INTRINSIC PROPERTIES OF THE MAGNETICALLY COLLIMATED H₂O MASER JET OF W43A

W. H. T. Vlemmings¹ and P. J. Diamond¹

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ABSTRACT

Water maser polarization observations in the precessing jet of W43A have revealed that it is magnetically collimated. Here we present a detailed description of the physical properties of the water maser environment in the jet. We discuss the maser saturation level and beaming angle as well as the intrinsic temperatures and densities. In addition, we show that the polarization angle of the strongest redshifted maser feature undergoes a fast rotation of ~90° across the maser. Along with the variation of linear polarization fraction, this strongly supports the current theoretical description of maser linear polarization.

Subject headings: magnetic fields — masers — polarization — stars: individual (W43A)

1. INTRODUCTION

W43A is an evolved star at a distance of 2.6 kpc (Diamond et al. 1985) and is surrounded by a thick circumstellar envelope (CSE) that exhibits OH, H₂O, and SiO masers (Imai et al. 2005 and references therein). Unlike the shell-like structure of the 22 GHz H₂O masers typically found in the envelopes of evolved stars, the H₂O masers of W43A occur in two clusters at 1000 AU from the star near the opposing tips of a collimated jet. The jet, with a velocity of 145 km s⁻¹, has an inclination of 39° with respect to the sky plane, has a position angle of 65°, and shows a 5° precession with a period of 55 yr. The inferred dynamical age of the jet is only approximately 50 yr (Imai et al. 2002). W43A is interpreted as belonging to a class of objects undergoing a rapid transition from an evolved star into a planetary nebula (PN). Owing to their short expected lifetime of less than 1000 yr, only four sources of this class have been identified to date (Imai et al. 2002, 2004; Likkel et al. 1992; Morris et al. 2003; Boboltz & Marvel 2005). H₂O masers at 22 GHz are excited in gas with temperatures of T ≈ 400 K and hydrogen number densities of n ≈ 10⁸–10⁹ cm⁻³ (Elitzur 1992). These conditions are typically found close to the star. The H₂O masers in the collimated jet of W43A, however, likely arise when the jet has swept up enough material previously expelled from the star so that conditions at the tip of the jet have become favorable for H₂O masers to occur. Alternatively, they occur in a shock between the collimated jet and dense material in the outer CSE, similar to the H₂O masers found in star-forming regions.

Observations of linear and circular polarization of the different maser species in CSEs are uniquely suited to study the strength and structure of magnetic fields. Close to the central star, at radii of 5–10 AU, SiO masers indicate ordered fields of the order of several gauss (e.g., Kemball & Diamond 1997; Herpin et al. 2006). At the outer edge of the CSE, the polarization measurements of OH masers reveal milligauss magnetic fields and indicate weak alignment with CSE structure (e.g., Etoka & Diamond 2004). Recently, the Zeeman splitting giving rise to the circular polarization of H₂O masers was measured for a sample of evolved stars (Vlemmings et al. 2002, 2005). It was shown that at distances of several tens to hundreds of AU, CSEs harbor large-scale magnetic fields with typical field strengths between a few hundred milligauss up to a few gauss. While the origin of the magnetic field is still unclear, theoretical models have shown that a dynamo between the slowly rotating stellar outer layers and the faster rotating core can produce the observed magnetic fields (Blackman et al. 2001). However, this likely requires an additional source of angular momentum to maintain the magnetic field, which could be provided by the presence of a binary companion or heavy planet (Blackman 2004).

Magnetic fields around evolved stars are thought to be one of the main factors in shaping the CSEs and producing the asymmetries during evolution of a spherically symmetric star into the often asymmetric PN. Theoretical models show that magnetic fields could be the collimating agents of the bipolar jets in young protoplanetary nebulae such as W43A (e.g., Garcia-Segura et al. 2005). In a recent paper, we have shown, using H₂O maser linear and circular polarization observations, that the magnetic field is indeed the collimating agent of the jet of W43A (Vlemmings et al. 2006a, hereafter Paper I). Here we present a more detailed analysis of the observations presented in Paper I. We discuss the physical properties of the maser region. We also show how the observed linear polarization characteristics strongly support the current maser theory.

