Planetary Nebulae: An Eye to the Future
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Magnetic fields during the evolution towards planetary nebulae

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Abstract. Magnetic fields appear ubiquitous throughout the envelopes of evolved stars. However, their origin and role in the formation of planetary nebulae is still unclear. As observations of magnetic fields are complicated and time consuming, the observed samples of AGB and post-AGB stars and planetary nebulae are still small. Still, magnetic energy seems to dominate the energy budget out to a distance of several tens of AU from the central star and the field morphology often appears to be well ordered. A short summary is given of the current observations and the potential of new instruments such as ALMA is discussed.

Keywords. Stars: AGB and post-AGB, planetary nebulae: general, magnetic fields

1. Introduction

After the AGB phase, the stellar envelopes undergo a major modification as they evolve to Planetary Nebulae (PNe). The standard assumption is that the initial slow AGB mass loss quickly changes into a fast superwind, generating shocks and accelerating the surrounding envelope (Kwok *et al.* 1978). It is during this phase that the typically spherical circumstellar envelope evolves into a Planetary Nebula. As the majority of PNe are aspherical, an additional mechanism is needed to explain the departure from sphericity. Specifically the discovery that the collimated outflows of the pre-PNe (P-PNe), where such outflows are common, have a momentum that exceeds that which can be supplied by radiation pressure alone (Bujarrabal *et al.* 2001), has led to a revision of the standard theory. The formation mechanism of in particular bipolar PNe is still a matter of fierce debate. Current theories to explain the PNe shapes include binaries, disks, magnetic fields or a combination of these. A promising mechanism could be a binary companion or massive planet that helps maintain a strong magnetic field capable of shaping the outflow (e.g. Nordhaus *et al.* 2007). However, the known fraction of binary systems cannot yet explain the large number of aspherical PNe. Since the shaping mechanism is likely related to the mass loss mechanism responsible for the enrichment of the interstellar medium, a better understanding of this mechanism is crucial.

Here I will review the observational evidence for strong magnetic fields in PNe as well as around their AGB and post-AGB progenitors. The predominant source of magnetic field strength information during the late stages of stellar evolution comes from maser circular polarization observations, and particularly the common SiO, H_2O and OH masers. These can show circular polarization fractions ranging from $\sim 0.1\%$ (H_2O) up to $\sim 100\%$ (OH) and are, because of their compactness and strength, excellent sources to be observed with high angular resolution. Unfortunately, the analysis of maser polarization is not straightforward (For a review, see Vlemmings 2007), and it has taken a long time before maser observations were acknowledged to provide accurate magnetic field measurements. More recently, the first attempts have been made to detect the Zeeman splitting of

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non-maser molecular lines, such as CN (Herpin *et al.* 2009). As many of these occur at shorter wavelength in the (sub-)mm regime, the advent of the Atacama Large (sub-)Millimeter Array will further enhance these types of studies.

2. Current status

The current status of magnetic field observations in the circumstellar envelopes of evolved stars is shown in Fig. 1. Observations have shown strong magnetic fields around Mira variable stars and in the figure I have indicated the magnetic field strength throughout the envelope. The corresponding magnetic energy densities, compared with the thermal and dynamical energy densities, are given in Table 1. While a clear trend with increasing distance from the star is seen, the lack of accurate information on the location of the maser with respect to the central stars makes it difficult to constrain this

