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DOI:
10.1017/S1743921317011486

Citation for published version (APA):

Published in:
Proceedings of the International Astronomical Union

Citing this paper
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Constraining Theories of SiO Maser Polarization: Analysis of a $\pi/2$ EVPA Change

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Abstract. The full theory of polarized SiO maser emission from the near-circumstellar environment of Asymptotic Giant Branch stars has been the subject of debate, with theories ranging from classical Zeeman origins in the presence of a magnetic field (eg. Goldreich et al. 1973; hereafter GKK) to predominantly anisotropic propagation effects (Asensio Ramos et al. 2005). Features with an internal electric vector position angle (EVPA) rotation of $\sim \pi/2$ offer unique constraints on theoretical models. In this work, results are presented for one such feature that persisted across five epochs of SiO $\nu = 1, J = 1 - 0$ VLBA observations of TX Cam. We examine the fit to the predicted dependence of linear-polarization and EVPA on angle ($\theta$) between the line of sight and the magnetic field against the GKK and other models. We also present results on the dependence of $m_c$ on $\theta$ and their theoretical implications. Finally, we discuss the applicability of our data to other theories, potential causes of the observed differences, and upcoming work.

Keywords. Keyword1, keyword2, keyword3, etc.

1. Introduction

Although many theories have endeavored to explain the polarization of SiO masers originating from the near circumstellar environments (NCSE) of Asymptotic Giant Branch (AGB) stars, no consensus has yet been reached. Prominent theories as to the polarization of SiO $\nu = 1, J = 1 - 0$ masers ascribe polarization to the local magnetic field (Goldreich et al. 1973, Elitzur 1996) or a change in the anisotropy conditions (Asensio Ramos et al. 2005).

However, these theories differ in their ability to explain rotations of the linear polarization angle by $\sim \pi/2$ within a single maser feature. In some theories, like Goldreich et al. (1973) (hereafter GKK), the EVPA is governed by the angle of the projected magnetic field on the sky and the angle, $\theta$, between the line of sight and the local magnetic field. When $\theta$ is small, the linear polarization would appear to be parallel to the projected magnetic field. However, when $\theta$ becomes larger than the Van Vleck angle ($\sim 55^\circ$), the polarization would be perpendicular to the projected magnetic field. In this case, a rotation of the electric vector position angle (EVPA) across the feature would be due to a slight variation in the direction of the magnetic field within the spatial extent of the masing material, spanning the Van Vleck angle.

This rotation could also be due to a change in the direction of the projected magnetic field across the spatial extent of the maser feature. In this case, the EVPA would again be defined by the direction of the projected magnetic field in the sky. However, the only
Figure 1. Target maser feature in epoch BD46AO. Contours denote frequency-averaged Stokes I with levels of \{-10, -5, 5, 10, 20, 40, 80, 160, 320\} \times \sigma, where \(\sigma_{AO} = 1.6430 \text{ mJy beam}^{-1}\). Vectors again denote the frequency-averaged linear polarization, with 1 mas in vector length corresponds to 4 mJy beam\(^{-1}\).

Figure 2. Polarization fraction as a function of projected angular distance in epoch BD46AP. Blue 'X's with errors indicate fractional linear polarization, \(m_l\). The best fit of the fractional linear polarization from GKK with \(K = 0\) is the dashed green line, while the fit with non-zero \(K\) is the dotted black line.

change necessary would be for the angle of the projected magnetic field to rotate within the masing material. This could be explained by variations in the local magnetic field orientation like those described in Soker & Clayton (1999).

Alternately, if the polarization is mainly governed by anisotropy conditions, such a rotation would indicate a change those conditions across the maser feature. In Asensio Ramos et al. (2005), this would mean a change in the anisotropy factor, \(w\), which is dependent on the optical depth, the illuminating intensity, and the maser source function.

Here, we discuss our analysis of a maser feature with an internal EVPA rotation of \(\sim \pi/2\) that persists across five epochs of observations, and our application of several tests of SiO maser polarization theories to the feature.
2. Observations

For this analysis, we used five epochs of the long-term, full-polarization SiO $\nu = 1J = 1 - 0$ (43 GHz) VLBA campaign of the Mira variable, TX Cam. These observations have been previously analyzed for total intensity and kinematics (Diamond & Kemball 2003, Gonidakis et al. 2010), and over-all linear polarization (Kemball et al. 2009).

This work focuses on five epochs with codes BD46AN, BD46AO, BD46AP, BD46AQ, and BD46AR. Observations were taken approximately two weeks apart and consisted of 128 31.25 kHz wide channels spanning 4 MHz bandwidths with full polarization, centered on the 43.122027 GHz rest frequency of the SiO $\nu = 1,J = 1 - 0$ maser, shifted $+9 \text{ km s}^{-1}$ to the LSR of TX Cam. For further information on the observations themselves, please see Diamond & Kemball (2003). For more on the data reduction process, please see the upcoming paper (Tobin et al., in prep).

In addition, the linear polarization of our target maser feature was analyzed for one epoch (BD46AQ) in Kemball et al. (2011). As was done in that work, we reduce the data using the method described in Kemball & Richter (2011), to obtain accurate circular polarization measurements at the low levels present here. Further, this work in particular expands on previous work by not only increasing the number of epochs analyzed, but also applying additional tests of maser polarization theory to the data.

