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UPPER LIMITS TO THE AMBIENT MAGNETIC FIELD IN SEVERAL DENSE MOLECULAR CLOUDS

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ABSTRACT

Observations of radiation from the interstellar SO molecule have been made at millimeter and centimeter wavelengths using switching circularly polarized receivers. Signals from the galactic sources Orion A (OMC 1), NGC 2264, Rho Oph, Sgr B2, and W51 were found to be unpolarized. Upper limits to the ambient magnetic field ranging from 5 to 140 milli-gauss are derived for the dense regions of these sources.

Subject headings: interstellar: magnetic fields — interstellar: molecules — polarization — Zeeman effect

I. INTRODUCTION

Spectral lines of the interstellar SO molecule, discovered by Gottlieb and Ball (1973), have an unusual shape in the Orion Molecular Cloud. In contrast to the combined plateau and spike features which characterize many other broad molecular lines in Orion (e.g., SO_2; Snyder *et al.* 1975), the SO lines display the single broad profile shown in Figure 1. SO is also distinct from the other molecules known in the Orion region in that it is both strongly paramagnetic and chemically stable. As a result, this molecule exhibits a pronounced Zeeman effect when exposed to large magnetic fields, and its chemical stability permits it to survive in the high-density regions of space where large magnetic fields may exist. Clark and Johnson (1974) explored the possibility that Zeeman broadening was responsible at least in part for the observed widths of SO lines. They concluded that fields in excess of 1 gauss were necessary for Zeeman broadening to contribute significantly to the SO line shapes in Orion. The effects of smaller magnetic fields would be masked by other (presumably kinematic) broadening processes. However, Clark and Johnson also point out that the presence of an ambient magnetic field will cause the radiation from SO to be polarized, whereas kinematic broadening processes will leave the radiation unpolarized. Current state-of-the-art techniques for observing circularly polarized radiation offer the potential for detection of magnetic fields

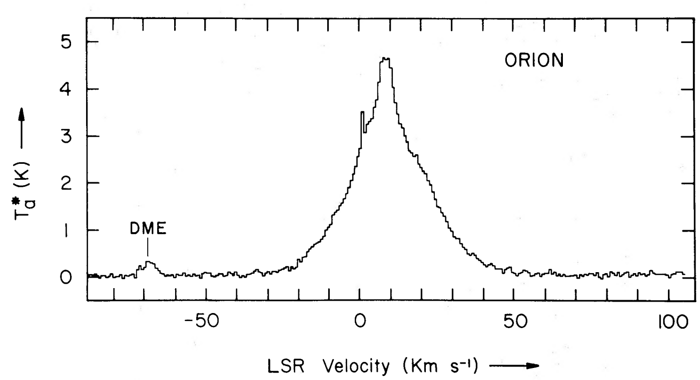

Fig. 1.—Position-switched spectrum of the $J_N = 3_2 \rightarrow 2_1$ millimeter transition of SO (99.3 GHz) in Orion. The ordinate is antenna temperature of an ideal antenna reduced to outside the Earth's atmosphere. The abscissa is velocity-reduced to the local standard of rest. Coordinates (1950.0) are $\alpha = 5^h32^m47^s.0$, $\delta = -5°24'21''$. The $4_{14} \rightarrow 3_{03}$ dimethyl ether line is marked DME.

perhaps two orders of magnitude below the limits obtained from line-shape data alone.

