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THE MAGNETIC FIELD IN THE VICINITY OF S106

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ABSTRACT

Studies of the Zeeman effect in the 18 cm OH absorption lines toward the bipolar nebula S106 yield a line-of-sight field strength of 137 ± 17 μG. This field is probably associated with the inner regions of a flared disk of molecular gas surrounding the H II region. The field is strong enough to have important dynamical effects upon the molecular disk, including possible magnetic braking. The field strength is comparable to those envisioned in magnetic acceleration mechanisms for bipolar outflows.

Subject headings: interstellar: magnetic fields — interstellar: molecules — nebulae: H II regions — nebulae: individual (S106)

I. INTRODUCTION

As part of a long-term study of magnetic field strengths in molecular clouds, we have searched for the Zeeman effect in (nonmasing) 18 cm OH main lines. Here we report the strongest magnetic field detected to date in a molecular cloud outside OH maser regions (see, e.g., Lo *et al.* 1975). This result is of particular interest, since it pertains to an outflow region closely associated with recent massive star formation, the region surrounding the bipolar nebula S106. Other magnetic detections that have come from this Zeeman effect study are reported by Crutcher, Kazès, and Troland (1987) and in references therein.

II. OBSERVATIONS AND RESULTS

The Zeeman effect observations of S106 were obtained in 1986 July with the NRAO[1] 43 m telescope using the prime-focus dual-channel field effect transistor (FET) receiver sensitive to opposite senses of circular polarization. At 18 cm the telescope beam has a full width at half-power (FWHP) of 18′ and a cold-sky system temperature of about 25 K. The 1024 channel autocorrelator was split into four banks of 256 channels, each with a bandwidth of 156 kHz (28 km s^{-1}). In this way, both OH main lines and both senses of circular polarization could be observed simultaneously.

Techniques for detection of the OH Zeeman effect are discussed by Crutcher, Kazès, and Troland (1987). Essential for the purpose are the line spectrum toward the source (i.e., the Stokes parameter I spectrum) and the Stokes parameter V spectrum. The former was obtained by dividing the on-source spectrum by a separately observed off-source spectrum. We spent a total of 16 hr observing the S106 main lines, which appear in absorption against the S106 continuum. All observations were made at the position $\alpha(1950) = 20^h25^m33^s$, $\delta(1950) = 37°13'01''$.

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In Figures 1 and 2 we present the OH spectra for S106 at 1665 and 1667 MHz, respectively. Figures 1*a* and 2*a* are the absorption-line spectra (i.e., Stokes $I/2$ spectra). Figures 1*b* and 2*b* are the Stokes parameter V spectra. The signature of the Zeeman effect appears in the V spectrum as a scaled-down replica of the derivative of the I spectrum. The amplitude of this derivative spectrum (determined by a least-squares fitting process) is a direct measure of $B_{\rm los}$, the line-of-sight magnetic field strength in the OH absorbing region. For S106 these field strengths are 137 ± 23 and 138 ± 24 μG from the 1665 and 1667 MHz lines, respectively. In Figures 1*c* and 2*c* we present the derivative spectra, scaled to the least-squares fitted field strengths. Combination of the results at the two frequencies yields $B_{\rm los} = 137 \pm 17$ μG toward S106. The *total* field strength $B_{\rm tot}$ is $B_{\rm los} \sec\theta$, where θ is the angle between the line of sight and the direction of the magnetic field.

As a consistency check, we also observed the S106 OH Zeeman effect with the Nançay radio telescope. This instrument has a half-power beamwidth of 3.′5 in right ascension and 19′ in declination. Results at Nançay were consistent with those at NRAO.

