

Magnetic fields in AGB stars and (proto-) Planetary Nebulae

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Abstract. During its quick transition to the Planetary Nebula stage, the Asymptotic Giant Branch star will completely change its geometry. This AGB stellar evolution stage is characterized by a high mass loss driven by the radiation pressure. Strong magnetic field may rule the mass loss geometry and the global shaping of these objects. Following our previous work on the polarization of the SiO maser emission in a representative sample of O-rich evolved stars, we present here a study towards C-rich objects and PPN/PN objects to obtain unbiased conclusions. Using Xpol at the IRAM-30 m telescope, we have conducted CN N=1-0 observations to investigate the Zeeman effect in this molecule and draw conclusion on the evolution of the magnetic field and its influence during the transition of an AGB star to the PN stage. Following the analysis described by Crutcher *et al.* (1996) we derive an estimate of the magnetic field.

Keywords. Magnetic field – stars: evolution – radio lines: stars – ISM: molecules

1. Introduction

The prodigious mass loss observed in the numerous and widespread evolved stars make these objects the main recycling agents of the interstellar medium, and thus one of the most important objects in the Universe. During its quick transition to the Planetary Nebula (hereafter PN) stage, the Asymptotic Giant Branch (hereafter AGB) star will completely change its geometry: the quasi-spherical object becomes axisymmetrical, point symmetrical or even shows more high-order symmetries (e.g. Sahai & Trauger 1998). The classical or generalized *Interacting Stellar Winds* models (cf. Kwok 2000) try to explain this shaping, but have serious difficulties in producing complicated structures with peculiar jets or ansae and do not fully address the origin of the wind.

Strong magnetic field may rule the mass loss geometry and could thus determine the global shaping of these objects. Some recent studies tend to demonstrate the importance of magnetic field in evolved objects. Bujarrabal *et al.* (2001) show that in 80% of the PPNe from their sample the fast molecular flows have too high momenta to be powered by radiation pressure (1000 times larger in some cases) what may be explained by magnetic field. Recently, magnetic field was discovered for the first time in central stars of PN (Jordan *et al.* 2005) and estimated to be at the kiloGauss level, but polarimetric observations toward AGB stars are needed to constrain the magnetic field strength. Moreover, new models involving the magnetic field B were developed where B plays the role of a catalyst and of a collimating agent.

2. Magnetic field in AGB stars

The circumstellar envelope of evolved stars can be probed at different depths through the study of the maser emission of three different molecules, OH, H₂O and SiO, located at different distances from the central star, respectively at 1000-10000, a few 100 and 5-10 AU (one stellar radius $R_{\star} \sim 1$ AU).

Measurement of the SiO maser radiation polarization can lead to an estimation of the value of magnetic field, $B_{//}$ on the line of sight (for a single dish antenna), or can reveal the structure of the magnetic field (interferometric observations). Until now numerous polarimetric observations of OH masers have been done, several of H₂O masers, but few of SiO maser emission. It must be stressed that SiO is a non-paramagnetic species. The Zeeman splitting exists but the sublevels overlap; the effect is thus undetectable and hence only net polarization can be used to trace magnetic fields. The current state of the knowledge of B is:

- between 1000-10000 AU, $B_{//} \sim 5 - 20$ mG (OH masers, e.g. Kemball & Diamond 1997, Szymczak & Cohen 1997),
- at a few 100 AU from the star, $B_{//} \sim$ a few 100 mG (H₂O masers, e.g. Vlemmings, Diamond & van Langevelde 2001),
- at 5-10 AU, $B_{//} \sim 5 - 10$ G (SiO masers; Kemball & Diamond 1997, VLBI observations in TX Cam).

3. The SiO maser polarization results

Simultaneous spectroscopic measurement of the 4 Stokes parameters (cf. Fig. 1) were carried out towards 57 O-rich evolved stars by Herpin *et al.* (2006) via observations of the SiO ($v=1, J=2-1$) line at 86.243 GHz. These observations were performed with the IF polarimeter installed at the IRAM 30m telescope at Pico Veleta, Spain (Thum *et al.* 2003). From the Stokes parameters measurements one deduces for each velocity channel:

- the circular polarization rate $p_C = V/I$
- the linear polarization rate $p_L = \sqrt{Q^2 + U^2}/I$
- the polarization angle $\chi = \frac{\arctan(U/Q)}{2}$

Assuming Elitzur *et al.* (1996) maser theory, we calculate the mean value of the magnetic field $B_{//}$ for each SiO maser component (cf. Herpin *et al.* 2006). $B_{//}$ is between 0 and 18 Gauss, with a mean value of 3.5 G. This value combined with the strength of the field in more outer layers of the envelope (given by OH and H₂O masers) agrees with a variation law for B in $1/r$.

