Two rings but no fellowship: LoTr 1 and its relation to planetary nebulae possessing barium central stars

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ABSTRACT
LoTr 1 is a planetary nebula thought to contain an intermediate-period binary central star system (that is, a system with an orbital period, $P$, between 100 and, say, 1500 d). The system shows the signature of a K type, rapidly rotating giant and most likely constitutes an accretion-induced post-mass-transfer system similar to other PNe, such as LoTr 5, WeBo 1 and A70. Such systems represent rare opportunities to further the investigation into the formation of barium stars and intermediate-period post-asymptotic giant branch systems – a formation process still far from being understood. Here, we present the first detailed analyses of both the central star system and the surrounding nebula of LoTr 1 using a combination of spectra obtained with Very Large Telescope-Focal Reducer and low dispersion Spectrograph, Anglo-Australian Telescope-UCL Coudé Echelle Spectrograph and New Technology Telescope-European Southern Observatory Multi-Mode Instrument, as well as SuperWASP (Wide Angle Search for Planets) photometry. We confirm the binary nature of the central star of LoTr 1 that consists of a K1 III giant and a hot white dwarf. The cool giant does not present any sign of s-process enhancement but is shown to have a rotation period of 6.4 d, which is a possible sign of mass accretion. LoTr 1 also presents broad double-peaked Hα emission lines, whose origin is still unclear. The nebula of LoTr 1 consists in two slightly elongated shells, with ages of 17 000 and 35 000 yr, respectively, and with different orientations. As such, LoTr 1 present a very different nebular morphology than A70 and WeBo 1, which may be an indication of difference in the mass-transfer episodes.

Key words: stars: AGB and post-AGB – binaries: general – stars: chemically peculiar – planetary nebulae: individual: LoTr 1 – planetary nebulae: individual: WeBo 1 – planetary nebulae: individual: A66 70.

1 INTRODUCTION
The interaction between the progenitor star and a binary or planetary companion is believed to shape the resulting planetary nebula (PN) and in some cases even thought to be almost essential for a PN to form (Moe & De Marco 2006). The shaping influence of a common-envelope (CE) evolution has been studied extensively (see e.g. Jones et al. 2010b; Tyndall et al. 2012) and understood in terms of either a collimated fast wind carving out an axisymmetric nebula (Soker & Rappaport 2000) or the ejected CE forming an equatorial density enhancement (Nordhaus & Blackman 2006) as required by the ‘generalized interacting stellar winds’ model (Kahn & West 1985). However, very little is known about intermediate period ($P = 100–1500$ d; van Winckel et al. 2009) post-asymptotic giant branch (AGB) binaries, including their effect on PNe formation and morphology, due to lack of observations. The intermediate-period binaries fall between post-CE systems (Miszalski et al. 2009) and

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visually resolved systems (e.g. Ciardullo et al. 1999). Soker (1997) claimed that these interacting systems are the most likely central stars of planetary nebulae (CSPNe) to form the classical ‘butterfly’, or bipolar, morphologies, but with few systems known and limited investigations, this has yet to be confirmed. Only by finding and studying CSPNe with intermediate periods can we substantiate this claim and relate the processes at work in formation of PNe by both post-CE and intermediate-period CSPNe.

The PN LoTr 1 (α = 05:55:06.6, δ = −22:54:02.4, J2000) was first discovered by A.J. Longmore and S.B. Tritton with the UK 1.2 m Schmidt telescope (Longmore & Tritton 1980). It is generally noted that LoTr 1 belongs to the so-called ‘Abell 35-type’ group (Bond, Ciardullo & Meakes 1993) of PNe showing evidence of a binary central star system consisting of a cool central star (a rapidly rotating subgiant or giant) and an optically faint hot companion [a white dwarf (WD) with effective temperature, \( t_{\text{eff}} \approx 100 \, \text{kK} \)] since these giant stars are too cool to ionize the surrounding nebula. Four PNe fell into this category: Abell 35 (hereafter, A35), LoTr 5 (Thevenin & Jasnièwicz 1997), WeBo 1 (Bond, Pollacco & Webbink 2003) and Abell 70 (Miszalski et al. 2012, hereafter, A70). However, Frew (2008) determined that A35 is most likely not a true PN, but rather a Strømgren zone in the ambient interstellar medium (ISM). This claim is substantiated by Ziegler et al. (2012), who find that the central star may in fact have evolved directly from the extended horizontal branch to the WD phase (a so-called AGB-manqué star). As such, we choose not to consider A35 in our comparisons among this group.

