1989ApJ...340L..37S

THE ASTROPHYSICAL JOURNAL, 340:L37–L40, 1989 May 1

FIRST DETECTION OF SO_2 AND CH_3OH EMISSION AND ONE UNIDENTIFIED LINE NEAR 800 GHz

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Received 1988 December 27; accepted 1989 February 17

ABSTRACT

We report the first detection of SO_2 $7_{7,1} \rightarrow 6_{6,0}$ and CH_3OH $13_1 \rightarrow 12_0$ E emission lines near 800 GHz from the Orion core. Peak main-beam brightness temperatures are 7 and 9 K, respectively, in a 25″ beam. The widths and center velocities of these lines, similar to those of the recently detected HCN $J = 9 \rightarrow 8$ and HCO^+ $J = 9 \rightarrow 8$ transitions, match the signature of the Orion plateau emission, indicating that the emission comes from outflowing or shocked gas. The SO_2 emission is best modeled by an optically thick, beam-diluted source. Excitation analysis shows that, despite of the very high critical excitation densities (above several 10^8 cm^{-3}), the newly discovered lines have rotational temperatures similar to those derived from the millimeter-wave transitions of the same molecules. Both the millimeter-wave and submillimeter emission therefore come from the very dense region of shocked gas around IRc2.

We have also detected a third, unidentified line with a rest frequency of 809,583 ± 5 MHz (assuming $v_{LSR} = 7$ km s^{-1}). Its peak main beam brightness temperature is 3.5 K, and the line width is ≈ 25 km s^{-1}, also characteristic of the plateau emission.

From all spectroscopic data available near 800 GHz, we estimate a line/continuum flux ratio in the Orion core of 30%–40% for the 350 μm atmospheric window.

Subject headings: interstellar: matter — interstellar: molecules — nebulae: Orion Nebula

I. INTRODUCTION

The recent detections of HCN $J = 9 \rightarrow 8$ (Stutzki *et al.* 1988) and HCO^+ $J = 9 \rightarrow 8$ (Jaffe *et al.* 1989) emission showed that, at least in the Orion core region, densities are high enough to excite the submillimeter transitions of heavy rotors with large dipole moments, with critical densities near 10^9 cm^{-3}. The very high density regions are likely to be small resulting in substantial beam dilution for submillimeter observations with the IRTF (beam size 30″ FWHM) and the UKIRT (25″ FWHM), even for the nearest source, the Orion core which has an angular extent of 5″–20″. We were thus surprised to discover several new lines near 800 GHz from the Orion core.

II. OBSERVATIONS AND RESULTS

The observations were carried out with the MPE cooled Schottky Heterodyne receiver (Harris *et al.* 1987*a*) near 800 GHz and its dual AOS backend of instantaneous bandwidth 1 GHz. Receiver temperatures were 3500–4500 K (DSB). For the observations near 802.5 GHz (IF band 250–1000 MHz) we used a warm mixer and a nonstandard IF setup resulting in a receiver temperature of 10,000 K (DSB). The atmospheric conditions were good and stable. The calibration procedure is described in Harris *et al.* (1987*b*).

During an observing run from 1988 January 4–7 at the IRTF, two new lines appeared near the [C I] line toward IRc2. We confirmed these detections during a second run from 1988 February 1–8 at the UKIRT and used the change of Earth's velocity relative to the source between the runs to identify the sideband of the newly discovered lines (the laser LO is fixed in frequency). In addition, we discovered a third new transition with unknown sideband identification during the successful search for HCO^+ $J = 9 \rightarrow 8$ emission (Jaffe *et al.* 1989) at the UKIRT.

Table 1 lists the observed parameters for the three newly discovered lines. Figure 1 shows the spectra together with a high S/N spectrum of the HCN $J = 9 \rightarrow 8$ transition (Harris *et al.* 1989). These lines all have widths of 15–30 km s^{-1} (FWHM), typical for the "plateau" or "low-velocity outflow" component in Orion.