2. OBSERVATIONS

The observations of W43A were performed with the NRAO² Very Long Baseline Array (VLBA) on 2004 December 8 at the frequency of the 6_J2−5_J3 rotational transition of H₂O: 22,235080 GHz. We used four baseband filters of 1 MHz width, which were pair-wise overlapped to get a velocity coverage of ±25 km s⁻¹ around both the blueshifted (V₁ = −56 km s⁻¹) and redshifted (V₁ = 124 km s⁻¹) tip of the H₂O maser jet. Similar to the observations of H₂O masers in star-forming regions described in Vlemmings et al. (2006b, hereafter V06), the data were correlated multiple times with a correlator averaging time of 8 s. The initial correlation was performed with modest spectral resolution (128 channels; 7.8 kHz ≈ 0.1 km s⁻¹), which enabled us to generate all four polarization combinations (RR, LL, RL, and LR). Two additional correlator runs were performed with high spectral resolution (512 channels; 1.95 kHz = 0.027 km s⁻¹), which therefore only contained the two polarization combinations RR and LL, to be able to detect the signature of the H₂O Zeeman splitting across the entire velocity range. The observations on W43A were interspersed with 15 minute observations of the polarization calibrator J1743−0350. Including scans on the phase

¹ Jodrell Bank Observatory, University of Manchester, Macclesfield, Cheshire SK11 9DL, UK; wouter@jb.man.ac.uk.

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calibrators (3C 345 and 3C 454.3), the total observation time was 8 hr. The data analysis path is described in detail in Vlemmings et al. (2002) and follows the method of Kemball et al. (1995). Fringe fitting and self-calibration were performed on a strong (~35 Jy beam\(^{-1}\)) maser feature (at \(V_{\text{lsr}} = -15.72 \text{ km s}^{-1}\)). Image cubes were created of Stokes I, Q, and U from the intermediate spectral resolution data and of Stokes I and V with high spectral resolution. Due to the low declination of W43A \([\alpha(2000.0) = 18^h47^m41.166, \delta(2000.0) = -01^o45'11''.7]\), the beam width is \(\approx 0.6 \times 1.3\) mas. In the high spectral resolution total intensity and circular polarization channel maps, the noise is \(\approx 14\) mJy beam\(^{-1}\). In the lower spectral resolution Stokes Q and U maps, the rms noise is \(\approx 10\) mJy beam\(^{-1}\). We estimate our polarization angles to contain a possible systematic error of \(\approx 8^\circ\) due to the error in the polarization angle of the calibrator J1743–0350.

3. RESULTS

We detected polarization in several 22 GHz \(\text{H}_2\text{O}\) maser features in both the redshifted and blueshifted tips of the jet of W43A. The complete map of detected maser features is shown in Figure 1 of Paper I. Here we show, in Figure 1, the maser features for which linear polarization was detected. In Table 1, we list the position offsets with respect to the reference feature (\(\Delta \alpha\) and \(\Delta \delta\)), peak flux, full width at half-maximum line width (\(\Delta v\)), and LSR velocity \((V_{\text{lsr}})\) of these maser features. The table also contains the fractional linear polarization \((P_f)\), polarization angle \((\chi)\), fractional circular polarization \((P_c)\), and magnetic field strength \((B)\) determined at angle \(\theta\) from the line of sight. The polarization properties and corresponding rms errors are determined from a flux-weighted average over \(\Delta v\) for each maser line. We only detected circular polarization, at a level of 3.7 \%, in one of the blueshifted maser features (feature 5), and its polarization spectrum is shown in Figure 2 of Paper I. The magnetic field strength and 3 \(\sigma\) field strength upper limits were determined as described in V06. This analysis resulted in an estimate of \(B \cos \theta = 85 \pm 33\) mG for the feature where circular polarization was detected.

We have detected linear polarization in the six brightest maser features. As discussed in Paper I, the weighted mean linear polarization fraction of these masers is 0.66\% \(\pm\) 0.07\%, and the 3 \(\sigma\) upper limits in the masers where no linear polarization was detected range upward from 0.68\%. In the brightest of the maser features (feature 1), we observe a 90\(^\circ\) flip of polarization angle across the maser, which is shown in Figure 2. This is not observed for any of the other maser features. The fractional polarization of feature 1 also varies across the maser, and the values in Table 1 represent the values at the location of the maximum and minimum polarization angle. The flux-weighted average of the linear polarization fraction of the maser feature is 0.99\% \(\pm\) 0.49\%.

4. DISCUSSION

4.1. Intrinsic Properties of the Maser Regions

As described in V06, the models used to determine the magnetic field from the maser total intensity and polarization spectra also yield the intrinsic maser thermal width \(\Delta v_{\text{th}} \approx 0.5(T/100)^{1/2}\), where \(T\) is the temperature in the maser region.