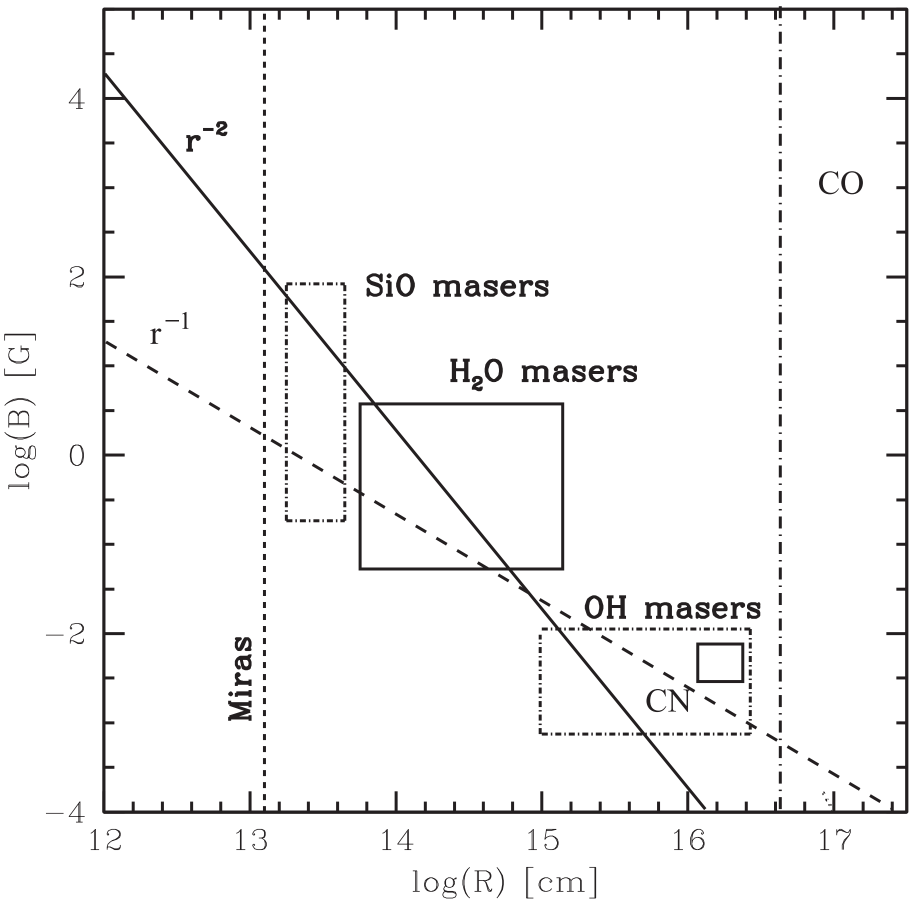

Figure 1. Magnetic field strength vs. radius relation as indicated by current maser polarization observation of a number of Mira stars. The boxes show the range of observed magnetic field strengths derived from the observations of SiO masers (Kemball *et al.* 2009, Herpin *et al.* 2006), H_2O masers (Vlemmings *et al.* 2002, Vlemmings *et al.* 2005), OH masers (e.g. Rudnitski *et al.* 2010) and CN (Herpin *et al.* 2009). The thick solid and dashed lines indicate an r^{-2} solar-type and r^{-1} toroidal magnetic field configuration. The vertical dashed line indicates the stellar surface. ALMA CO polarization observations will uniquely probe the outer edge of the envelope (vertical dashed dotted line).

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Table 1. Energy densities in AGB envelopes

		Photosphere	SiO	H_2O	OH
B	[G]	$\sim 50?$	~ 3.5	~ 0.3	~ 0.003
R	[AU]	-	~ 3	~ 25	~ 500
		-	$[2-4]$	$[5-50]$	$[100-10.000]$
$V_{\rm exp}$	[km s^{-1}]	~ 5	~ 5	~ 8	~ 10
$n_{\rm H_2}$	[cm^{-3}]	$\sim 10^{14}$	$\sim 10^{10}$	$\sim 10^{8}$	$\sim 10^{6}$
T	[K]	~ 2500	~ 1300	~ 500	~ 300
$B^2/8\pi$	[dyne cm^{-2}]	$\mathbf{10^{+2.0}}?$	$\mathbf{10^{+0.1}}$	$\mathbf{10^{-2.4}}$	$10^{-6.4}$
nKT	[dyne cm^{-2}]	$10^{+1.5}$	$10^{-2.8}$	$10^{-5.2}$	$10^{-7.4}$
$\rho V_{\rm exp}^2$	[dyne cm^{-2}]	$10^{+1.5}$	$10^{-2.5}$	$10^{-4.1}$	$\mathbf{10^{-5.9}}$
V_A	[km s^{-1}]	~ 15	~ 100	~ 300	~ 8

relation beyond stating that it seems to vary between $B \propto R^{-2}$ (solar-type) and $B \propto R^{-1}$ (toroidal). A significant increase of sample size is also crucial, as currently, the field at intermediate distances to the star (in the H_2O maser region) has only been measured for a handful of PNe progenitor stars. The environment close to the star, probed by SiO masers, has been observed in a much larger sample. However, the circular polarization of SiO masers could originate from non-Zeeman effects that only require a magnetic field three orders of magnitude weaker than required to explain the regular Zeeman effect. Current observations cannot yet distinguish between the two cases of SiO maser polarization (e.g. Amiri *et al.* 2011, in prep.). Regardless, the linear polarization observations have been shown to probe the magnetic field direction, and indicate well ordered magnetic fields throughout the circumstellar envelope.

The maser observations during the AGB phase are also consistent with the observations of a number of post-AGB objects. In the class of water-fountain sources, a strong toroidal magnetic field has been found for W43A (Vlemmings *et al.* 2006), and the poloidal field component is seen in IRAS 15445-5449 (Pérez-Sánchez *et al.* 2011). While an order of magnitude weaker then in the OH regions of Miras, the magnetic field is also significant in the OH maser region of the water fountains (Amiri *et al.* 2011). The observations of further post-AGB objects have also revealed a large scale magnetic field in the OH maser region of OH 17.7-2.0 (Bains *et al.* 2003) potentially consistent with a stretched dipole field. A magnetic field of several tens of mG is also measured in the H_2O maser region entrained by the jet of the binary post-AGB object OH 231.8+4.2 (Leal-Ferreira *et al.* 2011, in prep.).

During the PN phase, masers are rare and weak and until now only the PN K3-35 has had a few mG magnetic field measured in its OH masers (Miranda *et al.* 2001). Fortunately, there are a few other methods of measuring PN magnetic fields. The field orientation in the dust of the nebula can be determined using dust continuum polarization observations and current observations seem to indicate toroidal fields, with the dust alignment likely occurring close to the dust formation zone (Sabin *et al.* 2007). Similar observations will be possible in the near-future with ALMA.

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3. Outlook

While progress in studying the magnetic fields of evolved stars has been significant, a number of crucial questions remain to be answered. Several of these can be addressed with the new and upgraded telescopes in the near future. For example, the upgraded EVLA and eMERLIN will uniquely be able to determine the location of the masers in the envelope with respect to the central star, giving us, together with polarization observations, crucial information on the shape and structure of the magnetic field throughout the envelopes. ALMA will be able to add further probes of magnetic fields with for example high frequency masers and CO polarization observations, significantly expanding our sample of stars with magnetic field measurements. With the ALMA sensitivity, polarization will be easily detectable even in short observations and thus, even if not the primary goal, polarization calibration should be done. The new low-frequency arrays can potentially be used to determine magnetic fields in the interface between the ISM and PNe envelopes through Faraday rotation observations.

With the advances in the search for binaries and the theories of common-envelope evolution and MHD outflow launching, the new observations will address for example:

- Under what conditions does the magnetic field dominate over e.g. binary interaction when shaping outflows?
- Are magnetic fields as widespread in evolved stars as they seem?
- What is the origin of the AGB magnetic field - can we find the binaries/heavy planets that might be needed?
- Is there a relation between AGB mass-loss and magnetic field strength?

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