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Shaping the Envelope: Magnetic fields around evolved stars

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Although the outflows of evolved stars are one of the most important sources of interstellar dust, the driving forces of these outflows are still not fully understood. For instance, important questions are, what is driving the mass-loss and what is the mechanism that causes spherically symmetric stars to produce highly aspherical planetary nebulae (PNe)? Here I will discuss recent maser polarization observations that indicate the occurrence of strong magnetic fields in the circumstellar envelopes of evolved stars. The magnetic field could be the missing component needed to drive evolved star mass-loss and shape their envelopes. But, as the origin of the magnetic field is still unclear, various different observations with current and future instruments such as the SKA and eMERLIN are needed to resolve this issue.

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1. Introduction

Although the Asymptotic Giant Branch (AGB) and post-AGB are key phases in the life of a low-mass star, they are still poorly understood. They encompass a short time in which a star loses a large fraction of its mass. The AGB mass-loss provides the main contribution to the enrichments of the interstellar medium in dust and heavy elements, and its timescale and yield control the chemical evolution of galaxies (Habing & Olofsson 2004). Mass loss is a complex process thought to involve pulsations, dust formation and radiation pressure. However, recent studies have shown that an additional aspect must be considered to explain typical mass-loss characteristics, and there is evidence pointing to magnetic fields (e.g. Vidotto & Jatenco-Pereira, 2006). The studies of the mass-loss, dynamics, and magnetic fields in circumstellar envelopes, are almost exclusively the providence of masers and (sub-)millimeter molecular lines. After a stars AGB phase, the envelope undergoes a rapid and substantial modification by evolving into a Planetary Nebula (PN). The standard assumption is that the initial slow AGB mass-loss quickly changes into a fast superwind that generates shocks and accelerates the surrounding envelope (Kwok et al. 1978). It is during this phase that the typical spherical circumstellar envelope evolves into an a-spherical PN. However, the actual formation mechanism for these a-spherical shapes is still a matter of debate and is likely connected to companion planets, binaries, disks and/or magnetic fields.

Maser polarization observations are the predominant source of information about the role of magnetic fields during the late stages of stellar evolution. Most observations have focused on the masers in the CSEs of AGB stars, as OH, H_2O and SiO masers are fairly common in these sources. However, polarization observations of masers around post-AGB stars and (Proto-)PNe are becoming more common as more such sources with maser emission are found (Gómez, 2007).

1.1 AGB stars

While polarization observations of CSE 1.6 GHz OH masers are fairly commonplace, recent years have seen an increase in 22 GHz H_2O and 43 GHz SiO maser observations of mainly Mira variables and supergiants. As the different maser species typically occur in different regions of the CSE, combining observations of all three species allows us to form a more complete picture of the magnetic field throughout the entire envelope. Close to the central star, SiO maser linear polarization reveals an ordered *B*-field with a linear polarization fraction ranging from $m_l \sim 15\%$ to $m_l \sim 65\%$ (e.g. Kemball & Diamond 1997). Strikingly, radially elongated jet-like SiO maser structures ,that have been observed around for example *o* Ceti and R Aql, are apparently aligned with the *B*-field (Cotton et al. 2006). A recent large single dish survey of SiO maser polarization revealed an average field strength of 3.5 G when assuming a regular Zeeman origin of the polarization, indicating a dynamically important *B*-field (Herpin et al. 2006). The observations find no specific support for other (non-Zeeman) interpretations of the polarization.

Further out in the envelope, also 22 GHz H_2O maser measurements reveal significant *B*-fields, both around Miras and supergiants (Vlemmings et al. 2005, and references therein). The measured field strength is typically of the order of $\sim 100-300$ mG but can be up to several Gauss. The strongest field strengths are found around Mira variables, consistent with the H_2O masers occurring closer to the star. As no linear polarization has been detected thus far, describing the magnetic field shape is difficult. However, for the Supergiant VX Sgr, the complex maser structure reveals an ordered field reversal across the maser region consistent with a dipole *B*-field. Interestingly, the orientation of the field determined from the H_2O maser polarization is similar to the orientation of the outflow determined from other H_2O maser observations as well as the orientation of a dipole field determined from OH maser polarization (Vlemmings et al. 2005).

Finally, at typically even larger distances, 1.6 GHz OH maser are often strongly linearly polarized. Those masers reveal an ordered *B*-field at several thousands AU from the star. The field strength at these distances is typically of the order of a few mG (e.g. Deacon et al. 2007; Etoka & Diamond 2004).

1.2 Proto-Planetary nebulae

Most of the polarization work of P-PNe is done on OH masers. Similar to the magnetic field strengths around their progenitor stars, the P-PNe fields are ~ 1 mG in the OH maser region. Single dish surveys reveal linear and circular polarization in respectively $\sim 50\%$ and $\sim 75\%$ of the sources, dependent on the OH maser line (polarization is more common in the 1612 MHz OH satellite line than in the 1665 and 1667 main line masers). The polarization fraction is typically less than 15% (Szymczak & Gérard 2004). The OH maser polarization has also been mapped using MERLIN. As shown in Fig. 1(right), the linear polarization vectors reveal a highly ordered *B*-field (Bains et al. 2003 & 2004).