Another common factor amongst this particular group of PNe is evidence for the existence of ‘Barium (Ba II) stars’ (Bidelman & Keenan 1951) – Population I G/K-type AGB stars that show an overabundance of carbon and s-process elements, in particular barium (Thevenin & Jasnièwicz 1997). A now-canonical model for the formation of these Ba II stars states that they form not through CE evolution,\(^1\) as is the case for close binaries found within PNe, but rather via a wind-accretion scenario (Boffin & Jorissen 1988). Here, the future Ba II star is polluted whilst on the main sequence by the wind of its companion (Luck & Bond 1991; the companion having dredged up these s-process elements during its thermally pulsing AGB phase), but with the system remaining detached. After the envelope is ejected to form the surrounding nebula, the AGB star evolves into a WD, while the contaminated star retains its chemical peculiarities to form the remnant Ba II star.

One important prediction to come out of the wind-accretion model is that the accreting star, i.e. the future Ba II star, also accretes angular momentum from the companion to become a rapid rotator (Jeffries & Stevens 1996; Theuns, Boffin & Jorissen 1996). Indeed, photometric monitoring of LoTr 5 (Thevenin & Jasnièwicz 1997) and Webo 1 (Bond et al. 2003) has revealed that their cool components are in fact rapid rotators with a rotation period of a few days, thus providing further evidence for this formation scenario. This is further evidenced by the fact that Montez et al. (2010) found that the X-ray emission from the binary central stars of LoTr 5 is most likely due to the chromospheric activity from a spun-up companion.

Most Ba II stars are not observed to be within PNe, almost certainly because the lifetime of the PN is very short with respect to the lifetime of the stellar system. However, this does not completely rule out the possibility that some Ba II stars may be formed without passing through a PN phase. Indeed, there are a few examples of field stars that have been shown to consist of a rapidly rotating cool star linked to an optically faint hot component in a similar fashion to the A35 group, but without current evidence for a surrounding PN. As mentioned by Bond et al. (2003), HD 128220 (\( P = 872 \) d) is one such system, made up of an O subdwarf and a G0 giant companion. O subdwarfs overlap with CSPN in terms of their log \( g \) and \( t_{\text{eff}} \), implying that they too are found to be in a post-AGB phase of evolution (Howarth & Heber 1990). 56 Pegasi is another example, whereby it possesses a system consisting of a K0 giant and a hot WD companion with evidence for an overabundance of Ba II, and has an estimated orbital period of 111 d (Griffin 2006). It is possible that both of these systems have gone through a PN phase in the past, but it has since dissipated into the surrounding ISM. This fact, as well as the knowledge that in Ba II central stars the chemical pollution process happened very recently – either during or immediately prior to the formation of the PN – makes it highly important to study such systems as A70 and WeBo 1, as it will allow us to gain greater insight into both the s-process within AGB stars and mass-transfer mechanisms.

In this paper, we present photometric and spectroscopic observations of LoTr 1 and its central star along with complementary data of A70 and WeBo 1, in order to try to relate the evolutionary processes of these three systems\(^2\) and see if they belong to a common ‘fellowship’ of s-process enriched cool CSPN inside ring-like nebulae.

2 OBSERVATIONS AND ANALYSIS

2.1 LoTr1

2.1.1 Imaging

The deep [O III]λ5007 Å and H\(\alpha + [\text{N II}]\lambda 6584 \) Å images shown in Figs 1(a) and (b) were acquired on 2005 March 03 using the red arm of the European Southern Observatory (ESO) Multi-Mode Instrument (EMMI; Dekker, Delabre & Dodorico 1986), mounted on the 3.6 m New Technology Telescope (NTT) of the La Silla Observatory. EMMI was used with the mosaic of two MIT/LL CCDs, 2048 × 4096 15 μm pixels. The exposure time, \( t_{\text{exp}} \), in each filter was 1800 s, and the binning was set to \( 2 \times 2 \) (≈ 0.33 arcsec pixel\(^{-1}\)). The seeing was ≈ 0.7 arcsec.

The images show LoTr 1 to have an apparent double-shell structure, with the central shell having a circular profile with an angular diameter of 47 arcsec ± 4 arcsec and the outer shell a more irregular, but still roughly circular, appearance, with a diameter of 2 arcmin 26 arcsec ± 4 arcsec. Furthermore, in [O III]λ5007 Å, the outer shell appears brighter in the north-west and south-east – this, coupled with the slight deviation from circular symmetry, could be considered evidence for an inclined, elongated structure, where the brighter areas result from a projection effect.

