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CIRCULAR AND LINEAR POLARIZATION OF THE SiO MASERS IN VY CANIS MAJORIS

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ABSTRACT

The circular and linear polarization parameters of the SiO masers in VY CMa have been measured in the $v = 1$, $J = 2$–1 (86 GHz) and $v = 1$, $J = 1$–0 (43 GHz) transitions. The higher frequency is less circularly polarized than the lower frequency transition.

Subject headings: circumstellar matter — masers — polarization — stars: individual (VY Canis Majoris) — techniques: polarimetric

1. INTRODUCTION

Previously we have presented measurements of the circularly polarized component of the SiO $v = 1$, $J = 1$–0 maser transition (Barvainis, McIntosh, & Predmore 1987; McIntosh et al. 1988; McIntosh 1987). We have now measured the circular and linear polarization in both the $v = 1$, $J = 1$–0 and $v = 1$, $J = 2$–1 transitions in VY CMa and comparisons of the two transitions can be made.

Measurements of circular polarization are generally explained using the Zeeman effect and can be used to determine the magnitude of the longitudinal magnetic field (e.g., Troland & Heiles 1982). In order to produce measurable circular polarization, the Zeeman splitting must be comparable to the thermal line width. For SiO masers the thermal line width is approximately 1 km s^{-1}, and a Zeeman splitting of 0.1 km s^{-1} requires magnetic fields on the order of tens of gauss (Barvainis et al. 1987).

Since circularly polarized maser lines generally do not show pairs of left- and right-hand circularly polarized features, one of the Zeeman components is preferentially amplified. Several circular polarization filters resulting from velocity gradients and variations in other physical quantities have been suggested to account for the single-handed observations (Cook 1975; Deguchi & Watson 1986; Nedoluha & Watson 1990a).

According to the Zeeman effect the frequency splitting of the circularly polarized components is independent of the transition frequency. As the transition frequency increases the fractional splitting decreases and the observed signal is reduced. For an increase of a factor of 2 in the transition frequency, the observed signal should decrease by a factor of 2 (McIntosh 1987; McIntosh, Predmore, & Patel 1994). Therefore if similar physical environments exist for the material producing both observed maser transitions, the higher frequency transition should exhibit half the fractional circular polarization of the lower frequency transition.

Recently Nedoluha & Watson (1990b, 1993) have suggested a mechanism for producing circular polarization in masers through intensity dependent effects which are not easily related to the magnetic field. In this mechanism linearly polarized radiation passing through an anisotropic maser medium generates a circularly polarized component. A much smaller magnetic field is required compared to the Zeeman splitting theory. Although no predictions exist for the frequency dependence of circular polarization in this theory, it might be expected that as the linear polarization increases the circular polarization would also increase.

We have investigated the circular and linear polarization parameters of the SiO masers in VY CMa in different transitions to provide constraints on the theories of maser polarization and depolarization.

2. OBSERVATIONS, INSTRUMENTATION, AND DATA REDUCTION

The observations were made 1993 June 13–18 using the 13.7 m telescope of the Five College Radio Astronomy Observatory (FCRAO), New Salem, MA. Typical system temperatures were 500 K at 43 GHz and 700 K at 86 GHz. VY CMa and several other sources were observed during this time. Information on the other sources and further comparisons with existing theories will be presented in a future work (McIntosh et al. 1994).

The instrumentation and calibration for the linear polarization measurements have been described previously (Barvainis 1984; Barvainis & Predmore 1985; McIntosh 1987; McIntosh et al. 1988) and will not be presented here. The instrumentation and data acquisition techniques for the circular polarization measurements at 43 GHz were described briefly by Barvainis et al. (1987) and McIntosh (1987), but will be reviewed here. The same procedure was used at both 43 GHz and 86 GHz.

A computer controlled polarimeter was used to measure the flux density at specific polarization position angles and in left and right circular polarization. The polarimeter incorporated a half-wave plate to determine the linear polarization parameters and the combination of a half-wave plate and a quarter-wave plate, as discussed below, to determine the circular polarization parameters. These measurements were then combined to obtain the Stokes parameters, I, Q, U, and V. From the Stokes parameters the linearly polarized flux density and the circularly polarized flux density were calculated.