### Table 1

| Feature | \(\Delta \alpha\) (mas) | \(\Delta \delta\) (mas) | Peak Intensity \((\text{Jy beam}^{-1})\) | \(\Delta v\) (km s\(^{-1}\)) | \(V_{\text{lsr}}\) (km s\(^{-1}\)) | \(P_f\) (%) | \(\chi\) (deg) | \(P_c\) (%) | \(B \cos \theta\) (mG) |
|---------|----------------|----------------|-----------------|----------------|----------------|-------------|---------------|-------------|----------------|
| 1       | 0.0            | 0.0            | 38.57           | 0.54           | 126.11         | 2.29 \(\pm\) 0.40 | 54 \(\pm\) 3 | ...         | <36         |
| 2       | 1.1            | 0.7            | 4.89            | 0.68           | 126.69         | 2.25 \(\pm\) 0.42 | -29 \(\pm\) 1 | ...         | <278      |
| 3       | 21.2           | 48.9           | 6.45            | 0.79           | 123.42         | 0.82 \(\pm\) 0.23 | -25 \(\pm\) 12 | ...         | <306      |
| 4       | 36.1           | 10.7           | 18.66           | 0.75           | 121.21         | 0.59 \(\pm\) 0.17 | 64 \(\pm\) 4  | ...         | <101      |
| 5       | -561.2         | -195.0         | 10.85           | 0.88           | -57.19         | 0.64 \(\pm\) 0.19 | 69 \(\pm\) 8  | 0.33 \(\pm\) 0.09 | 85 \(\pm\) 33 |
| 6       | -562.0         | -196.0         | 12.45           | 0.66           | -59.73         | 0.65 \(\pm\) 0.06 | 82 \(\pm\) 6  | ...         | <93       |

* Polarization angle gradient across maser feature (see text).
In addition, the models produce the maser emerging brightness temperature $T_b \Delta \Omega$, where $T_b$ is the brightness temperature and $\Delta \Omega$ is the unknown beaming solid angle. Circular polarization measurements are necessary to optimally constrain $\Delta v_{\text{in}}$ and $T_b \Delta \Omega$, and we have been able to determine $\Delta v_{\text{in}}$ and $T_b \Delta \Omega$ for one of the maser features. We find that the intrinsic thermal width of feature 5, in the blueshifted tip of the jet, is $\Delta v_{\text{in}} = 1.1 \pm 0.3 \text{ km s}^{-1}$. This indicates an intrinsic temperature in the maser jet of $T \approx 500 \text{ K}$. For the emerging brightness temperature, we find $T_b \Delta \Omega \approx 8 \times 10^9 \text{ K sr}$.

The masers in the collimated jet of W43A are found at ∼1000 AU from the central star, much farther out than is typical for the H$_2$O masers in the CSE of evolved stars. They likely arise when the jet has swept up enough material to create suitable conditions for maser excitation. Alternatively, the masers occur in a shocked region between the jet and dense material in the outer CSE, similar to the shocked masers found in star-forming regions. If the masers occur in a shock, the temperature in the maser region indicates that it is likely a dissociative J-type shock (Kaufman & Neufeld 1996). Using the H$_2$O maser models developed for J-type shock masers in star-forming regions (Elitzur et al. 1989), we then find that the preshock hydrogen density would be $n \sim 3 \times 10^6 \text{ cm}^{-3}$. This is an order of magnitude higher than the typical hydrogen density at ∼1000 AU from the star ($n \sim 10^3 \text{ cm}^{-3}$). We thus conclude that the H$_2$O masers are likely excited in material swept up in the jet instead of in a J-type shock.

We can compare the emerging brightness temperature determined from the model, with the maser brightness temperature determined from the observations. We find that feature 5 is unresolved. Assuming a size of ∼0.4 mas, which corresponds to ∼1 AU, we find a brightness temperature lower limit $T_b \approx 1.5 \times 10^{11} \text{ K}$. Thus, the upper limit on the beaming solid angle $\Delta \Omega \approx 5 \times 10^{-2} \text{ sr}$, which is similar to the values found in star-forming regions (V06). Most of the other maser features are also unresolved, with only the brightest feature (feature 1) being marginally resolved. Thus, the W43A H$_2$O masers have brightness temperatures of $T_b \approx 10^{11}$–$10^{12} \text{ K}$. In addition, we can compare the emerging brightness temperature with the maser brightness temperature $T_b$ at the onset of saturation. Using Reid & Moran (1988), we find $T_b \Delta \Omega = 3.4 \times 10^9 \text{ K sr}$. This indicates, for $\Delta \Omega \approx 5 \times 10^{-2} \text{ sr}$, that the masers of W43A are mostly saturated.

