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AMMONIA ABSORPTION TOWARD NGC 7538 IRS 1: 2 ARC SECOND OBSERVATIONS IN THE (3, 3) LINE

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ABSTRACT

Absorption from the (3, 3) line of NH_3 has been detected at -60.0 km s^{-1} toward the ultracompact H II region IRS 1 in NGC 7538 with the VLA. In single-dish spectra, the line is blended with an emission component at -56.5 km s^{-1}. With the 2″.5 × 2″.2 beam, however, line emission is resolved out. This corresponds to a spatial extent of more than 10″. The measured width of the absorption line is 8.5 km s^{-1} (FWHP). Accounting for the total optical depth of approximately 25 (estimated from hyperfine ratios), we obtain an intrinsic unsaturated line width of approximately 3.5 km s^{-1}. The line shape appears not to be compatible with a single Gaussian-shaped velocity component of high optical depth. The molecular cloud covers at least 60% of the continuum source; this is approximately 1″, corresponding to 0.017 pc. From the line shape, the cloud may consist of several clumps of size less than 0.01 pc, each with a different radial velocity and smaller line width. In addition to the spectral line measurements, a 23.87 GHz continuum map of IRS 1, 2, 3 is presented. The electron density in IRS 1 is found to be roughly 2×10^5 cm^{-3}. It is suggested that IRS 1 and IRS 2 may be similar objects at a different state of their evolution.

Subject headings: interstellar: matter — interstellar: molecules — H II regions

I. INTRODUCTION

The H II region NGC 7538 (S158) is characterized at radio frequencies by an extended (~ 3′) H II region with a compact source to the southeast (see, e.g., Israel 1977). The compact source can be resolved into three components, IRS 1, 2, 3 (Martin 1973; Wynn-Williams, Becklin, and Neugebauer 1974). IRS 2 [NGC 7538(A) according to Martin 1973] is a compact H II region (angular diameter ~ 9″; Willner 1976). IRS 1, also known as NGC 7538(B), is an ultracompact H II region (angular diameter ~ 1″; Harris and Scott 1976) near H_2O and OH masers. It is also near an H_2CO maser (Forster *et al.* 1980). IRS 3 [NGC 7538(C)] may also be an H II region, which by comparison is much weaker at radio frequencies.

In a recent study of ammonia lines (resolution 43″) toward the compact sources, Wilson *et al.* (1983) reported the detection of six metastable transitions [$J = K$, $(J, K) = (1,1)\ldots(6,6)$]. All show an absorption feature at approximately -59.5 km s^{-1}. The lower lying lines [(J, K) less than (4, 4)] show emission at -56 km s^{-1}. In addition, two nonmetastable lines, the (3, 2) and the (2, 1), were detected only in absorption against the continuum background. For the absorption, the best fit to the column densities of the metastable lines gives a rotational temperature of 170 K. From model calculations, the kinetic temperature is 170 K $\leq T_k \leq$ 220 K. From a comparison of metastable and nonmetastable absorption lines, an H_2 density of $n(H_2) \geq 10^5$ cm^{-3} was found. The total column density of NH_3 is roughly 2×10^{18} cm^{-2}. Hence both the kinetic temperature and the NH_3 column density are exceptionally large. Molecular clouds with T_K ~ 200 K were previously found toward Orion KL, Sgr B2, and perhaps W51 (Genzel *et al.* 1982; Pauls *et al.* 1983; Wilson *et al.* 1982; Ho, Genzel, and Das 1983). The column density in NH_3 is comparable to that determined for Ori KL. However, the exact location of the NH_3 absorption, and a specific association with an H II region remained unclear, since according to Martin (1973), there are at least two distinct continuum sources within the 43″ beam of the 100 m dish. In order to obtain data with much higher resolution, we measured the (3, 3) transition of NH_3 with the Very Large Array (VLA) of the National Radio Astronomy Observatory.[4] The goals of these measurements were to obtain a continuum map at 23 GHz, to locate the NH_3 absorption, and to estimate the size of the molecular cloud. We chose the (3, 3) line, which is about 120 K above the NH_3 ground state, in order to maximize our sensitivity to relatively warm gas.

