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Circular Polarization of Circumstellar H_2O Masers: Magnetic Fields of AGB Stars

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Abstract. We present circular polarization measurements of circumstellar H_2O masers around 2 Mira variables and 4 supergaint stars. Both an LTE and non-LTE method are used to analyze the circular polarization and total intensity spectra and to obtain the magnetic field strength. The non-LTE method is found to be able to reproduce the observations best. Using this, we find fields from a few hundred milliGauss up to a few Gauss, indicating a solar-type r^{-2} dependence of the magnetic field on the distance, which leads to stellar surface magnetic fields of up to several hundred Gauss. No linear polarization is detected to less than 1.5%.

1. Introduction

The role of magnetic fields in the late stages of stellar evolution is still unclear. Blackman et al. (2001) have shown that AGB stars could produce fields of several hundreds of Gauss. Such strong fields can play an important role in driving stellar winds and shaping the outflows, giving rise to the non-spherical shapes observed in Planetary Nebulae.

Until recently, information on the magnetic field in the circumstellar envelopes was obtained by polarimetric observations of SiO masers at $\approx\ 2-4\ R_*$ from the central star, and OH maser at a distance of $1000-10000$ AU. The SiO observations indicated fields of 5-10 Gauss for Mira stars and up to 100 Gauss for supergiants (e.g. Barvainis et al., 1987). However, using a non-Zeeman interpretation of the observed circular polarization, the magnetic fields could be a factor 1000 less (Wiebe & Watson, 1998). The OH maser observations indicated field strengths of 1-2 mG (e.g. Szymczak & Cohen, 1997).

Now we have determined the magnetic field strengths in the H_2O maser region, at a few hundred AU. Although H_2O is a non-paramagnetic molecule, it has been possible to observe the circular polarization on some of the strongest circumstellar H_2O maser features. We have used both the LTE analysis pre-

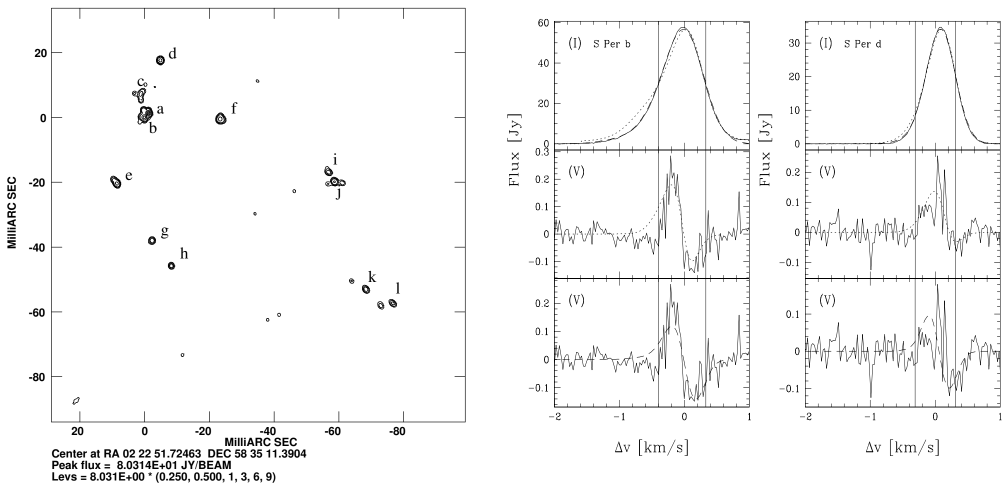

Figure 1. (left) Total intensity image of the H_2O maser features around S Per. (right) Total power (I) and V-spectra for selected maser features of S Per. The bottom panel shows the best fitting LTE model (dashed), the middle panel shows the best fitting non-LTE model (dotted).

sented in Vlemmings et al. (2001) and non-LTE models based on the models presented in Neduloha & Watson (1990). A full description of the analysis methods, observations and results are presented in Vlemmings et al. (2002).