The circularly polarized flux density can be extracted from measurements of the Stokes I and V parameters, where the Stokes I parameter represents the total flux density. If $S(\theta)$ is the flux density measured at angle θ with respect to the vertical, and S_L and S_R are the flux densities measured in the left and right circular polarization, then

$$I = S(45°) + S(135°) = S_L + S_R \, . \qquad (1)$$

Since both linear and circular polarization measurements have been made, I has been determined by combining measurements made in perpendicular linear polarizations and in opposite circular polarizations.

Stokes V is the left minus right circularly polarized flux density

$$V = S_L - S_R \, . \qquad (2)$$

The measurement of V can be contaminated by an admixture of both I and any linear polarization that may exist in the source. The polarimeter and data acquisition techniques have been developed to remove these instrumental effects. The effect from I is determined from observations of Orion, a strong source that is assumed to be circularly unpolarized. When the circularly polarized flux density is measured, a much reduced replica of the I spectrum is produced. This reduced I spectrum is due to the differential coupling of the left and right circular polarizations to the telescope. The fraction of I present in the V spectrum was determined to be -0.0035 at 43 GHz and -0.0085 at 86 GHz. This fraction of I was then added to the V spectra to reduce the contamination from I to less than 0.1% of I. (One feature in the 43 GHz V spectrum of Orion could not be removed using this technique and may represent a circularly polarized component to the Orion maser. This feature covered a very small fraction of the Orion maser line.)

The second instrumental effect, from the linearly polarized flux density, is removed by using a half-wave plate and a quarter-wave plate in combination in the polarimeter (Predmore, McIntosh, & Barvainis 1994). The Stokes V measurement contains a component due to any linear polarization inherent in the source. When the half-wave plate is rotated by 45° this coupling of linear polarization into the circular polarization measurement is inverted so that the effect is canceled out when the set of spectra are averaged. In practice it is necessary to rotate the half-wave plate through four angles separated by 45° to remove the effects of the anisotropy of the half-wave plate. This procedure reduces the coupling from linear polarization to less than 1% of I_L at 43 GHz and less than 2% of I_L at 86 GHz.

Once the corrected V spectrum has been obtained it can be used to determine the circularly polarized flux density. The circularly polarized flux density uncorrected for the effects of noise, I_0, is

$$I_0 = \sqrt{V^2} \, . \qquad (3)$$

In order to correct for noise (Wardle & Kronberg 1974), the error in the circularly polarized flux density, ϵ_C, is determined from the rms noise levels in the I spectrum, σ_I, and the rms noise level in the V spectrum, σ_V, where ϵ_C is

$$\epsilon_C = \sqrt{\frac{I_0^2 \sigma_I^2}{I^2} + \sigma_V^2} \, . \qquad (4)$$

The value for the circularly polarized flux density corrected for the noise is

$$I_C = I_0 \sqrt{1 - \frac{\epsilon_C^2}{I_0^2}} \, . \qquad (5)$$

If ϵ_C is greater than I_0, the circularly polarized flux density is set to zero.

Through a similar procedure, using Stokes I, Q, and U as explained in the references cited above, the linearly polarized flux density, I_L, and the error in the linearly polarized flux density, ϵ_L, have been calculated. This procedure has been applied to every velocity channel in the spectra. The velocity channel width was 0.70 km s^{-1} at 43 GHz and 0.35 km s^{-1} at 86 GHz.

3. RESULTS

Figure 1 displays I, V, I_C, and I_L versus $v_{\rm LSR}$ for the two transitions observed. Notice the similarities in the V spectra of the two transitions in the $v_{\rm LSR}$ range of 20 to 24 km s^{-1}. From the plots of I, we see that the relative intensities of the two strong features in the $v_{\rm LSR}$ range 13 to 17 km s^{-1} and 20 to 24 km s^{-1} in the 43 and 86 GHz transitions are in the opposite sense. A comparison of the I_L plots shows the stronger of these features to be less linearly polarized in both transitions.