\(^1\) We note, however, the existence of some exceptional systems that also experience similar enrichment in close binaries, i.e. the Necklace nebula (Miszalski, Boffin & Corradi 2013a), and which are most likely linked to dwarf carbon stars.

\(^2\) PN K 1-6 (Frew et al. 2011) is another potential candidate for this group of objects, as it also shows evidence of possessing both a G- or K-type giant (inferred from imagery, looking at both optical and 2MASS near-infrared colours) and a very hot subdwarf or WD (inferred from GALEX archival images) at its core. However, no stellar spectroscopy is available as yet to look for signs of chemical enrichment (Frew et al. 2011). More recently, Miszalski et al. (2013b) presented evidence for a carbon and s-process enriched giant at the centre of the PN Hen 2-39. Due to it being a newly investigated system, Hen 2-39 is not included in this study either.
Interaction with the ISM is also frequently invoked to explain deviation from symmetry and brightening of the nebular shell (e.g. Jones et al. 2010b); however, this would not produce the apparent axisymmetry in the nebular brightening (as the nebula would only interact strongly with the ISM in the direction of its motion; Wareing, Zijlstra & O’Brien 2007).

### 2.1.2 Nebular spectroscopy

Longslit echelle spectroscopy was carried out using Anglo-Australian Telescope-UCL Coude Echelle Spectrograph (AAT-UCLES) and NTT-EMMI, focusing on [O iii] emission over eight different slit positions (see Fig. 1b) in order to gain velocity profiles across a good sample of the nebula. It is important to ascertain the true three-dimensional shape of the surrounding nebula in order to fully understand and constrain the shaping process, and subsequently give a clearer insight into mass-transfer mechanisms. Imaging is insufficient on its own due to a degeneracy between PN inclination and morphology – for example, when the symmetry axis of a bipolar nebula is aligned perpendicular to the plane of the sky, it makes the nebula appear spherical (Kwok 2010). If the nebular morphology is classified incorrectly, then the fraction of aspherical PNe possessing a binary core will also end up being inaccurate, and this information is already exceedingly limited for longer period binaries due to selection biases for those stellar systems possessing wider orbits. Longslit spectroscopy can be used to acquire spatially resolved velocity maps of the constituent parts of the nebula in order to recover the ‘missing’ third dimension of the morphology that one cannot gain from imagery alone. The resulting spectra are then plotted as position–velocity (PV) arrays.

On 2005 March 03, a spectrum was acquired from the nebula using EMMI in its single-order echelle mode, employing grating #10 and a narrow-band [O iii] λ5007 Å filter to prevent contamination from overlapping echelle orders. The maximum slit length of 330 arcsec and a slit width of 1 arcsec was used to give a resolution, R ≈ 54 000 (5.5 km s$^{-1}$). A 1800 s exposure was taken at a position angle (PA) of 90° crossing the central star (slit position 1 in Fig. 1b), and the data were 2 × 2 binned to give a spatial scale of 0.33 arcsec and a velocity scale of 3.9 km s$^{-1}$ pixel$^{-1}$. The seeing was ~0.7 arcsec.

On 2005 January 14, spectra were acquired from the nebula of LoTr 1 using the 79 lines mm$^{-1}$ grating on the UCLES of the AAT. UCLES was operated in its longslit mode with a maximum slit length of 56 arcsec and a slit width of 1.97 arcsec to give a resolution R ≈ 20 000 (15 km s$^{-1}$). The EEV2 CCD (2048 × 4096 13.5 μm pixels) was used with binning of 2 × 3, resulting in a pixel scale of 3.88 km s$^{-1}$ pixel$^{-1}$ in the spectral direction and 0.48 arcsec pixel$^{-1}$ in the spatial direction. 1800 s exposures were taken at five different slit positions (shown in Fig. 1b) using a narrow-band filter to isolate the 45th echelle order containing [O iii] emission line profile. Slits 2–4 were taken at a PA of 0°, and slit 5 was taken at a PA of 90°. The seeing during the observations was ~2 arcsec. A further three slits (slit positions 6–8 in Fig. 1b) were acquired using the same instrument and CCD on 2013 January 3 with a seeing of ~1.5 arcsec and a binning of 2 × 2 (≈ 0.32 arcsec pixel$^{-1}$ in the spatial direction). Here, a slit width of 1 arcsec was employed for slits 6 and 8 ($R ∼ 45 000 ≡ 6.7$ km s$^{-1}$) and 1.5 arcsec for slit 7 ($R ∼ 30 000 ≡ 10$ km s$^{-1}$).3

