Discovery of magnetic fields in CPNs

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Abstract. For the first time we have directly detected magnetic fields in central stars of planetary nebulae by means of spectro-polarimetry with FORS1 at the VLT. In all four objects of our sample we found kilogauss magnetic fields, in NGC 1360 and LSS 1362 with very high significance, while in Abell 36 and EGB 5 the existence of a magnetic field is probable but with less certainty. This discovery supports the hypothesis that the non-spherical symmetry of most planetary nebulae is caused by magnetic fields in AGB stars. Our high discovery rate demands mechanisms to prevent full conservation of magnetic flux during the transition to white dwarfs.

1. Introduction

The reason why more than 80% of the known planetary nebulae (PNe) are mostly bipolar and not spherically symmetric (Zuckerman & Aller 1986, Stanghellini et al. 1993) is barely understood. A review on observational and theoretical studies of the shaping of planetary nebulae is given by Balick & Frank (2002). It is possible that magnetic fields from the stellar surface are wrapped up by differential rotation so that the later post-AGB wind will be collimated into two lobes Garcia-Segura et al. (1999). Another scenario says that magnetic pressure at the stellar surface plays an important role driving the stellar wind on the AGB (Pascoli 1997). The idea that magnetic fields are important has been supported by the detection of polarization in radio data of circumstellar envelopes of AGB stars (Kemball & Diamond 1997, Szymczak & Cohen 1997, Vlemmings et al. 2002). However, until now no magnetic fields have ever directly been detected in central stars of PNe.
2. Observations and data reduction

The observations in the spectral range 3400–5900 Å with a spectral resolution of 4.5 Å of the bright \((V \leq 12^{m}.5)\) central stars of NGC 1360, EGB 5, LSS 1362, and Abell 36 were obtained in service mode between November 2, 2003, and January 27, 2004, with the FORS1 spectrograph of the UT1 (“Antu”) telescope of the VLT, which is able to measure circular polarization with the help of a Wollaston prism and rotatable retarder plate mosaics in the parallel beam allowing linear and circular polarimetry and spectropolarimetry. NGC 1360 was observed four times, the other objects only once. The data reduction was performed analogously to Aznar Cuadrado et al. (2004). Wavelength calibration is particularly important for this kind of spectropolarimetric study, and special care was taken to ensure its accuracy.

3. Determination of the magnetic field strengths

The longitudinal component of the magnetic field for each measurement was determined by comparing the observed circular polarization for an interval of \(\pm 20 \text{ Å}\) around the four strongest absorption lines \(\text{H} \beta + \text{He} \text{ II}, \text{He} \text{ II} 4686, \text{H} \gamma + \text{He} \text{ II},\)
Hδ+He II with the prediction of the weak-field approximation for a given longitudinal component $B_l$ of the magnetic field as described in Angel & Landstreet (1970) and Landi & Landi (1973). The maximum field strength is in general larger than the longitudinal component. Test calculations with theoretical spectra have shown that the blending of the hydrogen lines and the He II lines introduces uncertainties of the order of 200 G. Only the He II 4686 line is not affected by blending.

We determined the statistical errors from the rms deviation of the observed circular polarization from the best-fit model. For the central star of NGC 1360 the weighted mean for the strongest four spectral lines (Hδ+He II, Hγ+He II, He II 4686, and Hβ+He II) for the four observing blocks was $B_l / G = -1343 \pm 259(\pm668)$ (68.3% and 99% confidence level), 1708±257(±664), 2832±269(±695), and 194±277(±548). For EGB 5 we obtained 1992±562(±1449), for LSS 1362 1891±371(±912), and for Abell 36 1169±466(±1202).

NGC 1360 clearly shows the effect of rotation between the observations: $-1343, 1708, 2832$, and 194 G. The difference in time between the three observations was 42, 0.8, and 1.0 days. The fits to the observations of the third observing block are shown in Fig. 1.

We carefully tested our $\chi^2$ fit procedure with several thousand artificial spectra and found that it is indeed possible to determine the magnetic field strength even when the magnetic polarization signal is of the same order of magnitude as the noise.

4. Discussion and conclusions

We have detected magnetic fields in 50%-100% of our small survey for magnetic fields in central stars of planetary nebulae, depending on how conservatively the criteria for statistical significance are set. This provides very strong support for theories which explain the non-spherical symmetry (bipolarity) of the majority of planetary nebulae by magnetic fields. In this first survey we have not performed a cross check with any spherically-symmetric nebulae, although we have submitted a proposal for follow-up observations.

Although based on only four objects, our extremely high discovery rate demands that magnetic flux must be lost during the transition phase between central stars and white dwarfs: if the magnetic flux was fully conserved, our four central stars will have fields between 0.35 and 2 MG when they become white dwarfs, deduced from the atmospheric parameters and the mass-radius relation of Wood (1994). Although the number of white dwarfs with magnetic fields is still a matter of debate, with a range between about 3 and 30%, even the latter value, which includes objects with kG field strengths (Aznar Cuadrado et al. 2004), is far off our high number. Liebert et al. (2003) quantified the incidence of magnetism at the level of $\sim 2$ MG or greater to be of the order of $\sim 10\%$. This argument would not change by much if we consider that we have so far only looked at central stars with non-spherical symmetric nebulae. An almost 100% probability of magnetic fields larger that 100 kG can be excluded by the data from the SPY survey (Napiwotzki et al. 2003) as well as the sample from Aznar Cuadrado et al. 2004). It is also worth mentioning that our central stars have typical white dwarf masses (0.48-0.65 $M_\odot$) and are not particularly massive.
White dwarfs with MG fields tend to be more massive than non-magnetic objects (Liebert 1988).

If the magnetic field is located deep in the degenerate core of the central star, it is very difficult to imagine a mechanism to destroy the ordered magnetic fields. Therefore, it would be more plausible to argue that the magnetic field in the central stars is present mostly in the envelope where it can be affected by convection and mass-loss. For central stars hotter than 100,000 K we do, however, not expect convection; only in the central star of EGB 5 we cannot exclude such a mechanism.

If we assume that the magnetic fields are fossil and magnetic flux was conserved until the central-star phase, we estimate that the field strengths on the main sequence were 9-50 G, which are not directly detectable. Therefore, our measurement may indirectly provide evidence for such low magnetic fields on the main sequence.

Polarimetry with the VLT has led to discovery of magnetic fields in a large number of objects in the final stage of stellar evolution: white dwarfs (Aznar Cuadrado et al. 2004), hot subdwarf stars O’Toole et al. (these proceedings), and now in central stars of planetary nebulae. Although we have now provided a good basis for the theoretical explanation of the planetary nebula morphology – which can more quantitatively be correlated with additional observations in the future – new questions about the number statistics of magnetic fields in the late stages of stellar evolution have been raised. The full details of our analysis can be found in Jordan et al. (2005).

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