The presence of magnetic fields is an attractive hypothesis for shaping planetary nebulae (PNe). We report on observations of the central star of the two PNe NGC 1360 and LSS 1326. 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, we find that the effective magnetic field, which 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 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 evidence (e.g., MASER emission) fully justify further efforts to point out the strength and morphology of such magnetic fields.

Key words: planetary nebulae: individual (NGC 1360, LSS 1362) – polarization – stars: magnetic field

1. INTRODUCTION

A large fraction of planetary nebulae (PNe; 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, e.g., Balick & Frank 2002). The presence of magnetic fields would indeed help to explain some features of the complicated shapes of PNe, as the ejected matter is trapped along magnetic field lines. There are several ways magnetic fields can be created in the vicinity of PNe. 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, interaction of winds, interaction with 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 PNe 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 PNe 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 PNe, namely NGC 1360 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 the Jordan et al. (2005) paper is testified to by the 50 citations counted at the end of 2010 and increasing efforts to include magnetic fields in theory of PNe. As an example, Tsui (2008) performed MHD calculations to model an equatorial plasma torus around the central stars of PNe.

Because of the achieved noise level and adopted setup, 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 it necessary to perform a large number of simulations to associate a statistical significance to their results.

In this Letter, we present the results of new spectropolarimetric measurements of NGC 1360 and LSS 1362 obtained on 2010 December 22 with FORS2 at the VLT, at higher signal-to-noise ratio (S/N), reciprocal dispersion, and spectral resolution than previously done by Jordan and co-workers, with the aim to finally obtain direct evidence of magnetic fields on the surface of the central star of these PNe.

2. OBSERVATIONS AND DATA REDUCTION

Jordan et al. (2005) observed NGC 1360 and LSS 1362 with the FORS1 spectrograph at the VLT using the R600B+22 grating, a 0.8 arcsec slit, an MIT 24 μm CCD, and adopting a total exposure time of 624 s. Dispersion was 1.18 Å pixel−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 λ/4 retarder with respect to the Wollaston axes, namely α = +45° and −45°.

To improve the precision of the measurements, we observed NGC 1360 and LSS 1362 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 0.35 Å pixel−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 s switching the angle $\alpha$ between $+45$ and $-45\,^\circ$. On the co-added spectra of NGC 1360 and LSS 1362, we measured $S/N \sim 2400$ and 800, respectively.

The combination of the ordinary and extraordinary 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 $\alpha$ angles, for example due to variation of sky transparency and slit illumination. Photon noise-dominated circular polarized signal can be obtained from the recorded spectra at $\alpha = +45\,^\circ$ and $-45\,^\circ$:

\[ S_{+45\,^\circ, o} = 0.5 (I + V) G_o F_{+45\,^\circ}, \]
\[ S_{+45\,^\circ, e} = 0.5 (I - V) G_e F_{+45\,^\circ}, \]
\[ S_{-45\,^\circ, o} = 0.5 (I - V) G_o F_{-45\,^\circ}, \]
\[ S_{-45\,^\circ, e} = 0.5 (I + V) G_e F_{-45\,^\circ}. \]

Hence,

\[ \frac{V}{I} = \frac{R_V - 1}{R_V + 1} \quad \text{with} \quad R_V^2 = \frac{S_{+45\,^\circ, o}/S_{+45\,^\circ, e}}{S_{-45\,^\circ, o}/S_{-45\,^\circ, e}}. \]

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:

\[ \frac{N}{I} = \frac{R_N - 1}{R_N + 1} \quad \text{with} \quad R_N^2 = \frac{S_{+45\,^\circ, o}/S_{+45\,^\circ, e}}{S_{-45\,^\circ, o}/S_{-45\,^\circ, e}}. \]

In an ideal polarimeter, signal extraction and wavelength calibration of ordinary and extraordinary spectra, $N/I$, is null and its absolute error is equal to $(N_{\text{total}})^{-1/2}$, where $N_{\text{total}}$ 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 HD 94660, whose field is at the intensity level of NGC 1360 and LSS 1362 as claimed by Jordan et al. (2005). Landstreet & Mathys (2000) have shown that the magnetic field of HD 94660 is variable with a 2700 day period between $-1.8$ and $-2$ KG. Projected rotational velocities are also comparable, as NGC 1360 shows $v_c \sin i < 20$ km s$^{-1}$ (García-Díaz et al. 2008) and HD 94660 < 30 km s$^{-1}$ (Levato et al. 1996). We did not find any estimate in the literature for the projected rotation velocity of LSS 1362, whose spectral lines appear in our spectra as broad as NGC 1360 lines.