The line at 796.983 GHz was subsequently identified by H. J. Clar from University of Cologne as the SO_2 $7_{7,1} \rightarrow 6_{6,0}$ transition (796.9825 GHz) using the molecular data by Sattler and Worchesky (1981). Based on the extensive CH_3OH study by Sutton and Herbst (1988), the line with ambiguous sideband identification (802.272 or 803.959 GHz) could be identified as the CH_3OH $13_1 \rightarrow 12_0$ E transition at a rest frequency of 802,269.72 ± 0.05 MHz (E. C. Sutton, private communication).

The third line is unidentified. We checked all known interstellar diatomic molecules and most other interstellar, linear molecules. The check included isotopic species of reasonable abundance, and vibrationally excited states where necessary. We also checked several asymmetric top molecules and found no identification.

III. DISCUSSION

a) CH_3OH *Excitation*

The 13_1 E state of methanol is 416 K above ground (224 K above the "ground" state of the E species). The $13_1 \rightarrow 12_0$ E

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[1] Visiting Observer at the Infrared Telescope Facility which is operated by the University of Hawaii under contract from the National Aeronautics and Space Administration.

TABLE 1

Line Parameters of Newly Discovered Transitions[a]

$\nu_{\rm rest}$ (GHz)[b]	Δv (km s^{-1})	$T_{\rm MB}$ (K)	Identification	$\nu_{\rm lab}$ (GHz)	$\nu_{\rm rest} - \nu_{\rm lab}$ (MHz)
796.9827 (20)	24.2 (1.9)	7.2 (0.5)	SO_2 $7_{7,1} \rightarrow 6_{6,0}$	796.9825	0.2 (2.0)
802.272 (4)	17.2 (3.8)	9. (1.)	CH_3OH $13_1 \rightarrow 12_0$ *E*	802.26972	2.3 (4.0)
809.583 (5)	27. (5.)	3.5 (0.6)	Unidentified	...	...

[a] Derived from single-component Gaussian fits; formal errors in last digits in parentheses.

[b] Assuming $v_{\rm LSR} = 7$ km s^{-1}, to match other submillimeter line center velocities.

