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Citation for the original published paper (version of record):
Vlemmings, W. (2018)
Magnetic fields around evolved stars
Contributions of the Astronomical Observatory Skalnate Pleso, 48(1): 187-193

Contrib. Astron. Obs. Skalnaté Pleso **35**, 1 – 8, (2005)

Magnetic fields around evolved stars

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Received: May 1, 2005; Accepted: August 28, 2005

Abstract. There has long been evidence of magnetic fields in the extended envelopes of asymptotic giant branch (AGB) and red supergiant (RSG) stars. These stars are important contributors to the enrichment of the interstellar medium by dust and heavy elements. Magnetic fields might play a role in the mass loss process responsible. Additionally, magnetic fields, typically in combination with binary companions, have often be suggested to be involved in shaping strongly a-spherical planetary nebulae (PNe). New telescopes and instruments are increasing our knowledge about magnetic fields around these evolved, mass losing, stars and their descendants.

Key words: supergiants, stars: AGB, post-AGB, PNe, mass-loss, magnetic fields, polarization, masers

1. Introduction

The role of magnetic fields around AGB stars is not clear. In principle, they could help levitate material off the stellar surface of AGB stars, 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). After the AGB phase, the stellar envelopes undergo a major modification as they evolve to PNe. 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 (Nordhaus et al., 2007). The mechanisms that drive mass loss from more massive evolved stars are also not well understood. The formation of dust grains that are non-transparent to stellar radiation, thought to drive the winds for several types of AGB stars, is inhibited close to evolved massive stars due to their extreme luminosity (e.g Norris et al., 2012). It is thus puzzling how the material is transported from the surface of the star to the radius where non-transparent dust species form. The distribution of material in the CSE of RSG stars is also highly a-spherical (e.g. Humphreys et al., 2007; O'Gorman et al., 2015). Models invoking e.g. convection, pulsations, scattering and magnetic waves have been proposed to explain the (anisotropic) mass loss in evolve massive stars, but it remains unclear which of these mechanisms plays the dominant role.

A previous review on AGB and (P-)PNe magnetic fields(e.g. Vlemmings, 2014) provides much of the background. Here I specifically focus on the most recent observational developments. I also predominantly focus on the observations of magnetic fields in the CSEs, although will present new observations that could indicate magnetic activity at the surface. This review concerns the magnetic field in RSG stars, AGB stars, and beyond. The earlier phases of cool giant stars are discussed in another review (Korhonen 2017, these proceedings).

2. Observational Techniques of CSE magnetic fields

2.1. Circular Polarization

The predominant source of magnetic field strength information during the late stages of stellar evolution comes from maser Zeeman splitting 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 (for a review, see Vlemmings, 2012). More recently, Zeeman splitting has also been detected in circumstellar CN (Duthu et al., 2017).

2.2. Linear Polarization

Linear polarization can be observed both in the dust (through aligned grains) and molecular lines (through radiation anisotropy - the Goldreich-Kylafis (GK) effect). The GK effect on CO has only recently been mapped for the first time in the envelope of evolved stars (Vlemmings et al., 2012) and allows for a systematic study of magnetic fields using ALMA. Typical percentages of linear polarization range from up to a few percent (e.g. dust, CO, H_2O masers) to several tens of percent (OH and SiO masers). Recent ALMA observations have confirmed that the linear polarization of OH masers probes the same large scale fields as observed in non-masing molecular lines (Tafoya & Vlemmings in prep.).

3. Observational status

3.1. AGB stars

Generally, AGB magnetic field measurements come from maser polarization observations (SiO, H_2O and OH). These have revealed a strong magnetic field throughout the circumstellar envelope. Figure 1, the magnetic field strength in the regions of the envelope traced by the maser measurements throughout AGB envelopes. The field appears to vary between $B \propto R^{-2}$ (solar-type) and $B \propto R^{-1}$ (toroidal). Although the maser observations trace only oxygen-rich AGB stars, recent CN Zeeman splitting observations (Duthu et al., 2017) indicate that similar strength fields are found around carbon-rich stars.

