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Letter to the Editor

Binary central stars of planetary nebulae with long orbits: the radial velocity orbit of BD+33°2642 (PN G052.7+50.7) and the orbital motion of HD 112313 (PN LoTr5)⋆,⋆⋆

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ABSTRACT

Aims. We study the impact of binary interaction processes on the evolution of low- and intermediate-mass stars using long-term monitoring of their radial velocity. Here we report on our results on the central stars of two planetary nebulae (PNe): the well-studied spectrophotometric standard BD+33°2642 (central star of PNG 052.7+50.7) and HD 112313 (central star of PN LoTr5), the optical light of which is dominated by a rapidly rotating G star.

Methods. The high-resolution spectra were cross-correlated with carefully selected masks of spectral lines. The individual masks were optimised for the spectral signatures of the dominant contributor of the optical light.

Results. We report on the first detection of orbital motion in these two objects. For BD+33°2642 we sampled 1.5 cycles of the 1105 ± 24 day orbital period. For HD 112313 a full period is not yet covered, despite our 1807 days of monitoring. The radial-velocity amplitude shows that it is unlikely that the orbital plane is co-planar with the one defined by the nebular waist of the bipolar nebula. To our knowledge these are the first detections of orbits in PNe that are in a range from several weeks to a few years.

Conclusions. The orbital properties and chemical composition of BD+33°2642 are similar to what is found in post-AGB binaries with circumbinary discs. The latter are probably progenitors of these PNe. For LoTr5 the Ba-rich central star and the long orbital period are similar to the Ba star giants, which hence serve as natural progeny. In contrast to the central star in LoTr5, normal Ba stars are slow rotators. The orbits of these systems have a low probability of occurrence according to recent population synthesis calculations.

Key words. binaries: spectroscopic – stars: chemically peculiar – planetary nebulae: individual: BD+332642 – planetary nebulae: individual: LoTr5 – techniques: radial velocities

1. Introduction

The role of binary interaction processes in the shape and shaping of PNe and their progenitors, the proto-planetary nebulae (PPNe), is far from understood (e.g. Balick & Frank 2002; Van Winckel 2003; De Marco 2009, and references therein). There is growing consensus that binary interaction processes play a fundamental role in many objects, but the theoretical understanding is subject to many unsupported assumptions such as the efficiency of envelope ejection, the physical description of the common-envelope phase (CE phase, Izzard et al. 2012; Ivanova et al. 2013), the accretion efficiency onto the companion (Ricker & Taam 2008), and the jet formation mechanisms in binaries. It also is an observational challenge to constrain the requirements for the most important shaping agents such as jets or magnetic fields and determine whether they are active or not.

Direct observational evidence of the binary nature of the central star of PNe and obscured PPNe is notoriously difficult to obtain (De Marco 2009) and all the techniques have their specific biases. The most successful method so far is the detection of orbital modulation in the light curve (e.g. Bond 2000; De Marco et al. 2008; Miszalski et al. 2009a,b, 2011), which led to the discovery of about 40 systems. The modulation can be caused by ellipsoidal deformation, eclipses, or irradiation of the cool component by the hot component (e.g. Hillwig et al. 2010). These photometric methods are only sensitive to systems that have spiraled-in during a CE phase and have now a period shorter than about 10 days. Several of these post-CE systems also show jets powered by accretion (e.g. Boffin et al. 2012; Miszalski et al. 2013). It is as yet unclear under which conditions wider systems will create accretion-powered jets; the main reason is the lack of observational data on the orbital characteristics of the central stars.

Here we report on the first discovery of two wide spectroscopic binaries among central stars of PNe. We introduce the objects (Sect. 2) and our radial-velocity programme (Sect. 3) in the next sections. We focus on the results in Sect. 4 and Sect. 5 and conclude in Sect. 6.

⋆ Based on observations made with the Mercator Telescope, operated on the island of La Palma by the Flemish Community, at the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias.

⋆⋆ Radial velocity data are only available at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/563/L10

2. Programme stars

2.1. BD+33°2642 (PNG 052.7+50.7)

BD+33°2642 is the central star of one of the rare halo PNe (PNG 052.7+50.7). It is very well observed because it is a spectrophotometric standard star (Oke 1990). The roundish faint nebula of about 5″ in diameter was discovered by Napiwotzki (1993) and found to be consistent with the characteristics of the central star with a $T_{\rm eff}$ of 20 200 K. Despite this rather low temperature, this star is thought to be the ionising source of the PN. Interestingly, the central star is now very metal poor, but the initial metallicity was most likely higher: the object shows a depletion of the refractory elements (Napiwotzki et al. 1994) similar to what is found in many post-AGB binaries (e.g. Van Winckel 2003; Giridhar et al. 2005; Van Winckel et al. 2009, and references therein). The abundances can be explained by assuming an accretion phase of circumstellar gas that was subject to a phase of dust production. The refractory elements are preferentially locked in the dust grains, and only the gas cleaned from the dust is accreted onto the star. For post-AGB stars, this depletion pattern is observed in binaries with circumbinary discs (Van Winckel et al. 1995; Van Winckel 2003).