The main bias in this study was the source sample, because SiO maser emission is only present in O-rich evolved objects and disappears soon after the star has reached the end of the AGB (Nyman *et al.* 1998), this method cannot be used in C-rich objects or PPN/PN. Moreover, no OH/H₂O maser lines are detected toward C-rich stars (e.g., Szczerba *et al.* 2002). As a consequence, none of the maser molecules can be used to estimate the magnetic field in these objects. Nevertheless, the same type of study we did in O-rich stars should also be conducted within C-rich objects to obtain unbiased conclusions on AGB stars and to investigate the evolution of the magnetic field and its influence during the transition of an AGB star to the PN stage.

4. CN as a tracer of the field in carbon stars ?

CN seems to be a good molecular tracer to perform such studies in carbon stars. First of all, the $N=1 \rightarrow 0$ and $N=2 \rightarrow 1$ lines have already been observed and easily detected

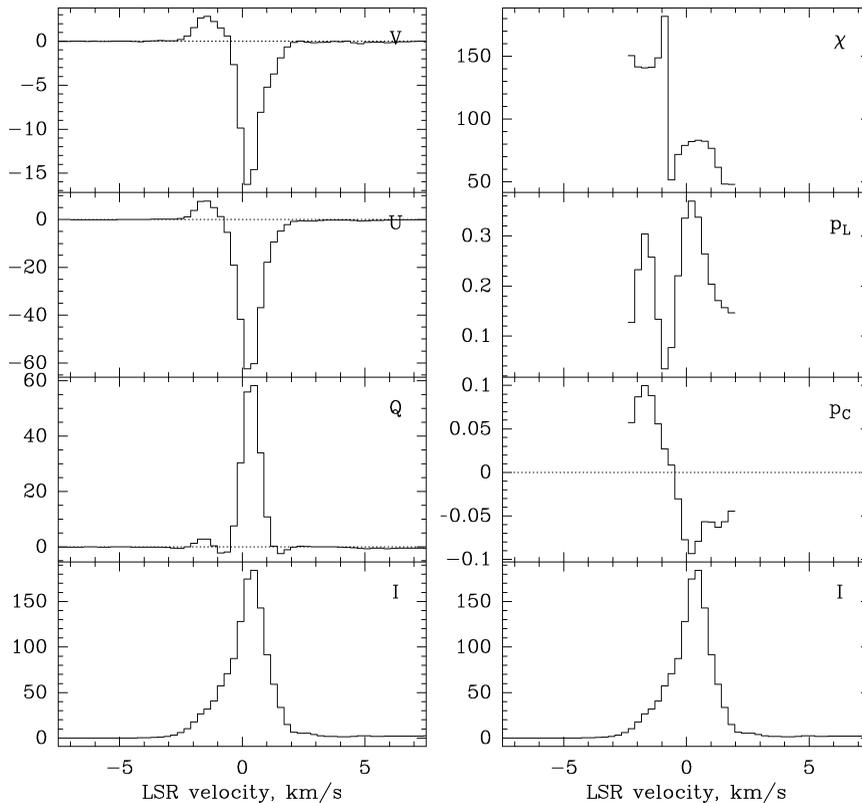


Figure 1. *Left:* V, U, Q et I Stokes parameters for R Leo (given in Kelvins T_{mb} ; SiO maser observations). *Right:* derived position angle of polarization (χ) in degrees, linear (p_L) and circular (p_C) polarization levels and intensity for R Leo.

Table 1. Zeeman Splittings for CN N=1 \rightarrow 0 (Crutcher *et al.* 1996). R.I. stands for *Relative Intensity* in LTE conditions.

(N', J', F') \rightarrow (N, J, F)	ν_0 (GHz)	Z (Hz μG^{-1})	R.I.	Z \times R.I.
1. (1, 1/2, 1/2) \rightarrow (0, 1/2, 3/2)	113.14434	2.18	8	17.4
2. (1, 1/2, 3/2) \rightarrow (0, 1/2, 1/2)	113.17087	-0.31	8	2.5
3. (1, 1/2, 3/2) \rightarrow (0, 1/2, 3/2)	113.19133	0.62	10	6.2
4. (1, 3/2, 3/2) \rightarrow (0, 1/2, 1/2)	113.48839	2.18	10	21.8
5. (1, 3/2, 5/2) \rightarrow (0, 1/2, 3/2)	113.49115	0.56	27	15.1
6. (1, 3/2, 1/2) \rightarrow (0, 1/2, 1/2)	113.49972	0.62	8	5.0
7. (1, 3/2, 3/2) \rightarrow (0, 1/2, 3/2)	113.50906	1.62	8	13.0

at the 30m by Bachiller *et al.* (1997a,b) and Josselin & Bachiller (2003) towards these objects. Moreover, CN is a paramagnetic species, thus exhibiting Zeeman splitting in its 3mm N=1-0 line emission when the spectral line-forming region is permeated by a field B . The CN Zeeman signal is thermal (as opposed to SiO) and therefore free of the idiosyncrasies of maser theory.