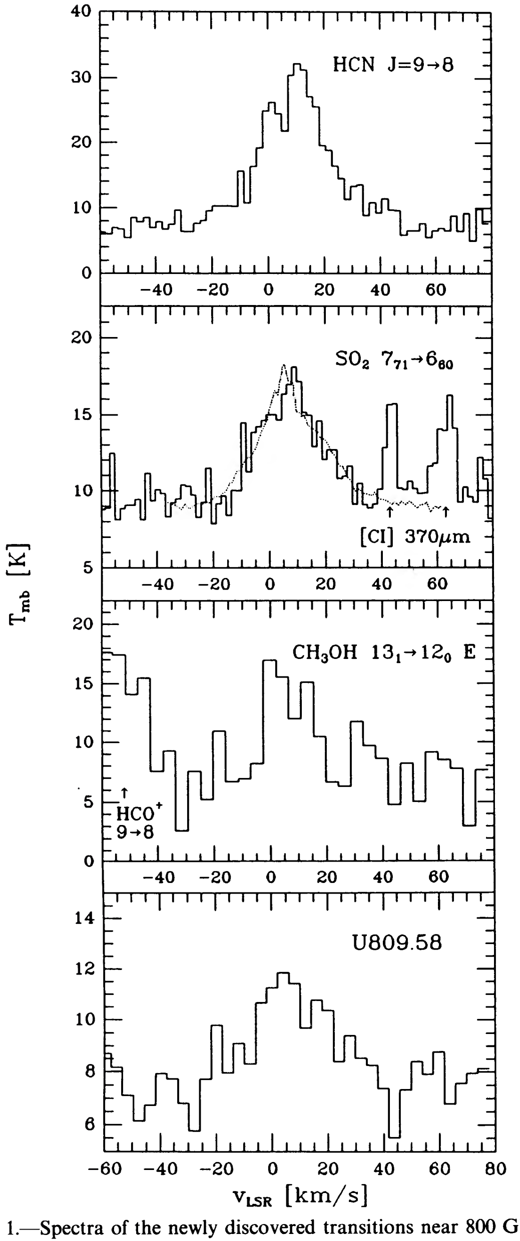

Fig. 1.—Spectra of the newly discovered transitions near 800 GHz in the Orion core toward IRc2. The HCN $J = 9 \rightarrow 8$ spectrum (Harris *et al.* 1989) is plotted for comparison in the uppermost panel. The SO_2 $7_{7,1} \rightarrow 6_{6,0}$ line has the $8_{1,7} \rightarrow 8_{0,8}$ profile superposed (*dotted line*; Schloerb *et al.* 1983). The [C I] 370 μm line from the other sideband appears twice in the spectrum due to the shifted observer's velocity relative to LSR in between two observing runs. The line visible to the low-velocity side of the CH_3OH line is the HCO^+ $J = 9 \rightarrow 8$ transition (Jaffe *et al.* 1989). The LSR-velocity scale for the unidentified line at 809.58 GHz assumes that the line has a center velocity of 7 km s^{-1}. The continuum offset in each spectrum is real; its level on a single-sideband scale is different in each case due to the variation of the correction for sideband imbalance in the atmospheric transmission with IF frequency.

transition has an Einstein *A*-coefficient of 1.37×10^{-3} s^{-1} and a critical density of a few times 10^8 cm^{-3} (assuming a typical collision rate coefficient of a few times 10^{-11} cm^3 s^{-1}). The methanol source in the Orion core is 5″ × 20″ in size (Plambeck and Wright 1988) implying an intrinsic peak brightness temperature of the $13_1 \rightarrow 12_0$ *E* line of 65 K after correcting for beam dilution. The Planck correction of about 18 K at 800 GHz thus gives a minimum excitation temperature of 85 K for the line.

If the $13_1 \rightarrow 12_0$ *E* transition is optically thin, its integrated intensity corresponds to a beam averaged CH_3OH column density of 7.8×10^{13} cm^{-2} in the 13_1 *E* state. This value fits well on the rotational excitation diagram for the observed CH_3OH transitions between 215 and 263 GHz (Sutton and Herbst 1988), which gives a rotational temperature of 146 K.

From the values quoted above, we calculate a source intrinsic optical depth of the $13_1 \rightarrow 12_0$ *E* transition of ≈ 0.5, implying that line trapping is not very important for the excitation. The density of the emitting gas can therefore not be substantially lower than the critical density of the transition, a few times 10^8 cm^{-3}. The CH_3OH $13_1 \rightarrow 12_0$ *E* transition most likely originates in the same gas as the millimeter-wave CH_3OH transitions, which are emitted from the compact ridge slightly west of IRc2 (Plambeck and Wright 1988). The width of the $13_1 \rightarrow 12_0$ *E* transition is 17 km s^{-1}, narrower than that of the other submillimeter lines, but slightly wider than the millimeter-wave transitions of CH_3OH.

b) SO_2 *Excitation*

The SO_2 $7_{7,1}$ state is 146 K above ground (Fig. 2*a*). The Einstein *A*-coefficient of the $7_{7,1} \rightarrow 6_{6,0}$ transition is 6.8×10^{-3} s^{-1}. Collision rate coefficients for SO_2 at 100 K kinetic temperature have been published by Palma (1987) for states up to $J = 5$. The $J_{J,1} \rightarrow J - 1_{J-1,0}$ (odd *J*) rate coefficients are all close to 9.5×10^{-12} cm^3 s^{-1}, essentially independent of *J*, and the related $J_{J-1,2} \rightarrow J - 1_{J-2,1}$ rate coefficients are similar. The same value for the $7_{7,1} \rightarrow 6_{6,0}$ rate coefficient results in a critical density of 7.2×10^8 cm^{-3}.