The object has been subject to radial-velocity monitoring (De Marco et al. 2004, 2007) but the data were too scarce to draw firm conclusions on the possible binary nature of the object. Between August 2002 and September 2003, 14 measurements were reported with a peak-to-peak amplitude of 15.3 km s^{-1}. In 2005, radial velocity variability was detected on a time scale of about four days and with an amplitude of ~5 km s^{-1}, but this variability was absent from the short data set obtained in 2006. A clear offset of 10 km s^{-1} was detected between the mean velocities of the two different runs in 2005 and 2006, which were about 420 days apart.

2.2. HD 112313 (PN LoTr5)

HD 112313 (BD+26°2405, central star of PN LoTr5) was discovered by Longmore & Tritton (1980) and is known to be a binary PN at high Galactic latitude because the optical light is dominated by a rapidly rotating G5 III star (e.g. Bond et al. 2003). The source of the PN is a very hot central white dwarf (WD; Feibelman & Kaler 1983). The rapidly rotating cold component ($v \sin i \sim 65$ km s^{-1}) is enriched in s-process elements (Thevenin & Jasniewicz 1997) and hence can be classified as a Ba star. The observed 5.9-day period in the photometry is consistent with the rotation of the giant (Jasniewicz et al. 1997; Strassmeier et al. 1997). The system has a long history of period determinations with earlier claims that the cool component was a narrow system (e.g. Strassmeier et al. 1997, and references therein), but so far without compelling evidence for either a short binary period, or for the claimed triple nature of the system. The X-ray spectrum is too hard to be emitted by the WD and probably originates in the coronal activity of the rapidly rotating G5 giant of the system (Montez et al. 2010). Long-slit spectra of the faint large nebula were modelled successfully by Graham et al. (2004), who assumed a bipolar outflow with the polar axes inclined by only 17° to the line of sight (see their Fig. 7).

3. Radial-velocity programme

We used the HERMES spectrograph (Raskin et al. 2011) mounted on the 1.2 m Mercator telescope. This highly efficient, fibre-fed spectrograph is located in a temperature-controlled environment. We used in this programme the high-resolution science fibre, yielding a spectral resolution ($\lambda/\Delta\lambda$) of 85 000 over the whole wavelength domain from 377 to 900 nm. We began operating our spectrograph in June 2009 and since then have accumulated data in our large radial-velocity monitoring programme, which covers a wide range of evolved objects (Van Winckel et al. 2010). The zero-point of our radial-velocity determinations are scaled to the IAU radial-velocity scale (e.g. Chubak et al. 2012). Our instrumental zero-point is subject to pressure variations during the night (Raskin et al. 2011) and we obtain a standard deviation of 70 m s^{-1} based on 2137 measurements of different radial-velocity standards and measured as a spread over the mean of every standard. These data cover the period from mid-2009 onward to August 2013.

Table 1. Overview of the monitoring data for the two objects.

Central star	#	JD first	Time span (d)
BD+33°2642	202	2 455 014.43	1684
HD 112313	50	2 454 885.72	1807

In this Letter we focus on the results obtained on two central stars of PNe, and the characteristics of the two data sets are given in Table 1. The requirements on both the length and the sampling of this programme is a non-trivial observational challenge. With our own 1.2 m Mercator telescope we monitor the targets throughout the year and can adjust the sampling rate to the expected variability.

4. Analysis of BD+33°2642

BD+33°2642 is a relatively bright central star (V = 10.7 mag). Our radial velocity was computed using a discrete cross-correlation technique in which the input is a list of spectral lines. The method does not include an a priori model of the spectral broadening function. The routine works in pixel-order space and on the basis of the extracted spectrum. The contribution of every line to the final cross-correlation function is weighted by the local signal.

For BD+33°2642 we optimised a spectral mask using the lines identified by Napiwotzki et al. (1994) in their chemical analysis of the central star. We omitted the lines that are affected by the nebular component. The cross-correlation function is well defined and an individual measurement has an average intrinsic error of 270 m s^{-1}.

In Fig. 1 we show the full time series of our radial-velocity programme. The crosses in the figure indicate the radial velocity of the nebular Hα emission line with a rest wavelength of λ6562.8 Å. There is a clear long-term trend in the photospheric data. We interpret this as caused by orbital motion. Our total time span covers more than one cycle, and the orbital elements are given in Table 2. The nebular velocities have a stable radial velocity with a standard deviation of 350 m s^{-1} and a slight indication of some modulation in antiphase. The errors on the orbital elements were computed using a Monte Carlo (MC) error simulation in which we used the standard deviation of the residuals after orbit removal as a proxy of the σ value in our simulation. Our χ^2 values yield eccentricities up to around e = 0.19 of the different equivalent MC datasets, but because of the scatter and the limited number of cycles covered, the eccentricity is only poorly determined. A possible eccentric fit is not significant according to the classical statistical test (Lucy & Sweeney 1971).