II. OBSERVATIONS

The observations were made on 1983 July 8 using 22 antennas in the D configuration with a maximum baseline of 1.0 km. A *K* band maser preamplifier was used on the innermost antenna of the east arm with a system temperature of approximately 100 K. The other antennas were equipped with cooled mixers, with single-sideband noise temperatures of roughly 800 K. The spectra were measured using 32 channels separated by 48.8 kHz and of width 59 kHz each. At the line rest frequency (23.870 GHz), this width corresponds to 0.74 km s^{-1}. To improve the signal-to-noise ratio, the data were Hanning smoothed. Our spectral window was centered at a

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radial velocity of -60 km s^{-1}. The phase center of the array was at $\alpha(1950) = 23^h11^m36^s.68$, $\delta(1950) = 61°11'49''.6$. Every hour the nominal central frequency was adjusted in order to track the local standard of rest (LSR) radial velocity to an accuracy better than 0.1 km s^{-1}. Our primary flux density calibrator was 3C 286 (assumed flux density: 2.41 Jy), which was observed at the beginning of the observing session. We monitored the phase calibrator, 0016 + 731 (α[1950] = $00^h16^m54^s.198$, δ[1950] = 73°10′51″.46), every 20 minutes for 5 minutes. The derived flux was 1.67 ± 0.25 Jy. After correcting for shadowing, the visibility data for each spectral channel were Fourier transformed and then cleaned with the algorithm implemented by Clark (1980); 5000 iterations were used. The resulting maps, with a 1″ cell size on a 256 × 256 grid, have a synthesized half-power beamwidth of 2″.5 × 2″.2 at a position angle of $-88°.5$. The typical rms noise level for a single-channel cleaned map was approximately 15 mJy per clean beam area, which is equivalent to a main beam brightness temperature of 5.9 K.

III. RESULTS

a) *Continuum Data*

Figure 1*a* shows the continuum map obtained with a bandwidth of 2.35 MHz at 23.87 GHz. In addition to IRS 1 and IRS 2, we may have detected IRS 3. The flux densities are 0.6 ± 0.1 Jy (IRS 1), 1.6 ± 0.2 Jy (IRS 2), and approximately 0.02 Jy (IRS 3), which is consistent with a flux density of about 2.2 Jy observed at Effelsberg (R. Mauersberger, private communication). The (3, 3) line of NH_3, seen in absorption against IRS 1 (for details see § III*b*) diminishes the actual flux density of IRS 1 by 5%–10%. A flux density of 3 Jy at 86 GHz (Wink, Altenhoff, and Mezger 1982) appears slightly too high but still agrees within twice the rms with our data and that of Harris and Scott (1976). IRS 1 appears slightly more extended than the synthesized beam. We find that the source appears to be elongated in a NW-SE direction. Deconvolving the Gaussian beam from an assumed Gaussian source along this axis, we find a maximum angular size of approximately 1″.3 and a minimum size less than 1″ (FWHP). This is consistent with the 4.8 GHz continuum maps of Rots *et al.* (1981) and Turner and Matthews (1984). While the turnover frequency for IRS 2 is roughly 2 GHz (Martin 1973), this frequency was previously not well known for IRS 1. Harris and Scott (1976) suggested a turnover frequency of approximately 20 GHz. Our data (Fig. 2) confirm this result. For the rms electron density, n_e, we obtain 2×10^5 cm^{-3}, if the electron temperature is 8000 K (Goss, van Gorkom, and Forster 1982), the source distance is 3.5 kpc, and the formula quoted by Lang (1974) applies. The main uncertainty is the distance to NGC 7538. The electron density is 4–5 times larger than that estimated by Martin (1973). For IRS 2, Martin (1973) reported $n_e \sim 10^4$ cm^{-3}.

b) NH_3 *Absorption in IRS 1*

Ammonia absorption is found only toward IRS 1. Figure 3 shows our NH_3 (3, 3) absorption spectrum together with the single-dish profile obtained by Wilson *et al.* (1983). The (3, 3)

