Magnetic fields in central stars of planetary nebulae?*

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ABSTRACT

Context. Most of the planetary nebulae (PN) have bipolar or other non-spherically symmetric shapes. The presence of a magnetic field in the central star may be the reason for this lack of symmetry, but observational works published in the literature have so far reported contradictory results.

Aims. We try to correlate the presence of a magnetic field with the departures from the spherical geometry of the envelopes of planetary nebulae.

Methods. We determine the magnetic field from spectropolarimetric observations of ten central stars of planetary nebulae. The results of the analysis of the observations of four stars was previously presented and discussed in the literature, while the observations of six stars, plus additional measurements for a star previously observed, are presented here for the first time.

Results. All our determinations of magnetic field in the central planetary nebulae are consistent with null results. Our field measurements have a typical error bar of 150-300 G. Previous spurious field detections obtained with FORS were probably due to the use of different wavelength calibration solutions for frames obtained at different position angles of the retarder waveplate.

Conclusions. Currently, there is no observational evidence for the presence of magnetic fields with a strength of the order of hundreds Gauss or higher in the central stars of planetary nebulae.

Key words. stars: post-AGB – stars: magnetic fields

1. Introduction

There is still no conclusive theory why more than 80% of the known planetary nebulae (PNe) have bipolar and non-spherically symmetric shapes. The presence of a magnetic field in the central star may be the reason for this lack of symmetry, but observational works published in the literature have so far reported contradictory results.

Such magnetic fields could be either fossil remnants from previous stages of stellar evolution, or could be generated by a dynamo at the interface between a rapidly rotating stellar core and a more slowly rotating envelope. Blackman et al. (2001) argue that some remnant field anchored in the core will survive even without a convection zone, although the convective envelope may not be removed completely.

The idea that magnetic fields are important ingredients shaping PNe has been supported by the detection of SiO, H₂, and OH MASER emission in circumstellar envelopes of AGB stars pointing at milligauss fields in these nebula (Kembell & Diamond 1997; Szymczak & Cohen 1997; Miranda et al. 2001; Vlemmings et al. 2002, 2005, 2006; Herpin et al. 2006; Sabin et al. 2007; Kembell et al. 2009; Gómez et al. 2009; Vlemmings 2011). Moreover, using an idea of Pascoli (1985), Huggins & Manley (2005) connected the extreme filamentary structures seen in high-resolution optical images of certain planetary nebulae to magnetic fields consistent with those measured in the MASER from the precursor circumstellar envelopes.

For the first time, and with the help of optical circular spectropolarimetry carried out with the FORS1 spectrograph of the UT1 (“Antu”) telescope of the Very Large Telescope (VLT) of the European Southern Observatory (ESO), Jordan et al. (2003) reported on the detection of magnetic fields in the central stars of the planetary nebulae NGC 1360 and LSS 1362. For the central stars of EGB 5 and Abell 36 the existence of a magnetic field was found to be probable but with less certainty.

Pascoli & Lahoche (2008) pointed out that the magnetic field at the surface of central stars of planetary nebulae is not necessarily connected to the magnetic fields in the nebula itself; the latter can be a fossil component of the primary field embedded in the AGB star. Nevertheless, the reported detection of magnetic fields in central stars of planetary nebulae has triggered several additional observational and theoretical studies on the shaping of planetary nebula, e.g. by García-Díaz et al. (2008), Tsui (2008), and Pascoli & Lahoche (2010) taking magnetic fields into account. On the other hand, Soker (2006) cast strong doubts that magnetic fields could be the main agent shaping planetary nebulae. He argued that a single star cannot supply the energy and angular momentum if the magnetic fields have a large-scale structure required to shape the outflow from an AGB star.

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Recently, the detection of magnetic fields in the central stars of planetary nebulae (CPNs) was called into question by Leone et al. (2011), who re-observed NGC 1360 and LSS 1362 with the FORS2 instrument, and concluded that their effective magnetic field is null within an uncertainty of ~ 100 G (NGC 1360), and ~ 290 G (LSS 1362). Furthermore, both Leone et al. (2011) and Bagnulo et al. (2012) re-analysed the observations previously obtained with FORS1 by Jordan et al. (2005), and could not confirm the original detection.