All the spectra were cleaned of cosmic rays and debiased appropriately. The UCLES spectra were wavelength calibrated against a ThAr emission lamp, rescaled to a linear velocity scale appropriate
for the [O III] 5007 Å emission and corrected to heliocentric velocity, \( V_{\text{hel}} \). Due to the optical setup of EMMI, it was necessary to perform the wavelength calibrations using a long-exposure (3600 s) ThAr emission lamp at the start and end of the night to gain a good number of arc lines, before cross-correlating with shorter exposure (200 s) Ne lamps taken immediately after each observation, to account for any drift due to telescope and instrument flexure (with small shifts accounted for with a linear correction).

The reduced nebular spectra of LoTr 1 are presented in Figs 2 and 3, as PV arrays. In each PV array, cross-section 0 arcsec defines where the central star is found. In Fig. 2(a), the bright lines located around the central star at cross-sections +3 and −3 arcsec are most likely artefacts due to the comparative difference in brightness between the central star and the nebula (Jones et al. 2010a).

The closed velocity ellipses shown in the PV arrays presented in Figs 2(a), 3(c) and the central PV array of Fig. 2(b) (i.e. representing slit positions 1, 4 and 7) have a major axis which has the same length as the diameter of the inner shell (see Section 2.1.1). This indicates that the nebular structure is indeed an isolated, closed shell rather than a projection effect related to a bipolar structure being viewed end on. No significant asymmetries are observed in these velocity ellipses, which are consistent with a spherical shell or an elongated ovoid viewed directly along the symmetry axis. The expansion velocity, \( V_{\text{exp}} \), for the inner shell is measured to be \( 17 \pm 4 \) km s\(^{-1}\) at the location of the central star, while the \( V_{\text{exp}} \) for the outer shell is measured to be \( 25 \pm 4 \) km s\(^{-1}\) falling within the typical range for a PN (Weinberger 1989). Assuming typical expansion properties for the nebula (i.e. velocity proportional to distance from the central star), the latter velocity is then the maximum expansion velocity (for an elliptical shell viewed pole-on) or the uniform expansion velocity of the shell (in the case of a sphere). The heliocentric systemic velocity, \( V_{\text{sys}} \), of this central shell was determined to be \( 14 \pm 4 \) km s\(^{-1}\).

In slit 1 (Fig. 2a), emission is clearly detected from outside of the central shell at cross-sections \( \sim 40 \) and \( \sim -40 \) arcsec, associated with the outer shell (see Section 2.1.1). Here, the emission from the eastern side appears blue shifted with respect to the nebular \( V_{\text{sys}} \), and the west appears red shifted; this is indicative of an inclined and extended structure, e.g. an elliptical nebula, where the approaching ‘lobe’ is tilted slightly to the east of its receding counterpart. Consideration of the other slits presented in 3(b), (c) and (d) confirms this asymmetry in the velocity profile across the nebula, but indicates that the symmetry axis may lie closer to the northeast–southwest direction than east–west. However, any deviation from the line of sight must be rather small given the almost circular appearance of the shell in the images (Fig. 1).

Determination of the exact structure and inclination of the nebula would require a more extensive, higher signal-to-noise ratio (SN; given the outer shells faintness) data set, covering more of the physical extent of nebula and a detailed spatiokinematical model such as that presented in Jones et al. (2012a). However, it is clear from both the imaging and spectroscopy presented here that LoTr 1 shows a double-shelled structure with evidence for an elliptical and slightly inclined outer shell, and a morphologically similar inner shell but with a different orientation.