A second possible indication of the Zeeman effect in the S106 region comes from the 1720 MHz maser line reported by Lucas *et al.* (1978). Centered close to 0 km s^{-1} (i.e., on the high-velocity edge of the absorption line), the maser lines of opposite circular polarization are comparable in strength but offset in frequency. Noting this effect, Lucas *et al.* (1978) estimated a line-of-sight field strength of 4.5×10^{-3} G, if the maser frequency offset is a result of the Zeeman effect. This estimate is uncertain because the spectral resolution of Lucas *et al.* was low, comparable to the width of the maser line itself (∼1 km s^{-1}). We reobserved the maser at NRAO with higher resolution (0.11 km s^{-1}), deriving a line-of-sight field of $(2.2 \pm 0.2) \times 10^{-3}$ G after 1.7 hr of integration time. No VLBI data exist to establish the exact position(s) of the 1720 MHz masers. Moreover, the maser is reported by Lucas *et al.* to be

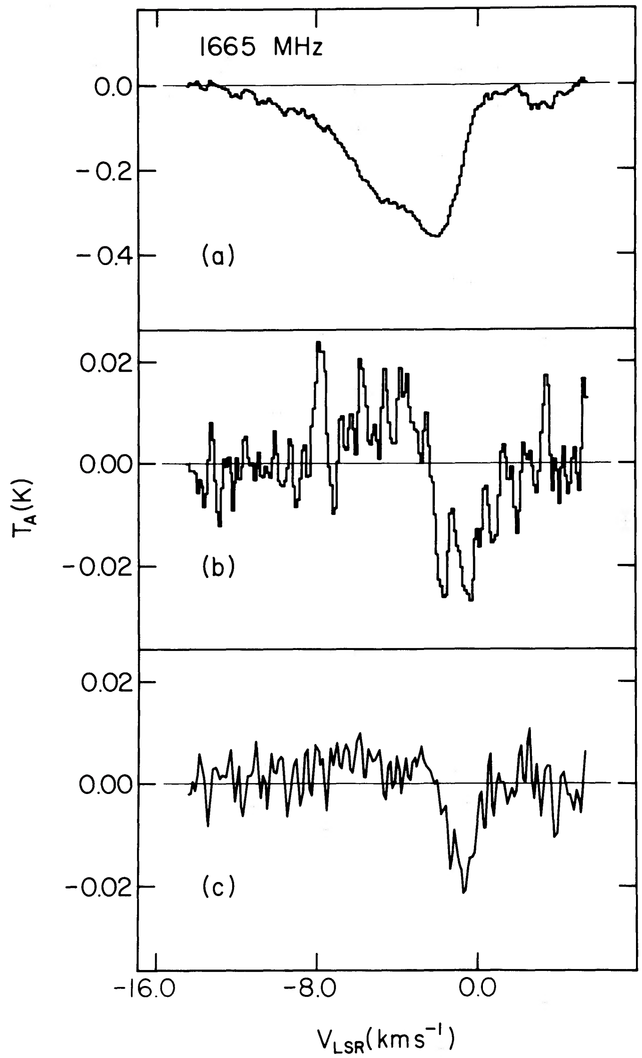

FIG. 1

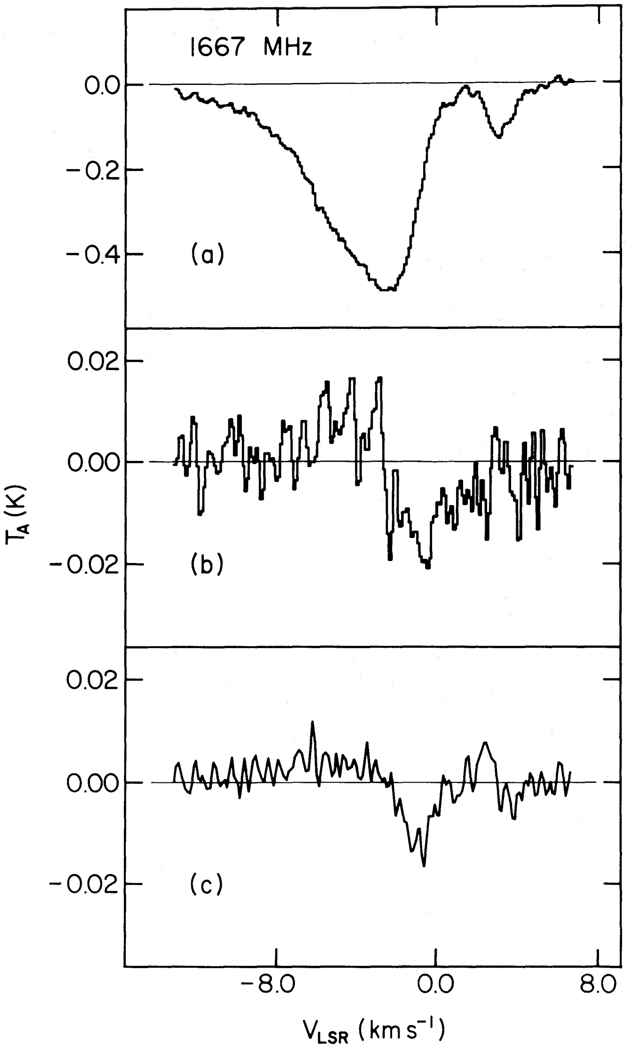

FIG. 2

FIG. 1.—1665 MHz OH spectra toward S106, including (*a*) the absorption-line spectrum, (*b*) the Stokes parameter *V* spectrum, and (*c*) the derivative of the absorption-line spectrum scaled for a field of 137 μG.

FIG. 2.—1667 MHz OH spectra toward S106; explanation as for Fig. 1

time-variable over periods of a few months to a few years. If they do exist near S106, milligauss fields may be restricted to relatively small regions.

During a separate observing run we also obtained spectra of the 5 cm $^2\Pi_{3/2}$, $J = 5/2$ OH main lines at 6031 and 6035 MHz. These spectra are presented in Figures 3*a* and 3*b*, respectively. They were also obtained on the NRAO 43 m telescope, which has FWHP of 5′ at this frequency.

III. THE S106 REGION

The S106 region consists of an H II region and associated molecular cloud. The distance to S106 has been estimated by Staude *et al.* (1982) as 600 ± 100 pc, a value we adopt here. Below we outline the major observational data concerning the S106 region, drawn from an extensive literature review on the subject.

a) Ionized Gas

