

# Magnetic fields of AGB and post-AGB stars

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**Abstract.** There is ample evidence for the presence of strong magnetic fields in the envelopes of (post-)Asymptotic Giant Branch (AGB) stars as well as supergiant stars. The origin and role of these fields are still unclear. This paper updates the current status of magnetic field observations around AGB and post-AGB stars, and describes their possible role during these stages of evolution. The discovery of magnetically aligned dust around a supergiant star is also highlighted. In our search for the origin of the magnetic fields, recent observations show the signatures of possible magnetic activity and rotation, indicating that the magnetic fields might be intrinsic to the AGB stars.

**Keywords.** magnetic fields, polarization, stars: AGB and post-AGB, supergiants, rotation, spots

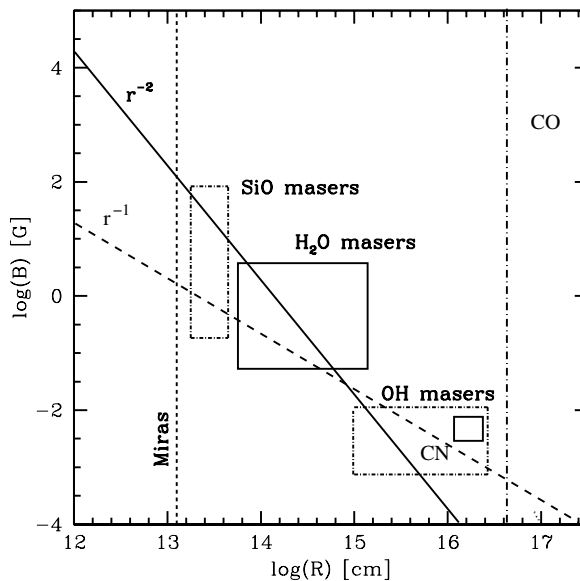
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## 1. Introduction

Magnetic fields are ubiquitous throughout the Universe and play an important role across a wide range of scales. Primordial magnetic fields could have played a role in the formation of the first stars just as magnetic fields in molecular clouds are an important ingredient in current star formation. Magnetic fields have also been detected in almost all stellar types and in almost all phases of stellar evolution (e.g. [Berdyugina 2009](#)), and have significant effects on stellar evolution through, e.g. their influence on the internal mixing. The magnetic field of stars can have either a dynamo origin, i.e. be generated by a dynamo process in the star itself (e.g. [Charbonneau 2014](#)), or can be the result of a remnant 'fossil' field, which are fields that originate from the star formation process (e.g. [Braithwaite & Spruit 2004](#)). The stellar magnetic field is affected by the changes of physical properties during stellar evolution and, because of flux conservation, becomes increasingly difficult to observe at the stellar surface when the star expands in the final phases of its life. However, in stellar end products, such as white dwarfs and neutron stars, magnetic fields are also shown to be significant.

The role of magnetic fields around AGB stars is not clear. In principle, they could help levitate material off the stellar surface through Alfvén waves (e.g. [Falceta-Gonçalves & Jatenco-Pereira 2002](#)), or through the creation of cool spots on the surface above where dust can form easier ([Soker 1998](#)). A specific model for the AGB star  $\alpha$  Ceti (Mira A) has shown that a hybrid magnetohydrodynamic-dust-driven wind scenario can explain its mass loss ([Thirumalai & Heyl 2013](#)). In such a model, Alfvén waves add energy to lift material before dust forms and radiation pressure accelerates a wind. Magnetic fields also play an important role in the internal mixing required for s-process (slow) neutron capture reactions that define the stellar yields (e.g. [Trippella \*et al.\* 2016](#)).

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



**Figure 1.** The circumstellar magnetic field strength vs. radius relation as indicated by current (maser) polarization observation. 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<sub>2</sub>O masers (Vlemmings *et al.* 2002, Vlemmings *et al.* 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. Observations of the Goldreich-Kylafis effect in CO (e.g. Vlemmings *et al.* 2012) will uniquely probe the outer edge of the envelope (vertical dashed dotted line).

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 (CSE) evolves into a PN. As the majority of pre-PNe are aspherical, an additional mechanism is needed to explain the departure from sphericity. This mechanism is still a matter of fierce debate. One possibility is that the interaction of the post-AGB star and a binary companion or massive planet supports a strong magnetic field that is capable of shaping the outflow (e.g. Nordhaus *et al.* 2007).

