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DETECTION OF INTERSTELLAR OH IN TWO EXTERNAL GALAXIES

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ABSTRACT

Molecular OH lines at 1665 and 1667 MHz have been detected in absorption in the spiral galaxy NGC 253 and the irregular galaxy M82. This is the first time that interstellar molecular lines, either radio or optical, have been observed outside the Galaxy. Observations were made with the Owens Valley interferometer; thus the amplitude and phase of the absorption features could both be measured. The run of phase versus velocity agrees with the sense of rotation of both galaxies. Abundances close to those found in the Galaxy are derived; however, this comparison is not very meaningful because of possible differences in excitation conditions.

I. INTRODUCTION

Unsuccessful attempts have been made in the past to detect OH in external galaxies (Radhakrishnan 1967; Roberts 1967). It must be noted that the most powerful OH emitters known in our Galaxy, if placed in the Andromeda Nebula, would be beyond the detection limit of any presently available instrument. Therefore, a more likely way to detect OH outside the immediate surroundings of the Galaxy seems to be through absorption techniques, since then its detectability is directly proportional to the continuum strength of the source.

This Letter reports the detection of OH absorption in the two main lines of the ground state of this molecule in two extragalactic systems, the spiral galaxy NGC 253 and the irregular galaxy M82. This detection was made with the two-element interferometer at the Owens Valley Radio Observatory. This is the first time that interstellar molecular lines, either radio or optical, have been detected outside the Galaxy.

II. OBSERVING TECHNIQUE

The sources have been observed with east-west–oriented baselines during the two observing periods described in Table 1. A longer baseline was used during the first attempt only so that the 130-foot antenna could be included for increased sensitivity. The two 90-foot antennas were used throughout the second trials. The receiver is a multichannel correlation receiver. Twenty-three channels are 100 kHz wide and separated by 100 kHz (18 km s^{-1}). A twenty-fourth channel carries a broad band approximately 5 MHz wide.

The continuum radio sources in the centers of NGC 253 and M82 are partially resolved at the baselines used in this work, with visibilities between 0.5 and 1. However, previous H I absorption work on M82 with the same instrument (Weliachew, unpublished) has shown that absorption features seen by 21 km s^{-1} channels do not start to show resolution when the continuum source is already appreciably resolved. This is simply due to the fact that the velocity spread across the central radio source of the galaxy is much in excess of 21 km s^{-1}. Thus the effective angular width of that part of the continuum source showing absorption in one 21 km s^{-1} channel is much smaller than the total width of the continuum source. Therefore, the absorbed flux as seen in each channel in this experiment is the same as for an experiment in which the continuum radio source is not resolved.

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TABLE 1

OBSERVATIONS

Galaxy	Line Rest Frequency (MHz)	Observing Period	Number of Runs*	Baseline Length (feet)	Transit Resolution (wavelength)	Fringe-Size Range (″)
NGC 253.......	1667	First (Oct. 1970)	4	3500	5890	35–49
NGC 253.......	1665	Second (Feb. 1971)	2	1600	2700	76–105
M82...........	1667	Second (Feb. 1971)	2	1600	2700	76–80
M82...........	1665	Second (Feb. 1971)	2	1600	2700	76–80

* A run means use of the full hour-angle coverage ($\pm 3^{h}5$ around transit for NGC 253 and $\pm 4^{h}$ for M82).

The radio source in the center of NGC 253 is a "core plus halo" source (Fomalont 1968). According to Fomalont the halo is completely resolved out at 1460λ. The radio source in the center of M82 is elongated along the major axis of the galaxy with half-power dimensions of $35'' \times 20''$ (Macdonald, Kenderdine, and Neville 1968).

Data were taken in 15-min records. Blocks of four 15-min records on the galaxy were alternated with a 15-min record on a calibration source. The rms noise on a 15-min record ranged from 0.1 to 0.15 f.u.[1] in a 100-kHz channel.

III. REDUCTION TECHNIQUE

The standard Owens Valley Radio Observatory reduction programs (Fomalont, Wyndham, and Bartlett 1967) were used. In addition to providing instrumental gain and phase information through the broad-band channel, the calibration sources listed in Table 2 were used to calibrate the gains and phases of the narrow bands relative to the broad band. For each line, the whole set of data on each galaxy was integrated after normalizing each 15-min record to the average of the broad-band visibility taken over all records. Therefore, the scatter of the results in each channel could only be accounted for by noise and/or relative channel-to-channel gain and phase calibration errors. The averages were performed on complex visibilities. Furthermore, calibrators were strong enough and were observed frequently enough that the final integration results were essentially noise limited. This was checked in several ways. First, at all points of all integrated spectra, the scatter of the n numbers being averaged was in agreement with the noise on an individual record as determined by the reduction program. In addition, the average dispersion of the scatter divided by $\sqrt{n}$ was consistent with the dispersion seen on integrated spectra outside the absorption features (see Figs. 1 and 2). Moreover, the calibration computer program determines the errors of the relative gains from all the calibration

