Magnetic fields around (post-)AGB stars and (Pre-)Planetary Nebulae

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Abstract. Observational evidence for strong magnetic fields throughout the envelopes of evolved stars is increasing. Many of the instruments coming on line in the near-future will be able to make further contributions to this field. Specifically, maser polarization observations and dust/line polarization in the sub-mm regime has the potential to finally provide a definite picture of the magnetic field strength and configuration from the Asymptotic Giant Branch (AGB) all the way to the Planetary Nebula phase. While current observations are limited in sample size, strong magnetic fields appear ubiquitous at all stages of (post-)AGB evolution. Recent observations also strongly support a field structure that is maintained from close to the star to several thousands of AU distance. While its origin is still unclear, the magnetic field is thus a strong candidate for shaping the stellar outflows on the path to the planetary nebula phase and might even play a role in determining the stellar mass-loss.

Keywords. Planetary Nebulae – Stars: AGB and post-AGB – Magnetic fields

1. Introduction

Strongly asymmetric planetary nebulae (PNe) have been shown to be common. The research into their shaping processes has become a fundamental part of our attempts to further the understanding of the return of processed material into the ISM by low- and intermediate-mass stars at the end of their evolution. Whereas the standard interacting winds scenario (Kwok et al. 1978) can explain a number of the PN properties, an important discovery has been 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). The source of this momentum excess has been heavily debated during the past several years, with the most commonly invoked cause being magnetic fields, binary or disk interaction or a combination of these (e.g. Balick & Frank 2002). Due to a number of similarities with the jets and outflows produced by young stellar objects, the study of P-PNe outflows provides further research opportunities into a potentially universal mechanism of jet launching.

Here I will review the observational evidence for strong magnetic fields in PNe as well as around their AGB and post-AGB progenitors. I will give an overview of the methods that can be used to study magnetic fields, especially in light of the plethora of new instruments that will be available shortly. Finally, I will discuss a number of questions related this topic that we can expect to be answered with the new instruments in the next few years.
2. Observational Techniques - Polarization

With the exception of observations where the magnetic field strength is estimated assuming forms of energy equilibrium, such as synchrotron observations, the magnetic field strength and structure is typically determined from polarization observations.

2.1. Circular Polarization

Circular polarization, generated through Zeeman splitting, can be used to measure the magnetic field strength. It measures the total field strength when the splitting is large and the line-of-sight component of the field when the splitting is small. 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$_2$O and OH masers. These can show circular polarization fractions ranging from $\sim$ 0.1% (H$_2$O) 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 non-maser molecular lines in circumstellar envelopes, 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.

2.2. Linear Polarization

Linear polarization, probing the structure of the plane-of-the-sky component of the magnetic field, can be observed both in the dust (through aligned grains) and molecular lines (through radiation anisotropy - the Goldreich-Kylafis effect). Typical percentages of linear polarization range from up to a few percent (e.g. dust, CO, H$_2$O masers) to several tens of percent (OH and SiO masers). Again the interpretation of maser polarization depends on a number of intrinsic maser properties, but in specific instances maser linear polarization can even be used to determine the full 3-dimensional field morphology. In addition to the geometry, the linear polarization of most notably dust, can also be used to obtain a value for the strength of the plane-of-the-sky component of the magnetic field. This is done using the Chandrasekhar-Fermi method, which refers to the relation between the turbulence induced scatter of polarization vectors and the magnetic field strength.

3. Current Status - Evolved Star Magnetic Fields

3.1. AGB Stars

Most AGB magnetic field measurements come from maser polarization observations (SiO, H$_2$O and OH). These have revealed a strong magnetic field throughout the circumstellar envelope. In Figure 1 I have indicated the magnetic field strength in the regions of the envelope traced by the maser measurements throughout AGB envelopes. 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 relation beyond stating that it seems to vary between $B \propto R^{-2}$.
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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$_2$O masers (Vlemmings et al. 2002, 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. CO polarization observations will uniquely probe the outer edge of the envelope (vertical dashed dotted line).

(solar-type) and $B \propto R^{-1}$ (toroidal). Future observations of CO polarization might be able to provide further constraints.

