ELECTRIC VECTOR ROTATIONS OF $\pi/2$ IN POLARIZED CIRCUMSTELLAR SiO MASER EMISSION

A. J. KEMBALL$^{1,4}$, P. J. DIAMOND$^2$, L. RICHTER$^3$, I. GONIDAKIS$^2$, AND R. XUE$^1$

$^1$ Department of Astronomy, University of Illinois at Urbana-Champaign, 1002 W. Green Street, Urbana, IL 61801, USA; akemball@illinois.edu
$^2$ CSIRO Astronomy and Space Science, Vimiera and Pembroke Roads, Marsfield, NSW 2122, Australia
$^3$ Department of Physics and Electronics, Rhodes University, P.O. Box 94, Grahamstown 6140, South Africa

Received 2011 June 5; accepted 2011 October 20; published 2011 November 22

ABSTRACT

This paper examines the detailed sub-milliarcsecond polarization properties of an individual SiO maser feature displaying a rotation in polarization electric vector position angle of approximately $\pi/2$ across the feature. Such rotations are a characteristic observational signature of circumstellar SiO masers detected toward a number of late-type, evolved stars. We employ a new calibration method for accurate circular very long baseline interferometric polarimetry at millimeter wavelengths to present the detailed Stokes $\{I, Q, U, V\}$ properties for this feature. We analyze the fractional linear and circular polarization as a function of projected angular distance across the extent of the feature and compare these measurements against several theoretical models proposed for sharp rotations of electric vector position angle in polarized SiO maser emission. We find that the rotation is most likely caused by the angle $\theta$ between the line of sight and a projected magnetic field crossing the critical Van Vleck angle for maser propagation. The fractional linear polarization profile $m_l(\theta)$ is well fitted by standard models for polarized maser transport, but we find less agreement for the fractional circular polarization profile $m_c(\theta)$.

Key words: masers – polarization – stars: individual (TX Cam) – stars: magnetic field

1. INTRODUCTION

Circumstellar SiO maser emission in commonly observed transitions, such as $v \in \{1, 2\}$, $J = 1-0$, or $v = 1$, $J = 2-1$, is ubiquitous toward large-amplitude, long-period variable (LALPV) stars (Habing 1996). The excitation conditions for these masers place them in the near-circumstellar environment (NCSE), between the stellar photosphere surface and the inner dust-formation radius (Elitzur 1980), but with the extent (NCSE), between the stellar photosphere surface and the inner dust-formation radius (Elitzur 1980), but with the extent of the latter separation dependent on stellar pulsation phase (Wittkowski et al. 2007). The maser emission is observed to be significantly linearly polarized (Troland, Herpin et al. 2006) but has a lower level of measured circular polarization (Barvainis et al. 1987; Herpin et al. 2006). The intrinsic high-brightness temperature and compact spatial structure of individual SiO maser components (Moran et al. 1979) make them valuable scientific probes of the astrophysics of the NCSE. Very long baseline interferometric (VLBI) polarimetry, in particular, allows the properties of the NCSE to be imaged at sub-milliarcsecond angular resolution by using the SiO maser components as tracers (Kemball 2002). Particularly important amongst the NCSE properties are the magnetic field magnitude and distribution, both at local and global stellar scales, and their associated dynamical influence in this environment.

Inference of magnetic field properties from the measured sub-milliarcsecond SiO maser polarization however requires the solution of an inverse problem involving the radiative transfer of SiO maser emission in full polarization.

There remain differences in theoretical models for the transport of polarized maser emission in the limit of small Zeeman splitting, as applicable to the non-paramagnetic SiO molecule (Elitzur 2002; Watson 2002). Both collisional (Elitzur 1980) and radiative (Bujarrabal & Nguyen-Q-Rieu 1981) mechanisms have also been proposed for SiO maser pumping. To complicate matters further, the physical conditions in the NCSE include complex phenomena such as shocks, anisotropic stellar illumina-
field inclined at an angle to the line of sight. Foundational work on polarized maser radiation transfer was undertaken by Goldreich et al. (1973). In general, the applicability of polarized maser transport solutions and their derivation is characterized by the relative magnitude of the maser stimulated emission rate \( R \), radiative decay rate \( \Gamma \), Zeeman rate \( g \Omega \), and bandwidth of the maser amplified radiation \( \Delta \omega \) (Goldreich et al. 1973). For the case of saturated linear masers isotropically pumped over quantum number \( m \), in the asymptotic limit \( \Delta \omega \gg g \Omega \gg R \gg \Gamma \), these authors derived a solution in which the measured EVPA will rotate by \( \pi/2 \) as the angle \( \theta \) between the magnetic field direction and the line of sight crosses the critical Van Vleck angle \( \theta_F \leq 55^\circ \), defined as \( \sin^2 \theta_F = 2/3 \) (Goldreich et al. 1973). This change in \( \theta \) can therefore be gradual but still result in an EVPA rotation of \( \pi/2 \). For \( \theta < \theta_F \) the measured polarization EVPA is parallel to the projected magnetic field direction, and perpendicular for \( \theta > \theta_F \) (Goldreich et al. 1973). Elitzur (2002) noted that a transition across \( \theta_F \) could be responsible for the reported \( \pi/2 \) rotations in EVPA across SiO maser features. We note that such an EVPA rotation has been detected in the polarized water maser emission toward W43A (Vlemmings & Diamond 2006).