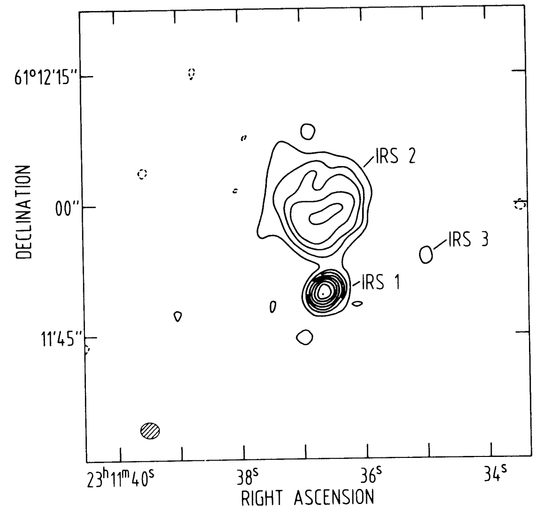

FIG. 1*a*

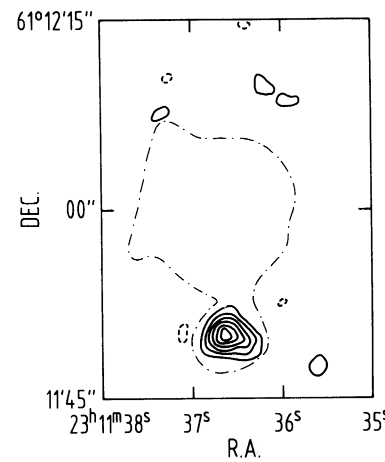

FIG. 1*b*

FIG. 1.—(*a*) A continuum map of IRS 1, 2, 3 at 23.87 GHz. The beam is shown in the lower left-hand corner. The contour levels are −10%, −5%, 5%, 10%, 15%, 20%, 30%, 40%, 50%, 70%, and 99% of the peak flux density of 450 mJy per beam. Dotted lines represent negative contours. For the synthesized beam of 2″.5 × 2″.2, the peak brightness temperature is 180 K. (*b*) A NH_3 (3, 3) map of IRS 1, 2, 3. Shown is the average of eight line channels at radial velocities between −61.3 and −56.9 km s^{-1}. The dash-dotted line represents the lowest continuum contour in Fig. 1*a*. *Dashed contours*, line emission; *solid curves*, line absorption. Contour levels are 0.050, −0.050, −0.075, −0.100, −0.125, −0.150, and −0.175 Jy per beam with a negative peak flux density of −0.193 Jy per beam.

line emission is completely resolved out. If this cloud is homogeneous, the source size is greater than 10″. A comparison with the (1, 1) and (2, 2) lines shows that the emission component is probably optically thin and that the rotational temperature is 27 K (Mauersberger 1983). In the single-dish spectrum, absorption is blended with the emission. Our high-resolution measurements provide a good opportunity to study the shape of only the absorption component. The entire central part of the absorption feature is blended with emission in the single-dish spectrum. A comparison of fits to the single-dish data and the VLA absorption-line flux densities shows that probably all of the absorption arises in front of IRS 1. This confirms the assumption of Wilson *et al.* (1983)

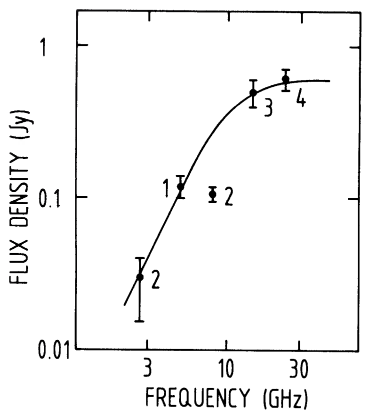

FIG. 2.—The spectrum of IRS 1, taken from Harris and Scott (1976). The curve is a theoretical spectrum for an electron temperature of 10^4 K. References: (1) Martin 1973; (2) Wink, Altenhoff, and Webster 1975; (3) Harris and Scott 1976; (4) this *Letter*.