Figure 1 shows the observed spectra of NGC 1360, LSS 1362, and HD 94660.

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 HD 24712 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 polarized intensities) $F_V$ is proportional to the derivative of the intensity flux $F_I$:

\[ \frac{F_V}{F_I} = -C g_{\text{eff}} \lambda_0^2 \frac{1}{F_I} \frac{dF_I(\lambda)}{d\lambda} B_{\text{eff}}, \]

where $C = -4.67 \times 10^{-13}$ G$^{-1}$ Å$^{-1}$, $g_{\text{eff}}$ is the effective Landé factor of the transition, $\lambda_0$ is the wavelength in Å, and

\[ B_{\text{eff}} = \frac{3}{2\pi} \int_0^{2\pi} d\phi \int_0^{1} B_\mu d\mu \]

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

The slope of the linear regression of $F_V/F_I$ versus $-C g_{\text{eff}} \lambda_0^2 \frac{1}{F_I} \frac{dF_I(\lambda)}{d\lambda}$ (forced to pass through the origin) gives the
effective magnetic field. In other words, we minimize the \( \chi^2 \) merity function

\[
\chi^2 = \sum_{ij} \frac{1}{\sigma^2} \left[ \left( \frac{F_i^s}{F_i}\right)_j + C g_{ij}^s \left( \lambda_j^i \right)^2 \frac{1}{(F_i^s)_j} \frac{d(F_i^s)_j}{d\lambda} B_{\text{eff}} \right]^2,
\]

where the standard deviation of the noise \( \sigma \) is independent of the spectral line \( i \) and wavelength \( j \). If \( (F_i^s)_j = (\lambda_j^i)^2 g_{ij}^s \frac{1}{(F_i^s)_j} \frac{d(F_i^s)_j}{d\lambda} \), after some algebra

\[
B_{\text{eff}} = -\frac{\sum_{ij} (F_i^s/F_i)_j (F_i^s)_j}{C \sum_{ij} [(F_i^s)_j]^2},
\]

while the error is obtained from the covariance matrix

\[
\delta B_{\text{eff}} = \pm \sqrt{\Delta \chi^2} \frac{\sigma}{C \sqrt{\sum_{ij} [(F_i^s)_j]^2}},
\]

where \( \Delta \chi^2 \) are isocontours of the \( \chi^2 \) 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, \( \Delta \chi^2 = 1, 4, \) and \( 9 \) 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 HD 94660. This is consistent with the absence of the 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 \( \pm \) 113 and 337 \( \pm \) 286 G, for NGC 1360 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 kG. It is important to stress that we measured the magnetic field by minimizing the sum of the merit function \( \chi^2 \) 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 HD 94660, Figure 1 shows that a clear Zeeman signature appears in all individual Balmer lines present in the spectrum of HD 94660. This is evident also from the clear linear relationship between \( F_i^s/F_i \) and \(-C g_{ij}^s \lambda_j^i \frac{d(F_i^s)_j}{d\lambda}\), in contrast to the behavior shown by the central stars of the PNe (Figure 2).

Table 1 summarizes the magnetic field inferred from individual lines. They are all consistent within errors \( B_{\text{eff}} = -1950\pm71 \) G, as expected from Landstreet & Mathys (2000). Moreover, the null spectra \( F_i^s/F_i \) shows no spurious polarization effects (Table 1 and Figure 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 HD 94660, are represented in Figure 3. In the selected velocity interval, the rms of \( F_i^s/F_i \) and \( F_i^s/F_i \) spectra are similar, \( \sigma(F_i^s/F_i) \sim \sigma(F_i^s/F_i) \sim 1.9 \times 10^{-4}, \)
for NGC 1360, and \( σ(F_0/F_1) \sim σ(F_0/F_1) \sim 5.9 \times 10^{-4} \), for LSS 1362. The large difference in the case of HD 94660, \( σ(F_0/F_1) \sim 6σ(F_0/F_1) \sim 10^{-4} \), is a further unquestionable evidence of a strong magnetic field in this star. Figure 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 the 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 NGC 1360 (LSS 1362) 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 NGC 1360 and LSS 1326. 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 disk is \( \sim 300 \) and \( \sim 600 \) G for NGC 1360 and LSS 1362, 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 (NGC 1360) and \( \sim 600 \) G (LSS 1362).

With this conclusion, no evidence is left for magnetic fields on PN central stars. On the other hand, a 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 Letter should not stop further efforts to detect magnetic fields in other PNe central stars. The method described in this Letter, 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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