A third theoretical explanation for significant EVPA rotation across SiO maser components has been presented by Soker (2002), as part of a larger analysis of the likely dynamical influence of magnetic fields in the evolution of late-type, evolved stars (Soker & Zoabi 2002). These authors do not support the model of a globally organized magnetic field that is active during asymptotic giant branch (AGB) evolution and acts dynamically to shape later planetary nebula geometry. However, their work does support cool spots on AGB stellar surfaces as sites of enhanced dust formation (Soker & Clayton 1999) with possible local magnetic fields of order 1–10 G (Soker 2002). The predicted local magnetic field geometry is radial above the cool spot, but tangential closer to the photosphere (Soker 2002). The NCSE is traversed by shocks caused by the pulsation of the central LALPV star (Bowen 1988). The contrast in magnetic field direction is expected to be enhanced by post-shock compression (Soker 2002). The intrinsic change in magnetic field orientation from tangential to radial over a short projected angular distance near a cool photosphere spot is accordingly proposed by Soker (2002) as the cause of EVPA changes of \( \pi/2 \) across individual SiO maser components.

In this paper, we utilize recent algorithmic developments that allow accurate circular polarization measurement in millimeter-wavelength spectral VLBI observations (Kemball & Richter 2011) to analyze the linear and circular polarimetric profile across an individual SiO component exhibiting an EVPA rotation of approximately \( \pi/2 \). We measure the fractional linear and circular polarization profiles across the feature, and assess them against the theoretical models discussed above. We find that the EVPA rotation is most likely caused by the angle \( \theta \) between the line of sight and a magnetic field crossing the critical angle \( \theta_F \) noted above.

The paper is organized as follows. The observations are described in Section 2 and their analysis and resulting science products presented in Section 3. The science results are discussed in Section 4, and conclusions presented in Section 5.

2. OBSERVATIONS

The current data are from a single epoch of a more extensive monitoring campaign using the Very Long Baseline Array (VLBA), operated by the NRAO, to image the \( v = 1 \), \( J = 1–0 \) circumstellar SiO maser emission toward the Mira variable, TX Cam. These observations were conducted at sub-milliarcsecond angular resolution and in full polarization Stokes \( I, Q, U, V \), over several pulsation periods of the central star. The larger survey has been published in total intensity by Diamond & Kemball (2003) and Gonidakis et al. (2010), and in linear polarization by Kemball et al. (2009).

The current epoch was observed under VLBA project code BD46AQ. The observations were scheduled on 1999 February 6 (MJD 51215), from 0 UT to 8 UT using all 10 VLBA antennas plus an additional single Very Large Array (VLA) antenna. A total of 6.5 hr were assigned to the 43 GHz observations, divided into on-source scans of 13 minute duration, and comprising the following total integration times: (1) seventeen scans on the target source, TX Cam; (2) seven scans on the continuum extragalactic calibrator J0359+509; and (3) one scan each on the continuum extragalactic calibrators 3C454.3 and J0609-157. The scans on TX Cam and J0359+509 were distributed as evenly as possible to maximize \( uv \) coverage. Approximately 86.7% of the elapsed schedule time was on-source, the remainder was allocated for antenna slewing, system initialization, or to balance the tape resources allocated at that time.