### 2.1.3 Stellar photometry

The field of LoTr 1 has been observed by Wide Angle Search for Planets-South (WASP-S) between 2006 May 4 and 2012 February 17 with a total of 21 407 photometric points obtained with the two cameras DAS 226 and 228. WASP-S is a wide field survey camera...
Figure 3. PV arrays showing reduced [O\textsc{iii}]\(\lambda5007\) AAT-UCLES spectra of LoTr 1. The velocity axis is heliocentric velocity, \(V_{\text{hel}}\). The display scale has been modified to highlight the spatiokinematic features referred to in the text. Slits 2–4 are N–S (north is to the top of the array), slit 5 is E–W (west is to the top of the array). Cross-section 0 arcsec defines where the central star is found. The continuum of a field star is visible at cross-section \(-8\) arcsec in figures (a) and (b), and at cross-section \(+18\) arcsec in figure (d).
2.1.4 Stellar spectroscopy

On 2012 February 10, a low-resolution spectrum was acquired of the central star of LoTr 1 using the Focal Reducer and low-dispersion Spectrograph (FORS2; Appenzeller et al. 1998) with grism 1200g, on the Antu unit (UT1) of the Very Large Telescope (VLT) based at ESO-Paranal. FORS2 was operated with a maximum slit length of 6 arcmin and a 0.5 arcsec slit width ($R \sim 3000$), and at a PA of 45°. The data were $2 \times 2$ binned to give a spatial scale of 0.25 arcsec pixel$^{-1}$, with a dispersion on the spectral axis of 0.3 Å pixel$^{-1}$. A single 600 s exposure was taken under seeing of ~0.7 arcsec.

The stellar data were extracted to 1D and flux calibrated against standard star Hz 4, and are presented in Fig. 5(a). All reductions were carried out using standard STARLINK routines.

The central star of LoTr 1 was classified as a K1 III-type giant by comparing the flux-calibrated FORS2 spectrum with Ultraviolet and Visual Echelle Spectrograph (UVES) Paranal Observatory Project standard stars (Bagnulo et al. 2003) that had been rebinned and smoothed to match the resolution of the FORS2 data. To refine the analysis and derive the possible s-process overabundance, we used the stellar spectral synthesis code of R. Gray, SPECTRUM version 2.76, with models from Castelli & Kurucz (2003). The best-fitting parameters were determined to be $t_{\text{eff}} = 4750 \pm 150$ K and log $g = 2.0 \pm 0.5$, which is in agreement with the K1 III spectral type. Using the average value of the absolute magnitude, $M_v = +0.7$, for a giant of this spectral type as given in Allen’s ‘Astrophysical Quantities’ (2000), the flux for the spectrum shown in Fig. 5(a) that allows the derivation of an apparent magnitude, $m_v = +12.6$ (accounting for 20 per cent slit-losses) and extinction $A_V = 0.1285$ (Schlegel, Finkbeiner & Davis 1998), one can determine a rough distance to the star of 2.6 kpc and a not-unreasonable radius of the giant of 11.5 $R_\odot$. Alternatively, one can use the average value of $V$ derived from SuperWASP (see Fig. 4), i.e. $V = 12.44$, to derive a distance of 2.1 kpc. Note that this observed SuperWASP magnitude is likely to be contaminated by line emission and close field stars because of the broad observing band and large (14 arcsec) pixels. Therefore, we think it is preferable to use the distance derived from the flux-calibrated spectra.

To check that the giant and the PN are indeed linked and not merely a chance superposition, we computed the radial velocity difference between the nebular lines in the FORS2 spectrum and the giant star’s absorption lines, cross-correlating our spectrum (shifted so that the nebular lines are at zero velocity) with our synthetic K1 III spectrum. The resulting stellar velocity of 4 ± 2 km s$^{-1}$ with respect to the nebula implies that the cool central star and nebula are physically related.

The FORS2 spectrum was used to check for signs of Ba II pollution at 4554 Å. Fig. 6 shows the FORS2 spectrum of LoTr 1 plotted alongside three synthetic spectra with various barium enhancements, from [Ba/Fe] = 0.1 to 0.5. An overabundance of 0.5 or greater classifies the system as a definite Ba II star, with a value of 0.2–0.5 being possibly a ‘mild’ Ba II star (Pilachowski 1977). Due to the relatively low S/N and resolution of the spectrum, we are unable to determine a definitive value for the barium abundance in LoTr 1, but we can clearly state that it is much less than 0.5 and therefore does not show any measurable barium enhancement. This is contrary to both A70 and WeBo 1 (see Miszalski et al. 2012 and Bond et al. 2002, respectively), which both possess definite Ba II stars.