S106 (also known as M1-99) is a prominent bipolar or biconical H II region (see, e.g., Calvet and Cohen 1978) about 2′ × 3′ in size with the two optically visible lobes separated by a dust lane. Within this lane lies the obscured star IRS 4 of spectral type B0–O7. IRS 4 is thought to be the single exciting source for the H II region (Gehrz *et al.* 1982). The star coincides with a weak, unresolved radio source having a spectral index 0.7, expected for an ionized stellar wind (Bally, Snell, and Predmore 1983). Studies of optical and near-IR emission lines from the nebula reveal a complex velocity field, with line widths as high as 200 km s^{-1} (Hippelein and Münch 1981; Solf and Carsenty 1982). The latter authors present a kinematic model of S106 in which a bipolar outflow exists in the ionized gas at a velocity of 75 km s^{-1}. In this model the axis of the outflow is inclined 16° to the plane of the sky, and the ionized gas is mostly confined to a thin layer along the periphery of the bipolar lobes.

b) Molecular Gas

The H II region is associated with molecular gas having structure on many size scales. The extended cloud has been mapped in CO by Lucas *et al.* (1978) with 2′ resolution. It is approximately 25′ × 25′ in extent and has a mass of about $1.5 \times 10^3\ M_\odot$. (Different authors have adopted different distances to S106; masses and volume densities quoted here have been adjusted as appropriate for our adopted distance of 600 pc.) Bally and Scoville (1982) mapped a somewhat smaller area in CO at 45″ resolution, distinguishing an outer (16′ × 16′) cold halo from an inner (8′ × 8′) warm halo of molecular gas. These authors estimate for the cold and warm halos, respectively, $N(H_2)$ of 0.5 and 2×10^{22} cm^{-2}, masses of 460 and 460 $M_\odot$, and $n(H_2)$ of 0.6 and 4×10^3 cm^{-3}. The ^{12}CO profile of Bally and Scoville toward the H II region center has broad wings extending from at least -8 to 8 km s^{-1}. On this basis S106 qualifies as an "intermediate-velocity" molecular outflow region in the list of Bally and Lada (1983). No evidence exists for *bipolar* molecular outflow. The S106 region may be an example of an evolutionary state beyond the molecular outflow stage, a state in which bipolar cavities previously created by neutral outflow have become filled with gas ionized by the massive emerging star (see, e.g., Bally 1986).