In Table 1, I_C, I_L, and the calculated errors have been summed over the velocity ranges listed and divided by the sum of I in the velocity range to produce the averaged fractional polarizations $\langle m_C \rangle$, $\langle m_L \rangle$, and the averaged fractional errors $\langle e_C \rangle$ and $\langle e_L \rangle$. Individual features with velocity ranges from 13 to 17 km s^{-1}, 20 to 24 km s^{-1}, 30.5 to 34.5 km s^{-1}, and the entire line profile, from 4 to 40 km s^{-1}, have been averaged.

Table 1 indicates that for all the features and the entire line profile the fractional circular polarization is always less than 5% and decreases in the higher frequency transition compared to the lower frequency transition. For the 20 to 24 km s^{-1} feature the ratio of $\langle m_C \rangle$ at 43 GHz to $\langle m_C \rangle$ at 86 GHz is a factor of 2 within the error. This ratio agrees with the ratio predicted from Zeeman theory. No other high signal-to-noise circularly polarized features exist in the 86 GHz data. The linearly polarized flux density is also low, less than 10%, and shows no consistent frequency dependence in this source—increasing with frequency in two features and decreasing with frequency in one feature and across the line.

4. CONCLUSIONS

The results indicate that the fractional circular polarization of the $v = 1$, $J = 1\text{–}0$ (43 GHz) transition is greater than the fractional circular polarization in the $v = 1$, $J = 2\text{–}1$ (86 GHz) transition for the SiO masers in VY CMa. One feature produces a fractional circular polarization ratio in agreement with the predictions of Zeeman splitting. A larger data set will be examined in a future publication (McIntosh et al. 1994).

If the Zeeman effect is responsible for producing the

TABLE 1

AVERAGED PERCENTAGE CIRCULAR AND LINEAR POLARIZATION OF THE SiO MASERS IN VY CANIS MAJORIS

Velocity Range (km s^{-1})	Transition	$\langle m_C \rangle$	$\langle e_C \rangle$	$\langle m_L \rangle$	$\langle e_L \rangle$
13 to 17	$J = 2\text{–}1$	<0.1%	0.2%	3.0%	0.3%
	$J = 1\text{–}0$	0.7	0.1	6.5	0.3
20 to 24	$J = 2\text{–}1$	0.8	0.2	7.3	0.3
	$J = 1\text{–}0$	1.8	0.1	3.7	0.3
30.5 to 34.5	$J = 2\text{–}1$	0.2	1.7	9.7	2.3
	$J = 1\text{–}0$	4.1	0.7	8.0	1.8
4 to 40	$J = 2\text{–}1$	0.4	0.6	4.0	0.8
	$J = 1\text{–}0$	1.7	0.3	5.1	0.7