On 2013 January 3, 3 × 30 min spectra were acquired from the CSPN of LoTr 1 using AAT-UCLES with the 79 lines mm$^{-1}$ grating, operated in full echelle mode with a slit width of 1 arcsec to give a resolution $R \sim 45 000$. All spectra were reduced using standard STARLINK routines, corrected to heliocentric velocity and then summed. Unfortunately, because of the large interorders in the spectra, it is not possible to assess the barium abundance, as none of the available orders contain the Ba II lines at 6141.7 and 6496.9 Å. We have verified, however, that the iron lines are well fitted with a solar abundance and our preferred model, in agreement with what we derived from the FORS2 spectrum. Looking at the La II 6390 Å and Y II 6222 Å lines, it is also clear that these elements are not overabundant, confirming the lack of s-process enhancement in LoTr 1.

\footnote{See http://www1.appstate.edu/dept/physics/spectrum/spectrum.html}
\footnote{UCLES operated in this mode gave non-continuous wavelength coverage from roughly 5200 to 8900 Å across 19 orders with interorder spacing of 100–200 Å.}
Figure 5. (a) Flux-calibrated FORS2 spectrum of the central star system of LoTr 1. (b) Flux-calibrated IUE spectra of LoTr 1 (solid line) and of NGC 7293 (dashed line) used to determine the parameters of the WD. Note also the presence of the Mg II emission at 2800 Å which is a sign of chromospheric activity from the cool companion (e.g. Jasniewicz et al. 1996; Montez et al. 2010).

Figure 6. LoTr 1 FORS2 stellar spectrum (solid line) alongside three synthetic spectra with [Ba/Fe] = 0.1, 0.2 and 0.5, smoothed to match the FORS2 resolution and plotted over a wavelength range which includes the Ba II 4554 Å line.

The AAT spectra allowed us to find that the stellar component of Hα is in emission (see Fig. 7). The line is very broad and is clearly double peaked, with an equivalent width of about 6 Å and the velocity spread 572 km s\(^{-1}\). Using the method of Hodgkin, Jameson & Steele (1995), we derive an Hα luminosity \(L_{H\alpha} = 0.044 \, L_\odot\). With the above-estimated total luminosity of the star \(L_\ast \sim 60 \, L_\odot\), this gives a value \(\log L_{H\alpha}/L_\ast = -3.12\).

Such Hα double-peaked emission lines have been found in the other stars we are concerned with here, LoTr 5 (Jasniewicz et al. 1992; Strassmeier, Hüb1 & Rice 1997) and A35 (Acker & Jasniewicz 1990; Jasniewicz et al. 1992), but the origin is still unknown. Rapidly rotating giants, such as RS CVn or FK Com stars, are known to have high chromospheric activity which is often revealed by emission cores in some lines. And indeed, Acker & Jasniewicz (1990) find a modulation of the Hα emission line with the rotation phase, while Jasniewicz et al. (1992) postulate that the variable double-peaked emission line is the result of an overlap between an absorption and an emission line at Hα, with the possibility for the absorption component to be formed in the photosphere or through a self-absorption process as in Be stars. However, the full width at half-maximum velocity we measure seems too high to be caused by mass motions inside the chromosphere, while the luminosity is too small to be due to accretion. Such double-peaked emission are also sometimes found in symbiotic stars – detached systems which interact via wind accretion. A few of them, out of an outburst event, produce bipolar nebulae very similar to PNe. It turns out that many symbiotic stars show double Hα profiles (e.g. Schild, Muerst & Schmutz 1996; Burmeister & Leedjärv 2009), which might be caused by a narrow absorption component from the giant overlaid with very broad Hα emission from high-velocity jets at the core of the system or by disc-like structures. It would thus be of interest to further study the possible link between LoTr 1 and symbiotic stars.
A spectrum of the central star system of LoTr 1 was acquired using the International Ultraviolet Explorer (IUE) satellite by Bond et al. (1989). Presented here in Fig. 5(b), it indicates a strong ultraviolet (UV) continuum of $t_{\text{eff}} \geq 100\text{kK}$. Comparing this IUE spectrum to a known WD within PN NGC 7293 ($d = 219^{+5}_{-3}$ pc, $m_v = +13.5$; Harris et al. 2007) gave us a reasonable fit: $t_{\text{eff}} \geq 123\text{kK}$ and $R = 0.017 R_{\odot}$. Based on values of $D = 2 \text{arcmin} 22\text{arcsec} \pm 4\text{arcsec}$ and $V_{\text{exp}} = 25 \pm 4 \text{km s}^{-1}$ at a distance of 2.1–2.6 kpc, we derived a kinematical age of $33000 \pm 9000\text{yr}$ for the outer nebular shell. For the inner shell, with given values of $D = 47 \pm 2\text{arcsec}$ and $V_{\text{exp}} = 17 \pm 4 \text{km s}^{-1}$, the age is derived as $16000 \pm 6500\text{yr}$. Using the WD evolutionary curves from Bloeker (1995) and assuming an average remnant mass of $0.6 M_{\odot}$, we derived a stellar temperature at the age of the PN of approximately $120\text{000 K}$. The derived radius and age of LoTr 1 are consistent with Bloeker’s evolutionary curves.