The conclusion based on the observations of four CPNs reduced by two independent groups is that there is no observational evidence for magnetic fields in the CPNs. The aim of this work is to enlarge the sample of CPNs checked for magnetic field, in order to estimate the occurrence of the magnetic field in CPNs and, if magnetic field is detected, whether its presence correlates with the asymmetry of their envelope. To achieve this goal, two of the teams that had presented (discordant) results on previous FORS measurements have joint their efforts to present here a more complete survey of magnetic fields of CPNs obtained during a three-night observing run with FORS1 carried out in 2005.

2. Observations, data reduction, and magnetic field determinations

All spectropolarimetric data reported in this paper were taken with the FORS1 instrument (Appenzeller et al. 1998) of the ESO Very Large Telescope. The polarimetric optics of FORS1, now moved to the twin instrument FORS2, are based on the principle described by Appenzeller (1997). FORS2 now is one of the few optical spectropolarimeters available for the study of stellar magnetism. Due to the large aperture of the telescope (8 m) FORS2 is best suited for the study of faint stars like white dwarfs (Aznar Cuadrado et al. 2004; Jordan et al. 2007), subdwarfs (Jordan et al. 2005), and CPNs (Jordan et al. 2005).

The FORS1 dataset previously analysed by Jordan et al. (2005), Leone et al. (2011), and Bagnulo et al. (2012) consists of observations of NGC 1360 = CD–26 1340, EGB 5 = PN G211.9+22.6, LSS 1362 = PN G273.6+06.1, and Abell 36 = ESO 577-24. These observations were obtained by Jordan et al. (2005), in service mode between November 2, 2003, and January 27, 2004, using grism 600B, and a 0.8′′ slit width, for a spectral resolution of about 1000.

Three additional nights of telescope time were obtained in visitor mode between June 4, 2005, and June 6, 2005, at the UT2 (“Kueyen”) of the ESO VLT. The instrument setup included again grism 600B, but a slit width of 0.7′′, for a spectral resolution of about 1200.

The criteria for the selection of objects were the optimum visibility during the observation nights and the brightness of the stars in order to reach an optimum signal-to-noise ratio. Moreover, we made sure that at least two of the stars were in the center of a nebula with almost spherical shape (LSE 125 and Hen 2-194) so that in case of positive detections the magnetic field can be correlated with the topology of the nebulae.

During the visitor run, six new CPNs were observed two or three times: HD 107969 = NGC 4361, LSE 125 = PN G335.5+12.4, Hen 2-194 = ESO 392-2, HD 154072 = IC 4637, HD 161044 = IC 1266, and WD 2226-210 = NGC 7293. Abell 36 = ESO 577-24, already checked for magnetic field in the previous service observing run, was re-observed three times. Additionally, we took one spectropolarimetric dataset for HD 160917, a non-magnetic B9V comparison star.

Figure 1 shows the summed up-high-quality spectra for all CPNs. Only Hen 2-194 and HD 161044 were subject to significant nebula emission.

We analysed all this old and new observational material by adopting a method described in detail by Bagnulo et al. (2012). Spectra are calibrated and extracted using the ESO FORS pipeline (Izzo et al. 2010), then combined using the difference method to obtain both the reduced Stokes V profiles (Pv) and the null profiles (Nv), as described by Bagnulo et al. (2012). The mean longitudinal magnetic field (Bz) was then calculated by using a least-square technique based on the relationship

\[ P_V(\lambda) = -g_{\text{eff}} C Z \frac{1}{I(\lambda)} \frac{dI(\lambda)}{d\lambda} (B_z), \]

where \( P_V \) is the reduced Stokes V profile, \( I(\lambda) \) is the Stokes I profile of a spectral line, \( g_{\text{eff}} \) is the effective Landé factor, and

\[ C Z = 4.67 \times 10^{-13} \text{ Å}^{-1} \text{ G}^{-1}. \]

For more details, see, e.g., Bagnulo et al. (2012). Compared with Bagnulo et al. (2012), in this work we have implemented a sigma-clipping algorithm in the determination of the magnetic field from the correlation diagram of circular polarisation against local flux derivative. We have also calculated the null profiles \( N_V \) and compared their oscillation about zero with the \( P_V \) error bars, and also measured the null field \( (N_V) \), i.e., the magnetic field obtained by applying Eq. (1) to the \( N_V \) profile instead of \( P_V \). The statistical significance of the null field values is extensively discussed in Bagnulo et al. (2012). Here we report that all null field values were found consistent with zero within error bars. We also note that the targets of this survey are relatively faint, and that most of the observations discussed here are not characterised by a ultra-high signal-to-noise ratio. The main contributor to the error bars is thus photon-noise and background subtraction (since our targets are embedded in a circumstellar envelope).