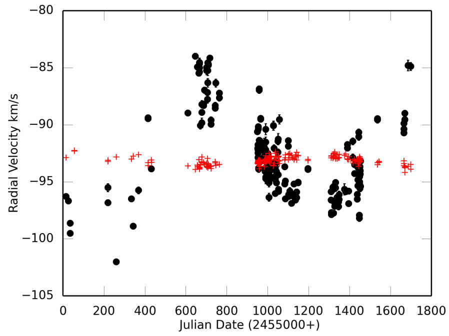

Fig. 1. Time series of barycentric radial velocity measurements of BD+33°2642. The crosses indicate the nebular velocity determined using the Hα emission line.

Table 2. Orbital elements of BD+33°2642.

		σ
Period (d)	1105.	24.
e	0	imposed
K (km s^{-1})	5.10	0.25
γ (km s^{-1})	−91.86	0.15
JD(0)	2 456 524.0	inferior conjuction
$a \sin i$ (AU)	0.52	0.02
f(M) ($M_\odot$)	0.015	0.002
RMS residuals (km s^{-1})	1.8	

The fit that imposes a circular orbit with a period of 1105 days has a fractional variance reduction of 74 % and the residuals have a standard deviation of 1.8 km s^{-1}, clearly larger than the intrinsic uncertainty of the velocity determinations. The shorter term variability, probably of atmospheric origin, was also reported by De Marco et al. (2007).

When we add the radial velocities obtained by De Marco et al. (2007) to increase the total monitoring length by some 1500 days, we obtain very similar orbital elements with a slight increase of the most likely orbital period to 1136 days. The disadvantage is that these data come from another instrument and the velocities were obtained with a different method. A potential systematic difference between the two instruments was not taken into account. What De Marco et al. (2004, 2007) observed as radial-velocity offsets between the mean velocities of their different runs is caused by orbital motion. The phased radial-velocity curve of the HERMES data alone is given in Fig. 2. With the phase dispersion minimisation (Stellingwerf 1978) technique, we were unable to find a significant frequency in these residuals. When we assume that the primary has an average mass of a WD (0.6 $M_\odot$), the mass function of 0.015 ± 0.002 $M_\odot$ translates into a companion mass of 0.22 $M_\odot$ (i = 90°) and 0.26 $M_\odot$, for an inclination of 60°.

5. Analysis of HD 112313

Similar to what we did for BD+33°2642, we optimised a specific spectral mask for HD 112313. Starting from a well-exposed spectrum, we selected 135 relatively isolated lines in the region between 4750 and 6550 Å. The dominant component is a rapidly rotating star, and the cross-correlation function was fitted with a rotation profile. In Fig. 3, we show the time series of our measurements. The long-term trend is clearly visible, but despite our monitoring efforts that were as long as 1807 days, we have not yet covered a full cycle. The peak-to-peak amplitude is

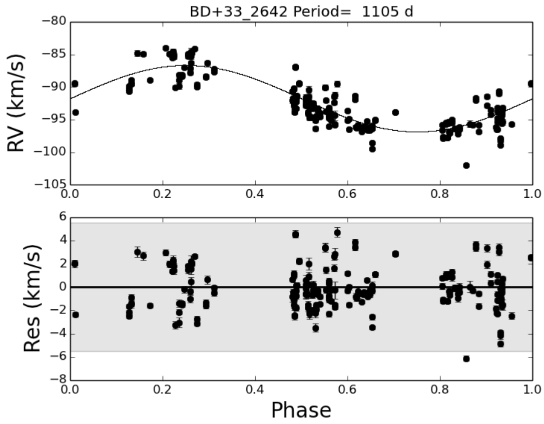

Fig. 2. *Top panel*: barycentric radial-velocity measurements of BD+33°2642 folded on the orbital period. The full line represents the Keplerian circular orbit. *The bottom panel* shows the residuals, and the grey area is the three-sigma level of the residuals.

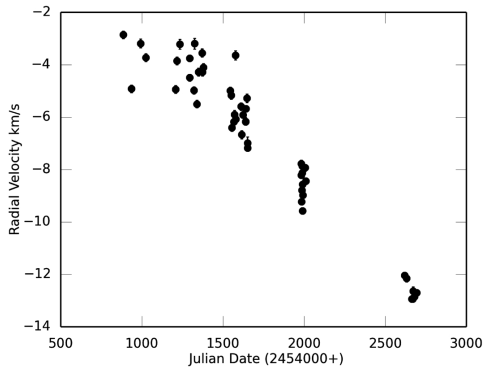

Fig. 3. Time series of radial-velocity measurements of HD 112313.

about 10 km s^{-1}. The $v \sin i$ of 66.2 ± 0.7 km s^{-1} agrees with the value in the literature (Strassmeier et al. 1997).

