for H, so radiative transitions play a more dominant role in establishing the equilibrium population distribution. A detailed evaluation of the processes that will be important in determining the OH excitation temperature has not been made, but a preliminary investigation shows that slow-moving positive ions may be very effective in inducing transitions between the two states, in spite of their low abundance in a H cloud.[11] This situation arises because the OH transition is of an electric dipole type, and therefore can be induced by the Coulomb field of electrons and ions which leads to large interaction radii. A similar result has been obtained by Purcell when considering the population of the fine-structure states of the n = 2 level of H in the solar atmosphere.[12] An upper limit on T_s can be set by our observations off Cassiopeia A from which one would expect to detect OH emission. From the preliminary observations we conclude that any OH emission adjacent to Cassiopeia A is less than $1^{\circ}K$; this result implies a T_s less than $50^{\circ}K$ for an optical depth of 0.02. For purposes of computing the total number of OH radicals from the equations above we have assumed a T_s of $10^{\circ}K$. More extensive observations for OH emission will enable a better estimate of this quantity to be made.

The values of the number of OH radicals per cm^2 in the direction of Cassiopeia A are shown in Table 1. The OH/H abundance ratio can be calculated from the results of the H absorption on Cassiopeia A[7], and gives typical ratios of 1×10^{-7} (see Table 1). This ratio can be compared with estimates of the CH/H abundance ratio 10^{-6} by Stromgren[13] and 2×10^{-8} by Bates and Spitzer.[14]

Our observations have enabled a more accurate determination of the frequencies of the two strongest Λ-type doublet lines of OH. The laboratory and astronomical values are shown in Table 2. It is possible that these values will be of interest to the molecular spectroscopist for a more accurate evaluation of the hyperfine coupling constants.

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TABLE 1. SUMMARY OF OH LINE ABSORPTION MEASUREMENTS IN THE CASSIOPEIA A RADIO SOURCE

Radial Velocity km/sec	1420.405 Mc H - Line Optical Depth[7]	1667.357 Mc OH - Line Optical Depth	Observed Line Width kc/sec	Number of OH Radicals Per cm^2	Abundance Ratio Relative to H
-0.8	1.85	.016 ± .005*	13	$\sim 2 \times 10^{14}$	$\sim 1.5 \times 10^{-7}$
-37.2	- -	.010 ± .005	13	$\sim 1.5 \times 10^{14}$	- -
-42.1	- -	.012 ± .005	20	$\sim 3 \times 10^{14}$	- -
-48.2	4.0	.016 ± .008	25	$\sim 5 \times 10^{14}$	$\sim 1 \times 10^{-7}$

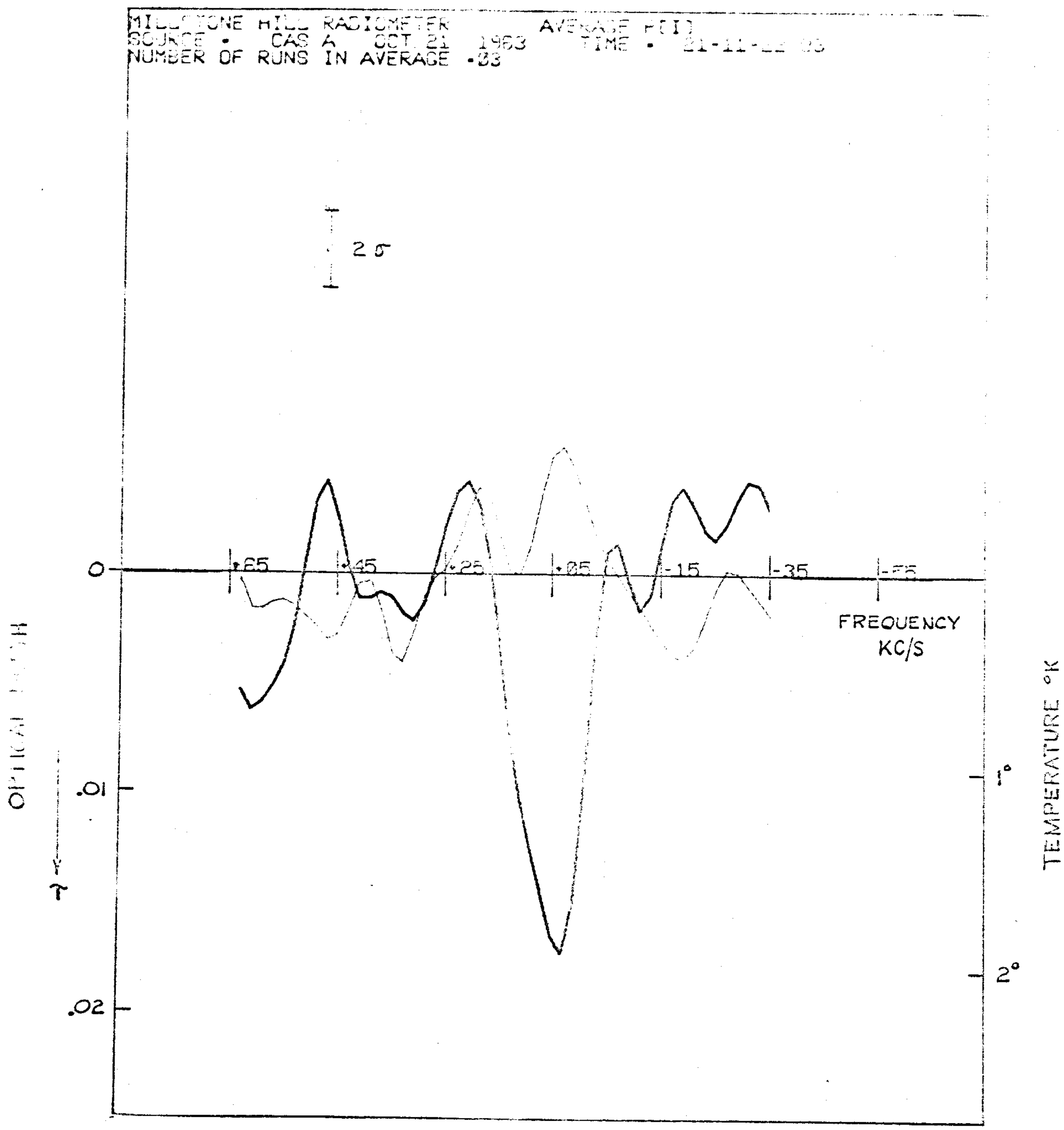
*An optical depth of .010 ± .003 with line width of 16 kc/sec was observed for the 1,665.402 Mc/sec line.

TABLE 2. REST FREQUENCY OF OBSERVED LINES

Transition	Laboratory Measurement	Astronomical Measurement
F = 2 → 2	1,667,340 ± 30kc/sec	1,667,357 ± 7kc/sec
F = 1 → 1	1,665,460 ± 100kc/sec	1,665,402 ± 7kc/sec

FIGURE CAPTION

Figure 1. Observed 1667 Mc/sec OH absorption spectrum in Cas A. The heavy line shows 8000 seconds of data taken with the antenna beam directed at Cas A, and the light line shows 6000 seconds of data taken with the beam displaced slightly from Cas A. The frequency scale is specified in kc/sec with respect to the local standard of rest assuming the line rest frequency to be 1,667,357 kc/sec.



NUMBER OF RUNS IN AVERAGE •03
2 σ
0
.01
.02
FREQUENCY
KC/S
TEMPERATURE °K
1°
2°

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