The present paper summarizes our efforts to detect polarized emission from the SO molecule in a variety of interstellar sources. Our first attempt was made in 1974 October using the NRAO[1] 11 m telescope with an uncooled 80–100 GHz mixer receiver and a quarter-wave plate mounted in a rectangular waveguide behind the feed horn. We failed to obtain reliable data during this early experiment due to difficulties with pointing and calibration which occurred when the polarimeter was switched between opposite senses of polarization. These technical problems have been overcome in a new rapidly switching polarimeter constructed by Payne and Howard of the NRAO. Using this new polarimeter, a search was made for circular polarization in the 99.3 GHz $J_N = 3_2 \rightarrow 2_1$ transition of SO, the transition exhibiting the largest Zeeman effect of any available in the millimeter-wavelength region. In a separate series of experiments the NRAO 45 m telescope was used to observe the $J_N = 1_2 \rightarrow 1_1$ transition of SO at 13.0 GHz in an attempt to resolve possible splittings in the SO spectra due to the Zeeman effect. Since the Zeeman effect is approximately frequency-independent, and the Doppler width of spectral lines is proportional to frequency, lower frequency spectral lines are more likely to exhibit resolved Zeeman splittings.

II. OBSERVATIONS

a) *Millimeter Data*

The NRAO 11 m telescope with the new cooled Cassegrain polarimeter receiver and 256 channel filters of 100 kHz, 250 kHz, and 500 kHz resolution was used to study the SO transition at 99.3 GHz during 1977 March. The sideband rejection filter was not used for the majority of the observations because of the possibility that it could interfere with the purity of the polarization.

A single polarization-switched observation consisted of one pair of spectra. The first spectrum of the pair was obtained by position-switching between the source and a nearby reference position. After integrating for 5 minutes, the sense of polarization was changed by rotating a quarter-wave plate located in front of the feed. A second spectrum was then obtained in orthogonal polarization with identical integration period. Before the integration for each spectrum was begun, the system gain was measured by inserting an absorbing disk in front of the polarizer. This was necessary because the system gains in the two polarizations were slightly different. No changes in any other parameters of the system were made between the pair of spectra. The difference between the two spectra provides the polarization-switched spectrum, while their average provides the standard position-switched spectrum. Thus a "polarization-switched spectrum" represents the difference between orthogonal polarization modes for a given source, while the "position-switched spectrum" represents the average of orthogonal polarizations.

The technique described above, although time-consuming, worked extremely well. The difference in system gain between the two polarizations, after their independent calibrations, was less than 1%. Baselines on both spectra were very flat, allowing the difference spectra to be used directly without baseline cosmetics. By contrast, an attempt to switch the sense of polarization rapidly, without independent calibration, produced polarization-switched spectra with unusable baselines which could not be minimized by subtracting an equivalent polarization-switched spectrum at a reference position.

Many of the SO sources originally observed by Gottlieb and Ball (1973) have recently been mapped by Gottlieb *et al.* (1978), who kindly provided us with data prior to publication. These data proved indispensable in determining the optimum sources and directions for position-switching. The list of observed sources is given in Table 1, with the spectra displayed in Figures 1–6. No circular polarization was detected in any of the sources studied.

A first-order perturbation treatment of the Zeeman splitting for SO, which is intermediate between Hund's coupling cases (*a*) and (*b*), was used to compute the sensitivity of a given transition to the ambient magnetic field (see Clark and Johnson 1974). The magnetic field limits cited in Table 1 were computed

[1] The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.

TABLE 1

SO Millimeter Polarization Results

Source	T_a^{max} (K)	ΔV (km s^{-1})	T_{rms} Pol. Sw. (K)*	Implied B Lim. (milligauss)
Orion	4.65 (0.05)	22 (1)	0.082	< 40
NGC 2264	1.5 (0.1)	3.6 (1)	0.195	< 95
ρ Oph	4.9 (0.3)	1.5 (0.3)	0.40	< 18
Sgr B2	3.4 (0.1)	13 (2)	0.2	< 140
W51	1.1 (0.1)	14 (1)	0.072	< 140

Note.—Errors estimated.

* Calculated rms value of the difference spectrum obtained by subtracting orthogonal polarizations.