The \( v = 1 \), \( J = 1–0 \) SiO maser transition was observed in a 4 MHz baseband, and centered on a systemic LSR velocity of +9 km s\(^{-1}\) for TX Cam. The adopted rest frequency was 43.122027 GHz. No real-time Doppler tracking was employed about the mean Doppler shift computed for the mid-point of the schedule and the array; these corrections were applied in post-processing, consistent with standard spectral-line VLBI practice (Diamond 1989). The data were sampled in one-bit quantization and correlated in full polarization over a maximum possible 128 frequency channels available at that time, yielding a nominal channel width of 31.25 kHz. The correlator accumulation interval was 4.98 s.

3. RESULTS

The data were reduced using the method described by Kemball & Richter (2011) for accurate circular VLBI polarimetry at millimeter wavelengths. The primary science products resulting from the reduction are image cubes in each of Stokes \( I, Q, U, V \), at a pixel spacing of 50 \( \mu \)as (2048 \( \times \) 2048) on the image tangent plane, with one image per sampled frequency channel over the inner 113 frequency channels in the spectrum. A common restoring beam of size 540 \( \times \) 420 \( \mu \)as at a position angle of 20\(^\circ\) was adopted across all epochs of the larger survey, as described by Kemball et al. (2009). The absolute EVPA of the linearly polarized emission was established from associated VLA observations, relative to the primary polarization EVPA calibrator, 3C138, as described by Kemball et al. (2009). The residual error in the absolute EVPA determination is estimated to be \( \sim 10^\circ \)–20\(^\circ\) peak-to-peak (Kemball et al. 2009).

The zeroth moment over frequency of the full Stokes \( I \) image cube is shown in Figure 1. The counterpart Stokes \( V \) image is shown in Figure 2. The linearly polarized intensity \( P = \sqrt{Q^2 + U^2} \), derived directly from the zeroth-moment images in Stokes \( Q \) and \( U \), is depicted in Figure 3. In Figure 4, the Stokes \( I \) image is shown overlaid with vectors proportional...
Figure 1. Stokes $I$ contour image of the $v = 1$, $J = 1$–0 SiO maser emission toward TX Cam, plotted as the zeroth moment over frequency of the image cube. In these averaged units, the contour levels are at $\{-10, -5, 5, 10, 20, 40, 80, 160, 320\} \times \sigma$, where $\sigma$ is the off-source rms of 2.1982 mJy beam$^{-1}$. The angular coordinates are in mas from the center of the sub-image enclosing the projected SiO maser ring.

Figure 2. Stokes $V$ contour image of the $v = 1$, $J = 1$–0 SiO maser emission toward TX Cam, plotted as the zeroth moment over frequency of the image cube. In these averaged units, the contour levels are at $\{-160, -80, -40, -20, -10, -5, 5, 10, 20, 40, 80, 160\} \times \sigma$, where $\sigma$ is the off-source rms of 1.7113 mJy beam$^{-1}$. The angular coordinates are in mas from the center of the sub-image enclosing the projected SiO maser ring, aligned with Figure 1.

Figure 3. Stokes $P$ contour image of the $v = 1$, $J = 1$–0 SiO maser emission toward TX Cam, plotted as the zeroth moment over frequency of the image cube. In these averaged units, the contour levels are at $\{7.5, 15, 30, 60, 120, 240, 480\} \times \sigma$, where $\sigma$ is the off-source rms of 1.1954 mJy beam$^{-1}$. The angular coordinates are in mas from the center of the sub-image enclosing the projected SiO maser ring, aligned with Figure 1.

Figure 4. Stokes $I$ zeroth-moment image over frequency, plotted at the contour levels in Figure 1; the overlaid vectors are drawn with position angle equal to the absolute EVPA of the underlying zeroth-moment linearly polarized intensity $P$ and with length proportional to $P$ such that $P = 16$ mJy beam$^{-1}$ has length 1 mas.

rotation in EVPA across the feature. We note that the image cubes lack absolute astrometric coordinates due to the use of VLBI phase self-calibration. This component, near the southwest circumstellar boundary, is shown in Stokes $I$ and $P$ in Figure 5, averaged over frequency as in earlier figures. As noted earlier, it is not uncommon to find adjacent individual SiO

in length to $P$ and drawn at a position angle equal to the absolute EVPA of the linearly polarized emission.

This paper concerns a feature located near relative coordinates $(-15, -7.5)$ mas in Figure 4 that has an approximate $\pi/2$
components with large (or perpendicular) rotations in relative EVPA. In the current epoch, we choose this particular individual feature for further analysis because it spans a relatively large range in velocity and has good signal-to-noise ratio (S/N).