TABLE 2

CALIBRATION SOURCES

Galaxy	Frequency	Calibrators
NGC 253.......	1667	3C 454.3, *3C 48*, *PO237−23*
NGC 253.......	1665	3C 409, *3C 48*
M82...........	1667	*3C 196*, *3C 273*, 3C 295
M82...........	1665	*3C 196*, *3C 273*

NOTE.—Calibration sources most frequently used are italicized.

[1] 1 flux unit = 10^{-26} W m^{-2} Hz^{-1}.

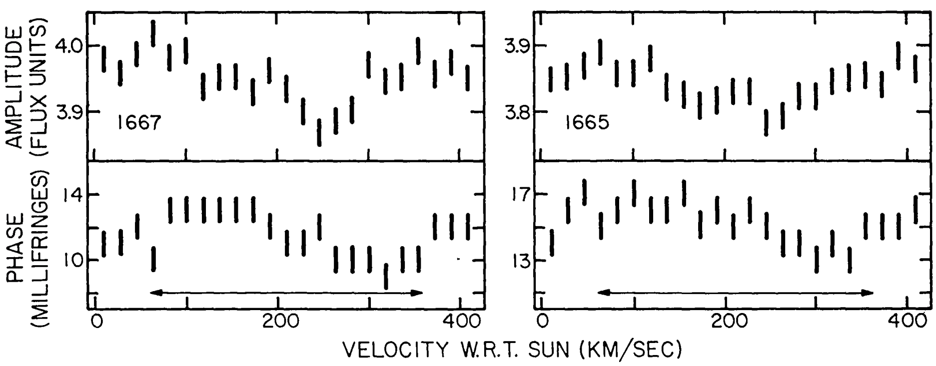

FIG. 1.—Amplitude and phase profiles for M82. The difference in amplitude between 1665 and 1667 MHz reflects the error in absolute calibration. Phases have only relative channel-to-channel meaning. The total velocity range in the H I absorption, as seen with the same instrument by the author (unpublished), is indicated by double arrows below the phase plots. All error bars are 2σ in length.

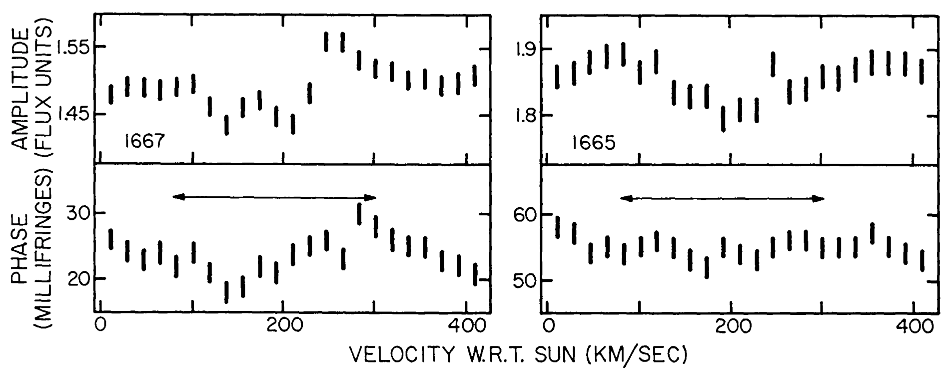

FIG. 2.—Amplitude and phase profiles for NGC 253. The difference in amplitude between 1665 and 1667 MHz is due to different baselines (see Table 1). Phases have only relative channel-to-channel meaning. The total velocity range in the H I absorption, as seen with the same instrument by the author, is indicated by double arrows above the phase plots. All error bars are 2σ in length. The enhanced amplitudes in the 1667 profile around 265 km s^{-1} are due to resolution effects (see § IV).

observations. These errors were always smaller than the noise for NGC 253 and M82.

In addition, systematic channel-to-channel errors could have occurred, for instance because of OH absorption of a calibrator at galactic velocities. To check on effects of this kind, relative channel gains were separately determined for each calibrator. No such effects were found in the sources used to calibrate NGC 253 to within the relative accuracy quoted for this galaxy.

Among the calibrators used for M82,[2] 3C 196 shows 0.8 ± 0.4 per cent absorption at 78 km s^{-1} and 3C 273 shows 0.6 ± 0.3 per cent absorption at 92 km s^{-1}. Since these two sources have been used to calibrate M82 with almost equal weight, this should imply corrections of 0.3–0.4 per cent to the gains of the corresponding channels (fourth and fifth from the left in Fig. 1).

