SPECTRA OF THE 1_0-0_1 TRANSITION OF SULFUR MONOXIDE IN INTERSTELLAR CLOUDS

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Emission from SO towards a number of HII regions and molecular clouds with embedded energy sources has been reported by several authors (e.g., Gottlieb et al. 1978; Clark et al. 1978; Wannier and Phillips 1977; and references therein; cf. also Loren et al., 1974; Loren et al. 1975; Lada et al. 1974). Transitions observed include the $4_5 \rightarrow 4_4$, $4_3 \rightarrow 3_2$, $3_2 \rightarrow 2_1$, $2_3 \rightarrow 1_2$, $2_2 \rightarrow 1_1$, $1_2 \rightarrow 1_1$, and $1_0 \rightarrow 0_1$, with the latter (to the ground state) seen only in Sgr B2. Recently Rydbeck et al. (1980) have detected SO in cold, dark clouds and have made the first astronomical measurements of the $1_0 \rightarrow 0_1$ transition in a variety of sources, including the corresponding ^{34}SO line. The latter authors find that the $1_0 \rightarrow 0_1$ transition of SO is an excellent tracer of structure in dark clouds, and they discuss the fractional abundance [SO]/[H_2] on the basis of column densities derived from observations of the two isotopic species. They also set limits to the magnetic field strength in dark clouds from the absence of observed Zeeman splitting. We shall provide here additional spectra and information on observing procedures, and shall discuss the rest frequencies for the SO and ^{34}SO $1_0 \rightarrow 0_1$ transitions.

The observations were performed between December 1978 and March 1979 with the 20 m millimeter wave telescope of the Onsala Space Observatory equipped with a new traveling-wave maser preamplifier (Kollberg and Lewin 1976). The zenith system noise temperature varied in the range 90-150 K, and the beam-width is about 120". An autocorrelation spectrometer was used to achieve resolutions between 120 and 2.4 kHz, corresponding to 1.2 and 0.024 km s^{-1}. Antenna temperatures T_A^* have been corrected for atmospheric, radome, and antenna losses, using a radome transmission factor of 0.76 and a beam efficiency of 0.72. Observations were performed by position switching in the total power mode, the azimuth offset typically being one degree. The data were calibrated by the use of a noise tube. An absolute intensity scale was obtained from matched loads at ambient and liquid

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nitrogen temperatures. Rest frequencies employed were, for ^{32}SO: 30 001.523 ± 0.010 MHz as calculated on the basis of many observed transitions by Clark and DeLucia (1976); for ^{34}SO: the measured value 29 678.98 ± 0.10 MHz (Tiemann 1974), which was subsequently revised as listed below.

Because of the relatively small velocity dispersion present, observations of L 134 N (α,δ = $15^h51^m30^s$, $-2°44'0''$) may be used to refine the determination of rest frequencies and to resolve hyperfine structure for molecular species which have not been accurately observed in the laboratory (e.g., Rydbeck et al. 1974, for CH; Rydbeck et al. 1977, for NH_3; Snyder et al. 1977, for N_2H^+ and N_2D^+). The core velocity structure as determined by previous observations is probably best represented by NH_3 (Rydbeck et al. 1977), for which rest frequencies are very accurately known, hyperfine splitting is resolved, and core optical depths are small or moderate. According to a comparison of spectra for L 134 N and the other dust clouds with available molecular line data (Rydbeck et al. 1980), the predicted ^{32}SO frequency (Clark and DeLucia 1976) appears to be accurate to within 20 kHz. However, we had to shift the ^{34}SO rest frequency by about -108 kHz from the measured value quoted by Tiemann (1974) to bring it into agreement with NH_3, $C^{18}O$ and ^{32}SO data. The new rest frequency (217 kHz lower than Tiemann's calculated as opposed to his measured value) is $\nu(^3\Sigma;\ 1_0-0_1;\ ^{34}SO)$ = 29 678.872 ± 0.020 MHz. This value is also supported by observations of both SO species at a nearby position in the cloud ($15^h51^m38^s$, $-2°47'30''$) and in TMC-1 (Rydbeck et al. 1980, Fig. 3). As a matter of fact, a ^{34}SO rest frequency shift was expected from a comparison of the calculated (using laboratory data) and measured ^{32}SO rest frequencies given by Tiemann (1974), and the calculated frequency of Clark and DeLucia (1976). The latter authors were able to measure a number of weak transitions around 1 mm which are necessary for a direct calculation of the previously only indirectly estimated electronic spin-spin interaction constant of SO (in fact dominated by second-order spin-orbit coupling due to higher electronic states, which in the Hamiltonian formally contributes in the same fashion as spin-spin coupling); as a result the difference between the measured and calculated frequencies for the 1_0-0_1 transition of ^{32}SO changed sign, consistent with our result for ^{34}SO.

