Non detection of magnetic fields in the central stars of the planetary nebulae NGC1360 and LSS1362

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ABSTRACT

The presence of magnetic fields is an attractive hypothesis for shaping PNe. We report on observations of the central star of the two Planetary Nebulae NGC1360 and LSS1326. We performed spectroscopy on circularly polarized light with the *FOcal Reducer and low dispersion Spectrograph* at the Very Large Telescope of the European Southern Observatory. Contrary to previous reports (Jordan et al. 2005, A& A, 432, 273), we find that the effective magnetic field, that is the average over the visible stellar disk of longitudinal components of the magnetic fields, is null within errors for both stars. We conclude that a direct evidence of magnetic fields on the central stars of PNe is still missing — either the magnetic field is much weaker (< 600 G) than previously reported, or more complex (thus leading to cancellations), or both. Certainly, indirect evidences (e.g., MASER emission) fully justify further efforts to point out the strength and morphology of such magnetic fields.

Subject headings: Stars: magnetic field — (ISM:) planetary nebulae: individual (NGC1360, LSS13632) — Polarization

1. Introduction

A large fraction of planetary nebulae (about 80%) are bipolar or elliptical rather than spherically symmetric. Many of them also harbor complex structures on small scales, such as knots, filaments, jets and jet-like features, etc. (see e.g. Corradi (2006)). But the reason for the departure during the PN phase from the spherical symmetry that has characterized most of the evolution of the progenitor stars, is still a matter of debate. Modern theories invoke

magnetic fields, among other causes, to explain the rich variety of aspherical components observed in PNe (see the review by Balick & Frank (2002)). The presence of magnetic fields would indeed help to explain some features of the complicated shapes of planetary nebulae, as the ejected matter is trapped along magnetic field lines. There are several ways magnetic fields can be created in the vicinity of planetary nebulae. Magnetic fields can be produced by a stellar dynamo during the phase when the nebula is ejected. It is also possible that the magnetic fields are fossil relics of previous stages of stellar evolution (Blackman et al. 2001). Under most circumstances, the matter in stars is so highly electrically conductive that magnetic fields can survive for millions or billions of years. In both cases, the magnetic field combined with other physical processes including stellar rotation, winds interaction, interaction wit the interstellar medium, and the dynamical action of evolving photoionization fronts, would produce the complex morphologies observed in PNe.

Until recently, the idea that magnetic fields are an important ingredient in the shaping of planetary nebulae was mostly a theoretical claim, since no such magnetic field was measured in the nebulae themselves. To obtain direct evidence for the presence of magnetic fields in planetary nebulae one can focus on their central stars, where the magnetic fields should have survived.

Jordan et al. (2005) report the detection of magnetic fields in the central star of two non-spherical planetary nebulae, namely NGC1360 and LSS 1362. The claim is based on circular light spectropolarimetry carried out with the *FOcal Reducer and low dispersion Spectrograph* (FORS) at the Very Large Telescope (VLT) of the European Southern Observatory (ESO). The impact of Jordan et al. (2005) paper is testified by the 50 citations counted at the end of 2010, and increasing efforts to include magnetic fields in theory of planetary nebulae. As an example, Tsui (2008) performed MHD calculations to model an equatorial plasma torus in around the central stars of PNe.

Because of the achieved noise level and adopted set-up, Jordan et al. (2005) could not obtain a direct measurement of these magnetic fields (see their figures 2 and 3). Controversial values were also obtained from different Balmer lines. These authors found necessary to perform a large number of simulations to associate a statistical significance to their results.