This paper expands on (and partly reproduces) the reviews presented in Vlemmings (2018) and Vlemmings (2014) and I refer interested readers to those review (and references therein) for further background.

## 2. Overview of magnetic field observations

### 2.1. AGB stars

Generally, AGB magnetic field measurements come from maser polarization observations (SiO, H<sub>2</sub>O and OH). These have revealed a strong magnetic field throughout the CSE. Figure 1 shows the magnetic field strength in the regions of the CSE 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 fields strengths are found around carbon-rich stars. The CSE magnetic fields are also consistent with the, thus far, only direct measurement of the

**Table 1.** Energy densities in AGB envelopes

		Photosphere	SiO	H <sub>2</sub> O	OH	CO/CN
$B$	[G]	$\sim 1 - 10^?$	$\sim 3.5$	$\sim 0.3$	$\sim 0.003$	$\sim 0.003 - 0.008$
$R$	[AU]	-	$\sim 3$	$\sim 25$	$\sim 50$	$\sim 50 - 100$
$V_{\text{exp}}$	[km s <sup>-1</sup> ]	$\sim 20$	$\sim 5$	$\sim 8$	$\sim 10$	$\sim 10$
$n_{\text{H}_2}$	[cm <sup>-3</sup> ]	$\sim 10^{11}$	$\sim 10^{10}$	$\sim 10^8$	$\sim 10^6$	$\sim 10^5$
$T$	[K]	$\sim 2500$	$\sim 1300$	$\sim 500$	$\sim 300$	$\sim 150$
$B^2/8\pi$	[dyne cm <sup>-2</sup> ]	<b><math>10^{-1.4, +0.6}</math></b>	<b><math>10^{+0.1}</math></b>	<b><math>10^{-2.4}</math></b>	$10^{-6.4}$	<b><math>10^{-6.0, -6.4}</math></b>
$nKT$	[dyne cm <sup>-2</sup> ]	$10^{-1.5}$	$10^{-2.7}$	$10^{-5.2}$	$10^{-7.4}$	$10^{-8.7}$
$\rho V_{\text{exp}}^2$	[dyne cm <sup>-2</sup> ]	$10^{-0.3}$	$10^{-2.5}$	$10^{-4.1}$	<b><math>10^{-5.9}</math></b>	$10^{-6.9}$
$V_A$	[km s <sup>-1</sup> ]	$\sim 20$	$\sim 100$	$\sim 300$	$\sim 8$	$\sim 8$

Energy densities through AGB star CSEs (dominating energy densities are in bold face). From left to right the columns indicate the stellar photosphere, maser regions and the region probed by CO/CN, with increasing distance to the central star. The top rows are the typical magnetic field strength  $B$ , distance to the star  $R$ , expansion velocity  $V_{\text{exp}}$ , hydrogen number density  $n_{\text{H}}$  and temperature  $T$ . The bottom rows are the magnetic, thermal and kinematic energy and a rough estimate of the Alfvén velocity  $V_A$ .

Zeeman effect on the surface of an AGB star, the Mira variable  $\chi$  Cyg (Lèbre *et al.* 2014). In Table 1 an overview is given of the energy densities throughout the AGB CSEs.

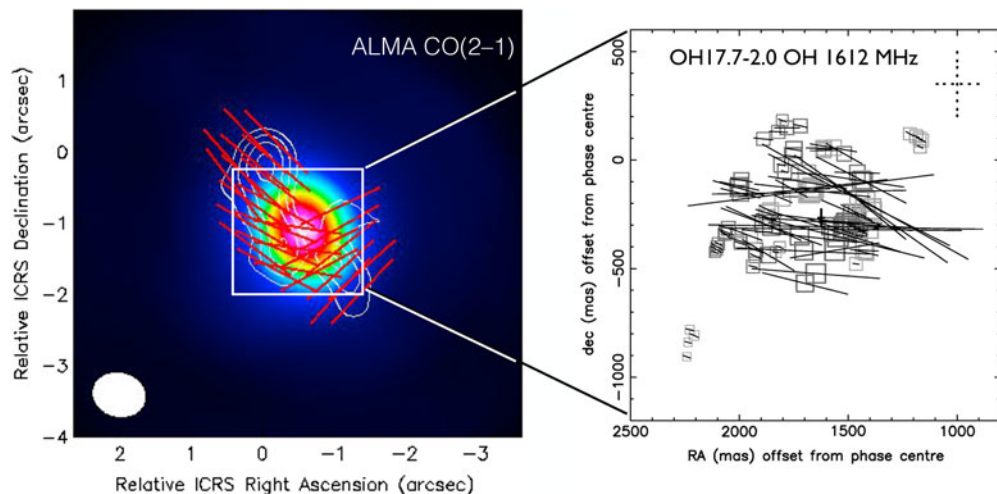
The large-scale structure of the magnetic field is more difficult to infer, predominantly because the maser observations often probe only limited line-of-sights. Even though specifically OH observations seem to indicate a systematic field structure, it has often been suggested that there might not be a large-scale component to the field that would be necessary to shape the outflow (Soker 2002). Until recently the only tight shape constraints throughout the CSE had been determined for the field around the supergiant star VX Sgr, where maser observations spanning 3 orders of magnitude in distance are all consistent with a large-scale, possibly dipole-shaped, magnetic field (Vlemmings *et al.* 2005, Vlemmings *et al.* 2011).