The degree to which SO can trace density and velocity structure in dark clouds is shown for TMC-1 in Figure 1. That the v = 5.8 km s^{-1} feature originates in the densest region of the source is confirmed by the corresponding emission from NH_3, HC_5N and HC_7N at this velocity (Rydbeck et al. 1977; Hjalmarson and Friberg 1979). In addition, as a relatively abundant species requiring intermediate densities for excitation, SO also shows features at $v \approx 5.0$ and 5.4 km s^{-1} which presumably arise in less dense regions and which are partially visible in H_2CO (Sume et al. 1975) and are absent for HC_5N and HC_7N. These SO "clouds" are all extended relative to our beam size, although their distributions are not identical. A more detailed mapping is obviously desirable, since it would contribute to our understanding of this interesting region. It should be borne in mind in this context that the rest frequencies of ^{32}SO and the linear carbon chains HC_nH are all uncertain by at least ~0.1 km s^{-1} at the frequencies of relevance here. Note also that the line-widths ($\lesssim$ 0.25 km s^{-1}) of the individual SO features imply very small internal velocity gradients (at 10 K the thermal line-width of SO would be 0.1 km s^{-1}). Winnewisser (1979) reports very narrow lines and considerable velocity structure in TMC-1, as delineated by Effelsberg NH_3 and HC_3N data.

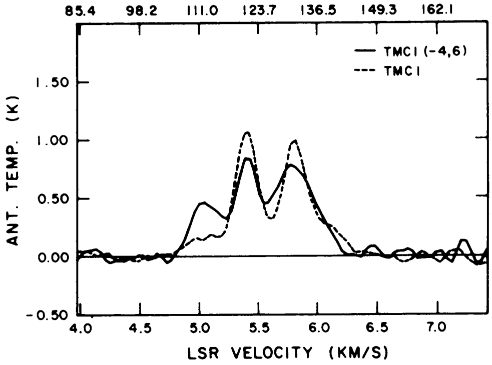

Fig. 1. Position-switched spectra of the 1_0-0_1 transition of ^{32}SO (rest frequency = 30,001.523 MHz) towards two positions in TMC-1 (Heiles Cloud 2). Antenna temperature corrected for radome, atmospheric, and antenna losses. Spectral resolution is 4 kHz = 0.04 km s^{-1}. Coordinates (α,δ) = ($04^h38^m20^s$, 25°41'45") for ____; ($04^h38^m38.6^s$, 25°36'18") for ---.

Figures 2 and 3 illustrate previously unpublished spectra for a number of dark clouds and molecular clouds (HII regions). Measured line parameters are tabulated in Rydbeck et al. (1980). Many of the features are asymmetric, indicating that the cloud velocity structure is not simple. Note also that the antenna temperature of the SO line towards the dark clouds is generally greater than towards the HII regions, either because of beam dilution or lower optical depths for the latter sources in the $1_0 \rightarrow 0_1$ transition.

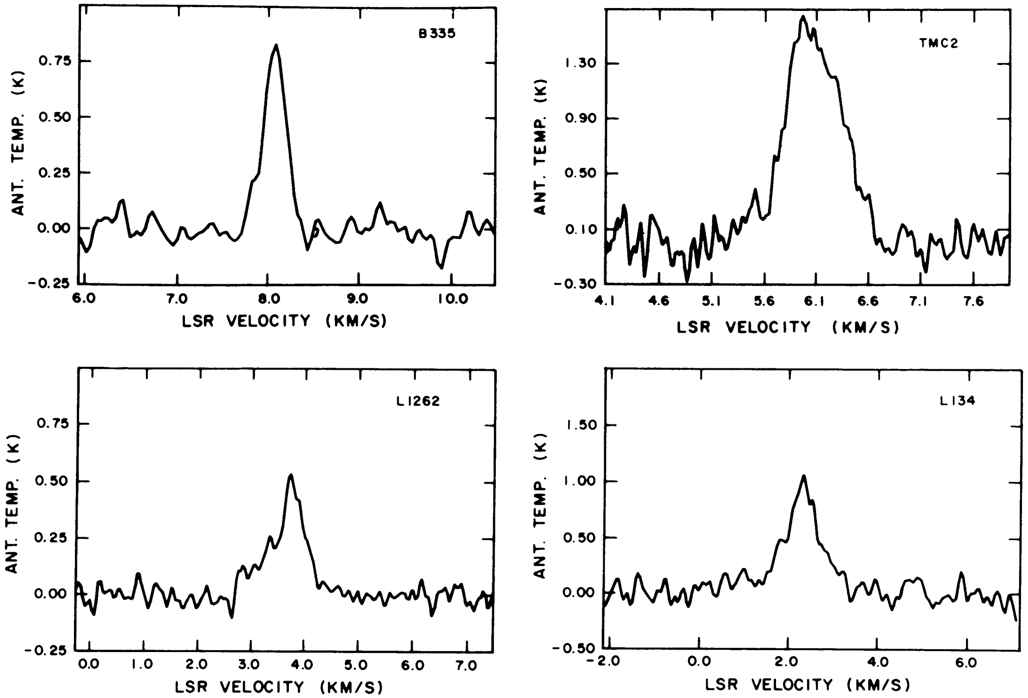

Fig. 2. SO(1_0-0_1) spectra towards several dark clouds. Note differences in scales for both ordinate and abscissa. Coordinates (α,δ) = ($19^h34^m34^s$, 07°27'00") for B335; ($04^h29^m43^s$, 24°18'15") for TMC-2; ($23^h24^m05^s$, 74°00'00") for L1262; ($15^h51^m00^s$, -04°26'57") for L134.