The original data reduction of the observations obtained within Programme ID 072.D-0089 by Jordan et al. (2005) was based on two distinct wavelength calibration solutions for the frames obtained at the two different position angles of the retarder plate adopted for the science observations: science frames obtained with the retarder waveplate at position angle ~45° were calibrated with calibration frames obtained at retarder waveplate at ~45°, and science frames obtained with the retarder waveplate at +45° were calibrated with calibration frames obtained at +45°. However, Bagnulo et al. (2006) and Bagnulo et al. (2009) showed that this method prevents wavelength calibration errors to cancel out, and may lead to spurious detections. While this problem did not occur in various tests (e.g., Bagnulo et al. 2002), in the case of for instance the 075.D-0289 data it would lead to spurious magnetic field measurements of the order of ~ 9kG.

In their analysis of the data obtained in 072.D-0089, Jordan et al. (2005) did compare the Stokes profiles obtained using a common wavelength calibration with those obtained using two distinct solutions, and concluded that both methods would produce similar Stokes profiles. However, at that time they did not notice that, although the profiles looked similar, field measurements were different: after the analysis of the profiles obtained using two wavelength calibration frames, a field was firmly detected, while using a unique wavelength calibration frame, field detections would disappear. We conclude that for that reason, the relatively high magnetic fields reported by Jordan et al. (2005) are spurious.

A similar conclusion was drawn by Bagnulo et al. (2012) and Landstreet et al. (2012) for the measurements of magnetic fields.
Table 1. Fundamental stellar parameters and FORS1 magnetic field measurements for ten central stars of planetary nebulae and for a (presumably non magnetic) B9 star observed for comparison.

| CPN name/alias | $T_{\text{eff}}$ /K | log g | Exp. time /s | Peak SNR /Å$^{-1}$ | MJD | $\langle B_z \rangle$ /G | remark |
|----------------|---------------------|-------|---------------|---------------------|-----|---------------------|--------|
| CD-26 1389     | NGC 1360            | 97 000| 5.3           | 1248                | 1440| 52946.291          | 207 ± 325 | 1.5 |
| CD-26 1389     |                    |       |               |                     |     |                     | 336 ± 283 | 1  |
| CD-26 1389     |                    |       |               |                     |     |                     | 358 ± 361 | 1  |
| CD-26 1389     |                    |       |               |                     |     |                     | 72 ± 320  | 1  |
| EGB5           | PN G211.9+22.6      | 34 060| 5.85          | 1986                | 552 | 52988.347          | −155 ± 780 | 1.6 |
| LSS 1362       | PN G273.6+06.1      | 114 000| 5.7          | 1986                | 930 | 52989.309          | 62 ± 406  | 1.5 |
| Abell 36       | ESO 577-24          | 113 000| 5.6          | 1500                | 1290| 53031.287          | 977 ± 445 | 1.5 |

Programme 072.D-0089:

| HD 107969      | NGC 4361            | 82 000| 5.5           | 6000                | 1308| 53525.093          | −348 ± 400 | 8  |
| HD 107969      |                    |       |               |                     |     |                     | 93 ± 295  | 5  |
| HD 107969      |                    |       |               |                     |     |                     | 507 ± 351 | 5  |
| Abell 36       | ESO 577-24          | 113 000| 5.6          | 3600                | 1880| 53525.972          | 110 ± 214  | 5  |
| LSE 125        | PN G335.5+12.4      | 85 000| 5.1           | 10000               | 2950| 53525.236          | −129 ± 116 | 9  |
| LSE 125        |                    |       |               |                     |     |                     | 135 ± 152 | 5  |
| LSE 125        |                    |       |               |                     |     |                     | 449 ± 239 | 5  |
| Hen 2-194      | PN H 2-1            | 33 000| 3.35          | 3400                | 995 | 53525.325          | 197 ± 523  | 2.8 |
| HD 154072      | IC 4637             | 50 000| 4.05          | 4800                | 1110| 53525.323          | −93 ± 216  | 8  |
| HD 161044      | IC 1266             | 34 700| 3.3           | 6600                | 2820| 53525.396          | −74 ± 123  | 3.0 |
| WD 2226-210    | NGC 7293            | 105 000| 7.0          | 6800                | 1065| 53526.442          | −309 ± 410 | 3  |
| WD 2226-210    |                    |       |               |                     |     |                     | 345 ± 410 | 3  |
| HD 160917      | CD-45 11850         | –     | –             | 300                 | 3431| 53527.450          | 110 ± 68  | 4  |