IV. RESULTS

The visibility amplitudes and phases of the integrated spectra are shown in Figure 1 for M82 and in Figure 2 for NGC 253. The relative errors, computed from the scatter of individual points with respect to their average, are 0.4 per cent of the continuum visibil-

[2] All velocities are with respect to the Sun.

ity for M82, and 0.8 per cent for NGC 253. They have been increased to 0.5 and 1 per cent, respectively, to take account of some systematic effects that might have been missed by the tests described at the end of the preceding section. The increases in error estimates were worked out from the errors on the same tests. The fourth and fifth points from the left in the amplitude curves in Figure 1 have been corrected downward by 0.4 and 0.3 per cent to account for the already mentioned absorption in 3C 196 and 3C 273. The velocity domains where H I absorption is taking place in the same objects as seen by the same instrument are indicated in Figures 1 and 2.

The use of an interferometer for this experiment has been very valuable in that it added phase information to amplitude information. Phases in both figures have only relative channel-to-channel meaning. The absorption features can be seen on all phase curves except for NGC 253 in the 1665 line. This is normal because the phase effect with a 1600-foot baseline (see Table 1) is expected to be about half that at 3500 feet, thus making it vanish in the noise.

The sign convention adopted for phase implies that, with east-west–oriented baselines, phase increases with increasing right ascension of the source. Hence, at a velocity where, say, absorption is taking place on the preceding side of the galaxy, the absorbed source is shifted to the east and therefore the phase of the absorbed visibility increases. The phase curves in Figure 1 on the one hand and the 1667 phase curve in Figure 2 on the other hand show opposite trends in velocity and are all in agreement with the sense of rotation of M82 where the following side is receding and of NGC 253 where the preceding side is receding (see Burbidge, Burbidge, and Rubin 1964 for M82; Burbidge, Burbidge, and Prendergast 1962 for NGC 253). This agreement is very strong additional evidence that the observed features are indeed associated with M82 and NGC 253.

The 1667 amplitude curve in Figure 2 shows enhanced amplitudes at velocities around 265 km s^{-1}. Since interferometry measures vectors, this is consistent with absorption taking place about half a fringe (20″ at the 3500-foot baseline) off the center. As mentioned earlier, NGC 253 is a "core plus halo" source. Its halo is several arc minutes in size (Fomalont 1968). According to more recent high-resolution work by Fomalont (private communication), the core is about 10″ between half-intensity points along the east-west direction. The enhanced amplitudes in Figure 2 at 1667 MHz are consistent with a nonuniform absorption which raises the visibility of the otherwise-resolved halo. For example, they may merely mean that the absorption around 265 km s^{-1} is concentrated at the outskirts of the core, or in front of the halo component. Furthermore, the transition from the core to the halo is certainly much smoother than in a simple core-and-halo model because, according to Fomalont (private communication), after the halo is resolved out at 1500λ, the visibility still shows a continuous decrease at higher resolutions. The 1665 profile in Figure 2 does not show enhanced amplitudes around 265 km s^{-1} because it is taken with more than 2 times lower spatial resolution than the 1667 profile. Hence, resolution effects such as those seen with the 3500-foot baseline do not show up with the 1600-foot baseline.

V. DISCUSSION

The opacities that can be derived from our measurements are only apparent, since the absorption features are unresolved and absorbed fluxes will be referred to the total continuum fluxes of the sources. In order to derive these opacities an estimate of the absorbed fluxes must be made. For both galaxies, velocities lower than 110 km s^{-1} and higher than 330 km s^{-1} have been used to estimate the continuum visibility by a vector average over all involved channels. The complex visibility at each frequency between the same velocity limits has been subtracted from the continuum complex visibility to yield the absorbed flux. The apparent opacities have then been derived by dividing the absorbed fluxes by the total unresolved flux of the source in M82 (3C 231) and the core flux in NGC 253. We have already indicated that, on the grounds of H I absorption work

(Weliachew, unpublished), this is quite fair for M82. For NGC 253, we know that the situation is slightly more complicated as suggested by the 1667 profile.

A flux of 7.5 flux units at 1666 MHz has been derived from the fluxes at 1400 MHz (8.4 f.u.) and 2695 MHz (5.59 f.u.) given by Kellermann, Pauliny-Toth, and Williams (1969). A flux of 2 f.u. has been derived for the central component in NGC 253 from our measurements with the 1600-foot and 3500-foot baselines. Similarly, fluxes of 8.3 and 2.4 f.u. have been derived at 1420 MHz. Absorbed fluxes have been derived from our unpublished H I absorption spectra at 800 feet E/W for M82 and 1600 feet E/W for NGC 253.