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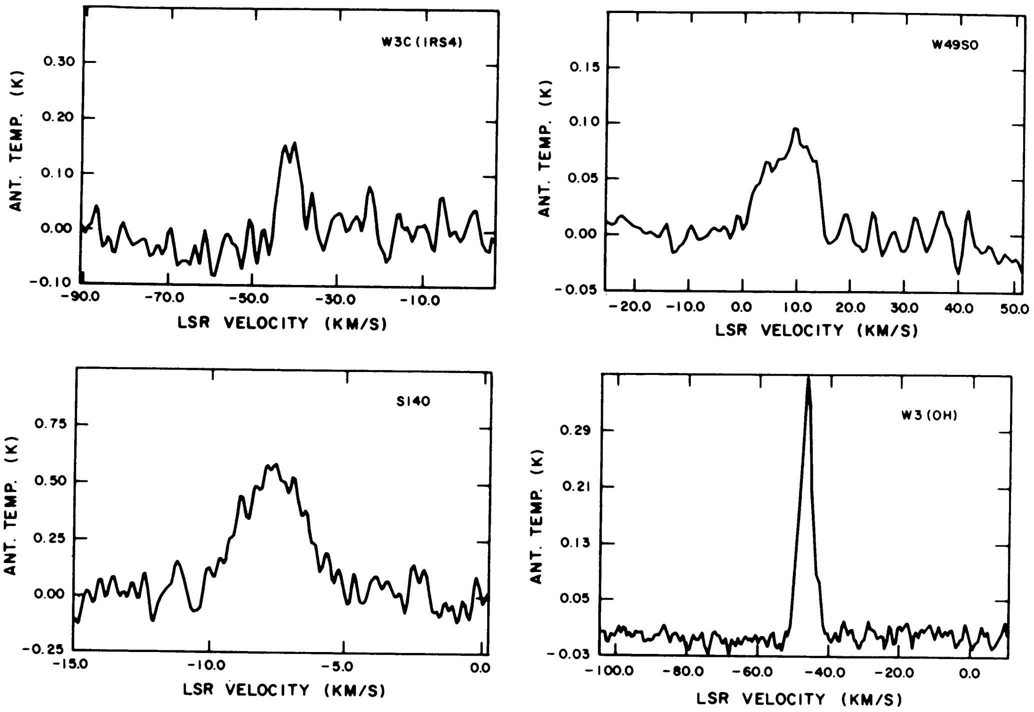

Fig. 3. SO(1_0-0_1) spectra towards several molecular clouds. Note differences in scales for both ordinate and abscissa. Coordinates (α,δ) = ($02^h21^m44^s$, 61°52'48") for W3C(IRS4); ($19^h07^m49.8^s$, 09°01'17") for W49SO; ($22^h17^m42.0^s$, 63°03'45") for S140; ($02^h23^m17^s$, 61°39'00") for W3(OH).

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DISCUSSION FOLLOWING IRVINE

Snyder: Were the different line components in the SO spectrum of Cloud 2 due to different velocities or to self-absorption?

Irvine: That is an important and a difficult question. From a comparison with published spectra for other molecular species, the simplest interpretation of the SO results does involve different velocity components rather than self-absorption. Because the individual features are so narrow, however, small uncertainties in rest frequencies for the different molecular species, or slight systematic errors in velocity determinations between different observatories, might change that interpretation. We hope to clarify the situation during the next observing season by mapping SO in Cloud 2, and by observing other molecules from both Onsala and other observatories in several clouds. We also hope to better define rest frequencies for the 1_0-0_1 transitions of SO and ^{34}SO.

Mouschovias: If the gas density in the clouds in which you searched for magnetic fields is $\sim 10^4$cm^{-3}, one expects from theoretical calculations that B$\simeq$200-300 μG. Could you have detected that field?

Irvine: Unfortunately not.

Kuiper: Nearly all the Orion "plateau" spectra are highly symmetrical. The 30 GHz SO line you observed† appears to have asymmetrical features. Are these real, or could they be attributed to baseline effects?

Irvine: Baseline effects are possible.

McCutcheon: You assumed a terrestrial value for (SO)/(^{34}SO) and derived $T_{ex} \sim 5$ K for L134N. If you assumed $T_{ex} \sim 10$-12 K (as for CO), would the derived ratio differ significantly from a terrestrial value?

Irvine: You would derive in that case an abundance ratio for the isotopes of about 10, instead of the terrestrial value of 22.5.

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†The figure referred to is not reproduced in the text but can be found in Rydbeck et al., 1980.