CN N=1-0 line has a total of 9 hyperfine components (split in two groups, one around 113.17 GHz, the other around 113.49 GHz), with 7 main lines. Of those 7, 4 exhibit strong Zeeman effect (see Table 1, line 1,4, 5 and 7). Crutcher *et al.* (1996) developed an analysis procedure consisting of a least-squares fit in frequency to all seven

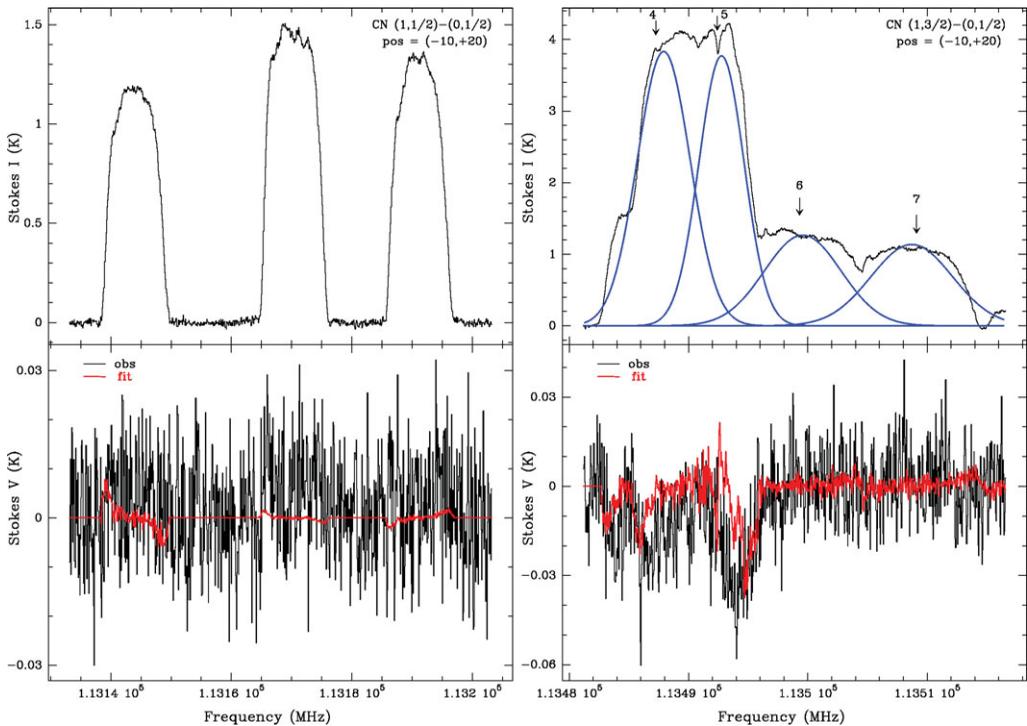


Figure 2. *Left:* CN (1,1/2) \rightarrow (0,1/2) Stokes I (*Top*) and V (*Bottom*) spectra for IRC+10216 (position $-10''$, $+20''$); *Right:* same for the CN (1,3/2) \rightarrow (0,1/2). Observations, gaussian fits for I and least-squares fits for V are respectively in black, blue and red. No Stokes V signal is detected toward the non(low)-paramagnetic hyperfines, demonstrating that the detected features are indeed due to Zeeman.

hyperfine transitions of the line V spectra, making possible to separate the spurious and Zeeman signals.

The main purpose of this work was to measure and analyze the polarization of the CN N=1-0 line emission in a sample of evolved stars: two C-rich AGB stars (RW LMi and IRC+10216 at a distance of respectively 440 and 120 pc), one PPN (AFGL618, at 900 pc), and one PN object (NGC7027, at 880 pc). As the diameter of the CN ring around IRC+10216 is larger than the 30m beam, our observations were focused on two selected positions for that source.

Simultaneous spectroscopic measurement of the 4 Stokes parameters for the seven hyperfine transitions given in Table 1 were made in november 2006 with the XPol polarimeter (Thum *et al.* 2008) at the IRAM-30m. Following the analysis procedure described by Crutcher *et al.* (1996), we do a least-squares fit in frequency simultaneously to all 7 hyperfine line V spectra ($i=1,7$):

$$V_i(\nu) = C_1 I_i(\nu) + C_2 (dI_i(\nu)/d\nu) + C_3 Z_i (dI_i(\nu)/d\nu) \quad (4.1)$$

This method enables us to distinguish between the Zeeman effect ($C_3 = B_{||}/2$) and instrumental effects ($C_{1,2}$).