In this paper, we present the results of new spectropolarimetric measurements of NGC1360 and LSS1362 obtained on Dec. 22, 2010 with FORS2 at the VLT, at higher signal to noise ratio, reciprocal dispersion and spectral resolution than previously done by Jordan and co-workers, with the aim to finally obtain a direct evidence of magnetic fields on the surface of the central star of these planetary nebulae.
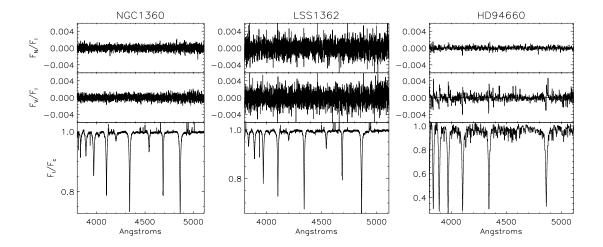
Fig. 1.— Observed Stokes $\mathcal{F}_I/\mathcal{F}_c$, $\mathcal{F}_V/\mathcal{F}_I$ and $\mathcal{F}_N/\mathcal{F}_I$ (see text) of the central stars of the PNe NGC1360 and LSS1362. The Zeeman signature in the Stokes V/I spectra of Balmer lines is absent in the case of PNe and well visible in the magnetic star HD94660.
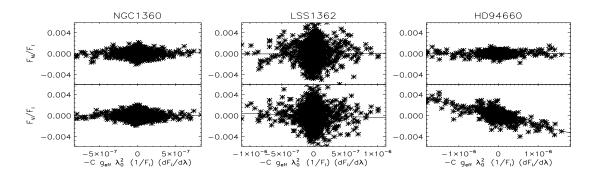

Fig. 2.— The slope of Stokes $\mathcal{F}_V/\mathcal{F}_I$ vs. $-C g_{\mathrm{eff}} \lambda_0^2 \frac{1}{\mathcal{F}_I} \frac{\mathrm{d}\mathcal{F}_I(\lambda)}{\mathrm{d}\lambda}$ measures the effective magnetic field (B_e). No slope is observed in the case of PNe. A B_e value consistent with the literature data is obtained for the magnetic star HD94660. The zero slope of $\mathcal{F}_N/\mathcal{F}_I$ spectra shows no spurious polarization effects.

2. Observations and data reduction

Jordan et al. (2005) observed NGC1360 and LSS1362 with the FORS1 spectrograph at the VLT using the R600B+22 grating, a 0.8 arcsec slit, a MIT $24\mu m$ CCD and adopting a total exposure time of 624 s. Dispersion was 1.18Å pix^{-1}, and spectral resolution R∼1200. Circular spectropolarimetry was carried out with the standard procedure consisting of a series of exposures at two different angles of the $\lambda/4$ retarder with respect to the Wollaston axes, namely $\alpha = +45$ and -45°.

To improve the precision of the measurements, we observed NGC1360 and LSS1362 for 3072 s each with the R1200B+97 grating, a 0.5 arcsec slit and the E2V blue-optimized 15 μm CCD. This setup results in a linear dispersion equal to 0.35Å pix^{-1} and R∼2700 as measured in the spectral lines of arcs. The effects of linear dispersion and line broadening in measuring stellar magnetic fields are discussed in Leone et al. (2000). To handle cosmic rays, observations were split in a series of exposures of 256 seconds switching the angle α between $+45$ and -45°. On the coadded spectra of NGC1360 and LSS1362, we measured S/N ∼ 2400 and 800 respectively.

The combination of the o-rdinary and e-xtraordinary beams emerging from the polarizer to measure the circular polarization degree is critical. There is a time independent (instrumental) sensitivity G, for example due to a pixel-to-pixel efficiency, together with a time dependent sensitivity F of spectra obtained at different α angles for example due to variation of sky transparency and slit illumination. Photon noise dominated Stokes I and V can been obtained from the recorded spectra at $\alpha=+45^o$ and -45°:

$$
\begin{aligned}
S_{+45^\circ,o} &= 0.5\,(I+V)G_oF_{+45^\circ} \\
S_{+45^\circ,e} &= 0.5\,(I-V)G_eF_{+45^\circ} \\
S_{-45^\circ,o} &= 0.5\,(I-V)G_oF_{-45^\circ} \\
S_{-45^\circ,e} &= 0.5\,(I+V)G_eF_{-45^\circ}
\end{aligned}
$$

Table 1: B_{eff} measurements from single Balmer lines, $g_{\text{eff}} = 1$. Average values are from a simultaneous fit of all available Balmer lines.