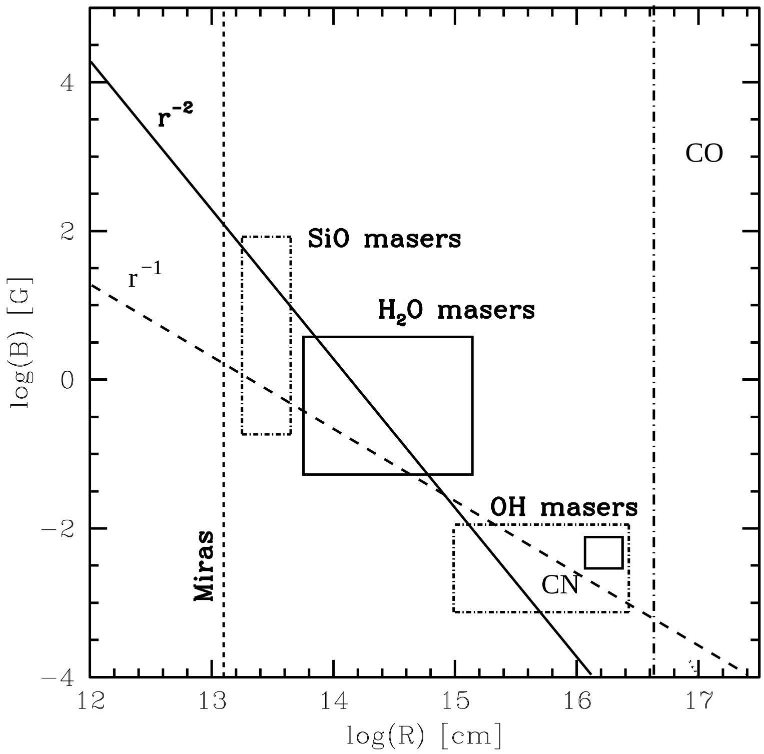

Figure 1. Magnetic field strength vs. radius relation as indicated by current maser polarization observation of a number of Mira stars. The boxes show the range of observed magnetic field strengths derived from the observations of SiO masers (Kemball et al., 2009; Herpin et al., 2006)), H_2O masers (Vlemmings et al., 2002, 2005; Leal-Ferreira et al., 2013), OH masers (Rudnitski et al., 2010; Gonidakis et al., 2014) and CN (Duthu et al., 2017). 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 (e.g. Vlemmings et al., 2012) will uniquely probe the outer edge of the envelope (vertical dashed dotted line).

The exact structure of the magnetic fields is more difficult to determine. Even though OH observations indicate a systematic field structure (e.g. Bains et al., 2003), 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). Observations of the linear polarization of CO (and other molecular lines) caused by the Goldreich-Kylafis effect (e.g. Vlemmings et al., 2012) allows for a much more detailed study of the magnetic field morphology. In the case of

IK Tau, the observations indicate a more or less uniform field from close to the star out to a few thousand AU. Recent ALMA observations of CO polarization around the post-AGB star OH17.7-2.0 further indicate that the magnetic field probed by the CO molecule is that same as that probed by the OH masers (Tafoya & Vlemmings, in prep.).

The envelope magnetic fields are also consistent with thus far the only direct measurement of the Zeeman effect on the surface of an AGB star, the Mira variable star χ Cyg (Lèbre et al., 2014). Interestingly, recently observations were made with ALMA of the surface activity of the AGB star W Hya (Vlemmings et al., 2017a, Figure 2). The activity could be related to magnetic fields. In Table. 1 an overview is given of the energy densities throughout the AGB envelopes.

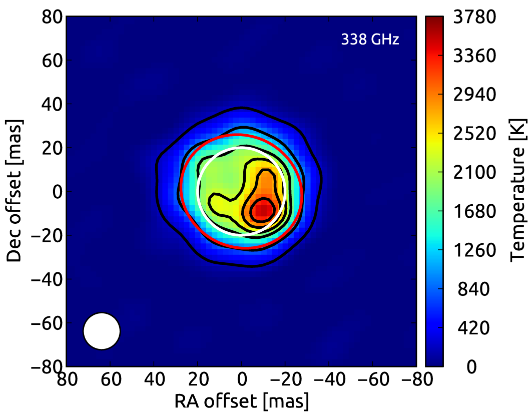

Figure 2. Brightness temperature map of the AGB star W Hya observed with ALMA at 338 GHz (Vlemmings et al., 2017a). The red ellipse indicates the size of the stellar disk at 338 GHz while the white circles indicates the size of the optical photosphere. The clear hotspot is unresolved and it brightness temperature in the map is a lower limit. From size measurements we can constrain the true brightness temperature to be > 50.000 K, which could be a sign of shock interaction or magnetic activity.

Table 1. Energy densities in AGB envelopes

		Photosphere	SiO	H_2O	OH
B	[G]	$\sim 1-10?$	~ 3.5	~ 0.3	~ 0.003
R	[AU]	-	~ 3	~ 25	~ 50
$V_{\rm exp}$	[km s^{-1}]	~ 20	~ 5	~ 8	~ 10
$n_{\rm H_2}$	[cm^{-3}]	$\sim 10^{11}$	$\sim 10^{10}$	$\sim 10^{8}$	$\sim 10^{6}$
T	[K]	~ 2500	~ 1300	~ 500	~ 300
$B^2/8\pi$	[dyne cm^{-2}]	$\mathbf{10^{-1.4,+0.6}}$?	$\mathbf{10^{+0.1}}$	$\mathbf{10^{-2.4}}$	$10^{-6.4}$
nKT	[dyne cm^{-2}]	$10^{-1.5}$	$10^{-2.7}$	$10^{-5.2}$	$10^{-7.4}$
$\rho V_{\rm exp}^2$	[dyne cm^{-2}]	$10^{-0.3}$	$10^{-2.5}$	$10^{-4.1}$	$\mathbf{10^{-5.9}}$
V_A	[km s^{-1}]	~ 20	~ 100	~ 300	~ 8

