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# High resolution spectra of bright central stars of bipolar planetary nebulae, and the question of magnetic shaping

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**Summary.** We present ESO NTT high resolution echelle spectroscopy of the central stars (CSs) of eight southern bipolar planetary nebulae (PNe) selected for their asymmetry. Our aim was to determine or place limits on the magnetic fields of the CSs of these nebulae, and hence to explore the role played by magnetic fields in nebular morphology and PN shaping. If magnetic fields do play a role, we expect these CSs to have fields in the range  $10^2 - 10^7$  G from magnetic flux conservation on the reasonable assumption that they must evolve into the high field magnetic white dwarfs. We were able to place an upper limit of  $\approx 20,000$  G to the magnetic fields of the central stars of He 2-64 and MyCn 18. The spectrum of He 2-64 also shows a P-Cygni profile in He I  $\lambda 5876$  and  $\lambda 6678$ , corresponding to an expanding photosphere with velocity  $\sim 100$  km s<sup>-1</sup>. The detection of helium absorption lines in the spectrum of He 2-36 confirms the existence of a hot stellar component. We did not reach the necessary line detection for magnetic field analysis in the remaining objects. Overall, our results indicate that if magnetic fields are responsible for shaping bipolar planetary nebulae, these are not required to be greater than a few tens of kilogauss.

## 1 Introduction

Planetary Nebulae (PNe) are found in a wide range of morphology, with the majority of shapes being round, elliptical, and bipolar. Several mechanisms have been proposed for shaping the bipolar structures, including a binary system, magnetic fields, and stellar rotation. Among them, magnetic fields have been an attractive hypothesis for shaping PNe into bipolar morphology for single stars.

Interestingly, magnetic fields have been detected in the progenitors and the progeny of PNe, namely, around proto-planetary nebulae (pPNe), and in white dwarfs (WDs). Since PNe and their central stars (CSs) are the evolutionary link between pPNe and WDs, at least a fraction of them should also contain magnetic fields. However, such observational evidence has been scarce. Very recently, some hints of the existence of magnetic fields in PNe have been given by means of

spectropolarimetry [1]. Among the four CSs of PNe observed, they found possible signature of magnetic fields in two CSs.

Isolated magnetic WDs (MWDs) with fields greater than  $10^6$  G show a mean mass of  $\sim 0.93 M_{\odot}$ , compared to the main peak of the mass distribution of  $\sim 0.57 M_{\odot}$  for the nonmagnetic white dwarfs [2]. This is interesting, since the statistical studies of PNe have shown that bipolar PNe may have more massive progenitors. The high mass distribution of isolated MWDs, together with more massive progenitors of bipolar PNe, seem to indicate that isolated MWDs could be the evolutionary product of magnetic CSs. If this hypothesis is correct, then, under the condition of magnetic flux conservation, we should expect a CS to MWD field ratio of

$$(B_{CS}/B_{MWD}) \sim (R_{MWD}/R_{CS})^2, \quad (1)$$

where  $B$  is the magnetic strength and  $R$  is the radius of the star. Depending on the mass of the CS and how evolved it is,  $R_{MWD}/R_{CS}$  could have a range of  $\sim 0.01 - 0.1$ . Therefore with a range of magnetic fields of  $\sim 10^6 - 10^9$  G found in MWDs, we should expect CS magnetic fields in the range of  $\sim 10^2 - 10^7$  G. Thus our aim is to search for magnetic fields in CSs of bipolar PNe in this range in order to investigate if CSs of bipolar PNe can be progenitors of MWDs.

We have obtained high resolution echelle spectroscopy of central stars (CSs) of eight southern bipolar planetary nebulae, to look for Zeeman splitting of the stellar lines caused by possible magnetic fields associated with the CSs. We selected bipolar nebulae whose central stars are bright and well separated from the nebulae, and most of them do not have direct evidence of being a binary system. The spectra were acquired with the ESO Multi-Mode Instrument (EMMI) on the 3.58 m NTT. Table 1 lists the properties of the central stars and the observing log.