Estimates of N/T_S, where N is the projected column density in the line of sight and T_S is the excitation temperature, have been made from $\int \tau(\nu)d\nu$ by means of standard relations (see, e.g., Robinson and McGee 1967 for OH, and Shklovskii 1960 for H I). Separate calculations have been made for the 1665 and the 1667 lines of OH. Table 3 shows $\int \tau(\nu)d\nu$ for the different lines and OH/H I abundances derived under the usual assumptions made in the Galaxy, namely, $T_S = 100°$ K for H I, and $T_S = 3°$ K for OH. For comparison, Table 3 also shows similarly derived abundances for several regions in the Galaxy.

This derivation of N/T_S when τ is estimated from the ratio of absorbed to total fluxes is fair provided the absorbing gas is not too clumped. If the actual τ in an individual clump is too high, N/T_S is underestimated. The ratio between integrated opacities $\int \tau(\nu)d\nu$ in the 1667 and the 1665 lines of OH is 1.4 ± 0.3 in M82 and 1.35 ± 0.3 in NGC 253 as compared with the theoretical 1.8. These ratios, if taken as saturation indicators, yield an actual optical depth of 0.75 (+1.45, −0.6) for M82 and of 0.9 (+2, −0.7) for NGC 253 in the 1665 line. These numbers, together with the average apparent opacities of 0.7 per cent for M82 and 2.3 per cent for NGC 253 in the same line, yield filling factors of the order of 2 per cent. Also, the corresponding correction factors to N/T_S range from 1 to 3 and, due to their great uncertainty, have not been applied to the results shown in Table 3. It is also well known that departures from the theoretical line ratio may arise from nonequilibrium conditions as well.

The line ratios found in M82 and NGC 253 match quite well with the values of 1.2

TABLE 3

OH/H I ABUNDANCES

Object	$\int \tau(\nu)d\nu$ (kHz) (with errors*)	Assumed Total Continuum Flux (flux units)	OH/H I	Reference
M82 (H I)	92(3)	8.3	...	Weliachew (unpublished)
M82 (OH 1665)	7.6(1)†	7.5	4.8×10^{-7}	This work
M82 (OH 1667)	10.2(1)†	7.5	3.5×10^{-7}	This work
NGC 253 (H I)	161(10)	2.4	...	Weliachew (unpublished)
NGC 253 (OH 1665)	24(4)†	2.0	8.6×10^{-7}	This work
NGC 253 (OH 1667)	31(3)†	2.0	6.2×10^{-7}	This work
A feature in the center of the Galaxy‡	...	...	6×10^{-6}	McGee (1970)
A feature in the 4-kpc arm in the Galaxy	...	...	2×10^{-7}	McGee (1970)
A feature in W51	...	...	1.5×10^{-7}	Goss (1968)
A feature in W43	...	...	7.2×10^{-8}	Goss (1968)

NOTE.—Assumed excitation temperatures are 3° K for OH and 100° K for H I.

* Errors are derived from the error bars in Figs. 1 and 2.

† Corrections for finite optical depth have not been made (see § V).

‡ In this region OH/H I shows very large variations (Robinson *et al.* 1964).

(Robinson *et al.* 1964) and 1.5 (Goldstein *et al.* 1964) found in the center of the Galaxy. This, together with the similarities in derived abundances, suggests that the OH absorption detected in M82 and NGC 253 does not arise from a completely new excitation mechanism. However, the derived abundances must be regarded as not very reliable because, more than saturation effects, possible differences in excitation conditions are a serious bias in comparing the derived abundances. In particular both M82 and NGC 253 have strong radio sources in their centers. The continuum photons at 18- and 21-cm wavelengths may significantly increase the excitation temperature. For example, the source in M82 has an average brightness temperature of 5350° K as derived from a flux of 7.5 f.u. and a size of $35'' \times 20''$ at 18 cm. The radio source subtends a solid angle of 0.2 square minutes of arc as seen from the Earth. If we take the distance to M82 as 3.2 Mpc (Burbidge *et al.*, 1964), the solid angle is 2×10^5 square minutes of arc from a point located at, say, 3.2 kpc from the center of M82 on the line of sight. The energy density at that point gives a radiation temperature of 90° K. Therefore, the excitation temperature will be considerably increased above the 3° K assumed. On the other hand, the H I excitation temperature, assumed to be 100° K, will be relatively less affected. This means that the OH abundances shown in Table 3 are probably underestimated. In addition, excitation conditions in M82 might be complicated by the strong infrared radiation (Kleinmann and Low 1970) of the central source.

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