2. Observations

We have observed 8 late-type stars with the VLBA. The first observations, on December 13th 1998, were performed on the supergiants S Per, VY CMa and NML Cyg, and the Mira variable star U Her. Recently, on May 20th 2003, additional observations were performed on the Mira variable stars U Her, U Ori and R Cas, and the supergiant VX Sgr. To get the highest spectral resolution, required for the circular polarization measurements, the data were correlated twice. Once with modest spectral resolution (0.1 km/s), to get all 4 polarization combinations (RR, LL, RL and LR), and once with high resolution (0.027 km/s), with only RR and LL. The calibration was mainly performed on the modest spectral resolution data and the solutions were copied and applied to the high resolution data. This data set was then used to produce circular polarization and total intensity image cubes. The modest resolution data set was used to determine the linear polarization.

3. Results

We have examined the strongest H_2O maser features around the 7 stars observed. Circular polarization between 0.1% and 25% of the total intensity was detected on $\approx 50\%$ of the brightest maser features. An example of the features around S Per is shown in Fig.1. We rule out any systematic effects as a cause of the observed spectrum, because various percentages of circular polarization are observed as well as different directions of the magnetic field. No linear polarization was detected in excess of $\approx 1.5\%$.

The magnetic field strengths were determined with both the LTE and the non-LTE method. The LTE method predicts the circular polarization spectrum to be directly proportional to the derivative of the total power spectrum. We found that the observed spectra were narrower, which can only be explained with the non-LTE analysis. The non-LTE field strengths are $\approx 40\%$ lower than those determined by the LTE method.

From the observations and analysis, we estimate the magnetic field strengths in the H_2O maser region to be ≈ 200 mG for S Per and VY CMa. The field around NML Cyg is ≈ 500 mG, while the Mira variable U Her shows a much higher field of ≈ 1.5 G. Preliminary results for the second set of observations indicate a magnetic field of up to several Gauss on VX Sgr and U Ori. Unfortunately the masers around R Cas were not detected. The second observations of U Her provide an upper limit to the magnetic field of several hundred mG on the observed features. Since the velocity of the features observed around U Her at the observation dates are significantly different, we are now observing different maser spots. These spots are likely further out in the circumstellar envelope and have larger angles between line of sight and the magnetic field, which results in a lower observed field strength.

4. Discussion

Our results favor the non-LTE approximation and because we do not detect any linear polarization, a non-Zeeman interpretation is also highly unlikely. The lack of linear polarization can be easily explained in the non-LTE case, because linear polarization is only produced by strongly saturated masers. A line widths analysis indicates that the circumstellar H_2O masers are not saturated. Even for large angles between the line of sight along the maser and the direction of the magnetic field we do not expect any linear polarization. In the LTE analysis, the lack of linear polarization can only be explained by having the maser line of sight beam along the magnetic field lines.

We can compare the strength of the magnetic field in the H_2O maser region with the values obtained from SiO and OH maser polarization observations. This seems to indicate that the magnetic field strength values inferred from the SiO maser observations are indeed due to the normal Zeeman effect, although Elitzur (1996) has argued that the field strength can still be a factor 10 lower on both SiO and OH masers. Fig.2 shows the dependence of the magnetic field strength on distance from the star. Our observed values are plotted at the observed maximum extent of the H_2O maser region. Because our observations are most sensitive for the highest magnetic fields, we are actually probing the inner edges of the H_2O maser shell. The arrows indicate the typical thickness of such a shell. These results indicates that the magnetic field strength is best represented by a solar-type dependence on distance (r^{-2}). The exact shape of the magnetic field strength cannot easily be determined from our observations. The SiO polarization maps indicate mostly radial field lines close to the star.