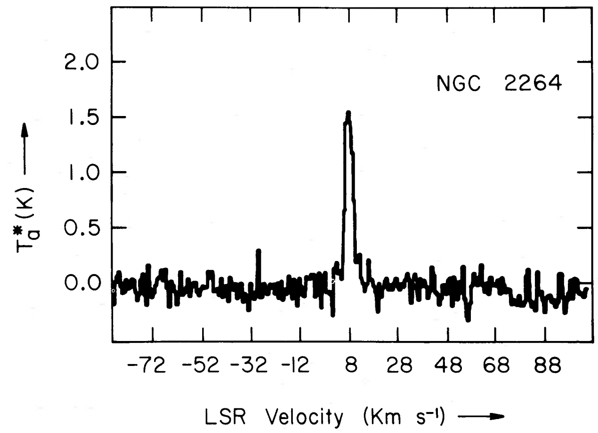

FIG. 2.—Position-switched spectrum for NGC 2264. Coordinates (1950.0) are $\alpha = 6^h38^m24^s.0$, $\delta = 9°32'06''$.

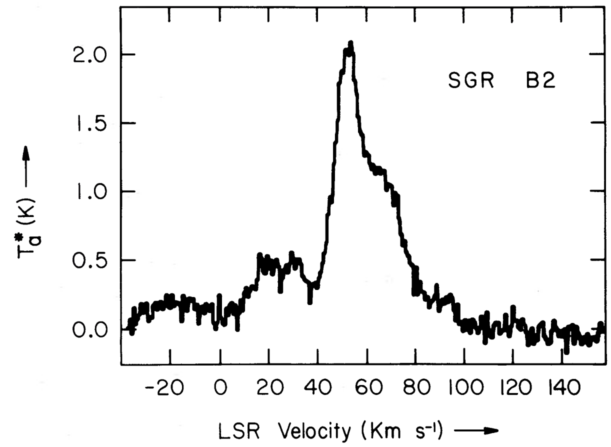

FIG. 4.—Position-switched spectrum for Sagittarius B2. Coordinates (1950.0) are $\alpha = 17^h44^m11^s.0$, $\delta = -28°22'30''$.

by a least-squares fitting procedure in which each polarization-switched spectrum was fitted to a function of the form

$$T^{\mathrm{pol}}(\nu) = 2 \sum_{i=1}^{5} g_i I_i \frac{dT^{\mathrm{pos}}(\nu)}{d\nu} B .$$

$T^{\mathrm{pol}}(\nu)$ is the polarization-switched line temperature, $T^{\mathrm{pos}}(\nu)$ is the position-switched line temperature, and ν is frequency. In the presence of a magnetic field, the 99.3 GHz SO line is split into five pairs of circularly polarized components. The effective Zeeman component for the line as a whole is given by the term

$$G = \sum_{i=1}^{5} g_i I_i ,$$

where g_i and I_i are the Zeeman coefficients and relative intensities, respectively, for a given pair of components. The values for these latter two parameters are taken from Table 2 of Clark and Johnson (1974). The values for g were calculated from

$$g = \frac{1}{2J(J+1)} \left\{ 1 \pm \frac{(2J+1)^2 - (\lambda/B)}{[(1-\lambda/B)^2 + 4J(J+1)]^{1/2}} \right\} ,$$

where $\lambda/B = +7.3528$. Each field limit given in Table 1 is the sum of the fitted field plus twice the standard deviation of the fitted field.

b) *Centimeter Data*

Centimeter data were obtained with the NRAO 45 m antenna using the 12.4–18 GHz tunnel-diode amplifier. Observations made in 1976 February were position-switched, with a nominal system temperature of 1200 K. Observations made during 1977 March were polarization-switched, with a nominal system temperature of 1000 K. All data were taken with a resolution of 52 kHz (1.2 km s^{-1}). Atmospheric opacity was observed to be strongly variable at 2 cm, and pointing and antenna gain were also noticeable