A very small fraction of the Post-AGB/P-PNe maser stars show highly collimated H_2O maser jets. These so-called water-fountain sources are likely the progenitors of bipolar PNe and there are indications that they evolve from fairly high-mass AGB stars. The archetype of this class is W43A (Imai et al. 2002) and polarization observations have recently revealed that the maser jet is magnetically collimated (Fig.1(left) and 2(right); Vlemmings et al. 2006; Vlemmings & Diamond 2006). This lends strong support to the theories of magnetic shaping of PNe (e.g. García-Segura et al. 2005). In addition to the observations of W43A, recent Australia Telescope Compact Array (ATCA) observations of the likely water-fountain source IRAS 15445-5449 (Vlemmings & Chapman 2008, in prep.) also indicate a magnetic H_2O maser jet.

1.3 Planetary Nebulae

There are only a handful of PNe known which show maser emission, and even less of these have masers that are strong enough to provide *B*-field measurements from polarization observations. One of the sources that shows both OH and H_2O maser emission is the very young PNe K3-35. In this source, the OH masers indicate a *B*-field of a few mG at 800 AU from the central object (Gómez et al. 2006).

2. The origin of the Magnetic Field

The origin of the strong, large scale magnetic fields around evolved stars remains a topic of debate. The generation of an axisymmetric magnetic field requires a magnetic dynamo in the interior of the star. Several models have been discussed in the literature that include the interaction between the differential rotation and turbulence in the convection zone around the degenerated core (e.g. Blackman et al. 2001). While this might be used to explain the magnetic fields for the Mira stars, a supergiant core is supposedly not degenerate. However, in this case a dynamo

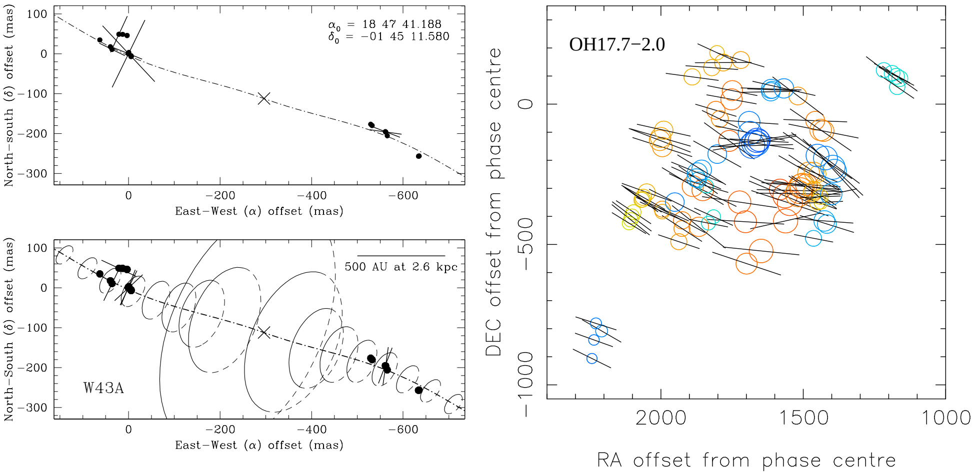

Figure 1: (left; top) The H_2O masers in the precessing jet (dashed-dotted line) of W43A (indicated by the cross). The maser features with the determined linear polarization vectors scaled linearly according to the fractional linear polarization. The polarization vectors lie predominantly along the jet with a median angle of $\chi = 63 \pm 12^\circ$ east of north. (left; bottom) The toroidal B-field of W43A. The vectors indicate the determined direction of B, perpendicular to the polarization vectors, at the location of the H_2O masers. The ellipses indicate the toroidal field along the jet, scaled with $B \propto r^{-1}$ (Vlemmings et al. 2006). (right) The spatial distribution of the 1612 MHz linearly polarized maser components around the P-PNe OH17.7-2.0. Symbol size is proportional to Stokes I flux density; vector size is proportional to logarithmically scaled linearly polarized flux density. More blue-shifted components are represented by darker (blue) symbols and more red-shifted are lighter (red). The clear, overall regular magnetic field structure is consistent with a stretched dipole field (Bains et al. 2004)

driven by the differential rotation between the contracting non-degenerate core and the expanding outer envelope has also been shown to also be able to generate strong magnetic fields (Uchida & Bappu 1982). In other models the magnetic field is generated though an additional source of angular momentum, as magnetic drag would otherwise halt any rotation and dynamo action. In such models, a strong magnetic field can be generated when the star is spun up by a close binary or when a circumstellar disk provides an additional source of angular momentum. The sources in our sample do not however, show any indication of binarity, although this cannot yet be ruled out.