HJD/B/Seeing	NGC 1360 2455553.503/10.99/1"		LSS 1362 2455553.832/12.27/2"		HD 94660 2454181.658/6.02/0.6"	
	$B_{\text{eff}}(V/I)$ [G]	$B_{\text{eff}}(N/I)$ [G]	$B_{\text{eff}}(V/I)$ [G]	$B_{\text{eff}}(N/I)$ [G]	$B_{\text{eff}}(V/I)$ [G]	$B_{\text{eff}}(N/I)$ [G]
All	$+154 \pm 113$	$+121 \pm 103$	-337 ± 286	$+34 \pm 221$	-1950 ± 71	-14 ± 29
H_θ	–	–	–	–	-1982 ± 300	-313 ± 122
H_η	–	–	–	–	-2051 ± 371	$+293 \pm 151$
H_ζ	-78 ± 1656	-659 ± 1502	$+2094 \pm 3580$	$+1506 \pm 2870$	-2218 ± 378	$+109 \pm 154$
H_ϵ	$+220 \pm 867$	$+200 \pm 787$	$+372 \pm 1613$	-533 ± 1293	-1680 ± 369	-131 ± 150
H_δ	-556 ± 523	-217 ± 474	-528 ± 1223	$+1137 \pm 980$	-1805 ± 364	-181 ± 149
H_γ	$+104 \pm 379$	$+35 \pm 344$	-843 ± 882	$+389 \pm 707$	-1940 ± 362	$+370 \pm 147$
H_β	$+450 \pm 318$	$+325 \pm 288$	-236 ± 734	-154 ± 588	-1973 ± 351	-88 ± 143

Hence:

$$\frac{V}{I} = \frac{R_V - 1}{R_V + 1} \qquad \text{with} \quad R_V^2 = \frac{S_{+45^o,o}/S_{+45^o,e}}{S_{-45^o,o}/S_{-45^o,e}}$$

We have reduced the data following the previous relations as in Leone (2007). In addition to V/I we have also computed the *Noise* spectrum:

$$\frac{N}{I} = \frac{R_N - 1}{R_N + 1} \qquad \text{with} \quad R_N^2 = \frac{S_{+45^o,o}/S_{-45^o,e}}{S_{-45^o,o}/S_{+45^o,e}}$$

In an ideal polarimeter, signal extraction and wavelength calibration of ordinary and extraordinary spectra, N/I is null and its *absolute* error equal to $(N_{total})^{-1/2}$, where N_{total} is the total number of photons. Any anomalous behavior of N/I would be present, at the same level, in Stokes V/I by definition.

To test our capability to recover the circular polarized signal from FORS spectra and measure stellar magnetic fields, we have applied the previous procedures to the spectropolarimetric data, obtained from ESO archive, of the magnetic star HD94660, whose field is at the intensity level of NGC1360 and LSS1362 as claimed by Jordan et al. (2005). Landstreet & Mathys (2000) have shown that the magnetic field of HD94660 is variable with a 2700 day period between -1.8 and -2 kG. Projected rotational velocities are also comparable, as NGC1360 shows $v_e \sin i < 20$ km s^{-1} (García-Díaz et al. 2008) and HD94660 < 30 km s^{-1} (Levato et al. 1996). We did not find any estimate in the literature for the projected rotation velocity of LSS1362, whose spectral lines appears in our spectra as broad as NGC1360 lines.

Fig. 1 shows the observed spectra of NGC1360, LSS1362 and HD94660.

3. Measuring magnetic fields

High resolution circular spectropolarimetry of metal lines gives the possibility to distinguish photospheric regions with positive and negative magnetic fields, as for instance done on HD24712 by Leone & Catanzaro (2004, R =115 000). It is also proved useful at moderate resolution (Leone & Catanzaro 2001, R = 15 000), but is still prohibitive to detect magnetic fields of faint stars. For faint white dwarfs, Angel & Landstreet (1970) introduced a method based on narrowband ($\sim$30 Å) circular photopolarimetry on the wings of the H$_\gamma$ Balmer line.

In the weak field approximation for stellar atmospheres (Landstreet 1982; Mathys 1989), the disk integrated Stokes-V parameter (the difference between the opposite circular polar-

ized intensities) $\mathcal{F}_V$, is proportional to the derivative of the intensity flux $\mathcal{F}_I$:

$$\frac{\mathcal{F}_V}{\mathcal{F}_I} = -C g_{\text{eff}} \lambda_0^2 \frac{1}{\mathcal{F}_I} \frac{\mathrm{d}\mathcal{F}_I(\lambda)}{\mathrm{d}\lambda} B_{\text{eff}} \qquad (1)$$

where $C = -4.67 \times 10^{-13}$ G^{-1}Å^{-1}, g_{eff} is the effective Landé factor of the transition, λ_0 the wavelength in Å, and

$$B_{\text{eff}} = \frac{3}{2\pi} \int_0^{2\pi} \mathrm{d}\phi \int_0^1 B_\| \mu \mathrm{d}\mu \qquad (2)$$

is the longitudinal component of the magnetic field ($B_\|$) integrated over the stellar disk.