5. CN results and consequences

From the fit of the observed Stokes V spectra (see Fig. 2 for IRC+10216), we then estimate the magnetic field strength along the light-of-sight within the CN layer for the

Table 2. For each object in our sample are given for the CN layer the molecular abundance (χ , relative to H_2), its distance to the central star in AU (and in its size in arcseconds). B_{8r_\star} and B_{r_\star} are the extrapolated strengths of the magnetic field (following a $1/r$ law) at $8 r_\star$ (equivalent to the SiO maser zone for O-rich objects) and at one stellar radius.

Object	$\chi(\text{CN})$	d_{CN} [AU]	B_{8r_\star} [Gauss]	B_{r_\star} [Gauss]	r_\star [AU]
RW LMi	$8.3 \cdot 10^{-6}$	2200 (5'')	2	16	1
IRC+10216	$6.2 \cdot 10^{-7}$	2500 (21'')	2.7	21.6	1
CRL618	$2.1 \cdot 10^{-6}$	5000 (5'')	<300	<2400	$2.3 \cdot 10^{-3}$
NGC7027	$2.3 \cdot 10^{-7}$	10000 (11'')	<250	<2000	$2.3 \cdot 10^{-3}$

4 objects: 7.2 (poor S/N ratio) and 8.6 Gauss, respectively for RW LMI and IRC+10216. Only upper limits are derived for CRL618 (≤ 0.9 Gauss) and NGC7027 (≤ 0.3 Gauss) as no Stokes V signal is detected.

The objects from our sample have been already observed in CN lines by some authors, making hence possible to estimate the size (and distance to the central object) of the CN layer (see Table 2) that we are investigating through our polarization observations: Lindqvist *et al.* (2000), Lucas *et al.* (1995), Josselin *et al.* (private communication) respectively for RW LMi, IRC+10216 and NGC7027. Only HCN observations are available for CRL618, but HCN being a molecule of photospheric origin that gets photodissociated by the ambient UV-field into CN (e.g. Huggins & Glassgold 1982), we can assume CN molecules are surrounding the HCN envelope, leading to a rough estimate of the CN envelope size.

First of all, the detection or non-detection of the Stoked V signal cannot be explained by the CN abundances as shown in Table 2. Therefore, we checked any instrumental effect or bias that could have lead to a non-detection, but the instrumental polarization is very low and the same for all sources. Furthermore, the size of the CN layer is smaller than the 30m beam (21'' at that frequency), and the side-lobe contamination has been well constrained.

We also tried to verify that our magnetic field estimates are consistent with previous works. Hence, following Herpin *et al.* (2006) conclusion, we have applied a $1/r$ variation law for the magnetic field strength across the envelope. We have therefore extrapolated the B value at a distance of 8 stellar radius, roughly the same distance than the SiO layer in O-rich objects and at one stellar radius. For AGB objects, the derived strength of the magnetic field is between 2 and 2.6 Gauss, entirely compatible with the estimate of B by Herpin *et al.* (2006) in O-rich objects from SiO maser observations. In PPN and PN objects, we have estimated upper limits for B of 2000 and 2400 kGauss at $1 r_\star$ respectively in CRL618 and NGC7027, in agreement with Jordan *et al.* (2005), who measured magnetic field of a few kGauss at that distance to the central star.

We then conclude that our CN results are completely reliable and consistent. Moreover, even for AGB stars, the strength of the magnetic field at the stellar surface is strong enough to allow B to play a major role in the object shaping.

6. Conclusion

We have extended the magnetic field study in evolved stars made by Herpin *et al.* (2006) in order to study its evolution and its influence during the transition of an AGB star to the PN stage. We have observed the Zeeman effect in CN line emission in C-rich objects and more evolved stars (one PPN and one PN). Our B estimates are consistent with

previous studies and confirm that the magnetic field varies as $1/r$ across the circumstellar envelope.

The magnetic field is sufficiently strong to be determinant during the evolution of the AGB star: magnetic field seems to be able to help in the process of collimating, and more generally, of shaping in AGB objects, but is not the main agent at this stage. The increasing strength of the magnetic field in the following stages of evolution, as shown by our results and Jordan *et al.* (2005), will make B a determinant shaping agent.

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Discussion

JORDAN: Did you see any correlation between magnetic field strength and object's asymmetry? If not, this will indicate that the magnetic field does not play any role in the object's shaping.

HERPIN: Actually, the shape of the AGB stars is only known for few objects. It is therefore difficult to conclude on any correlation. Moreover, the shaping occurs – or more exactly is seen – after the star has left the AGB phase.

BECKMAN: How accurate/reliable are the magnetic field strength estimates you make?

HERPIN: For SiO masers, the magnetic field estimate is indeed model-dependent, but the values we derived, assuming Elitzur's theory, are consistent with former water and OH observations, i.e. **B** varying in $1/r$ across the envelope. The location of SiO maser cells is also very well known. The Zeeman effect observed for the CN line emission is well understood too.