MAGNETIC FIELDS IN THE ENVELOPES OF LATE-TYPE STARS

Circular Polarization of H$_2$O Masers

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Abstract
We present the first circular polarization measurements of circumstellar H$_2$O masers around a sample of late-type stars. These observations are used to obtain the magnetic field strength in the H$_2$O maser region with both an LTE and non-LTE analysis. 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. No linear polarization is detected to less than 1%.

Keywords: masers - polarization - stars: circumstellar matter - stars: magnetic fields - techniques: interferometric

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.

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). OH maser observations indicated field strengths of 1-2 mG (e.g. Szymczak & Cohen, 1997).
Now we have been able to determine the magnetic field strengths in the intermediate region, at a few hundred AU, where the H$_2$O masers occur. Although H$_2$O is a non-paramagnetic molecule, it has been possible to observe the circular polarization on some of the strongest circumstellar H$_2$O maser features. We have used both the LTE analysis presented 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).

1. Observations

We have observed 4 late-type stars with the VLBA, the supergiants S Per, VY CMa and NML Cyg, and the Mira variable star U Her. 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.
2. Results

We have examined the strongest H$_2$O maser features around the 4 stars observed. Circular polarization down to 0.2% of the total intensity was detected on $\approx 50\%$ of the brightest maser features. An example of the features around VY CMa 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. No linear polarization was detected above the limit of $\approx 0.5\%$.

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$_2$O maser region to be $\approx 200$ mG for S Per and VY CMa. The field around NML Cyg is $\approx 500$ mG, while the Mira variable U Her shows a much higher field of $\approx 1.5$ G.

3. Conclusions

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$_2$O 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$_2$O 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$_2$O maser region. Because our observations are most sensitive for the highest magnetic fields, we are actually probing the inner edges
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; 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.

of the H$_2$O 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$_2$O maser region dominates the thermal pressure by a factor of 20. Using the solar-type field, extrapolated surface field strengths are of the order of 100 – 1000 Gauss, strong enough to drive and shape the outflows.

References

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