As the masers used for these studies are mostly found in oxygen-rich AGB stars, it has to be considered that the sample is biased. However, recent CN Zeeman splitting observations (Herpin et al. 2009) seem to indicate that similar strength fields are found around carbon-rich stars.

Beyond determining the magnetic field strength, the large scale structure of the magnetic field is more difficult to determine, predominantly because the maser observations often probe only limited line-of-sights. Even though specifically OH observations seem to indicate a systematic field structure, it has often been suggested that there might not be a large scale component to the field that would be necessary to shape the outflow (Soker 2002). So far the only shape constraints throughout the envelope have been determined for the field around the supergiant star VX Sgr (Fig. 2), where maser observations spanning 3 orders of magnitude in distance are all consistent with a large scale, possibly dipole shaped, magnetic field.
Figure 2. (left) The dipole magnetic field of the supergiant VX Sgr as determined from a fit to the H$_2$O maser magnetic field observations (Vlemmings et al. 2005). (right) Positions and polarization of the VX Sgr $v = 0, J = 5 - 4$ $^{29}$SiO masers observed with the SMA (Vlemmings et al. 2010). The masers spots are plotted with respect to the peak of the continuum emission. The black vectors are the observed polarization vectors scaled linearly according to polarization fraction. The long dashed inner circle indicates the star and the solid circle indicates the location of the 43 GHz SiO masers. The short dashed circle indicates the minimum radius of the $^{28}$SiO masers. The dashed lines indicate the position angle and its uncertainty of the inferred orientation of the dipole magnetic field of VX Sgr observed using H$_2$O and OH masers (Vlemmings et al. 2005; Szymczak et al. 2001).

3.2. Post-AGB Stars and P-PNe

Similar to the AGB stars, masers are the major source of magnetic field information of post-AGB and P-PNe, with the majority of observations focused on OH masers. These have revealed magnetic field strengths similar to those of AGB stars (few mG) and a clear large scale magnetic field structure (e.g. Bains et al. 2003).

The most promising results have come after the detection of the so-called 'water-fountain' sources. These sources exhibit fast and highly collimated H$_2$O maser jets that often extend beyond even the regular OH maser shell. With the dynamical age of the jet of order 100 years, they potentially are the progenitors of the bipolar (P-)PNe. Although the masers are often too weak for a detection of the magnetic field, observations of the arch-type of the water-fountains, W43A, have revealed a strong toroidal magnetic field that is collimating the jet (Fig. 3 and Vlemmings et al. 2006).

3.3. Planetary Nebulae

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
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Figure 3. (top left) Total power (I) and V-spectrum for one of the H$_2$O maser features in red-shifted lobe of the collimated jet of W43A including the best model fit of the V-spectrum corresponding to a magnetic field (Vlemmings et al. 2006). (top right) Confirmation of the magnetic field from single-dish GBT observations in the blue-shifted side of the lobe. As expected for being toroidal, the magnetic field reverses sign across the blue-shifted masers (Amiri et al. 2010). (bottom) The H$_2$O masers in the precessing jet (dashed-dotted line) of W43A (indicated by the cross) and the toroidal magnetic field of W43A. The vectors indicate the determined magnetic field direction, perpendicular to the polarization vectors, at the location of the H$_2$O masers. The ellipses indicate the toroidal field along the jet, scaled with magnetic field strength $\propto r^{-1}$.

alignment likely occurring close to the dust formation zone (Sabin et al. 2007). Faraday rotation studies are potentially also able to study the magnetic field in the interaction region between the interstellar medium and the stellar outflow.
In contrast to AGB stars, the central stars of PNe also show atomic lines that can be used to directly probe the magnetic fields on the surface of these stars. While measurements are still rare, observations of for example the central star of NGC 1360, indicate a field of order several kG (Jordan et al. 2005).

4. Origin of the Magnetic Field

Despite the strong observational evidence for evolved star magnetic fields, the origin of these fields is still unclear. In single stars, differential rotation between the AGB star core and the envelope could potentially result in sufficiently strong magnetic field (Blackman et al. 2001). However, as the energy loss due to a rotating magnetic field drag drains the rotation needed to maintain the field within several tens of years, an additional source of energy is needed (e.g. Nordhaus & Blackman 2006). If AGB stars would be able to have a sun-like convective dynamo, magnetically dominated explosions could indeed result from single stars. Alternatively, the energy could be provided by the interaction with a circumstellar disk, although the origin of the disk is then another puzzle.