The individual frequency channel images across this feature, labeled by line-of-sight velocity (in km s\(^{-1}\)), are plotted in Stokes \(I\) and \(P\) in Figure 6, and in Stokes \(V\) in Figure 7.

In the absence of knowledge of the astrometric position of the central star relative to the SiO emission, we adopt the approximation that radially extended maser features point back to the photosphere, an assumption for SiO masers discussed by Zhang et al. (2011). The corresponding vector obtained by fitting a straight line to the projected coordinates of the peak Stokes \(I\) component brightness across the velocity extent of the \(\pi/2\) EVPA rotation feature is drawn as an arrow at the upper left panel in Figures 5–7, and annotated accordingly as the approximate assumed direction toward the photosphere.

The integrated mean-intensity spectrum, computed across the full image region in Figure 5 enclosing the \(\pi/2\) rotation feature, is plotted in Stokes \(I\), Stokes \(V\), and linearly polarized intensity \(P = \sqrt{Q^2 + U^2}\) in Figure 8.

4. DISCUSSION

The large-scale morphological properties of the \(v = 1, J = 1\)–0 SiO maser emission distribution at this epoch in Stokes \(I\) and \(P\) are consistent with the summary results for the broader monitoring campaign, as discussed by Diamond & Kemball (2003) and Kemball et al. (2009). The total intensity distribution, depicted as an average over frequency in Figure 1, shows the projected ring-like shell morphology frequently found for circumstellar SiO maser emission (Diamond et al. 1994). The corresponding linearly polarized intensity, shown in Figures 3 and 4, has the characteristic tangential distribution of EVPA found to be persistent across the broader monitoring campaign (Kemball et al. 2009). However, this tangential polarization morphology is not universal for circumstellar SiO masers as a class (Cotton et al. 2009).

The individual component studied in this paper is located at the projected shell boundary in the southwest region of the overall SiO maser distribution. As shown in Figure 5, there is a rotation of approximately \(\pi/2\) in EVPA across the component, with a tangential orientation on the inner shell boundary and a radial orientation at a larger projected angular distance from the central star (which lies toward the northeast in Figure 5).

The component is elongated in total intensity along the radial axis. This is consistent with tangential amplification of the underlying maser emission, as described by Diamond et al. (1994), and consistent with radial shock acceleration predicted in the circumstellar shells of LALPV stars (Humphreys et al. 2002; Gray et al. 2009). The total intensity contour images of each frequency channel across the feature (Figure 6) show that the projected center of the Stokes \(I\) emission moves inward toward the central star with decreasing LSR velocity, showing a radial velocity gradient at the position of this SiO maser component in this shell.

The linear polarization channel images shown in Figure 6 span the feature in velocity. They indicate an abrupt transition in EVPA of \(\pi/2\) near \(V_{LSR} \sim 6.2\) km s\(^{-1}\) and a corresponding local minimum in linearly polarized intensity near this point. The corresponding circular polarization channel images in Figure 7 show a sharp decline in peak Stokes \(V\) with decreasing LSR velocity, i.e., in the direction toward the inner projected shell boundary.

The fractional linear \((m_l)\) and circular \((m_c)\) polarization magnitude profiles across the feature are plotted in Figure 9, for all measurements with a S/N exceeding 3. The magnitudes of the fractional polarizations are measured at the single-pixel position of maximum Stokes \(I\) in each channel image. The \(x\)-ordinate in this plot is the projected angular separation \(\Delta (\text{mas})\) from the component peak in the channel image at \(V_{LSR} = 7.91\) km s\(^{-1}\) in the upper left panel of Figure 6. In this sense, the projected angular separation increases toward the central star—with decreasing \(V_{LSR}\) due to the radial velocity gradient discussed above.