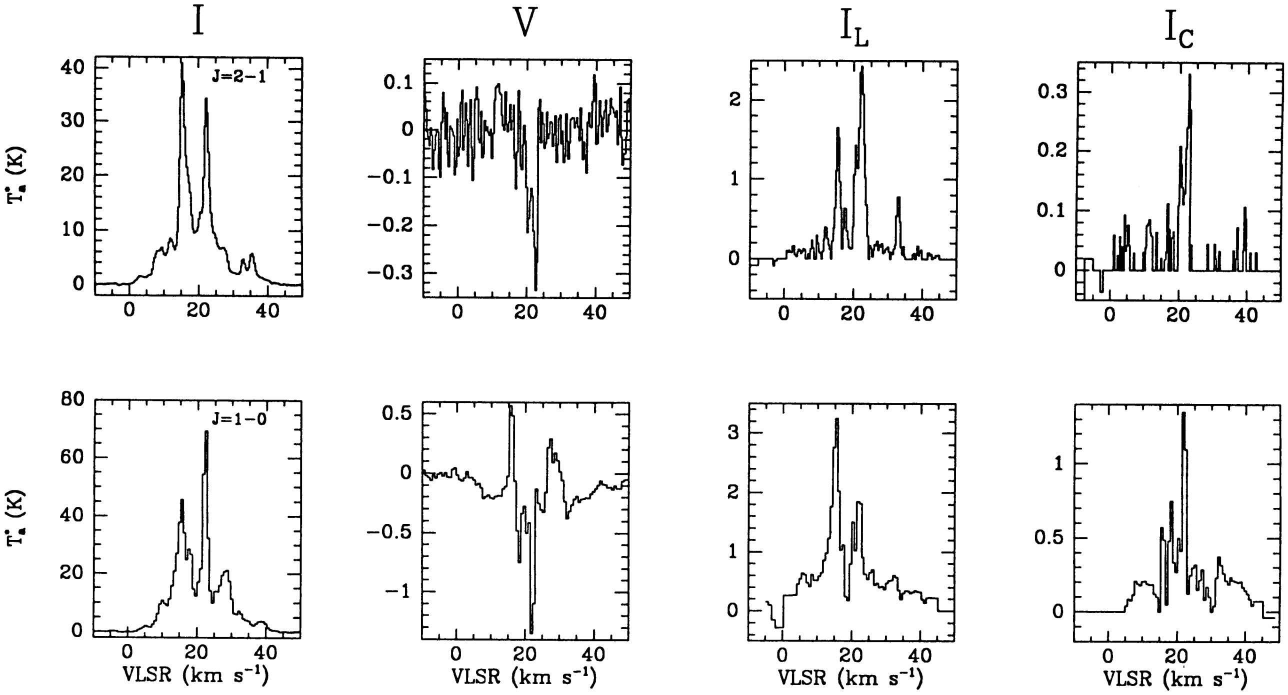

FIG. 1.—SiO ($v = 1$) maser observations of VY CMa during 1993 June. The antenna temperature vs. $v_{\rm LSR}$ is plotted for I, V, I_L, and I_C as indicated at the top of the columns. The data for the $J = 2$–1 transition are in the top row.

observed circular polarization, magnetic fields on the order of tens of gauss are required. Magnetic fields of tens of gauss existing in the circumstellar environment would dominate the dynamics of the circumstellar material in which the masers originate. Barvainis et al. (1987) calculated that the magnetic field energy density would exceed the thermal energy density of the gas by a factor of $\sim 10^6$.

There is support for the existence of magnetic fields of this magnitude in the circumstellar material. Such fields are in agreement with the extrapolations of magnetic fields derived from OH maser circular polarization measurements in other stellar sources (Reid et al. 1979; Chapman & Cohen 1986; Claussen & Fix 1982). Also measurements of the Zeeman splitting of optical lines by Babcock (1958) in several late-type stars indicated a surface magnetic field of several hundred gauss. Babcock listed R Leo, a long term variable SiO maser source, as a probable magnetic star, but did not present results for VY CMa.

Water masers polarization may present a problem for the Zeeman interpretation. Water masers also originate in the circumstellar regions of late type stars approximately four times as far from the stars as the SiO masers (Chapman & Cohen 1986). These water masers exhibit only very low linear and circular polarization (Barvainis & Deguchi 1989). Fiebig & Güsten (1989) reported observations of the circular polarization of water masers that indicated a magnetic field of less than 0.2 gauss for VY CMa using the Zeeman interpretation. The decrease in magnetic field with distance from the star is not known but it is reasonable to assume a power law dependence, with the magnetic field inversely proportional to the square or the cube of the distance (Barvainis et al. 1987; Reid 1989). At the distance of the water masers the magnetic field would be reduced by a factor of 20 to 60 and the results of the observations would not be inconsistent.

According to Elitzur (1993), the overlapping of hyperfine transitions in the water molecule may alter the magnetic sublevel populations and reduce the observed fractional polarization for water masers. Extensive calculation by Nedoluha & Watson (1992) contradict Elitzur's statement. Their work indicates that the interaction of the hyperfine transition affects the line shape of the water masers but has little effect on the value of the magnetic field extracted from the observations of circular polarization.

If the suggested mechanism of Nedoluha & Watson (1990b, 1993) is operating, the circular polarization is not directly related to the magnetic field. The difference in the circular polarizations of water and SiO is due to differences in saturation levels and fractional linear polarizations. In this limited data set, the fractional circular polarization shows no obvious dependence on nor relationship to the fractional linear polarization as might be expected in the theory of Nedoluha & Watson (1990b, 1993). A larger data set will be examined in a future publication (McIntosh et al. 1994).

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