### 4.2. Linear Polarization

Maser theory has shown that the percentage of linear polarization $P_L$ of H$_2$O masers depends on the degree of saturation and the angle $\theta$ between the maser propagation direction and the magnetic field (e.g., Deguchi & Watson 1990). In addition, when the Zeeman frequency shift $g \Omega$ is much greater than the rate for stimulated emission $R$, the polarization vectors are either perpendicular or parallel to the magnetic field lines, depending on $\theta$. For the typical emerging brightness temperature in the H$_2$O maser jet of W43A, $T \Delta \Omega \approx 10^{10} \text{ K sr}$, $R \approx 1 \text{ s}^{-1}$, while for a magnetic field of $\approx 100 \text{ mG}$, the strongest 22 GHz hyperfine transitions have $g \Omega \sim 1000 \text{ s}^{-1}$. Thus, $g \Omega \gg R$ is easily satisfied. As a result, when $\theta > \theta_{\text{crit}} \approx 55^\circ$ the polarization vectors are parallel to the magnetic field, and when $\theta < \theta_{\text{crit}}$ they are parallel (Goldreich et al. 1973). The strongest linear polarization is found when $\theta > \theta_{\text{crit}}$; thus, it was concluded in Paper I that most of the linear polarization vectors were perpendicular to the magnetic field, indicating a toroidal magnetic field configuration. If, alternatively, they are parallel to
the magnetic field we are actually probing the poloidal component.

When \( \theta \) is close to \( \theta_{\text{crit}} \), the linear polarization vectors can flip 90° on very small scales. According to maser theory, a minimum in \( P_L \) occurs when \( \theta = \theta_{\text{crit}} \). This can be seen in Figure A.1 of V06, which gives \( P_L \) as a function of \( \theta \) and saturation level. Here we observe a 90° flip across the brightest of the maser features in the jet of W43A, as shown in Figure 2. Similar flips were observed in circumstellar SiO masers (Kennell & Diamond 1997) and H2O masers in star-forming regions (V06). However, here we have for the first time been able to detect the expected minimum in \( P_L \) when the flip occurs. The minimum is most pronounced in the slice across the maser along the position angle of the jet. The linear polarization characteristics are dominated by the condition along the maser path where the strongest amplification occurs (Vlemmings 2006). Thus, we conclude that by the condition along the maser path where the strongest amplification occurs (Vlemmings 2006). Thus, we conclude that the strongest amplification in the maser region giving rise to feature 1 occurs at the location along the line of sight where \( \theta \) is close to \( \theta_{\text{crit}} \). The position angle changes from \( \chi = 54° \), which is perpendicular to the magnetic field, to \( \chi = 29° \), which is parallel to the magnetic field. Most of the other maser features have polarization angles that are perpendicular to the magnetic field except possibly feature 3 with \( \chi = 25° \), possibly because this maser feature is located at the edge of the jet, where a projected toroidal magnetic field will lie along the jet.

4.3. Magnetic Field

After correcting for the angle between the line of sight and the magnetic field, and taking into account the saturation level, we find a toroidal magnetic field of \( B \approx 200 \, \text{mG} \) in the H2O maser jet of W43A (Paper I). The magnetic field is increased in the density-enhanced H2O maser jet due to partial coupling to the gas. The magnetic field outside the jet is found to be \( B \approx 0.9–2.6 \, \text{mG} \) if the masers exist in swept-up material at a density of \( n = 10^6–10^{10} \, \text{cm}^{-3} \). If the masers are excited in a dissociative shock, the magnetic field outside the jet is \( B \approx 0.07 \, \text{mG} \); however, as discussed above, this is unlikely to be the case. In Paper I, it was shown that if we are probing the toroidal field, with \( B_t \propto r^{-1} \), this implies an average magnetic field of \( B \approx 20 \, \text{G} \) on the surface of the star. This is in excellent agreement with the magnetic field values determined by extrapolating the field strengths found using SiO, H2O, and OH maser observations throughout the CSEs of a large number of evolved stars. If, instead of the toroidal field, we are probing the poloidal field (with its radial component), the surface magnetic field would be a factor of \( \approx 10^2 \) larger. As this is inconsistent with the other observations, we conclude that the H2O maser polarization vectors are indeed tracing the toroidal magnetic field.

5. Conclusions

Using polarization observations of the H2O masers in the tips of the jet of W43A, we have shown that the masers most likely occur in swept-up material and are not shock excited. The masers are saturated with a typical beaming solid angle of \( \Delta \Omega \approx 5 \times 10^{-2} \, \text{sr} \) and occur at temperatures of \( T \approx 500 \, \text{K} \). The polarization vectors trace the toroidal magnetic field, which has a density enhanced field strength of \( B \approx 200 \, \text{mG} \). This implies, as shown in Paper I, a magnetic field strength that is sufficiently strong to produce a magnetically collimated jet. In addition, a 90° flip of the polarization angle and a corresponding minimum in fractional linear polarization is observed across the brightest maser feature. This strongly supports the current maser polarization theory.

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