The slope of the linear regression of $\mathcal{F}_V/\mathcal{F}_I$ versus $-C g_{\text{eff}} \lambda_0^2 \frac{1}{\mathcal{F}_I} \frac{\mathrm{d}\mathcal{F}_I(\lambda)}{\mathrm{d}\lambda}$ (forced to pass through the origin), gives the effective magnetic field. In other words, we minimize the χ^2 merit function

$$\chi^2 = \sum_{ij} \frac{1}{\sigma^2} \left[(\mathcal{F}_V/\mathcal{F}_I)_j^i + C\ g_{\text{eff}}^i\ (\lambda_0^i)^2\ \frac{1}{(\mathcal{F}_I)_j^i} \frac{\mathrm{d}(\mathcal{F}_I)_j^i}{\mathrm{d}\lambda} B_{\text{eff}} \right]^2 \qquad (3)$$

where the standard deviation of the noise σ is independent of the spectral line i and wavelength j. If $(\mathcal{F}_I')_j^i = (\lambda_0^i)^2\ g_{\text{eff}}^i\ \frac{1}{(\mathcal{F}_I)_j^i} \frac{\mathrm{d}(\mathcal{F}_I)_j^i}{\mathrm{d}\lambda}$, after some algebra:

$$B_{\text{eff}} = -\frac{\sum_{ij}(\mathcal{F}_V/\mathcal{F}_I)_j^i(\mathcal{F}_I')_j^i}{C \sum_{ij}[(\mathcal{F}_I')_j^i]^2} \qquad (4)$$

while the error is obtained from the covariance matrix:

$$\delta B_{\text{eff}} = \pm\sqrt{\Delta\chi^2} \frac{\sigma}{C\sqrt{\sum_{ij}[(\mathcal{F}_I')_j^i]^2}} \qquad (5)$$

where $\Delta\chi^2$ are isocontours of the χ^2 function that contain a certain confidence level. The values of $\Delta\chi^2$ are tabulated and depend on the number of degrees of freedom. In our case, with only one degree of freedom, $\Delta\chi^2 = 1, 4, 9$ for a confidence level of 68.3%, 95.4%, and 99.7%, respectively.

Results of our measurements are listed in Table 1. No single magnetic field fits the polarization of all Balmer lines, as is instead observed in the reference magnetic star HD94660. This is consistent with the absence of Zeeman signal in any line for the two PN central stars. Taking into account the information of all spectral lines consistently (i.e., fitting all the signals with the same field), the magnetic fields obtained are 154 ± 113 and 337 ± 286 G,

for NGC1360 and LSS 1362, respectively. In other words, the magnetic field is essentially undetermined within errors, with the most probable value compatible with the observations lying well below the kG. It is important to stress that we measured the magnetic field by minimizing the sum of the merit function (χ^2) for all spectral lines simultaneously, and not as the weighted average of the magnetic fields obtained from individual spectral lines, which is not correct.

Magnetic fields $\sim$kG should be apparent in the circular polarization spectrum, as it is in the case of the magnetic star HD94660. Fig. 1 shows that a clear Zeeman signature appears in all individual Balmer lines present in the spectrum of HD94660. This is evident also from the clear linear relationship between $\mathcal{F}_V/\mathcal{F}_I$ and $-Cg_{\mathrm{eff}}\lambda_0^2\frac{1}{\mathcal{F}_I}\frac{\mathrm{d}\mathcal{F}_I(\lambda)}{\mathrm{d}\lambda}$, in contrast to the behavior shown by the central stars of the PNe (Fig. 2). Table 1 summarizes the magnetic field inferred from individual lines. They are all consistent within errors $B_{\mathrm{eff}} = -1950\pm71$ G, as expected from Landstreet & Mathys (2000). Moreover, the null spectra $\mathcal{F}_N/\mathcal{F}_I$ shows no spurious polarization effects (Table 1, Fig. 2).