Nearly centered upon the H II region in the CO maps of Bally and Scoville, and nearly parallel to the dust lane that bisects the nebula, is a bar-shaped distribution of molecular gas about 6′ × 2′.5 in extent. At either end of the bar are peaks in the CO line strength. The molecular bar (including the peaks) appears also in the lines of CS (Bally and Scoville 1982), CN (Churchwell and Bieging 1982) and NH_3 (Little *et al.* 1979; Stutzki, Ungerechts, and Winnewisser 1982). Bally and Scoville estimate $N(H_2) \approx 2 \times 10^{22}$ cm^{-2}, $M \approx 140\ M_\odot$, and $n(H_2) \approx 3 \times 10^4$ cm^{-3} for the bar, values that are consistent with those implied by the data of other authors. The observations are consistent with the bar having the three-dimensional geometry of a torus. However, there is no evidence for a rotating torus, since the highest spatial resolution molecular line studies (Stutzki, Ungerechts, and Winnewisser 1982; Kaifu and Hayashi 1986) do not reveal a simple velocity gradient along the length of the bar.

On a still smaller scale, Bieging's (1984) aperture synthesis study of the HCN line has revealed a molecular "disk" 35″ in diameter and 7″ or less in width. The disk is parallel to the larger molecular bar described above and nearly coincident with the dust lane separating the two lobes of the H II region. Bieging's data suggest a velocity gradient across the disk consistent with rotation at a period of 2×10^5 yr. However, more recent synthesis maps of HCO^+ and CS lines from S106 show no evidence for a velocity gradient (Loushin, Crutcher, and Bieging 1988).

The existence of such a thin region of neutral gas possibly surrounding the central star had been inferred previously by Bally, Snell, and Predmore (1983) from their 5 GHz VLA continuum map of S106. This map reveals a very striking narrow (5″ wide) lane of greatly diminished continuum emission bisecting the two lobes of the H II region. Far-IR maps of dust emission also seem to reveal the presence of such a disk of material (Harvey, Lester, and Joy 1987; Mezger *et al.* 1987). The observed thinness of this disk is consistent with the small angle (16°) between the axis of the disk and the plane of the sky in the kinematic model of Solf and Carsenty (1982). Bieging estimates that $M \leq 2\ M_\odot$ and $n(H_2) \geq 3 \times 10^5$ cm^{-3} for the disk. Mezger *et al.* estimate that the mass and density of the disk are both about an order of magnitude greater, attributing the discrepancy to depletion of molecules in the disk via accretion onto grains.

The morphology of the combined disk and bar regions may be that of a flared disk—that is, a disk whose thickness increases with distance from the center (Harvey, Lester, and Joy 1987). In this model the thickness of the disk increases from about 5″ near the center to about 2′.5 at a radius of 3′, and the ionized lobes fill the inner volumes where the disk is very thin. In the discussion that follows, we adopt this flared-disk geometry.

c) Locale of OH *Absorption*

The 18 cm OH absorption spectra (Figs. 1 and 2) are highly asymmetric, with steep edges on the high-velocity sides (-2 to 0 km s^{-1}) and extended tails on the low-velocity sides out to at least -12 km s^{-1}. The ^{12}CO spectrum of Bally and Scoville (1982) in the direction of the center of S106 also has broad, weak wings (§ III*b* above), and the HCN spectrum of Bieging (1984) toward IRS 4 is nearly triangular in shape, extending from -20 to 20 km s^{-1}. Therefore, the asymmetry of the OH absorption spectra establishes that the wings of the millimeter-wavelength lines arise from outflow (rather than inflow) and that the outflow is occurring on either side of the H II region, as expected on other grounds.

