PHYSICAL REVIEW LETTERS

VOLUME 13 6 JULY 1964 NUMBER 1

DETECTION OF THE INTERSTELLAR OH LINES AT 1612 AND 1720 Mc/sec

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(Received 18 May 1964)

The two strongest microwave lines of OH produced by the Λ doubling of the ground state, $^2\Pi_{3/2}, J=\frac{3}{2}$, were first detected in the laboratory by Ehrenstein, Townes, and Stevenson,[1] and then in the absorption spectrum of the radio source Cassiopeia-*A* by Weinreb et al.[2] The latter measurement gave rest frequencies of 1665.402 and 1667.357 Mc/sec. We have detected[3] these lines in the spectrum of Sagittarius-*A* with a velocity corresponding to the strongest atomic hydrogen absorption, and more recently have found[4] an unexpectedly deep and wide OH absorption at a radial velocity of +40 km/sec. The strong absorption at 1667 Mc/sec suggested that it should be possible to detect the two satellite lines ($F=2\rightarrow1$ and $F=1\rightarrow2$) in this feature. Barrett and Lilley[5] had originally predicted frequencies of 1632 and 1700 Mc/sec for these lines. However, a brief search of the spectrum of Sagittarius-*A* near 1632 Mc/sec produced no positive result. On the basis of improved constants from Radford's laboratory measurements,[6] Posener[7] computed frequencies of 1612 and 1720 Mc/sec for the satellite lines.

The 1612-Mc/sec line was detected on 23 April 1964 using the Australian 210-ft. radio telescope and a frequency-switched receiver of bandwidth 50 kc/sec and input noise temperature 350°K. The measured absorption profile is shown by the points in Fig. 1, where it is compared with the previously measured[4] 1667-Mc/sec line profile (dashed line). In Fig. 1 the amplitude of the 1667-Mc/sec line has been reduced by a factor of 2.7 and the frequency appropriately shifted for best fit to the 1612-Mc/sec points. The shape of the major feature at +40 km/sec agrees closely for both lines (the 1612-Mc/sec profile being slightly narrower) and permits an accurate determination of the difference in frequency of the two transitions. From this difference the rest frequency of the 1612-Mc/sec line is found to be 1612.201 ± 0.017 Mc/sec, using Weinreb et al.'s[2] rest frequency of 1667.357 ± 0.007 Mc/sec. There appears to be some difference in the relative line intensities in the absorption near zero velocity, which is believed to be due to relatively nearby gas. The lower signal-to-noise ratio of

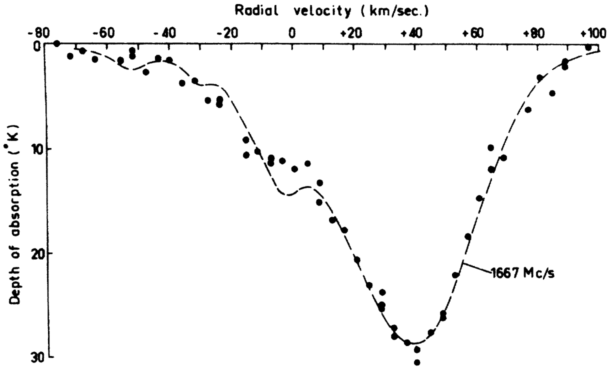

FIG. 1. The measured absorption profile of Sagittarius-*A* at 1612.201 Mc/sec, shown by the points. The dashed line is the 1667-Mc/sec profile reduced in intensity by a factor of 2.7. 1 km/sec is equivalent to 5.37 kc/sec at 1612 Mc/sec.

the 1612-Mc/sec results does not permit comparison of the features at -30 and -53 km/sec.

Having determined the third frequency, we could then compute the frequency of the fourth line ($F = 1 \rightarrow 2$) more accurately as 1720.559 ± 0.024 Mc/sec. As the switched-frequency receiver could not be tuned as high as 1720 Mc/sec, observations were made with a total power receiver of lower frequency and output stability. An absorption dip was observed which corresponded to a rest frequency of 1720.515 ± 0.04 Mc/sec.

The data on the rest frequencies of the four OH lines are summarized in Table I. Also included is the peak absorption observed on Sagittarius-A at a radial velocity of +40 km/sec.

In the notation of Radford[6] the hyperfine splitting is given by

$$W_{\mathrm{hfs}}^{\pm} = (A_1 \pm A_2) m_J m_I,$$

where

$$m_J m_I = -\tfrac{5}{4} \text{ for } F = 1$$

$$= \tfrac{3}{4} \text{ for } F = 2.$$

Thus, in frequency units, the hfs constants are given by

$$4A_2 = \nu_{1667} - \nu_{1665}$$

and

$$4A_1 = \nu_{1720} - \nu_{1612}$$

or

$$4A_1 = \nu_{1667} + \nu_{1665} - 2\nu_{1612}.$$

The measurement of Weinreb *et al.*[2] gives $A_2 = 0.494 \pm 0.004$ Mc/sec. The measured frequencies of the 1612- and 1720-Mc/sec lines give $A_1 = 27.079 \pm 0.014$ Mc/sec, while combining the 1612-Mc/sec result with those of Weinreb *et al.* gives $A_1 = 27.090 \pm 0.004$ Mc/sec. These results may be compared with Radford's values of $A_1 = 27.01 \pm 0.05$ Mc/sec and $A_2 = 0.51 \pm 0.05$ Mc/sec, derived from measurements with $\Delta J = 1$.