that the NH_3 component absorbs only the compact H II region IRS 1. From the intensity of the VLA absorption line relative to the unblended hyperfine satellites detected in the 43″ resolution spectrum, we derive a total optical depth of approximately 25. In the following discussion, we assume that $\tau \gg 1$. If the angular size of the continuum source is 1″, we obtain a true peak brightness temperature of $T_c \sim 1100$ K and a line temperature of $T_L \sim -550$ K. We assume that the NH_3 excitation temperature $T_{ex} = T_k$. [For the (3, 3) line, Walmsley and Ungerechts 1983 predict a T_{ex} much larger than T_k for some H_2 densities. This effect may explain the unusual strength of the (3, 3) line toward W33 (Wilson, Batrla, and Pauls 1982). However, we consider this to be unlikely here because the high total optical depth and density ($\geq 10^5$ cm^{-3}) should reduce the importance of such processes.] We find $T_{ex} = T_k \leq 550$ K. The upper limit for T_k is above the value of roughly 200 K determined by Wilson *et al.* (1983). Because the angular size of the background source and T_k are known, the mean size (but not shape and exact position) of the molecular cloud can

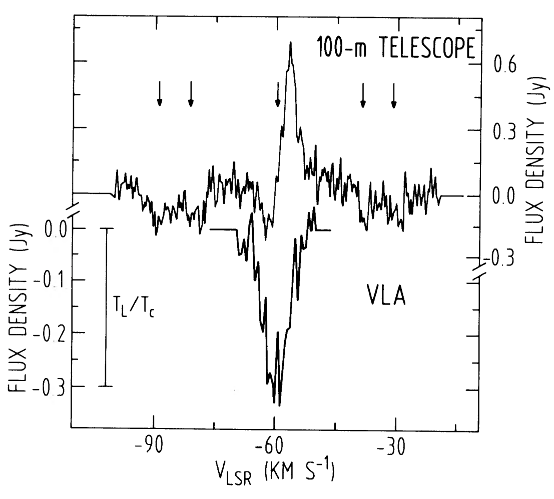

FIG. 3.—A comparison of NH_3 (3, 3) spectra obtained with the 100 m telescope at (*upper*) Effelsberg and (*lower*) the VLA. Arrows indicate the centers of hyperfine component groups of the absorption component. The bar to the left of the VLA spectrum represents a line to continuum ratio of 0.5.

be estimated. For a uniform cloud ($T_{ex} = 200$ K) centered on a uniform continuum source ($T_c = 1100$ K, diameter: 1″), we obtain a coverage of 61% and a size of 0″.8. With a uniform molecular cloud centered on a Gaussian continuum source ($T_c = 1100$ K, FWHP: 1″), we obtain instead a size of approximately 1″.2. If dense molecular material is not only located in front of IRS 1, but surrounds the compact source, the coverage and size of the cloud as determined above is only a lower limit. If the radial velocities were equal, emission within the synthesized beam but not in front of the continuum source would reduce the absorption. Assuming the highest possible coverage (100%) of the continuum source, we thus obtain a maximum size for the -60 km s^{-1} molecular cloud of approximately 2″.0. This is confirmed by limits from an average over the central line channels (Fig. 1*b*). The resulting map shows the absorption feature at a high signal-to-noise ratio. We do not find, however, any sign of weak emission located adjacent to IRS 1.