Other indications of the locale of the absorbing OH gas come from the observed ratio of 1667 to 1665 MHz line strengths and also from the excited rotational state transitions (Fig. 3). The 1667 to 1665 MHz ratio of 1.3 is smaller than expected for thermally excited optically thin lines (i.e., 1.8). Therefore, the true optical depths at 1665 and 1667 MHz are 1.0 and 1.9, respectively, for thermal excitation. Since the observed (i.e., continuum-source–averaged) optical depths for these lines are at least a factor of 10 lower, the absorbing OH gas may occult only a small fraction of the continuum source. This circumstance suggests that the OH absorption arises close to the continuum source, a conclusion consistent with the excited rotational state line profiles. These profiles are similar in shape to the 18 cm profiles despite the fact that the 5 cm transitions lie 120 K above the ground state. From a comparison of the ratios of 1667 to 6035 MHz line strengths and also 1665 to 6031 MHz line strengths, we derive a rotational temperature of about 30 K. Therefore, the OH absorption certainly does not arise primarily in the outer, cooler regions of the S106 molecular cloud.

Bieging (1984) argues on both observational and dynamical grounds that the observed outflow is not expansion of the disk but ablation of disk material by the ionized gas flows. In this model, the weak negative-velocity wings in the OH profiles would most likely arise from ablating gas at the neutral/ionized gas interface. The steep edges of the profiles (-2 to 0 km s^{-1}), which are most sensitive to the Zeeman effect, would come from a more quiescent region located closer to the equatorial plane of the flared disk and farther from the neutral-ionized gas interface. Most likely, this OH absorbing region also lies toward the inner edge of the flared disk, where it occults only a small fraction of the continuum source.

IV. MAGNETIC EFFECTS IN THE S106 REGION

a) Magnetic Acceleration of Bipolar Flows

S106 is now the second molecular outflow region within which a magnetic field has been detected. (The other is S88B, for which $B = 69 \pm 5\ \mu$G; Crutcher, Kazès, and Troland 1987.) Detection of such fields is of interest because theoretical and observational results suggest a possible connection between the outflow phenomenon and the field. Uchida and