In order to push forward the detection limit, we decrease the noise level by adding Balmer lines in the velocity frame. The line addition technique introduced by Semel & Li (1996) is a widespread technique that has been successfully applied to detect Zeeman signatures in a large variety of stars (e.g., Donati & Landstreet 2009). The mean spectral lines thus obtained, of the two central stars of NGC 1360 and LSS 1362, and the magnetic star HD94660 are represented in Fig. 3. In the selected velocity interval, the r.m.s. of $\mathcal{F}_V/\mathcal{F}_I$ and $\mathcal{F}_N/\mathcal{F}_I$ spectra are similar, $\sigma(\mathcal{F}_V/\mathcal{F}_I) \sim \sigma(\mathcal{F}_N/\mathcal{F}_I) \sim 1.9 \times 10^{-4}$, for NGC 1360 and, $\sigma(\mathcal{F}_V/\mathcal{F}_I) \sim \sigma(\mathcal{F}_N/\mathcal{F}_I) \sim 5.9 \times 10^{-4}$, for LSS 1362. The large difference in the case of HD94660, $\sigma(\mathcal{F}_V/\mathcal{F}_I) \sim 6\sigma(\mathcal{F}_N/\mathcal{F}_I) \sim \times 10^{-4}$, is a further unquestionable evidence of a strong magnetic field in this star. Fig. 2 shows how large indeed is the circular polarization in Balmer lines of a star harboring a $\sim$2 kG field.

At our polarimetric sensitivity (better than previous work by Jordan et al. 2005), we can say that we do not detect any signal in circular polarization due to the Zeeman effect. More precisely, the magnetic field is below $\sim$300 G ($\sim$600 G) for the central stars of NGC1360 (LSS1362) with a probability of 68.2%, and below $\sim$400 G ($\sim$900 G) with a probability of 95.4%. These values correspond to the magnetic field obtained with all the spectral lines plus the values of the error at 68.2% and 95.4% confidence levels, see equation (4).

4. Conclusions

Contrary to Jordan et al. (2005), we find no evidence for the existence of kG magnetic fields in the central stars of the PNe NGC1360 and LSS1326. Our conclusion is based on spectropolarimetric observations deeper and at higher spectral resolution than those of Jordan et al. (2005), as well as on a rigorous analysis of the polarization signal in several Balmer lines, considered individually or added in the velocity space. The upper limits that we found for the longitudinal magnetic field integrated over all stellar disc is $\sim$ 300 and $\sim$ 600 G for NGC1360 and LSS1362, respectively. An application of our method to the Jordan et al. (2005) data, obtained from ESO archive, gives an upper limit of $\sim$ 400 G (NGC1360) and $\sim$ 600 G (LSS1362).

With this conclusion, no evidence is left for magnetic fields on PN **central stars**. On the other hand, positive indication of magnetic fields was obtained for the **nebulae** in a handful of objects: mG fields were found in the young PN OH 0.9+1.3 by OH circular polarization (Zijlstra et al. 1989), and in the bipolar PNe NGC 7027, NGC 6537, and NGC 6302 by polarimetry of magnetically aligned dust grains (Greaves 2002; Sabin et al. 2007). Therefore the negative result for the two PNe studied in this paper should not stop further efforts to detect magnetic fields in other PNe central stars. The method described in this paper, sensitive to $\sim$ kG fields, may be attempted on other PNe which display morphological features expected for magnetically active PN central stars, such as elongated bipolar lobes, jets, and ansae (cf. e.g. García-Segura et al. (1999)). It should be remarked, however, that NGC 1360 was exactly one of these promising targets, as it possesses polar jets with increasing speed with distance from the central star, expected for a magnetically collimated outflow (García-Díaz et al. 2008). Other morphologies should be tested.

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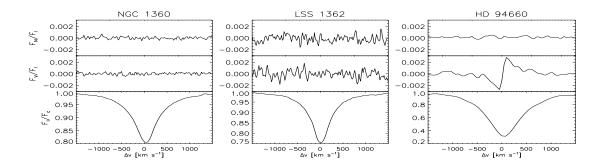
Fig. 3.— Mean Stokes $\mathcal{F}_I/\mathcal{F}_c$, $\mathcal{F}_V/\mathcal{F}_I$ and $\mathcal{F}_N/\mathcal{F}_I$ Balmer line profiles of the central stars of PNe NGC1360 and LSS1362. For comparison we report the same profiles of the magnetic star HD94660, whose effective magnetic field is -1950 G.