The single-pixel measurements of \(m_l\) include the effects of spatial linear depolarization arising from convolution by the synthesized beam during image formation. The magnitude of this effect can be assessed for a given deconvolved source component size \(\sigma_m\), a synthesized geometric beamwidth \(\sigma_s\), and an adopted linear rate of change of EVPA \(\alpha = \dot{\chi}\) with angular spatial scale in the image. The angular sizes \(\sigma\) are expressed here as the full width at half-maximum (FWHM) intensity. The components in Figure 5 with the largest apparent values of \(\alpha\)
Figure 6. Stokes I channel images, labeled with LSR velocity (km s$^{-1}$), plotted at contour levels \{-12, -6, -3, 3, 6, 12, 24, 48, 96, 192, 384, 768\} \times \sigma$, where $\sigma = 15.7$ mJy beam$^{-1}$ is the off-source rms in an early frequency channel in this sequence. Overlaid linear polarization vectors are drawn as in Figure 5 but with scale such that $P = 1.05$ Jy beam$^{-1}$ has length 1 mas.
Figure 7. Stokes V channel images, matching Figure 6, plotted at contour levels \([-96, -48, -24, -12, -6, 3, 6, 12, 24, 48, 96]\) \(\times\) \(\sigma\), where \(\sigma = 15.7\) mJy beam\(^{-1}\).
are at $V_{LSR} = +6.18 \text{ km s}^{-1}$ and $V_{LSR} = +5.96 \text{ km s}^{-1}$. The mean deconvolved source component size across the minor axis (which is almost perpendicular to the EVPA) for these velocities is $\sigma_m \sim 1.2 \text{ mas}$. The geometric synthesized beamwidth for the current data is $\sigma_b \sim 0.48 \text{ mas}$ (see above). The linear beam depolarization arising in this case is approximately $m_i = \frac{\sin \Delta \theta B}{\sigma_b} m_1 = \beta m_1$, with $\alpha = \frac{\Delta \chi_2}{\Delta \chi_4}$. Adopting $\Delta \chi_2 = \pi/2$ and $\Delta \chi_4 = \pi/4$ produces $\beta = 0.94$ and $\beta = 0.98$, respectively, with values closer to unity for the other components in Figure 6, due to significantly lower apparent values of $\alpha$. Thus, for the single-pixel measurements of $m_i$ presented here, spatial beam depolarization is not believed to substantially affect the current analysis.

For the case of the single-channel fractional circular polarization measurements, $m_c$, it is similarly appropriate to consider the effect of depolarization arising from averaging over frequency. As noted earlier, the nominal channel increment in the data is 31.25 kHz; in uniform spectral weighting the effective FWHM spectral resolution is $\sigma_v \sim 0.26 \text{ km s}^{-1}$. The mean observed FWHM component line width in Stokes $I$ over the feature is $\sigma_{obs} \sim 0.9 \text{ km s}^{-1}$. To first order, for a classical Zeeman “S-curve,” the peak Stokes $V$ obeys the proportionality $V_{max} \propto \Delta \chi_2$, for a Zeeman splitting $\Delta \chi$ and component line width $\sigma$. Convolution by the instrumental frequency response therefore scales $V_{max}$ by a factor $\eta \sim \sqrt{\sigma_{obs}/\sigma_v}$. For the values of $\sigma_v$ and $\sigma_{obs}$ for the current data, $\eta \sim 0.96$, which does not significantly affect the results presented in the current work. This calculation is illustrative only however, as the Stokes $V$ component profiles do not take simple Zeeman form, as evident from the integrated spectrum plotted in Figure 8. However, we believe the calculation is nonetheless representative of the magnitude of the circular depolarization effect. We discuss the broader question of depolarization caused by line-of-sight integration below.

The asymptotic linear polarization solution for saturated, $m$-isotropic linear masers derived by Goldreich et al. (1973) for the case where $\Delta \omega \gg g \Omega \gg R \gg \Gamma$ predicts a fractional linear polarization dependence on the angle $\theta$ between the magnetic field and the line of sight taking the form (Goldreich et al. 1973)

$$m_i(\theta) = \frac{2-3 \sin^2 \theta}{3 \sin^2 \theta} \text{ for } \theta \geq \theta_B \quad m_i(\theta) = 1 \text{ for } \theta \leq \theta_B,$$

where $\tan^2 \theta_B = 1/2$. In this solution, the measured EVPA rotates by $\pi/2$ at $\theta_B$, where $\sin^2 \theta_F = 2/3$ (Goldreich et al. 1973). We denote this solution as GKK in what follows. We note that the GKK solution was derived specifically for a $J = 1-0$ transition, as applies to the transition observed here.

We model the fractional linear polarization data across the SiO maser feature by fitting the lowest-order polynomial form of $\theta(d)$ on the projected angular distance $d$ across the feature that yields a reasonable fit. For the current feature this is a quadratic fit:

$$\theta(d) = a(d^2 - d_f^2) + b(d - d_f) + \theta_F,$$

where $d_f = 2.822 \text{ mas}$ is the projected angular separation at which the EVPA rotates by $\pi/2$ in the measured data—here chosen to be the channel at $V_{LSR} = 6.18 \text{ km s}^{-1}$. The free parameters in the fit are $a$ and $b$. In Figure 9, we plot the best chi-square fit of the measured $m_i$ data to the GKK solution as a dashed line. The associated solution for $\theta(d)$ is plotted in Figure 10.