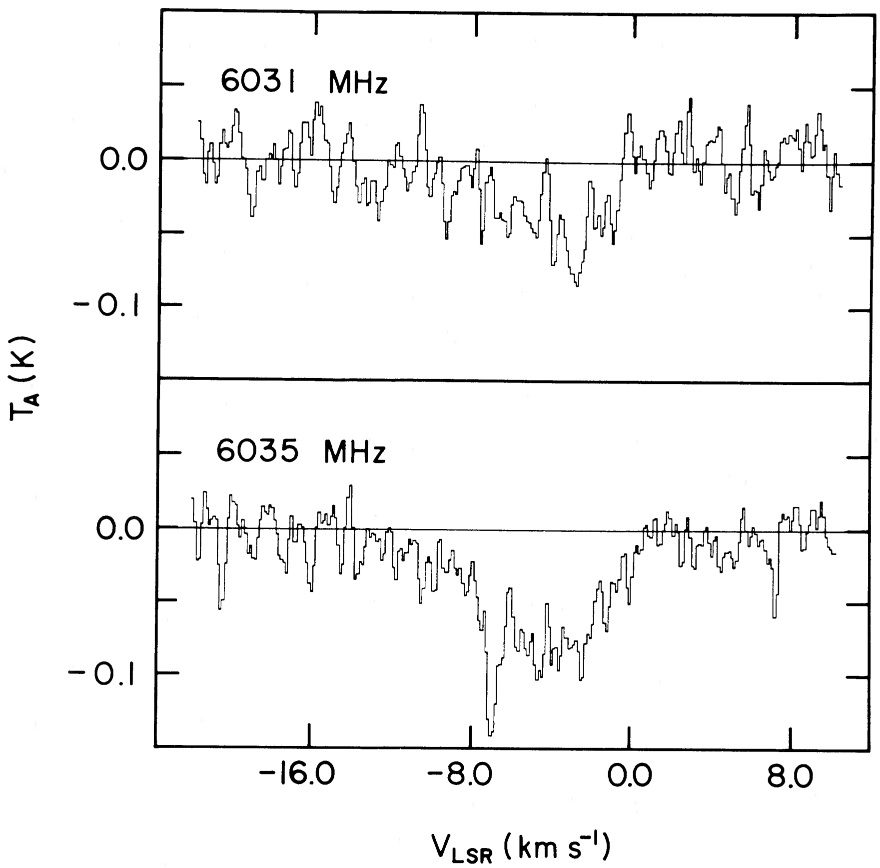

FIG. 3.—Spectra of the $^2\Pi_{3/2}$, $J = 5/2$ OH transitions at 6031 MHz (*top*) and 6035 MHz (*bottom*). The sharp spike near -7 km s^{-1} in the 6035 MHz spectrum is an interference feature in the comparison band.

Shibata (1984, 1985) have suggested a mechanism for bipolar outflow in which magnetic field lines, twisted by the rotation of a disk, relax along the large-scale field pattern and screw material outward along the axis of the disk (see also Pudritz 1985). Uchida and Shibata take $n \approx 10^7$ cm^{-3} and $B \approx 300$ μG within the rotating disk. The inner part of the flared disk probably has conditions similar to these. However, severe drawbacks exist in such models which depend upon rotating disks to provide energy for the outflow process. These objections are discussed by Shu, Adams, and Lizano (1987).

b) *Optical and IR Polarization*

Independent of the exact nature of the outflow mechanism in S106 (and a number of nonmagnetic models have been suggested), there is striking observational evidence of an association between bipolar outflows and magnetic fields. This evidence has been assembled from the literature by Cohen, Rowland, and Blair (1984), who note that, for a majority of the 10 bipolar flow regions considered, the axis of the outflow (having arcminute scales) is closely aligned in position angle with optical polarization vectors for stars distributed over tens of arcminutes. However, S106 is not a good example of this phenomenon, since the angle between the axis of the bipolar flow in the H II region and the ambient magnetic field is 38°.

A second type of magnetic alignment has been considered by Dyck and Lonsdale (1979) for young stellar objects in general and by Staude *et al.* (1982) for S106 in particular. This is the alignment of the IR polarization vector for a young (optically obscured) stellar object with optical polarization vectors for nearby stars. Dyck and Lonsdale find a strong tendency for the alignment to be very close in a sample of 31 such objects; in the case of S106, the alignment is to within about 7°. Such alignment would be natural if both the optical and the IR polarization arose within the same foreground region of aligned interstellar grains and uniform field direction. However, Staude *et al.* point out that the magnitude of the IR polarization for IRS 4 is much too high for this to be the case; they argue that the IR polarization must arise mostly within the dust lane bisecting the bipolar H II region and that this polarization most likely occurs because of magnetically aligned dust within this region. If so, then the magnetic field in the dust lane is parallel to the ambient Galactic magnetic field.

c) *Virial Considerations*

A straightforward estimate of the dynamical importance of the field comes from the virial theorem. A general virial criterion has been given by Spitzer (1968) (see also Mouschovias 1983; Elmegreen 1978) as follows:

$$B \approx 5 \times 10^{-21} N_p \ (\mu\text{G}) ,$$

where N_p is the proton column density of a cloud.. A field of this strength is capable of stabilizing a cloud against gravitational collapse irrespective of external pressure. In the flared disk, where our field measurement is most likely applicable, $N_p = 2N(H_2) \approx 4 \times 10^{22}$ cm^{-2} (§ III*b*), so that a field of order

200 μG is capable of stabilizing the disk. On this basis, we conclude that the magnetic field in the vicinity of S106 is sufficiently strong to have an important dynamical influence on the molecular gas.