Besides polarization measurements there are thus variety of observations needed to locate the origin of the magnetic field. For instance, high angular resolution dust observations can possibly reveal disks, while spectral line observations can probe the dynamics in the inner region of the circumstellar envelope to look for the signature of for instance binary interaction.

3. Summary

Fig. 2(right) gives a summary of the current magnetic field measurements in CSEs of both Mira and supergiants. Although the exact relation between the magnetic field strength and distance to the central star remains uncertain, the field strengths are obvious strong enough to dynamically influence the shaping of the outflow and help shape asymmetric PNe. This is further supported by recent observations of strong B-fields on the surface of the central stars in several PNe (Jordan et

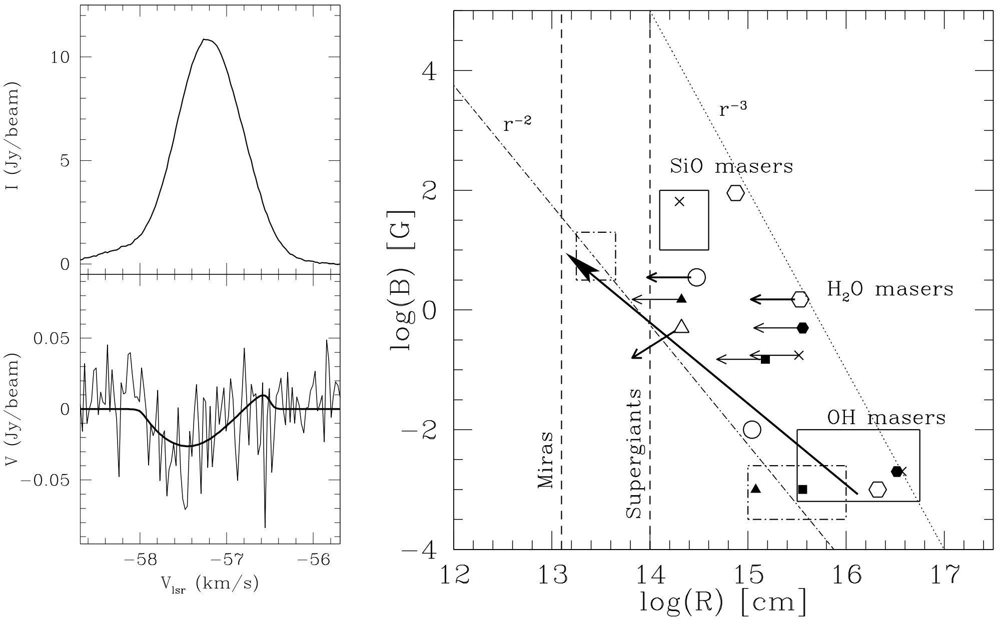

Figure 2: (left) The total intensity and circular polarization spectrum of the H_2O maser feature of W43A for which circular polarization was detected corresponding to a magnetic field strength of 85 mG (Vlemmings et al. 2006). (right) The figure, reproduced from Vlemmings et al. (2005), of measured *B*-fields on the masers in the CSEs of evolved stars. The dashed-dotted boxes indicate the range of magnetic field strengths measured on the SiO and OH masers of Mira stars and the solid boxes those of Supergiant stars. The thin arrow indicate the H_2O maser *B*-fields measured in Vlemmings et al. (2002, 2005), where the length of the arrows indicate the thickness of the H_2O maser shell with the symbols drawn on the outer edge. The symbols without arrows are the measurements on SiO and OH masers from the literature on the same sample of stars. The thick solid arrow indicates *B* in the jet of W43A.

al. 2005) as well as recent PNe dust polarization observations (e.g.Sabin et al. 2007). The magnetic field could also the missing component in the stellar mass-loss mechanism, as recent models indicate the pulsation and radiation pressure alone might not be enough (Woitke 2006). However, as discussed above, the question of the origin of the magnetic field remains and will possibly have to be sought in the interaction with a heavy planet, a binary companion or a circumstellar disk.

4. Future perspectives

Maser polarization observations will likely remain the dominant source of magnetic field measurements close to the star during the AGB and P-PNe phases of stellar evolution. With the advent of new instruments such as the SMA and ALMA, high resolution dust polarization observations will soon be able to bridge the gap between the small scale maser magnetic field measurements and the larger scale single dish dust polarization observations. Further in the future, the SKA should be able to bring H_2O maser observations to a new level, fully imaging the polarization of the H_2O envelopes of evolved stars and PNe. But already in the near future, existing and soon to be upgraded instruments such as (e)MERLIN, the (e)VLA and the VLBA will be able to answer the questions about the role of magnetic fields during late stellar evolution by further increasing the size of the source samples and accurately tying the maser distribution to the central star.

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