Assuming optically thin emission from all lines, the integrated intensities can be converted to upper state column densities (Fig. 3*a*). Although the points roughly follow a straight line corresponding to a rotational temperature of 110 K and a beam-averaged column density of 8.3×10^{16} cm^{-2} in a 30″ beam, the scatter is much larger than the error bars. Note especially the discrepancy between the points from the 3 mm observations (Schloerb *et al.* 1983) and those from the 1.3 mm OVRO molecular line survey (Sutton *et al.* 1985; Blake *et al.* 1986) around an upper state energy of about 100 K. Furthermore, the integrated intensity of the newly discovered 800 GHz line is a factor of 5 too low compared with the line survey data, although the observations were carried out with almost identical beam size.

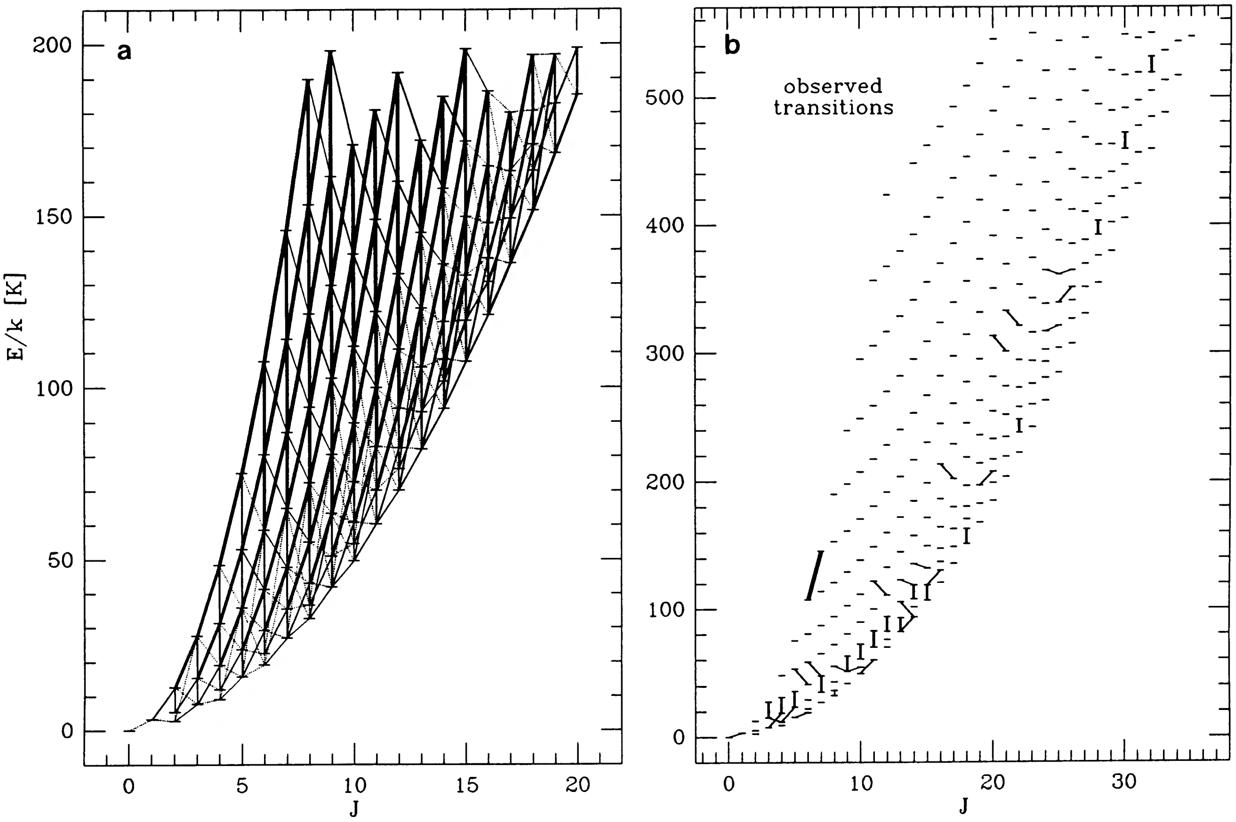

FIG. 2.—(*a*) The energy level diagram of SO_2. For each value of rotational quantum number J the values for K_a, K_c run from 0, J at the bottom to J, 0 at the top in the case of even J, and from 1, J at the bottom to J, 1 at the top in the case of odd J. All allowed transition with $\nu < 1$ THz are shown. Line thickness represents the A-coefficient on a logarithmic scale, where the heaviest lines have $A > 3 \times 10^{-3}\ s^{-1}$ and the dashed ones have $A < 1 \times 10^{-5}\ s^{-1}$. (*b*) SO_2 transitions observed by Schloerb *et al.* (1983) (*thin solid lines*; 69–91 GHz), Sutton *et al.* 1985 and Blake *et al.* 1986 (*medium thick lines*; 215–263 GHz), and the newly detected $7_{7,1} \rightarrow 6_{6,0}$ transition (*heavy line*).

Upper state column densities derived from lines with higher A-coefficients, and therefore higher optical depth, are systematically lower than those derived from lines with lower optical depth. The most extreme case is the newly discovered 800 GHz line with a beam-averaged optical depth of 0.6, derived from the column density and a rotational temperature of 110 K. The intrinsic optical depth will be substantially higher because of the beam dilution for the compact SO_2 source (Plambeck 1987). Much of the scatter in the rotation diagram is therefore due to optical depth effects (Schloerb *et al.* 1983), rather than to a nonuniform excitation temperature.