Another explanation for maintaining a magnetic field is the interaction between a binary companion or potentially a heavy planet, with common-envelope evolution providing paths to both magnetically as well as thermally driven outflows (Nordhaus & Blackman 2006). A companion could be the cause of the precession seen in a number of water-fountain and (P-)PNe jets. However, to date, the majority of the stars with measured magnetic fields do not show any other indication of binarity.

| Table 1. Energy densities in AGB envelopes |
| --- | --- | --- | --- | --- |
|   | Photosphere | SiO | H\(_2\)O | OH |
| **B** [G] | ~ 50? | ~ 3.5 | ~ 0.3 | ~ 0.003 |
| **R** [AU] | - | ~ 3 | ~ 25 | ~ 500 |
| **V\(_{\text{exp}}\)** [km s\(^{-1}\)] | ~ 5 | ~ 5 | ~ 8 | ~ 10 |
| **n\(_{\text{H}_2}\)** [cm\(^{-3}\)] | ~ 10\(^{14}\) | ~ 10\(^{10}\) | ~ 10\(^{8}\) | ~ 10\(^{6}\) |
| **T** [K] | ~ 2500 | ~ 1300 | ~ 500 | ~ 300 |
| **B^2/8\pi** [dyne cm\(^{-2}\)] | 10\(^{+2.0\text{\footnotesize +1.0}}\) | 10\(^{+1.0\text{\footnotesize +0.1}}\) | 10\(^{-2.4}\) | 10\(^{-6.4}\) |
| **nKT** [dyne cm\(^{-2}\)] | 10\(^{+1.5\text{\footnotesize +1.5}}\) | 10\(^{-2.8\text{\footnotesize -2.8}}\) | 10\(^{-5.2}\) | 10\(^{-7.4}\) |
| **\(\rho V_{\text{exp}}^2\)** [dyne cm\(^{-2}\)] | 10\(^{+1.5\text{\footnotesize +1.5}}\) | 10\(^{-2.5\text{\footnotesize -2.5}}\) | 10\(^{-4.1}\) | 10\(^{-5.9}\) |
| **V\(_A\)** [km s\(^{-1}\)] | ~ 15 | ~ 100 | ~ 300 | ~ 8 |
5. Effect of the Magnetic Field

Until a more complete sample of magnetically active AGB stars, post-AGB stars and (P-)PNe is known, it is hard to observationally determine the effect of the magnetic field on these late stages of evolution. Starting with the AGB phase, a number of theoretical works have described the potential of magnetic fields in (at least partly) driving the stellar mass-loss through Alfvén waves (e.g. Falceta-Gonçalves & Jatenco-Pereira 2002), or through the creation of cool spots on the surface above with dust can form easier (Soker 1998). As current models of dust and radiation driven winds are still unable to explain especially the mass-loss of oxygen-rich stars, magnetic fields might provide the missing component of this problem, with tentative evidence already pointing to a relation between the magnetic field strength and mass-loss rate.

Other theoretical works have focused on the magnetic shaping of the stellar winds (e.g. Chevalier & Luo 1994; García-Segura et al. 2005; Frank & Blackman 2004). But to properly determine the possible effect of the magnetic fields, it is illustrative to study the approximate ratios of the magnetic, thermal and kinematic energies contained in the stellar wind. In Table 1 I list these energies along with the Alfvén velocities and typical temperature, velocity and temperature parameters in the envelope of AGB stars. While many values are quite uncertain, as the masers that are used to probe them can exist in a fairly large range of conditions, it seems that the magnetic energy dominates out to $\sim 50 - 100$ AU in the circumstellar envelope. This would correspond to the so-called 'launch' region of magneto-hydrodynamic (MHD) outflows, which typically extend to no more than $\sim 50R_i$, with $R_i$ the inner-most radial scale of launch engine (e.g. Blackman 2009). A rough constraint on $R_i$ thus seems to be $\sim 1 - 2$ AU, close to the surface of the star.

6. 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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