**Table 1.** Target List

Object	PN G	V (CS)	Tz ( $\times 10^3$ K)	Ob. Date	Exposures (sec)
HDW 5	218.9-10.7	16.29		Feb 4, 2003	$4 \times 1800$
He 2-25	275.2-03.7	16.96	< 61	Feb 4, 2003	$4 \times 1800$
He 2-36	279.6-03.1	11.37		Feb 4, 2003	$2 \times 900$
He 2-64	291.7+03.7		48.3	Feb 5, 2003	$4 \times 1800$
He 2-123	323.9+02.4	16.84	< 60	Feb 5, 2003	$1 \times 1200 + 3 \times 1800$
He 2-186	336.3-05.6	16.62	95.5	Feb 5, 2003	$2 \times 1800$
MyCn 18	307.5-04.9	14.5 (B)	51.6	Feb 4, 2003	$4 \times 900$
NGC 2818	261.9+08.5	19.58	215.0	Feb 5, 2003	$2 \times 1800$

## 2 Results

Overall the spectra of seven objects, except HDW 5, show many nebular features. He 2-25, NGC 2818, and He 2-186 also show high expansion velocities in the hydrogen emission lines. Here we focus our attention to the stellar spectra. We found no

evidence of stellar emission or absorption in three objects, He 2-25, He2-186, and NGC 2818. HDW 5 has one stellar absorption line detected, and He 2-123 has two stellar C IV emission line detected. Only in He 2-36, He 2-64, and MyCn 18 we detected several stellar lines. We show the images of these three objects in Figure 1. For full description of our results, please see [3].



Fig. 1. R-band images of He 2-36, He 2-64, and MyCn 18

### 3 Discussion

If a Zeeman split of magnetic origin is detected in the spectrum, the field strength could be inferred with:

$$\Delta\lambda = 4.67 \times 10^{-13} g_{\text{eff}} \lambda_0^2 B \quad (2)$$

where  $\Delta\lambda$  is the split separation,  $\lambda_0$  is the wavelength of the spectral line,  $g_{\text{eff}}$  is the effective Landé factor and  $B$  is the magnetic field strength in Gauss [4]. Equation (2) can be also used to estimate upper limits to the magnetic field.

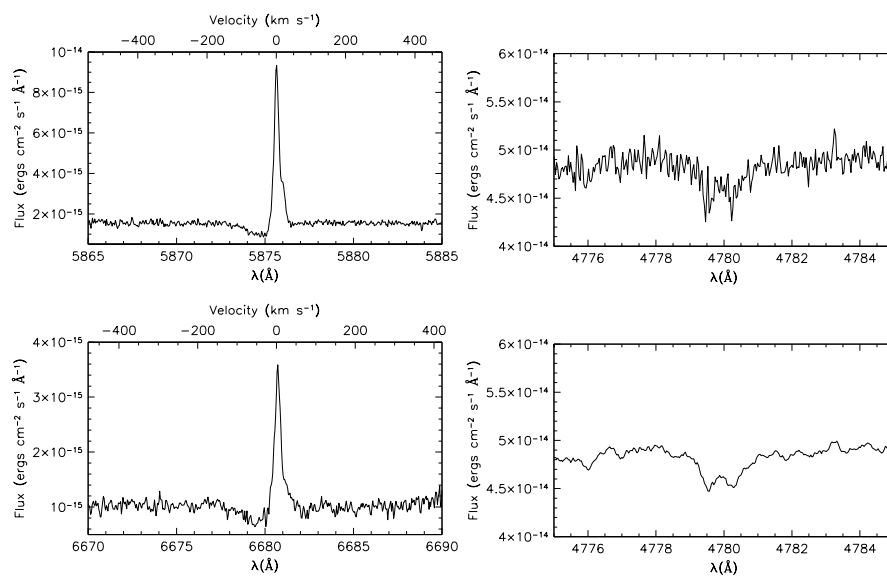
Among the 8 CSs observed, only the spectra of He 2-36, He 2-64, and MyCn 18 have high enough S/N to determine whether their stellar lines might be Zeeman split. No evidence of Zeeman splitting was found in the spectra of He 2-64 and MyCn 18. We could place an upper limit to the magnetic field associated with these two CSs using Equation (2). Due to the nature of our data – faint central stars thus low S/N for stellar continuum ( $\sim 10$  to  $20$  for He 2-64 and MyCn 18), we believe that we are unable to detect a split feature with a separation of less than  $0.4 \text{ \AA}$ . This translates to a field strength of  $\sim 20,000 \text{ G}$ . Therefore no magnetic field stronger than  $20,000 \text{ G}$  was found in the central stars of He 2-64 and MyCn 18. The spectrum of He 2-64 also shows P-Cygni profiles of the He I lines, most clearly shown at  $\lambda 5785$  and  $\lambda 6678$  (Figure 2, left). The velocity range of the wind is of the order  $\sim 100 \text{ km/s}$  from the emission maximum. This finding indicates that the star has an extensive expanding atmosphere.