Very recent ALMA observations have shown that it will soon be possible to finally overcome the problems with determining the circumstellar magnetic field structure. This involves observations aimed at measuring the Goldreich-Kylafis effect, which allows us to use the polarisation of non-maser molecular lines (in this case CO) to determine the magnetic field morphology in the more diffuse circumstellar gas. The first of these observations, for the post-AGB star OH 17.7-2.0, indicate that the magnetic field structure probed by the CO is consistent with that derived from OH maser observations (Fig. 2, Tafoya & Vlemmings, in prep.). This puts to rest the decades old question if maser magnetic field measurements can really be used to probe the large-scale fields. The second set of observations has given us the first velocity-resolved view of the large-scale magnetic field in the AGB star IRC+10216 (Fig. 3, Vlemmings *et al.*, in prep.).

## 2.2. post-AGB stars

Similar to the AGB stars, masers are the main source of magnetic field information of post-AGB and pre-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<sub>2</sub>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 (pre-)PNe. Observations



**Figure 2.** A comparison of the magnetic field determined using ALMA observations of the Goldreich-Kylafis effect on circumstellar CO (left, Tafoya & Vlemmings, in prep.) and MERLIN observations of OH masers (right, Bains *et al.* 2003) around the post-AGB star OH 17.7-2.0. These observations show that CO and OH trace the same large-scale magnetic field.

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).

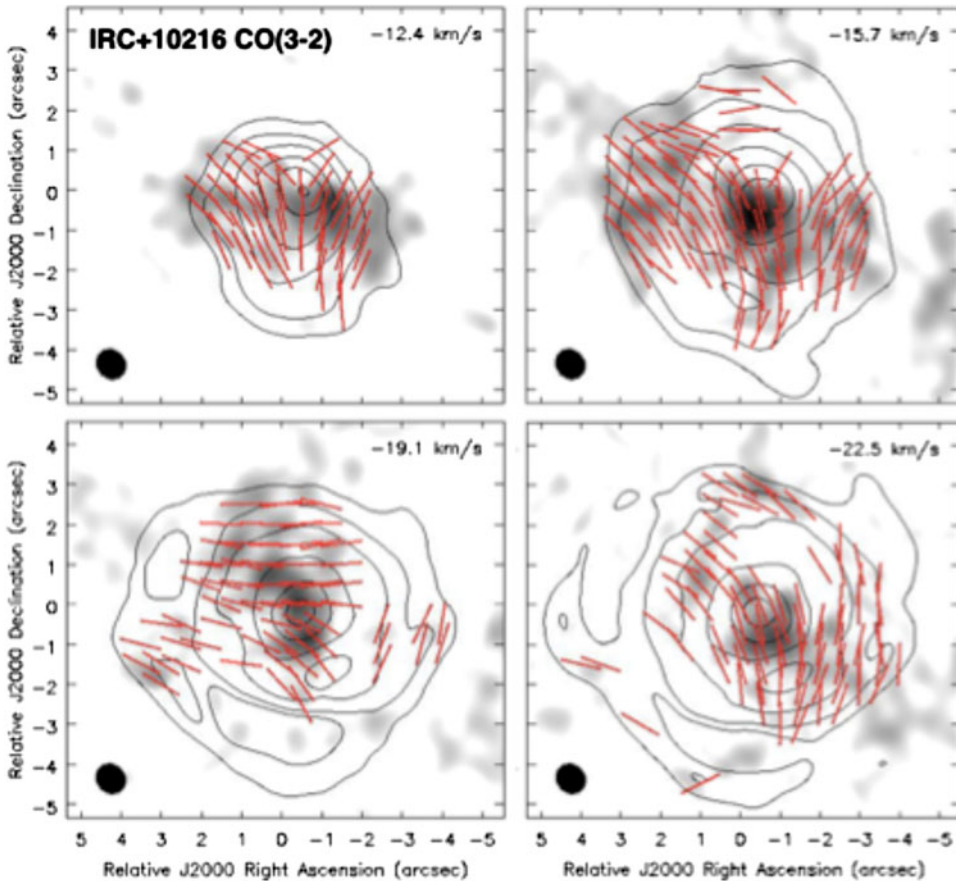
Finally, recently also surface fields have been measured for 2 post-AGB stars (Sabin *et al.* 2015b). These fields are consistent with the fields inferred from the CSE measurements.

