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Magnetic fields in PNe and other evolved low-mass and intermediate-mass stars

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Abstract. Magnetic fields are likely to be an efficient mechanism which can affect evolved intermediate mass stars (i.e. post-AGB stars and planetary nebulae) in different ways such as via the shaping of their envelope. However, observational probes for the presence of those fields are still scarce. I will present a summary of the works, including those from our group, on the detection and measurement of magnetic fields in various evolved objects.

Keywords. magnetic fields, polarization, stars: AGB and post-AGB, (ISM:) planetary nebulae: general

1. Introduction

One of the reasons why we investigate magnetism in evolved intermediate mass stars (i.e. post-AGBs stars (PAGBs), proto-planetary nebulae (PPNe) and planetary nebulae (PNe)) is to understand its role in the structure and dynamics of these objects. Indeed, we are looking for magnetic field-related effects such as the collimation of outflows or the generation and launching of jets which are expected to occur at this phase of stellar evolution, as they are found happening in other objects like the Sun, T Tauri stars or Herbig-Haro objects for example. In a similar vein we also want to establish a direct correlation between the magnetic fields (MFs) and the different morphological structures found in PPNe and PNe. While it has been emphasized in recent years that these fields are not likely the main shaping agent (binary systems are more likely the principal actor), this absolutely does not discard the action of MFs at other scales.

MFs have been searched for in circumstellar envelopes (CSE) via the polarized emission from aligned dust grains, molecular lines and MASERs; and at the surface of central stars via the direct measurement of Zeeman splitting of atomic lines.

2. Review of searches for magnetic fields in circumstellar envelopes

Using the theory of dust alignment by MFs, Greaves (2002) and Sabin *et al.* (2007, 2014, 2015) have shown the presence of MFs and traced their structure in a small set of evolved stars. Large scale toroidal and polar MF structures were found in CRL 2688, NGC 7027, NGC 6302 and NGC 6537 (resolution ∼7"– 14") and a toroidal or helicoidal MF geometry was seen in OH231.8+4.2 at medium scales (resolution ∼2") using interferometric arrays. For this bipolar object a magnetic launching mechanism has also been invoked.

Assuming the Goldreich-Kylafis effect and that the linear polarization of the thermal emission of molecules (CO, SiO, CS ..) traces the MF, Vlemmings *et al.* (2012) and Girart *et al.* (2012) investigated two AGB stars (IK Tau and IRC+10216 respectively) and presented first time detection of molecular line polarization (not MASERS). The polarized emission distribution might indicate a complex MF geometry associated with the CSE geometry. However a full radiative transfer analysis is required to define the actual direction of the MF (see Kylafis 1983 & Morris *et al.* 1985).

In an analysis to be published, Sabin *et al.*, investigated the PPN Frosty Leo using both dust and molecular polarization and found an overall marginal MF detection.

Aside from those results, Pérez Sánchez *et al.* (2013) detected synchrotron emission towards the post-AGB star IRAS 154455449 tracing the bipolar shape: this tends to indicate that the jet is likely collimated by MFs.

Finally, several works have been carried out over the years to investigate MASERs in evolved stars and the correlation with MFs via circular and linear polarization (e.g. Herpin *et al.* 2006, Vlemmings *et al.* 2007, Etoka *et al.* 2009, Leal Ferreira *et al.* 2013, Gomez *et al.* 2016). Ordered field structures have been found (e.g. the red supergiant (RSG) VX Sgr). And, in PNe field strengths between ∼0.8 and 24 mG have been measured via the analysis of OH masers in K3-35 (Gómez *et al.* 2009), IRAS 16333-4807 (Qiao *et al.* 2016), JaSt 23 and IRAS 17393-2727 (Gómez *et al.* 2016). In addition to the fact that masers, being compact and bright sources, can give both the strength and direction of the MF in CSE; surface MFs can be extrapolated based on different distribution laws ($1/r$, $1/r^2$,$1/r^3$) representative of the different MF geometries (toroidal, poloidal/solar or dipole structure respectively).

3. Review of searches for magnetic fields in central stars

The method applied is based on the detection of circularly polarised Zeeman splitting patterns in atomic lines using medium to high resolution spectropolarimeters. It is then clear that objects showing many emission lines in their spectrum (due to the nebular contribution) as well as the faint ones i.e. $\geqslant$ 9–10 mag in B- or V-band are not the best candidates. Hence there is no clear and definite detection of MFs at the stellar surface of PNe so far (see Leone *et al.* 2011,2014; Todt *et al.* 2014, Asensio Ramos *et al.* 2014, Steffen *et al.* 2014). Our group's (LS, GAW, AL) attempt to look for MFs at the stellar surface of the PN NGC 6826 with the high resolution spectropolarimeter ESPaDOnS used the least squares deconvolution technique (LSD, Donati *et al.* 1997) to investigate the presence of a field. A subsequent analysis using the first-order moment method (Rees & Semel 1979) yielded a value for the longitudinal field B_l = 620±500 G. No magnetic field was unveiled for this PN (see Fig.1).

PAGBs appear to be the most suitable objects as they have fewer emission lines and the brightest objects have sharp absorption lines. Sabin *et al.* (2014) studied a group of seven Post-AGB stars with the spectropolarimeters ESPaDOnS and Narval (R=65000), and found a definite MF detection for the RV Tauri stars U Mon (10.2±1.7 G) and R Sct (0.9±0.5 G). The latter result was confirmed and extended by Tessore *et al.* (2015).