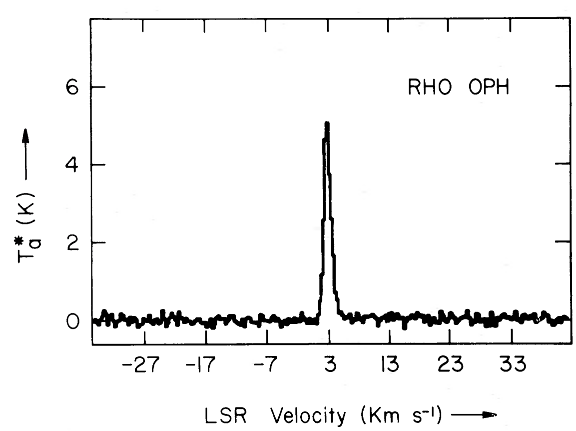

FIG. 3.—Position-switched spectrum for ρ Ophiuchi. Coordinates (1950.0) are $\alpha = 16^h23^m20^s.0$, $\delta = -24°16'20''$.

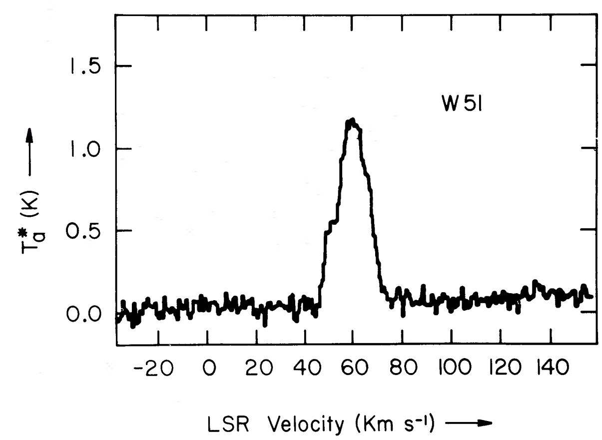

FIG. 5.—Position-switched spectrum for W51. Coordinates (1950.0) are $\alpha = 19^h21^m23^s.0$, $\delta = 14°24'29''$.