The fit to $m_i$ shows broad agreement with the functional form of the GKK solution. In this model, there is a gradual change in the angle $\theta$ between the line of sight and the projected magnetic field over the range 37:5 to 70° across the feature (with increasing $d$). The angle $\theta$ crosses the Van Vleck angle $\theta_F$ at $d = d_f$ near $V_{LSR} = +6.2 \text{ km s}^{-1}$. We note that for this feature the lower bound of 37:5 is consistent with the lack of a stable solution for $\theta < \theta_B$ predicted by Elitzur (1996).

If we assume that $m_i(\theta)$ originates from a GKK solution then we can derive the dependence of fractional circular polarization...
on $\theta$ by direct inversion of Equation (1) as

$$\cos \theta = \sqrt{1 - \frac{2}{3(m_l + 1)}}. \tag{3}$$

We plot the resulting dependence of measured fractional circular polarization on $\theta$ in the form $m_c(\cos \theta)$ in Figure 11. Here, the measured values of $m_l$ are used to compute $\cos \theta$ using Equation (3); the matching values of $m_c$ are then plotted against the derived $\cos \theta$ abscissa. The plot shows an increase of $m_c$ with $\cos \theta$ over a relatively narrow range of angles $\theta$ for which the projected magnetic field is closest to the line of sight.

We can assess the measured component-level polarization properties presented here relative to the different theoretical models that have been proposed to explain EVPA rotations of approximately $\pi/2$ across individual SiO maser features, described in the Introduction. However, there are important caveats that apply; we know this region has magnetic field and velocity gradients and is in a shock-traversal region; many theories were developed within more idealized conditions, by necessity. Furthermore, our observations are integrated over the synthesized angular beamwidth along lines of sight within this complex environment. We do not believe this affects substantially the primary conclusions of this paper however, but more complex three-dimensional modeling of this region is planned in future work.

The non-magnetic ($g \Omega = 0$) model of Asensio Ramos et al. (2005) explains the EVPA rotation as due to changes in radiative isotropy across the SiO maser feature. We believe that the current data do not provide support for this model. If the tangential linear polarization at the inner edge of the shell is predominantly caused by $m$-anisotropic pumping in a non-magnetic environment, then the measured circular polarization would have to arise from non-Zeeman effects (Watson 2009); in this case the inter-conversion of linear polarization to circular polarization is due to a change in optical axes along the propagation path. In a non-magnetic model, we might expect from first principles that non-Zeeman circular polarization would be found preferentially at positions with the greatest EVPA rotation rate; however the circular polarization is not pronounced at this position in our data. We also note that the greatest fractional linear polarization is measured in our data at the feature position that is furthest from the central star. Further, the relatively close agreement with the GKK functional form for $m_l(\theta)$ argues against a model of EVPA rotation due primarily to changes in radiation isotropy. For these reasons we believe that our data do not provide support for the EVPA rotation model described by Asensio Ramos et al. (2005).

In considering models with non-zero magnetic fields $g \Omega \neq 0$, we believe that contemporary observational evidence suggests that circumstellar SiO masers are in the regime $g \Omega \gg R \gg \Gamma$ or $g \Omega > R \gg \Gamma$ (Kemball et al. 2009). Evidence in support of the partial subsidiary condition $g \Omega > R$ is provided by Watson (2009). This condition excludes intensity-dependent non-Zeeman circular polarization that is possible if $g \Omega \sim R$ (Nedoluha & Watson 1994). The condition $g \Omega > R$ also ensures that the magnetic field is always either parallel or perpendicular to the measured EVPA (as in the GKK model presented above), but not necessarily at the same value of the Van Vleck angle $\theta_V$ (Watson 2009) or with the same functional form for $m_l(\theta)$.