If the lines are optically thick, the upper state column densities derived in the optically thin approximation must be corrected up by a factor $G(\tau)$, where $G(\tau) = \int [1 - \exp(-\tau \times \phi(\nu)] d\nu / (\tau \times \Delta\nu)$. We applied this correction, calculating the beam-averaged optical depth for each line from the beam-averaged column density and rotational temperature, and then scaling this optical depth up by the reciprocal of an assumed source filling factor. The source filling factor was varied to obtain the best fit to a straight line in the rotation diagram. The procedure was iterated with a new guess of beam-averaged column density and rotational temperature until it converged. Figure 3*b* shows the result. The best-fit rotational temperature is 86 K, the beam-averaged column density is $6.8 \times 10^{16}\ cm^{-2}$, and the source filling factor for our 25″ beam is 0.08. The source intrinsic optical depth in the $7_{71} \rightarrow 6_{60}$ transition is about 10. The scatter in Figure 3*b* is much smaller than in Figure 3*a*, and the $^{32}SO_2$ rotational temperature now agrees with the best fit to the optically thin $^{34}SO_2$ lines ($T_{rot} = 85$ K), also plotted in Figure 3*b*.

The low source filling factor implies that the emission is very clumpy, both in velocity and spatial distribution. This is independently supported by the similarity of the observed line profiles from transitions that have very different upper state energies and optical depths, shown by the overlay in Figure 1.

The rotational temperature of 85 K is significantly lower than the kinetic temperature of the dynamically active gas in the Orion core (≥ 150 K). The uniform rotational temperature over many levels with different energies above ground and very different radiative lifetimes (see Fig. 2*b*) implies strong collisional coupling. The collisional transfer of population from levels with slower radiative decay rates, on the right-hand side in Figure 2*a*, to levels on the left-hand side, followed by rapid radiative decay, leads to subthermal population in all levels. A density around several 10^7–$10^8\ cm^{-3}$, slightly lower than the critical density of the fast radiative transitions, is necessary for this mechanism to work.

IV. CONCLUSIONS

Analysis of the newly discovered 800 GHz transitions of CH_3OH and SO_2 provides additional support for the very high densities in the Orion core recently derived from observations of HCN $J = 9 \rightarrow 8$ (Stutzki *et al.* 1988) and far-IR OH lines (Melnick, Genzel, and Lugten 1987).