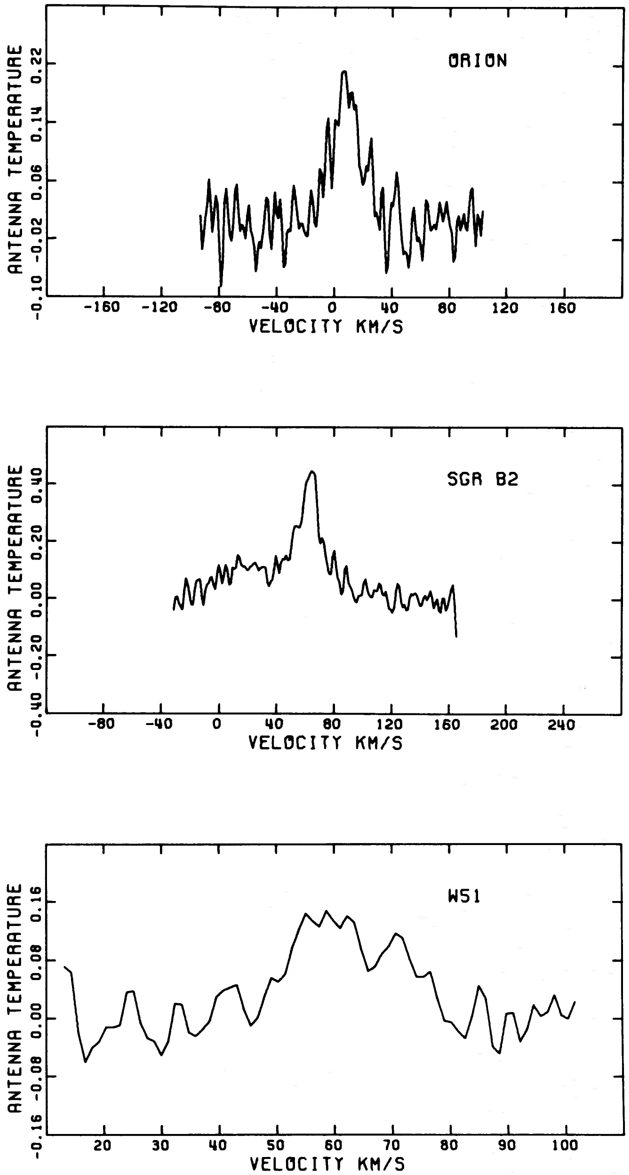

FIG. 6.—Position-switched spectra of the $J_N = 1_2 \rightarrow 1_1$ centimeter transition of SO (13 GHz). The ordinate is indicated antenna temperature. The abscissa is velocity reduced to the local standard of rest. Coordinates are the same as given previously.

problems. Thus quoted line temperatures are lower limits to the true values. Instrumental polarization was unmeasurable at the 5% level on H79α in Orion and M17. Table 2 lists positions observed and the results for these observations.

The maximum polarization limits in Table 2 are rms limits over the entire passband, while the line temperatures are peak values. The centimeter lines appear to be well represented by Gaussians, so a slightly different analysis from that previously described was applied. If the cloud is assumed to have an approximately constant magnetic field, then the Zeeman effect would produce two orthogonally polarized sets of Zeeman components displaced by a characteristic amount μ. The polarization can then be represented by the difference between the orthogonally polarized spectra divided by their sum, or:

$$\text{pol.} = \frac{e^{-1/2}[(\nu + \mu)/\sigma]^2 - e^{-1/2}[(\nu - \mu)/\sigma]^2}{e^{-1/2}[(\nu + \mu)/\sigma]^2 + e^{-1/2}[(\nu + \mu)/\sigma]^2} \times e^{-1/2}\left(\frac{\nu}{\sigma}\right)^2 ,$$

where it is assumed that the lines are Gaussian and the $e^{-1/2}(\nu/\sigma)^2$ takes the peak line temperature into account. Here ν is the frequency displacement from the Doppler-shifted, non–Zeeman-shifted line center, μ is frequency shift due to the Zeeman effect, and σ is the standard deviation of the line profile. This expression must be summed over all of the Zeeman components. The $J_N = 1_2 \rightarrow 1_1$ spectral line is split into two sets of two components. From this sum it can be shown that the maximum observable polarization will occur at approximately $\nu = \sigma$. When the previous expression is compared to the data, it yields a maximum magnetic field (assumed uniform) consistent with the observed polarization limits. These maximum values for B are shown in the last column of Table 2. This technique yields nearly identical values (within 10%) for the millimeter data, with the exception of Orion, where the observed lines have a markedly non-Gaussian profile. The assumption of Gaussian profiles for the millimeter Orion data yields a limit which is a factor of 2 greater than that shown in Table 1.

III. DISCUSSION

There is little astrophysical information that can be derived from the millimeter-wave position-switched spectra, since we have only a single SO line taken at one position for each source. Gottlieb *et al.* (1978) have presented detailed data and interpretation for many of these sources. A weak line is present in our Orion millimeter spectrum at 99326.0 (0.1) MHz (Fig. 1; sideband verified with rejection filter) which we have identified with the $4_{14} \rightarrow 3_{03}$ transition of dimethyl ether. The new dimethyl ether line is consistent with other lines for this molecule in Orion (Clark, Lovas, and Johnson 1979), and is apparently not present in the other sources displayed in Figures 2, 4, and 5.

The centimeter-wave position-switched spectra represent new observational data. The low center velocity of the Orion spectrum (Fig. 6 and Table 2) may be real (e.g., Clark *et al.* 1976) or it could reflect an uncertainty (+0.12 MHz) in the rest frequency (13043.7 ± 0.10 MHz; Tiemann 1974). Unfortunately, W51 and Sgr B2 are the only other detected sources, and their internal velocity structure is too complex to clearly differentiate these two possibilities. However, the velocity width of this line is in good agreement with the millimeter lines, indicating that the observed shape is the result of a kinematic broadening process.