### 2.3. Supergiant stars

Many maser observations show that strong magnetic fields are also present in the envelopes of Red Supergiant stars (e.g. Vlemmings *et al.* 2002; Herpin *et al.* 2006). The questions about local or large-scale fields, are the same as around AGB stars. As noted above, 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. At (sub-)millimeter wavelengths it is now possible to simultaneously study the polarization of masers, regular molecular lines, and circumstellar dust using ALMA. Recent observations of VY CMa indicate magnetically aligned dust and consistent structures between the maser and non-maser molecular lines (Fig. 4, Vlemmings *et al.* 2017a). The observations indicate that magnetic fields could be involved in the mass loss of these massive stars.

## 3. Indirect tracers and origin of the magnetic field

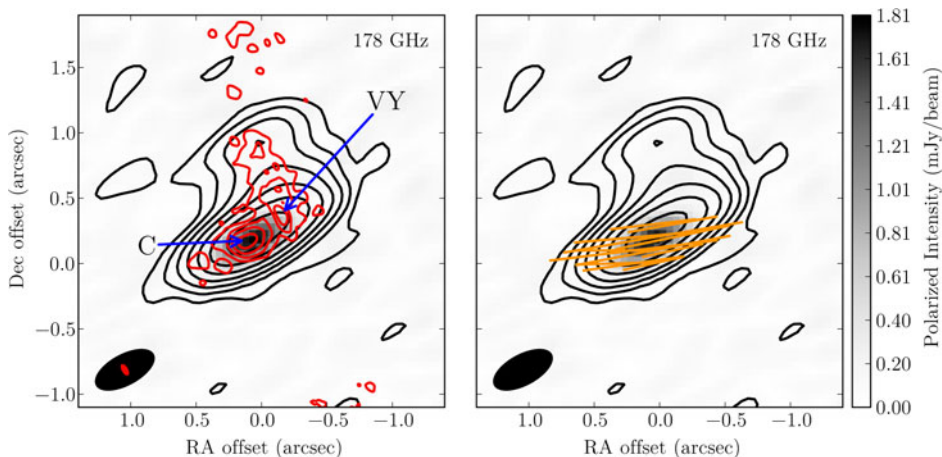
The origin of AGB magnetic fields is unclear and might require an extra source of angular momentum to maintain a stellar dynamo. This however depends strongly on the magnetic coupling throughout the star itself. If a sufficiently strong magnetic field persists at the AGB stellar surface, it might be possible to detect signs of magnetic activity. Recently, it has been shown that the majority of the AGB stars are UV-emitters



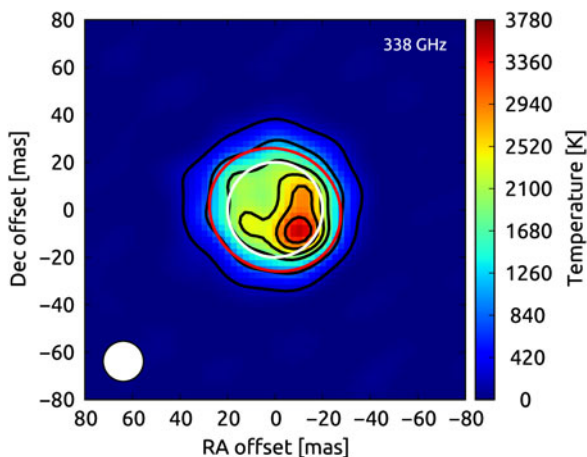
**Figure 3.** Four channel maps showing the Goldreich-Kylafis effect on the CO(3-2) line in the CSE of the AGB star IRC+10216. The ALMA observations for the first time clearly resolve the magnetic field structure throughout the CSE. The red vectors indicate the polarisation direction. The linearly polarised emission is shown in greyscale. The contours indicate the total intensity emission. A structure function analysis will be able to reveal the velocity resolved field strength and an initial analysis indicates a structured field with a strength  $> 1$  G at the stellar surface (Vlemmings *et al.*, in prep.).