The spectrum of He 2-36 is more difficult to interpret. We know that this star has two components, the cool companion being an A2 III star, and the hot companion detected to date only in the ultraviolet spectra [5]. The prominent features of our He 2-36 spectrum are those metal lines expected in a A2 III stellar spectrum. We have successfully fitted the Balmer lines in our spectrum by using a model with  $T_{\text{eff}} = 8500 \text{ K}$  and  $\log g = 2$ . There is no need to invoke a hot component to justify

these lines. On the other hand, when comparing He 2-36 with the spectrum of HD 210111, we were also able to identify two absorption lines at  $\lambda 4686$  and  $\lambda 5876$ , where no metal lines typical of an A2 III star are expected. We believe that these two lines correspond to He II  $\lambda 4686$  and He I  $\lambda 5876$ , and that we have confirmed the presence of the hot companion of He2-36 in the optical spectrum with the present observations.

The spectrum of He 2-36 also shows a feature at  $\lambda 4780$  (Figure 2, right). Since the absorption line looks split in the middle, we focused our attention to it, in order to determine its nature. First, we checked against the possibility of nebular emission contamination and concluded that this feature is of stellar origin. Second, we need to establish whether the cool or the hot companion is responsible for the split feature  $\lambda 4780$ . If absorbed by the cool component, this feature should be interpreted as Ti II  $\lambda 4779.99$ . In this case, though, this would be the only split line among the several Ti II absorption observed. If, on the other hand, this transition originates in the hot stellar photosphere, it could be identified as O IV  $\lambda 4779.10$ . But even this possibility is puzzling, since in the present spectrum we could not detect the other components corresponding to the  $2s2p(3P0)3p - 2s2p(3P0)3d$  transition of O IV. If the feature was indeed O IV, and the observed splitting was produced by the magnetic field, we could use equation (2) to estimate the field strength. This O IV transition has  $g_{\text{eff}}=4/3$ , thus the observed  $0.7 \text{ \AA}$  split could imply a field strength of the order of  $\sim 25,000 \text{ G}$  if we assume that the line splits into a doublet in the weak field regime. If we use the sequence of spectra of hot sub-dwarfs published by [6], our deduced relative strengths of He II  $\lambda 4686$  and He I  $\lambda 5876$  would appear to indicate a star with  $\log g \sim 4.5 - 5.0$  and  $T_{\text{eff}} \sim 50,000 - 70,000 \text{ K}$ . Such a star would evolve into a magnetic white dwarf with a surface dipole field strength of  $\sim 8 \times 10^7 - 2.5 \times 10^8 \text{ G}$  if we adopt a  $\log g \sim 8.5$  as being typical of magnetic white dwarfs. This field is comfortably within the range observed for the field distribution of isolated magnetic white dwarfs.

We realize that our proposal that we are seeing absorption lines from the hot star in He 2-36 superposed on the A star spectrum is not without difficulty, since such absorption features would require a comparable contribution by the two stars in the optical. A possible resolution to this dilemma is that the A star is not physically linked to the nebula and the hot component that we have found is indeed the central ionizing star of the PN. Whether or not we have measured a magnetic field in He2-36 hinges on the identification of the split absorption feature at  $4780$  which we have tentatively attributed to O IV from the hot star. This remains to be confirmed through the detection of other components of the multiplet with their associated Zeeman splitting. Higher resolution data should also reveal Zeeman splitting in the helium lines.



**Fig. 2.** Left: Spectrum of He 2-64: P-Cygni profiles. The upper panel shows He I  $\lambda 5876 \text{ \AA}$ , the lower panel shows He I  $\lambda 6678 \text{ \AA}$ . The expansion velocity inferred from these profiles is in the order of  $\sim 100 \text{ km s}^{-1}$ . The velocity scale at the top of each panel is set to 0 at the peak of the emission. Right: Spectrum of He 2-36.  $\lambda 4780$  absorption line showing splitting into two components. The bottom panel is the smoothed spectrum, which shows the splitting more clearly.

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