1. Observations already published by Jordan et al. (2005)
2. The field is estimated from absorption lines only.
3. Many spectral lines are in emission, and the field is estimated from absorption lines only.
4. Non magnetic B9V star observed for comparison.
5. $T_{\text{eff}}$ and log g from: Traulsen et al. (2005).
6. Lisker et al. (2005).
7. Napierwotzki (1999).
8. Mendez et al. (1992).
9. Mendez et al. (1988).
10. Pottasch et al. (2011).

3. Results

Table 1 lists our field determinations from all new FORS observations. We have also included new field determinations from the observations carried out in service mode by Jordan et al. (2005). Note that the field estimates for the observations obtained in 072.D-0089 slightly differ from those published by Bagnulo et al. (2012) because of the implementation of the sigma-clipping algorithm, and also a slightly different choice of the spectral points considered for field determination. Figure 2 shows an example of reduced data.

4. Discussion

Our analysis of ten CPNs does not show significant evidence for the existence of longitudinal magnetic fields above a few hundred Gauss. This is in contradiction with the result of Jordan et al. (2005), who determined magnetic field strengths of several kG in their analysis of four CPNs. Our current results are consistent with the investigation of the central star of NGC 1360 by Leone et al. (2011), who determined an upper limit for the magnetic field of 300 G (while Jordan et al. 2005, reported a longitudinal magnetic field of up to 3 kG). For the central star of LSS 1362 Leone et al. (2011) obtained an upper limit of 600 G. We conclude that a non-optimal wavelength calibration method in subdwarfs by O’Toole et al. (2005): the kG magnetic fields are also disappearing when using a single wavelength calibration frame for the entire science dataset. We note instead that the detections of weak magnetic fields in white dwarfs by Aznar Cuadrado et al. (2004) were basically confirmed by Bagnulo et al. (2012).
has led Jordan et al. (2005) to a spurious detection of magnetic fields.

Our re-reduction of the 072.D-0089 data leads to a weighted mean magnetic field (see Table 1) for NGC 1360 of 244 ± 162 G, assuming that a possible (and weak) magnetic field appears constant with time.

With our sample of ten stars (Abell 36 has been observed in both observation campaigns) we conclude that there is no confirmed case for a magnetic field in the central star of a planetary nebula at a kG level. Magnetic fields of the order to 100-300 G, however, cannot be discarded. Indirect evidence for the existence of mG fields in proto-planetary nebulae could still support an influence of magnetic fields on the shape of PN. However, these fields need no be connected to a field of the central star (Pascoli & Lahoche 2008).

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Fig. 1. Normalised spectra of all central stars of planetary nebulae observed in the 075.D-0289 campaign ordered by increasing effective temperature from top to the bottom. The 072.D-0089 are shown in Fig. 1 of Jordan et al. (2005).

Fig. 2. The observations of Abell 36 were obtained with FORS1 on 2005-06-03. The top panel shows the observed flux F (black solid line, in arbitrary units, and not corrected for the instrument response), the P_V = V/I profile (red solid line centred about 0), and the null profile N_V (blue solid line, offset by −0.75 % for display purpose). The null profile is expected to be centred about zero and scattered according to a Gaussian with σ given by the P_V error bars. The P_V error bars are represented with light blue bars centred about −0.75 %. The slope of the interpolating lines in the bottom panels gives the mean longitudinal field from P_V (left bottom panel) and from the null profile (right bottom panel) both calculated using the H Balmer and metal lines. The corresponding (B_z) and (N_z) values are −33 ± 158 G and −420 ± 161 G, respectively.
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