(Montez *et al.* 2017) which could be a sign of (magnetic) activity. Similarly, recent observation of the surface of the AGB star W Hya show high brightness temperature hotspots (Fig 5, Vlemmings *et al.* 2017a). These spots can arise from strong shocks but could also point to magnetic activity.

As previously noted, the angular momentum imparted by a stellar (or sub-stellar) companion might be needed to maintain a stellar dynamo that can generate the observed magnetic fields. However, rotation is very difficult to measure for the extended AGB stars that are undergoing pulsations and show large convective cells. Only very recently has ALMA been able to measure the fast ( $\sim 1 \text{ km s}^{-1}$ ) rotation of the AGB star R Dor (Fig. 6, Vlemmings 2018). As the rotation is almost two orders of magnitude larger than otherwise expected, it is a likely sign of interaction with a hitherto unknown companion. Unfortunately, no magnetic field observations exist yet for R Dor and it is thus not yet possible to establish a link between the generation of a magnetic field and the fast rotation.



**Figure 4.** ALMA observations of the dust around the RSG VY CMa at 178 GHz (Vlemmings *et al.* (2017b)). Arrows indicate a strong dust clump (C) and the star (VY). The grey scale image is the linearly polarized intensity. 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 the magnetic field traced by magnetically aligned dust grains.

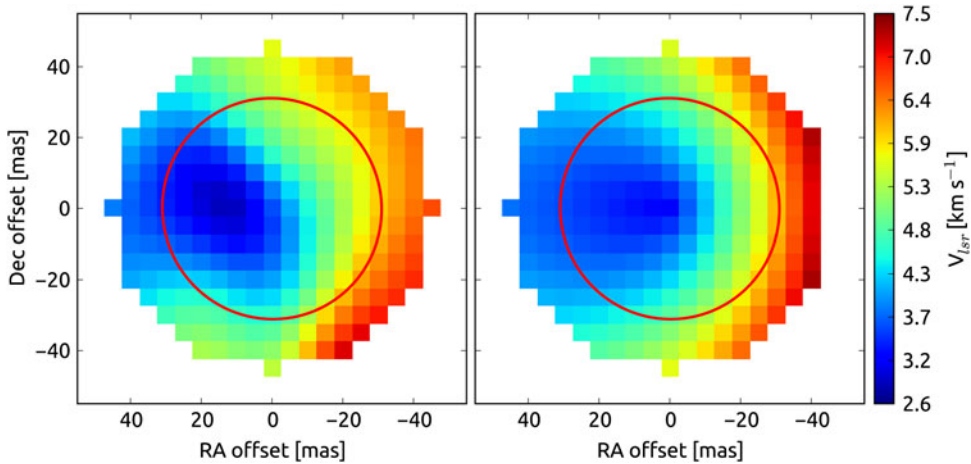


**Figure 5.** Brightness temperature map of the AGB star W Hya observed with ALMA at 338 GHz (Vlemmings *et al.* 2017a). The red ellipse indicates the size of the stellar disk at 338 GHz while the white circle indicates the size of the optical photosphere. The hotspot is unresolved and its brightness 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.

#### 4. Conclusions

Magnetic fields are ubiquitous around AGB and post-AGB stars, and several observations indicate a link between the magnetic field and the collimated outflows found in pre-PNe. Additionally, indirect observations of hotspots and UV-emission might point to magnetic activity on the surface of AGB stars. However, it is only now becoming possible to start probing the morphology of the magnetic field in AGB CSEs and to finally determine the role of magnetism around evolved stars.





**Figure 6.** From [Vlemmings \*et al.\* \(2018\)](#) (left): Center velocity of the SiO  $v = 3, J = 5 - 4$  emission line indicating the fast rotation in the inner CSE of R Dor. The red ellipse indicates the measured size of the star at 214 GHz. (right): The best fit model of solid-body rotation including a small expansion velocity component.

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## Discussion

DE MARCO: There seem to be too many AGB stars with B-fields to be justified by a close-by companion. So, are you saying that there *must* be an alternative scenario to the binary scenario?

VLEMMINGS: Yes. Although the sample can still be considered small, magnetic fields appear to be present in all studied sources with extrapolated surface field strengths of a few Gauss. Certainly these sources do not all have close-by *stellar* companions.