We can estimate a mass function of 0.05 $M_\odot$ by assuming an amplitude of 5 km s^{-1} and a period that is twice as long as the total time we covered till now. The amplitude is a lower limit, and a probable increase impacts strongly on the mass function with its dependency on the third power. The dependency on a different orbital period is much weaker.

Assuming that the orbital plane is co-planar with the waist of the bipolar nebula (Graham et al. 2004), our inclination angle to the system is only 17°. With a typical mass of 1.1 $M_\odot$ for the G star and the above mass function, the mass of the hot source in the system must be 3.5 $M_\odot$, clearly incompatible with a WD mass. A more massive G giant in the system would increase this mass even more. The most likely larger mass function will exacerbate this conflict as well. We conclude that either the inclination angle of the bipolar model of Graham et al. (2004) is incorrect or that the orbital plane is not co-planar with the waist of the bipolar nebula. The alternative is that we see a triple system in which the hot component is a double star with a combined mass of 3.5 $M_\odot$. The close companion of the hot WD must then be an object of some two to three solar masses.

Obviously, we should continue our efforts to monitor this object to cover a full orbital cycle, which will allow us to constrain the dynamics of the system better.

6. Results and discussion

We reported here on the detection of two wide spectroscopic binaries among the central stars of PNe: one with a period of about 1100 days and one whose orbital period is longer than 1800 days. To our knowledge these are the first spectroscopic binaries among central stars of PNe with orbits longer than several weeks. Radial-velocity monitoring nicely complements the photometric techniques, which are only sensitive to systems that spiraled-in during a CE phase (e.g. Miszalski et al. 2012, and references therein).

The separations are puzzling because any binary with a separation within approximately several giant radii will be tidally captured and, if unstable mass transfer ensues, a common envelope arises with a dramatic shortening of the orbital separation, depending also on the envelope binding energy. The separation indicates that either the common envelope was rapidly ejected without much in-spiralling, or that a form of stable mass transfer occurred. Population-synthesis models (e.g. Keller et al., in prep., and references therein for an overview) predict a CE channel to be representative of only 14−15% of all PNe, which includes a small fraction that are formed through post-RGB interaction (Hall et al. 2013). The binary channel for PNe formation also predicts wider systems that primarily interacted by wind accretion (e.g. Soker 1997). The final period distribution of binary PNe is predicted to be bi-modal, in which the CE channel populates the short-period binaries and the wider systems interacted by wind interaction. The orbital periods that are least often predicted are in the middle of the bi-modal distribution and occur at about 1000 days (Keller et al., in prep.). Wide binaries are also expected to exist among central stars of PNe, but the periods found by us here fall in the minimum of the predicted period distribution. Obviously, two systems are not enough to draw far-reaching conclusions.

It is a long-standing problem that the predictions of population-synthesis computation also starkly contrast with the periods found in post-AGB binaries (e.g. Van Winckel et al. 2009) and those found in wide binaries with WD companions such as Ba stars (e.g. Jorissen 1999). The periods (and eccentricities) found in these systems are not predicted by the population-synthesis models because they almost all fall in the minimum of the expected period distribution. Period-wise the PNe binaries described here form a natural link to the post-AGB binaries (as potential precursors) and Ba-stars (as potential successors). The dynamic information from the orbits lead to interesting conclusions:

– BD+33°2642 is a spectrophotometric standard star and one of the few PNe in the Galactic halo. It is a binary with abundance anomalies, very similar to what is found in many Galactic post-AGB binaries with circumbinary discs. The orbit of BD+33°2642 is similar to the orbits found in the post-AGB binaries. This object is therefore a natural progeny of the class of depleted F-K type post-AGB binaries with circumstellar discs (Van Winckel 2003) and shows that the latter can also become PNe.
– Although the full orbit of HD 112313 is not yet covered, the lower limit of the mass function led to a conflict between the nebular and orbital properties. The obtained mass function implies that either the orbital plane is not co-planar with the waist of the bipolar nebula, or that the WD is member of a close binary with a total mass of 3.5 $M_{\odot}$. The cool Ba-rich component of the system must be spun-up by wind accretion, and we disproved the statements in the literature that the rapidly rotating G star may be a close binary.

Our project shows that detecting radial-velocity orbits in central stars of PNe is possible but intensive long-term monitoring is clearly needed. This requires a dedicated long-term observational project. Many prime candidates for PNe with binary central stars can be found, but they are very faint (e.g. De Marco et al. 2013) and will require regular telescope time on large infrastructure.

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