We have also estimated the values of various terms in the virial equation (see, e.g., Spitzer 1978) for conditions applicable to the flared disk. The only terms of significance are those associated with macroscopic motions of the gas, the magnetic field, and gravitation. Terms for thermal gas pressure, external pressure, and rotation of the bar (if any) are quite insignificant. Of the significant terms, those for macroscopic gas motions and the magnetic field are the largest; evidently, dynamics in the molecular bar are largely determined by these two phenomena.

d) Field Strength and Gas Density

Although relatively high, the field strength in the vicinity of S106 is consistent with theoretical expectations regarding the field strength–gas density relationship. Studies by Mouschovias and others (e.g., Mouschovias 1985 and references therein) suggest that field strengths should remain constant with increasing density until a contracting interstellar cloud has reached a high enough density for self-gravitation to become important. Mouschovias (1985) provides a convenient formula for estimating this (proton) density:

$$n_{p,0} = 1.4 \times 10^2 (B_{\rm bk})^{3/2} M^{-1/2}\ {\rm cm}^{-3}$$

where $B_{\rm bk}$ is the background field in μG and M is the cloud mass in solar masses. If $B_{\rm bk} \approx 5\ \mu$G (Troland and Heiles 1986) and $M \approx 1.5 \times 10^3\ M_\odot$ for the molecular cloud as a whole (§ III*b*), then the cloud should have become self-gravitating in the past once it had reached a density of about 40 cm^{-3}. Studies by several authors suggest that the field strength should rise as n^κ with $\kappa \leq \frac{1}{2}$ once self-gravitation becomes important (Mouschovias 1976*a*, *b*; Scott and Black 1980; Mestel and Paris 1984). Therefore, if $\kappa = \frac{1}{2}$ and the present (proton) density in the flared disk is 6×10^4 cm^{-3} (§ III*b*), then the predicted field in the flared disk is 200 μG, consistent with the Zeeman measured value. Using the same scaling law, the density in the 1720 MHz maser region should be $\sim 8 \times 10^6$ cm^{-3}, comparable to the density estimated by Mezger *et al.* (1987) for the thin, innermost part of the molecular disk. Such an extrapolation may not be valid, however, since ambipolar diffusion at high densities will likely reduce the effective value of κ and thereby increase the density expected in regions where the field is as strong as 2.2 mG. Theoretical studies of such OH maser regions suggest that densities are of order 10^6 cm^{-3} (M. Elitzur 1988, private communication).

e) Magnetic Braking in the Molecular Disk

Bieging (1984) noted that if the HCN velocity gradient he observed is an effect of rotation, then the angular momentum per unit mass in the inner disk is at least 3 orders of magnitude greater than in the central star. This circumstance suggests that an efficient process has transferred angular momentum from the protostar to the disk, and Bieging notes that the magnetic field could be responsible. Although the reality of the velocity gradient is in doubt (§ III*b*), an indication of the feasibility of this process comes from a comparison of the magnetic and rotational virial terms in the disk. Taking the disk parameters given by Bieging (i.e., mass, radius, thickness, and rotational period) and assuming a field strength of 300 μG, we find that the two virial terms are nearly equal. This equality implies that the field is indeed strong enough to be effective in magnetic braking. Mezger *et al.* (1987) derive an order of magnitude higher mass and density for this same region (§ III*b*). However, if B scales as $n^{1/2}$, then the ratio of magnetic to rotational virial terms remains the same, and the conclusion stated above remains valid.

V. CONCLUSIONS

S106 is one of the six warm molecular clouds with massive star formation in which we have detected magnetic fields via the OH Zeeman effect. The others are Orion B (Crutcher and Kazès 1983), Orion A (Troland, Crutcher, and Kazès 1986), W3 (possible detection, Kazès and Crutcher 1986), W40, and S88B (Crutcher, Kazès, and Troland 1987). The field strength in the molecular region surrounding S106 is strong enough to have important dynamical consequences in the region, and it is comparable to field strengths proposed for theoretical acceleration mechanisms driving bipolar flows. The field strength is also consistent with theoretical expectations regarding the relationship between the magnetic field and interstellar gas density, and the field in the molecular disk about the central object is likely to be effective in magnetic braking.

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