Other sources of non-Zeeman circular polarization are possible for maser models with $g \Omega \neq 0$, due also to differences between the direction of maser linear polarization and the optical axes along the propagation path, in this case caused by changes in magnetic field direction or Faraday rotation (Wiebe & Watson 1998; Watson 2009). It is important to consider whether these sources of non-Zeeman circular polarization could explain our current observations. For this mechanism, we expect a correlation between fractional circular polarization and fractional linear polarization, and that the greatest circular polarization will occur at positions with the greatest rate of change of magnetic field direction (Watson 2009). Our current data are inconclusive on this point. There is a partial correlation between $m_l$ and $m_t$, and within the constraint $m_c < m_l^2/4$ put forward by Wiebe & Watson (1998) for this mechanism, but over too small a number of samples to allow a robust statistical conclusion from these data (see Figure 9 for reference). In contrast, the magnetic field angle gradient plotted in Figure 10 (derived from the GKK fit) is anti-correlated with $m_c$.

The linear polarization profile shown in Figure 9 can also be examined in terms of the information it provides on predicted maser saturation in different models of maser polarization propagation. The GKK solutions assume strong saturation...
\( R \gg \Gamma \). In the work of Elitzur (1996) a linear polarization solution of GKK form can be attained well before saturation; in contrast the models of Watson & Wyld (2001) require strong saturation in a uni-directional \( J = 1-0 \) maser to achieve the value of \( m_{\perp} \sim 0.7 \) reported here. However, we do note that the latter model assumes \( m \)-isotropic pumping. In light of these aggregate predictions, we believe our linear polarization profile is consistent with these masers being saturated.

This admits an interpretation in which our linear polarization data are explained as resulting from saturated maser emission \( R \gg \Gamma \) from a region threaded by a magnetic field that changes direction smoothly relative to the line of sight across the maser feature. The angle between the magnetic field and line of sight is approximately 37\(^\circ\) at the furthest point from the star, and approximately 70\(^\circ\) at the inner shell boundary of the feature. The relative orientation crosses the critical Van Vleck angle \( \theta_F \) within this region, causing an abrupt \( \pi/2 \) change in measured EVPA (Elitzur 2002). We know from earlier work (Kemball et al. 2009; Cotton et al. 2008) that individual maser motions appear to be influenced by individual magnetic field lines. There are also very plausible mechanisms for producing such field curvature, even if only local fields are considered such as those associated with proposed AGB cool spots, as noted earlier (Soker 2002).

Our measured circular polarization profile raises several theoretical issues. The GKK solution used earlier makes no prediction about circular polarization—it is identically zero at line center in their asymptotic solutions (Watson 2009). The foundational work of GKK has been generalized to a wider range of parameter space in subsequent studies however (Elitzur 1996; Watson & Wyld 2001), and we examine those predictions here.

The current data show a possible increase in \( m_{\perp} \) with \( \cos \theta \), perhaps of linear form, but with a sharper than expected falloff with increasing \( \theta \). These conclusions are tempered by the limited number of points however, and clearly further data are needed. A \( \cos \theta \) functional dependence occurs for thermal Zeeman emission, and for the case of widely separated Zeeman maser components (Goldreich et al. 1973). The work of Elitzur (1996) predicts a \( m_{\perp} \propto \cos^{-1}\theta \) dependence for the small Zeeman-splitting case. Watson & Wyld (2001) predict a circular polarization profile over \( \theta \) that changes in shape as a function of degree of saturation \( R/\Gamma \). A linear relation between \( m_{\perp} \) and \( \cos \theta \) is not predicted in this theory except for highly unsaturated emission; for increasing saturation \( m_{\perp} \) increases sharply toward a peak in the region \( \cos \theta \leq 0.5 \), then declines to zero as expected at \( \theta = \pi/2 \) (Watson & Wyld 2001). However, as noted earlier, this model is for \( m \)-isotropic pumping. Further observations are needed to elucidate the nature of the circular polarization profile.

5. CONCLUSIONS

We have examined an individual SiO maser feature that shows an EVPA rotation of approximately \( \pi/2 \) over the projected extent of the emission. From our analysis, we find the following.

1. The fractional linear polarization, as a function of the angle \( \theta \) between the line of sight and the magnetic field, reproduces the functional form of the maser polarization solution of GKK form. The fractional linear polarization, as a function of the angle \( \theta \) between the line of sight and the magnetic field, reproduces the functional form of the maser polarization

radiative transfer solution derived by Goldreich et al. (1973) for the case \( \Delta \omega \gg g\Omega \gg R \gg \Gamma \). A simple model is adopted for the relation between \( \theta \) and the projected angular separation across the feature.

2. The rotation in EVPA by approximately \( \pi/2 \) is explained within this model by \( \theta \) crossing the Van Vleck angle \( \theta_F \) near the mid-point of the component.