Detection of these lines allows us to place limits on the line contribution to broad-band flux measurements. We estimate a

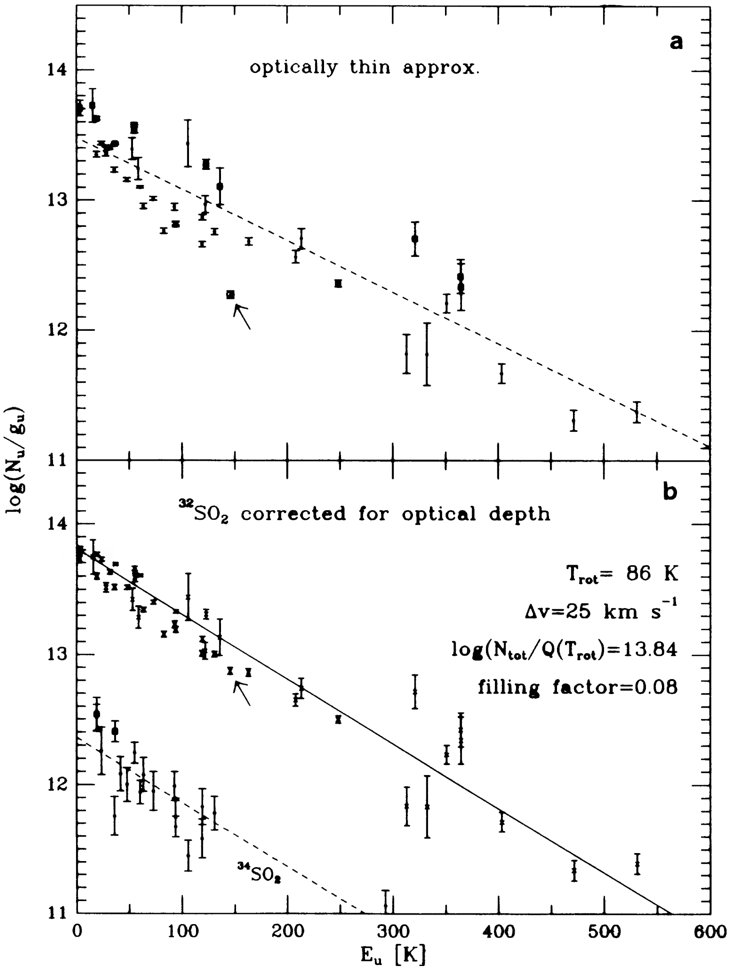

FIG. 3.—Rotation diagrams for SO_2: (*a*) Beam-averaged column densities in a 30″ (FWHM) beam vs. energy above ground state derived in the optically thin limit (*solid squares*: Schloerb *et al.* 1983; *dots*: Sutton *et al.* 1985 and Blake *et al.* 1986; *open circle* [highlighted by an arrow]: this *Letter*); (*b*) the same with the optical depth correction applied as described in the text. The column densities derived from the optically thin $^{34}SO_2$ lines are included in the lower left.

line-to-continuum flux ratio of about 22%, averaged over the about 6.4 GHz wide band covered by our present Orion observations near 800 GHz. This excludes the very bright and wide CO $J = 7 \rightarrow 6$ line which, by itself contributes an integrated flux about equal to the continuum in this band. One may argue that this proportion is too high because of the selection effect near strong lines which were searched for intentionally (HCN $9 \rightarrow 8$, HCO^+ $9 \rightarrow 8$). On the other hand, several other presumably strong lines have not yet been observed (e.g., the high-J lines of CS). Also, many more transitions of CH_3OH and SO_2, but also of SO and other molecules which are likely as strong as the ones reported here, are present in the 350 μm atmospheric window and larger numbers of weaker lines may be present as well. Extrapolating the deduced line-to-continuum flux ratio over the whole atmospheric window and adding the flux of the one, very strong CO line, we estimate an averaged line-to-continuum flux ratio for the whole 350 μm window of about 30%–40%, a value similar to the one estimated for the 1300 μm region (Sutton *et al.* 1984).

We thank the staffs of the IRTF and UKIRT for their excellent support during the observing runs.

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