3.2. post-AGB stars and (P-)PNe

Similar to the AGB stars, masers are the main source of magnetic field information of post-AGB and P-PNe and even for some PNe. OH maser observations indicate magnetic field strengths similar to those of AGB stars (few mG) and a clear large scale magnetic field structure (Bains et al., 2003; Gómez et al., 2016). Also dust polarization observations indicate a large scale magnetic field (e.g. Sabin et al., 2015a).

Magnetic fields have also been detected around the so-called 'water-fountain' sources. These sources exhibit fast and highly collimated H_2O 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. Observations of the arch-type of the water-fountains, W43A, have revealed a strong toroidal magnetic field that is collimating the jet (Vlemmings et al., 2006). For another water-fountain source, IRAS 15445-5449, a synchrotron jet related to strong magnetic fields has been detected (Pérez-Sánchez et al., 2013). Similar, synchrotron emission has been found from what could be one of the youngest PNe (Suárez et al., 2015).

Finally, recently also surface fields have been measured for 2 post-AGB stars (Sabin et al., 2015b). These fields are consistent with the fields inferred from the envelope measurements

3.3. RSG stars

Maser observations have also long indicated strong magnetic fields in the envelopes of RSG stars (e.g. Vlemmings et al., 2002; Herpin et al., 2006). Most of the points that are relevant for AGB stars, such as the questions about local or large scale fields, are the same. The supergiant VX Sgr is one of the first stars where a large scale magnetic field, with a structure consistent throughout the envelope, was found (e.g. Vlemmings et al., 2005). With ALMA it is now possible to simultaneously study the polarization of regular molecular lines, maser lines, and circumstellar dust. Recent observations of VY CMa indicate magnetically aligned dust and consistent structures between the maser and non-maser molecular lines (Vlemmings et al., 2017b, Figure 3). The observations indicate the magnetic processes might be involved in the mass loss of these massive stars.

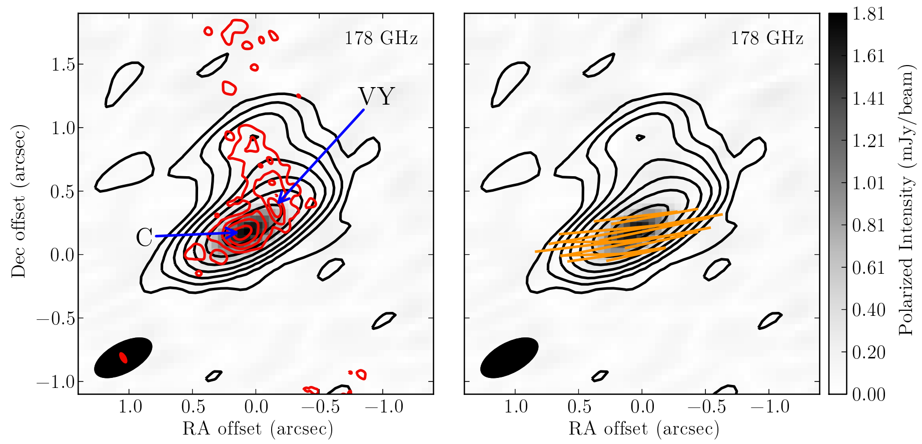

Figure 3. ALMA observations of the dust around the RSG VY CMa at 178 GHz (Vlemmings et al., 2017b). Arrows indicate dust clump C and the star (VY) identified in previous ALMA observations (O'Gorman et al., 2015). The grey scale image is the linearly polarized intensity, which is seen to peak at the bright dust component Clump C in the South-East. The similarly spaced red contours (left) indicate the ALMA 658 GHz continuum from O'Gorman et al. (2015). The vectors (right) indicate the direction of polarization rotated by 90° to indicate the magnetic field direction traced by magnetically aligned dust grains.

4. Conclusions

Many observations have now shown that ordered magnetic fields are present throughout the envelopes of AGB, post-AGB, (P-)PNe and RSG stars. The question on their origin and influence however, has not yet conclusively been answered. In the near future, it will finally be possible to relate dust and gas structures and kinematics, to the strength and morphology of the magnetic field for significant samples of stars.

Acknowledgements. WV acknowledges support from the European Research Council (ERC) through the ERC consolidator grant nr. 614264 and from the Swedish Research Council.

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