Table 1 summarizes the field strengths measured at the surface (or photosphere) of different stars along the HR diagram, from the literature. One of the least studied and therefore rather unknown groups consists of the AGB/Post-AGB/PPNe/PNe objects.

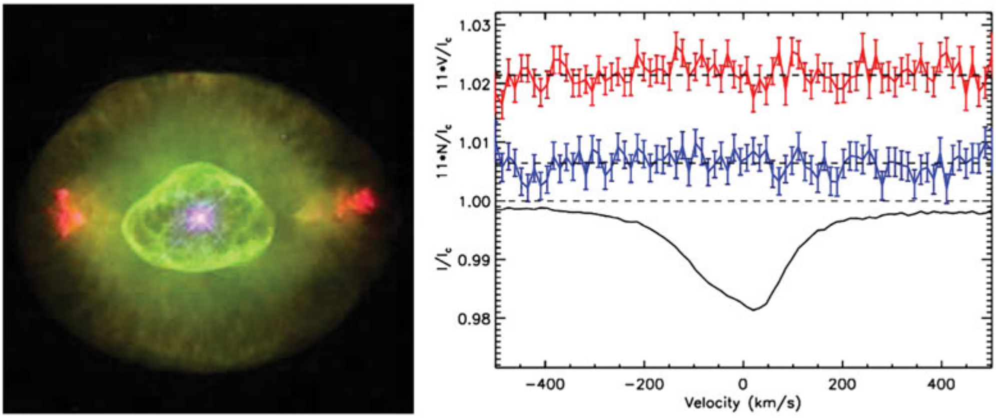

Figure 1. Stellar surface magnetic field analysis of the PN NGC 6826 with ESPaDOnS. The red line (top) indicates the Stokes V spectrum, the blues line (middle) is for the null spectrum an the black line (bottom) indicates the Stokes I spectrum. No MF detection is seen in this case.

Table 1. MFs strength along the HR diagram

Evolutionary phase	MFs range
T Tauri and low mass stars on the Main Sequence (MS)	Up to $\sim$ 2 kG
Cool MS solar type stars	$\sim$10 G and $\sim$ kG in the spots
Intermediate and massive stars on the PreMS and MS	$\sim$100 G up to 20–30 kG
Post-MS stars (RSGs, AGBs, PostAGBs and PNe)	**$\sim$ 1–10 G ?**
White Dwarfs	$\sim 10^3$-10^9 G

The difficulty in measuring surface MFs for these objects is likely related to the fact that their fields are both weak and complete, and consequently are below the detection limit.

4. Future and prospects

The detection of MFs in the envelopes of PPNe and PNe is now possible with ALMA via dust (since cycle 2) and line polarization (since cycle 4). This polarimetric array will allow us to reach higher resolutions and then trace the field closer to the central star to detect any magnetic launching mechanism. In cycle 4, three programs targeting evolved stars involve the use of polarization. The measurement of MFs at the stellar surface is an ongoing investigation with the currently available facilities.

In particular, several projects aiming at the search for MFs are now underway in Mexico and will help in our studies of evolved stars: I) a fiber-fed polarimeter which can be coupled with medium and high resolution optical spectrographs on the 2.1m telescope of the Observatorio Astronómico Nacional is set to be operational for 2017 and plans are already made to also equip the future 6.5m San Pedro Martír Telescope (with an expected first light in 2023); II) TolTEC, a polarimeter on the Large Millimeter Telescope is also expected to be available around 2019.

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5. Conclusions

• Magnetic fields are found in PNe, although they are more easily accessible in the envelope than in the central star. This is likely due to sensitivity issues for the detection. Spectropolarimetry of these evolved stars is a delicate and time consuming work. Hence, an upgrade in the instrumentation (resolution and permitted waveband) and telescope (size) would certainly help to resolve this issue.

• A magnetic launching mechanism seems to be a viable explanation for the morphology found in some objects but this would need confirmation with deeper data from ALMA for example and modelling with MHD tools.

• Although the detection rate is rather slow and the detection numbers still pretty low, we are entering in an exciting time for polarization studies with much needed and more sensitive instrumentation either already available or about to become available!

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Discussion

De Marco: Many AGB have now detected magnetic fields (MF). Only a minority of AGB stars are part of an interacting binary. So are we saying that single AGB stars can sustain long term MF, contrary to what theory predicts (Nordhaus *et al.* 2007)?

Zijlstra: The AGB star B fields measure B fields in the outflows and, with masers, in clumps where the MF could be intensified. Hence it is hard to determine what these measurements mean for the global MF in the AGB star.

Q: In systems like U Mon is the magnetic field detectable in the central star? Is it strong enough to affect the stellar system, e.g. the orbital separation?

Zijlstra: Magnetic fields should be detectable in principle: in stars like UMon and R Sct we suspect that the shocks in the stellar atmospheres play a role in detectability as they could amplify the fields by compression. In the weakfield regime, you need to combine high resolution spectropolarimetry, bright stars and good timing (when stars are at maximum). We have not yet conducted any study on the effects of a strong magnetic field. The current work (e.g. Ramirez Velez *et at al.* 2016) are aimed at recovering aspects such such as the geometry of the magnetic field.

Q: The key issue is whether the fields shape the gas or vice versa. When will we get an answer, and how will we be able to tell?