3. Discussion

GKK and Linear Polarization. GKK gives the formula for fractional Q and U polarization, $Y$ and $Z$, respectively, as

$$
Y = \frac{3\sin^2\theta - 2}{3\sin^2\theta}, \quad Z = K \quad \text{for } \sin^2\theta \geq \frac{1}{3},
$$

$$
Y = -1, \quad Z = 0 \quad \text{for } \sin^2\theta \leq \frac{1}{3}. \quad (3.1)
$$
Figure 4. Fractional circular polarization, $m_c$, as a function of $\cos \theta$, as determined by the K=0 GKK fit. The shape of the data points is coded by epoch, and includes only points with $m_c S/N > 3$.

where Stokes V is assumed to be zero and K is some number such that $Y^2 + Z^2 \leq 1$. Typical applications of this theory assume $K = 0$ (Kemball et al. 2011). In Figure 2, we fit the predicted linear polarization fraction, $m_l$, as a function of projected angular distance to the prediction by GKK. To do this, we assumed $\theta$ was a quadratic function of projected angular distance, $d$, and fit for the first- and second-order coefficients and the projected angular distance at which the Van Vleck angle would be crossed, $d_f$:

$$\theta = p_0(d^2 - d_f^2) + p_1(d - d_f) + \arcsin \sqrt{2/3}. \quad (3.2)$$

For completeness, we fit for both $K = 0$ and some non-zero $K$ that is constant across the spatial extent of the feature.

Notably, while this profile fit some epochs better than others, it provides a remarkably good fit considering that the original formulation was made under such asymptotic limits and approximations as no circular polarization or Faraday rotation.

We also examined the shape of the EVPA profile as compared to that expected by GKK. For this, we took the best-fit parameters from the linear polarization fitting described above and calculated the expected EVPA profile that would result. The results, after fitting for a simple vertical offset - as we are not accounting for absolute EVPA - can be seen in Figure 3.

In this case, $K = 0$ GKK predicts a that the EVPA profile will be a strict step function, whereas the data show a smooth rotation of the linear polarization. Similarly, a smooth rotation of the EVPA was also observed in an H$_2$O maser of W43A by Vlemmings & Diamond (2006). Generally, adding some non-zero K smooths out the rotation. However, it also causes the extremal angles to be approached asymptotically and can result in less of a net rotation. In contrast, most epochs of our data actually show a rotation of slightly more than $\pi/2$.

Zeeman Circular Polarization. Although GKK assumed Stokes $V = 0$, others have expanded on this theory by deriving the behavior of circular polarization due to Zeeman splitting in this environment. Elitzur (1996) predicted that the $m_c \propto 1/\cos \theta$. Gray (2012) predicted that $m_c$ is roughly proportional to $\cos \theta$ but it may not be a purely linear
Figure 5. Fractional circular polarization, $m_c$, as a function of fractional linear polarization, $m_l$. Again, the shape of the data points is coded and with $m_c S/N > 3$. Grey shading denotes region consistent with $m_c < m_l^2/4$.

relation. Finally, Watson & Wyld (2001) predicted a more complex, peaked function for $m_c(\cos \theta)$.

Figure 4 shows measured $m_c$ as a function of $\cos \theta$ as determined from the $K = 0$ GKK fit to the linear polarization fraction profile. Although there is scatter at higher $\cos \theta$, our data appears most consistent with the prediction from Gray (2012).

**Non-Zeeman Circular Polarization.** Wiebe & Watson (1998) suggested that circular polarization may be a result of conversion from linear polarization due to, for example, different optical axes in the medium or a change in the magnetic field orientation along the line of sight. This type of non-Zeeman circular polarization would be limited by

\begin{equation}
    m_c < m_l^2/4.
\end{equation}

As shown in Figure 5, the vast majority of our data are not consistent with this limit. Wiebe & Watson (1998) suggest that, individual points may fall outside this limit, but the average values should be consistent if the circular polarization is arising via this mechanism. Even averaging our values over epoch, not a single epoch is consistent with this limit. This is consistent with the findings of Cotton et al. (2011).

**Alternative Theories.** Other possible explanations of this EVPA rotation include a curvature of the magnetic field itself within the region of the masing material. Small scale changes in the direction of the magnetic field such as this have been predicted in Soker & Clayton (1999). In this case, the EVPA would be tracing the projected magnetic field as it rotates. However, if this was the case, we wouldn’t expect to see the $m_l$ profile that so closely resembles GKK, as $m_l$ is not expected to be dependent on the direction of the projected magnetic field.

Another possibility is that, instead of resulting from interaction with magnetic fields, the change in EVPA is a result of changing anisotropy conditions. Asensio Ramos et al. (2005) propose that a change the anisotropic pumping conditions could cause a rotation in the EVPA. However, in this case, EVPA rotations are not expected to exceed $\sim 45^\circ$, which is inconsistent with the feature analyzed here.
4. Conclusions

We analyzed a single SiO $\nu = 1, J = 1 - 0$ SiO maser feature with an EVPA rotation of $\sim \pi/2$ that persisted across five epochs of VLBA observations. We found that the GKK $m_l$ profile provides a reasonable fit to the data given the theory’s asymptotic regime and simplifying assumptions, but the EVPA predicted by GKK is not consistent with our data. This could be due to, for example, the theory’s neglect of Faraday rotation. If the mechanism is similar to that proposed in GKK, the circular polarization most closely resembles that predicted by Gray (2012). In addition, the circular polarization distinctly does not agree with the non-Zeeman predictions put forth by Wiebe & Watson (1998). We also discussed the alternative theories of magnetic field rotation in the image plane and changing anisotropy conditions, but neither could fully explain the $m_l$ and EVPA behavior we observe.

Acknowledgements

This material is based upon work supported by the National Science Foundation Graduate Research Fellowship Program under Grant No. (NSF grant number). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

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