TABLE 2

SO CENTIMETER POLARIZATION RESULTS

Source	T_a^{max} (K)	ΔV (km s^{-1})	V (km s^{-1})	T_{rms} Pol. Sw. (K)	Implied B Lim. (milligauss)
Orion.........	0.18 (0.06)	18 (1)	5.74 (0.5)	0.017	< 25
Sgr B2*.......	0.1 (0.04)	41 (5)	14 (10)	0.013	< 80
	0.13 (0.04)	17 (3)	50 (1)	0.013	< 25
	0.42 (0.04)	11 (3)	64 (1)	0.013	< 5
W51..........	0.15 (0.05)	12 (3)	58 (1)	...	...
	0.09 (0.05)	6 (3)	72 (1)	...	...

NOTE.—Errors estimated.

* Components indicated by residuals of least-squares Gaussian fits to data.

The Sagittarius B2 spectrum in Figure 6 shows complex structure. The residuals from a least-squares Gaussian fit to raw data indicate the features shown in Table 2. Our millimeter spectrum shown in Figure 2 also exhibits structure, but is different in detail. The 1976 February position-switched data indicate that the 49.6 km s^{-1} feature is probably more localized than the 64 km s^{-1} one. The W51 spectrum (Fig. 6), although very weak, appears to be reproducible and indicates the presence of the two well-known velocity features from this source.

IV. MAGNETIC FIELD LIMITS

Gottlieb (1978) has observed seven SO transitions in Orion. By calculating the radiative transition rates from data given by Tiemann (1974) and making an approximate correction for the molecule's own radiation field ("radiation trapping") based on Gottlieb's (1977) observed line intensities, we estimate that the H_2 volume density in Orion at the scale of these observations (1′) must be at least 2×10^5 cm^{-3} to provide the necessary collisional excitation rate.

It is often assumed that $B \propto n^x$, $x = \frac{2}{3}$ for an isotropic collapse. However, theoretical work (Mouschovias 1974, 1976) implies $\frac{1}{3} \leq x \leq \frac{1}{2}$, which is consistent with observational limits on magnetic fields placed by attempts to detect the Zeeman effect in various types of regions (Troland and Heiles 1977; Heiles 1976). If $x = \frac{1}{3}, \frac{1}{2}$, or $\frac{2}{3}$, a density of 2×10^5 cm^{-3} would imply a field of 0.18, 1.3, or 10 milligauss, respectively, if the field had increased in this manner from typical interstellar conditions (1 cm^{-3} and 3 microgauss). This value is smaller than our limits for Orion in Tables 1 and 2, so our negative results are not surprising. However, they do rule out the possibility that the SO line shape is affected by the magnetic field and provide a good upper limit to the field in quite dense regions. The broad width and peculiar shape of the Orion SO profile are not inconsistent with an appreciable fraction of the line emission coming from a complex core of the cloud. The kinematic extent of emission encompasses that of known maser spectra from this source. Therefore, the Orion results may apply to an even higher density region where the implied limits become more significant. Interpretation along these lines must, unfortunately, await a detailed understanding of the dynamics and excitation of SO in Orion.

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Note added in proof.—Unfortunately, a study of SO by Clark and De Lucia (1976 *J. Molec. Spectrosc.*, **60**, 332) was previously overlooked. Their Table 3 lists a calculated frequency of the $l_2 \rightarrow l_1$ transition at 13,043.832(0.008) MHz, which (as suggested in the text, § III) results in a centimeter center velocity of 8.8(0.5) km s^{-1} for Orion in excellent agreement with other lines for this source. All center velocities in Table 2 should therefore have 3.03 km s^{-1} added to them.