The magnetic pressure of the field in the H_2O maser region dominates the thermal pressure by a factor of 20. Using the solar-type field, extrapolated

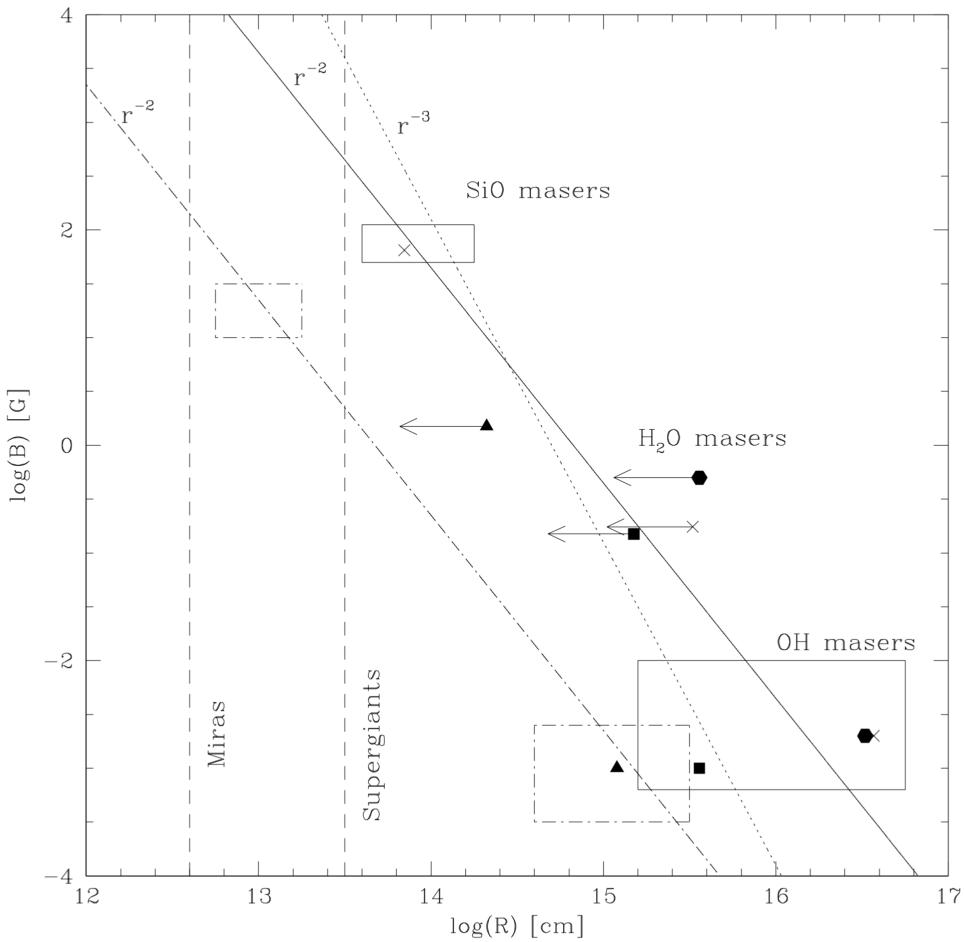

Figure 2. Magnetic field strength B, as function of distance R from the star. Dashed-dotted boxes are the SiO and OH maser estimates for Mira stars, solid boxes are those for supergiant stars. Symbols indicate observations (Dec 1998); U Her is represented by triangles, S Per by the square, VY CMa by the crosses and NML Cyg by the hexagonal symbol. The dashed vertical lines are an estimate of the stellar radius.

surface field strengths are of the order of $100 - 1000$ Gauss, strong enough to drive and shape the outflows.

References

Barvainis, R., McIntosch, G., Predmore, C.R., 1987, Nature, 329, 613

Blackman, E.G., Frank, A., Markiel, J.A., et al., 2001, Nature, 409, 585

Elitzur, M., 1996, ApJ, 457, 415

Nedoluha, G.E., Watson, W.D., 1992, ApJ, 384, 185

Szymczak, M., Cohen, R.J., 1997, MNRAS, 288, 945

Vlemmings, W., Diamond, P.J., van Langevelde, H.J., 2001, AA, 375, L1

Vlemmings, W., Diamond, P.J., van Langevelde, H.J., 2002, AA, 394, 589
Wiebe, D.S., Watson, W.D., 1998, ApJ, 503, L71