3. Further observations are needed to clarify the functional dependence of circular polarization on \( \cos \theta \).

We are grateful to our colleagues for their comments on earlier drafts of this paper. We also thank the journal referee for comments that improved the clarity and scientific content of the manuscript.

Facility: VLBA

REFERENCES

Asensio Ramos, A., Landi Degl’Innocenti, E., & Trujillo Bueno, J. 2005, ApJ, 625, 985

Barvainis, R., McIntosh, G., & Read Pendmore, C. 1987, Nature, 329, 613

Bower, G. H. 1988, ApJ, 329, 299

Bujarrabal, V., & Nguyen-Q-Rieu. 1981, A&A, 102, 65

Cotton, W. D., Perrin, G., & Lopez, B. 2008, A&A, 477, 853

Cotton, W. D., Ragland, S., Pluzhnik, E. A., et al. 2009, ApJS, 185, 574

Cotton, W. D., Vlemmings, W., Mennesson, B., et al. 2006, A&A, 456, 339

Desmurs, J. F., Bujarrabal, V., Colomer, F., & Alcolea, J. 2000, A&A, 360, 189

Diamond, P. J. 1989, in ASP Conf. Ser. 6, Synthesis Imaging in Radio Astronomy, ed. R. A. Perley, F. R. Schwab, & A. H. Briddle (San Francisco, CA: ASP), 379

Diamond, P. J., & Kemball, A. J. 2003, ApJ, 590, 1372

Diamond, P. J., Kemball, A. J., Junor, W., et al. 1994, ApJ, 430, L61

Elitzur, M. 1980, ApJ, 240, 553

Elitzur, M. 1996, ApJ, 457, 415

Elitzur, M. 2002, in IAU Symp. 206, Cosmic Masers: From Protostars to Blackholes, ed. V. Migenes & M. J. Reid (San Francisco, CA: ASP), 452

Goldreich, P., Keeley, D. A., & Kwan, J. Y. 1973, ApJ, 179, 111

Gonidakis, I., Diamond, P. J., & Kemball, A. J. 2010, MNRAS, 406, 395

Gray, M. D., Wittkowski, M., Scholz, M., et al. 2009, MNRAS, 394, 51

Habing, H. J. 1996, A&AR, 7, 97

Herpin, F., Baudry, A., Thum, C., Morris, D., & Wiesemeyer, H. 2006, A&A, 450, 667

Humphreys, E. M. L., Gray, M. D., Yates, J. A., et al. 2002, A&A, 386, 256

Kemball, A. J., Diamond, P. J., & Kemball, A. J. 2002, in IAU Symp. 206, Cosmic Masers: From Protostars to Blackholes, ed. V. Migenes & M. J. Reid (San Francisco, CA: ASP), 359

Kemball, A. J., & Diamond, P. J. 1997, ApJ, 481, L111

Kemball, A. J., Diamond, P. J., Gonidakis, I., et al. 2009, ApJ, 698, 1721

Kemball, A. J., & Richter, L. 2011, A&A, 533, A26

Moran, J. M., Ball, I. A., Predmore, C. R., et al. 1979, ApJ, 231, L67

Nedoluha, G. E., & Watson, W. D. 1994, ApJ, 423, 394

Soker, N. 2002, MNRAS, 336, 826

Soker, N., & Clayton, G. C. 1999, MNRAS, 307, 993

Soker, N., & Zoabi, E. 2002, MNRAS, 329, 204

Troland, T. H., Heiles, C., Johnson, D. R., & Clark, F. O. 1979, ApJ, 232, 143

Vlemmings, W. H. T., & Diamond, P. J. 2006, ApJ, 648, L59

Watson, W. D. 2002, in IAU Symp. 206, Cosmic Masers: From Protostars to Blackholes, ed. V. Migenes & M. J. Reid (San Francisco, CA: ASP), 359

Watson, W. D. 2009, RevMexAA, 36, 113

Watson, W. D., & Wyld, H. W. 2001, ApJ, 558, L55

Western, L. R., & Watson, W. D. 1983, ApJ, 275, 195

Wiebe, D. S., & Watson, W. D. 1998, ApJ, 503, L71

Wiebe, D. S., & Watson, W. D. 1998, ApJ, 503, L71

Wittkowski, M., Boboltz, D. A., Ohnaka, K., Driebe, T., & Scholz, M. 2007, A&A, 470, 191

Zhang, B., Reid, M. J., Menten, K. M., & Zheng, X. W. 2011, ApJ, in press (arXiv:1109.3036)