For $J = \frac{3}{2}$, $I = \frac{1}{2}$, and $F = 1, 2$ the intensity ratios of the four lines predicted from Eq. 6-6(b) of Townes and Schawlow[8] are 1:5:9:1. The observed absorptions are in the ratio 1:2.2:2.7:1. As the antenna temperature of that component of the source being absorbed[4] is approximately 135°K, the apparent optical depth is about 0.9 at 1667 Mc/sec. This optical depth would modify the relative intensities of the lines, but not sufficiently to explain the observations if the theoretical ratios held. We have previously suggested[4] that the ratio of the absorptions at 1667 and 1665 Mc/sec could be explained by a distribution of OH in small condensations of optical depth 2.7. The 1612- and 1720-Mc/sec results suggest a higher value of about 3.5. While the experimental errors permit the observed ratios to be fitted the condensation model, an alternative explanation, such as perturbation of the populations of the levels, cannot be excluded.

We wish to thank J. A. Roberts and D. D. Dunn for assistance with the observations of the 1720-Mc/sec line, and D. W. Posener for helpful discussions.

Table I. Rest frequencies of OH lines from astronomical observations.

Transition	Rest frequency (Mc/sec)	Peak absorption[a] (°K)	Notes
$F = 2\text{-}1$	1612.201 ± 0.017	29 ± 4	Present observations
$F = 1\text{-}1$	1665.402 ± 0.007	65 ± 2	Frequency from reference 2
$F = 2\text{-}2$	1667.357 ± 0.007	78 ± 2	Frequency from reference 2
$F = 1\text{-}2$	1720.515 ± 0.040	28 ± 7	Present observations
$F = 1\text{-}2$	1720.559 ± 0.024	...	Computed from first 3 lines

[a] The absolute temperature scale is not known to better than 10%. The errors quoted arise from uncertainties in the receiver baseline.

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[6] H. E. Radford, Phys. Rev. 122, 114 (1961).

[7] D. W. Posener, private communication.

[8] C. H. Townes and A. L. Schawlow, Microwave Spectroscopy (McGraw-Hill Book Company, New York, 1955).

INSTABILITIES IN PENNING DISCHARGES

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(Received 25 May 1964)

This Letter describes some experimental studies of the generation of electromagnetic energy in the microwave region in a cold-cathode Penning discharge operating at gas pressures of a few microns. Studies of electromagnetic radiation from Penning discharges in this frequency region have been reported by several authors. The work described by Bonnal, Briffod, and Manus[1] and by Briffod, Gregoire, and Manus[2] seems to have the closest relation to our work.

The experiments reported here have been carried out with the Penning discharge tubes shown in Figs. 1 and 2. The dimensions of the tubes are given in the figures. The distance between the two cathodes could be varied in tube 1. The cavity (operating in the TM$_{010}$ mode) in tube 1 was introduced in order to measure the electron density in the discharge and the movable rf probe in tube 2 to measure the fields outside the central region of the plasma. Aluminum and graphite were used as cathode materials. This made it possible to work with anode-cathode voltages from 400 to 2000 volts. The dc magnetic field, which was directed along the axis of the tubes and had a constant value in the discharge volume, could be increased up to 2500 gauss in continuous operation. The tubes were operated in a current region of 1-100 mA, and most measurements were made in air at pressures of 1-10 mμ.

The discharge current generally had a low-frequency component of 20 kHz or higher—not caused by the external circuits—and the rf signals appeared as pulses around the maxima of the modulated current. The external low-frequency circuits did not materially affect the generation of the rf noise. The spectrum of the microwave noise could be analyzed by a receiver connected to the coaxial output of the tubes. The peak level of the pulsed noise detected was generally above 10 μW/MHz.

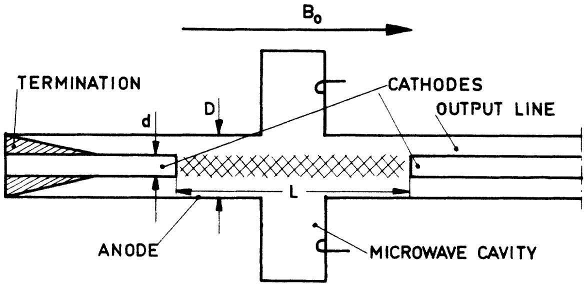

FIG. 1. Tube 1 with dimensions $d = 9$ mm; $D = 21$ mm; $L = 39$-189 mm.

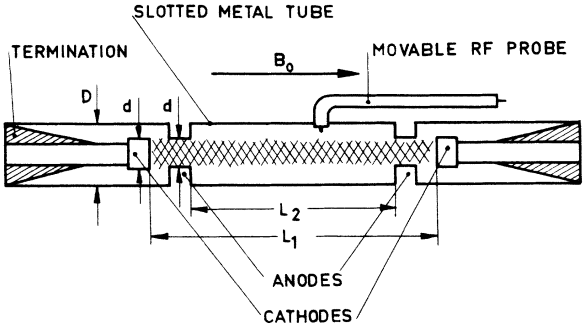

FIG. 2. Tube 2 with dimensions $d = 12$ mm; $D = 21$ mm; $L_1 = 140$ mm; $L_2 = 120$ mm.

Measurements on tube 1 in the frequency range 0.5-10 GHz with magnetic fields of up to 2500 gauss showed that there is a difference of several orders of magnitude between the amplitudes of the noise for frequencies below and above the cyclotron frequency of the electrons. In fact, noise could not be detected at frequencies above the electron-cyclotron frequency with the receiver used.

The microwave cavity measures the number of electrons in the volume given by the axial length of the cavity and an equivalent diameter of the plasma, probably larger than the diameter of the cathode and smaller than the diameter of the anode. The cavity measurements thus allow an estimate of the electron density, N, from which the plasma frequency for electrons, $f_p = (2\pi)^{-1}(e^2N/\epsilon_0 m_e)^{1/2}$, can be calculated. The measurements show that noise is detectable only for frequencies