The apparent line width (FWHP) of the absorption feature is $\Delta v_{1/2} = 8.5 \pm 1.0$ km s^{-1}. The intrinsic line width of a single hyperfine component must be smaller because of magnetic hyperfine splitting and large optical depth. To obtain an estimate of the line broadening, we used the fitting procedure described by Pauls *et al.* (1983). The main assumptions are (1) a Gaussian distribution in optical depth for each hyperfine component and (2) local thermodynamic equilibrium (LTE) among the components. From this we obtain a LSR radial velocity of -60.0 ± 0.1 km s^{-1} and a line width of 3.6 ± 0.7. Thus our results for the NH_3 radial velocity and line width agree with those of Wilson *et al.* (1983). However, the line shape is not compatible with such a large optical depth. For a total optical depth greater than 10, the spectrum should have a flat bottom and steep line wings. This is not observed. A fit in which the optical depth is allowed to vary reproduces the observed line shape much better and gives an optical depth $\tau = 1.2$. Since the hyperfine satellites are nearly as strong as the main component, τ would be very large under LTE conditions (Wilson *et al.* 1983). Other reasons for the difference between the observed and fitted line shapes may be: (1) deviations from LTE intensities in some of the hyperfine components; or (2) that we observe not one cloud, but a superposition of several very small clumps, each with its own internal motion and radial velocity. Explanation (2) seems to be the most reasonable, since large optical depths are found in many metastable lines. If so, the sizes of the clumps would be ≤ 0.01 pc. This is comparable to the fine structure at a linear scale of approximately 0.005 pc found in Ori KL and in W3(OH) (Pauls *et al.* 1983; Guilloteau, Stier, and Downes 1983).

The relation between the H II region IRS 1 and the molecular cloud remains to be investigated. While 43″ resolution measurements with the 100 m telescope which include both IRS 1 and IRS 2 suggest a radial velocity of -62 km s^{-1} for the ionized gas at 23 GHz (R. Mauersberger and J. E. Wink, unpublished), Goss, van Gorkom, and Forster (1982) find -68 km s^{-1} at 4.9 GHz with an angular resolution of 9″. At 4.9 GHz, continuum emission from IRS 1 is small compared with emission from IRS 2 (0.1 vs. 1.5 Jy), while at 23 GHz the contribution of IRS 1 to the total continuum flux density is larger (0.6 vs. 1.6 Jy). Hence a more positive radial velocity at the higher frequency may indicate that the ionized gas in IRS 1 has a radial velocity greater than -62 km s^{-1}.

We can also investigate the relationship between the OH, H_2O, and H_2CO masers and the molecular cloud. There are maser lines at three different radial velocities: each of the OH and H_2CO maser pairs is found at a radial velocity of -57 to -58 km s^{-1} and at -60 km s^{-1}. The H_2O maser at -61.2 km s^{-1} is displaced by 1″ from IRS 1 (Rots *et al.* 1981) and may not be directly related to the NH_3 region. However, each pair of OH and H_2CO masers has one component which agrees in radial velocity with the molecular cloud seen in absorption against IRS 1. If the component at -57 to -58 km s^{-1} belongs to dense molecular material behind IRS 1, this component may not be seen in our NH_3 spectrum because of the extremely high optical depth of the -60 km s^{-1} cloud and the line broadening due to optical depth and hyperfine splitting. The motion of these clouds relative to IRS 1 remains unknown (for a discussion, see Dickel *et al.* 1982).

IV. CONCLUSIONS

The unusually compact, dense, and warm molecular cloud associated with IRS 1 is, as far as ammonia results are concerned, similar to the hot component in the Orion molecular cloud. The main points presented in this *Letter* are summarized below.

1. NH_3 seems to absorb only the ultracompact H II region IRS 1 [NGC 7538(B)]. About 50% of the intensity of IRS 1 is absorbed.

2. If the molecular gas is hot ($T_{ex} \sim 200$ K) and optically thick, as reported by Wilson *et al.* (1983), the coverage of the continuum source is $\geq 60\%$ and the size of molecular absorption ranges between 0″.8 and 2″.0 (corresponding to 0.014–0.034 pc at a distance of 3.5 kpc).

3. The observed line width is 8 km s^{-1}. The intrinsic line width of a single unsaturated hyperfine component is 3.5 km s^{-1}. The radial velocity is -60.0 km s^{-1}, and the total optical depth is approximately 25. The line shape cannot be made up of Gaussian-shaped hyperfine components with a single velocity and relative LTE intensities. Most probably, the absorption is caused by a number of clouds, each with a narrower line width. The observed line shape could be caused by a Gaussian velocity distribution of the clouds.

4. The continuum flux density of IRS 1 is 0.6 ± 0.1 Jy. Combined with the source size, this gives a rms electron density of roughly 2×10^5 cm^{-3}.

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