2.2 A70

2.2.1 Imaging

The Hα+[N II]λ6584 Å image of A70 shown in Fig. 8 was acquired on 2012 July 08, using FORS2 under programme ID 0.89.D-0453(A), with an exposure time of 60 s and seeing of 0.8 arcsec. At first glance the image shows a general ring-like appearance similar to that of other ring-like PNe (e.g. SuWt 2; Jones et al. 2010a); however, just as noted by Miszalski et al. (2012), a closer inspection reveals a ‘ridged’ profile more like that of a bipolar nebula viewed end-on (e.g. Sp 1; Jones et al. 2012b). Furthermore, this image shows in detail the low-ionization knots first identified by Miszalski et al. (2012). Many of these structures seem to be akin to the cometary globules seen in the Helix Nebula (dense condensations of molecular gas embedded in the ionized nebula; see Meaburn et al. 1992), with knotty heads closest to the nebula centre and extended tails reaching out towards the outer rim. Extended material is also visible outside the east-southeasterly edge of the nebular ring (the emission visible to the north of the ring originates from a background field galaxy).

Assuming that the ‘ring’ is a physical structure rather than a projection effect, one can deduce the inclination of the nebula by deprojection. The angular size of the nebula was determined to be $44\text{arcsec} \times 38\text{arcsec} \pm 2\text{arcsec}$, falling in line with the previously given value of $45.2\text{arcsec} \times 37.8\text{arcsec}$ by Tylenda et al. (2003), giving an inclination of $30^\circ \pm 10^\circ$.

2.2.2 Nebular spectroscopy

On 2011 June 10–11, high-resolution data of the nebula of A70 were acquired in [O III] using grating #3 on the visual-to-red arm of the UVES on Kueyen Unit (UT2) of the VLT (Dekker et al. 2000), under programme ID 087.D-0174(A). UVES was operated in its 30 arcsec long slit mode with a 0.6 arcsec slit width ($R \sim 70000, 4.3 \text{ km s}^{-1} \text{ pixel}^{-1}$) to give a spatial scale of $0.17\text{arcsec pixel}^{-1}$. A filter was used to isolate the [O III] emission lines and prevent contamination from overlapping orders. The seeing was between 0.5 arcsec and 0.7 arcsec for all observations. Four 1200 s exposures were taken over four different slit positions. Slits 1 and 2 were taken with VLT-UVES at a PA of 160° and slits 3 and 4 at a PA of 70°, to line up with the major and minor axis of the nebula, respectively. Slit 5 was acquired in both [O III] and Hα on 2011 May 15 using the Manchester Echelle Spectrograph (MES) mounted on the 2.1 m San Pedro Martir (SPM) telescope based at the Observatorio Astronomico Nacional in Mexico (Meaburn et al. 2003; López et al. 2012). The full slit length of 5 arcmin was used with a slit width of 150 µm ($\equiv 2\text{arcsec}$, $R \sim 30000$) and taken at a PA of 90°. The data were $2 \times 2$ binned to give a spatial scale of $0.75\text{arcsec pixel}^{-1}$. The seeing was $\sim 3\text{ arcsec}$.

The nebular spectra acquired from VLT-UVES shown in Fig. 9 show two highly filamentary components, one red shifted and one blue shifted, joined by bright knots of emission where the slits cross the nebular ring to form a closed velocity ellipse in both axes. These filamentary and irregular structures are typical of disrupted...
Figure 9. PV arrays showing reduced VLT-UVES spectra in [O\textsc{iii}]λ5007 Å from A70. Figures (a) and (c) show emission from the major axis, figures (b) and (d) are from the minor axis. The positive spatial offsets are to the northern (1 and 2) or eastern (3 and 4) ends of the slits. The velocity axis is heliocentric velocity, $V_{\text{hel}}$. The display scale has been modified to highlight the spatiokinematic features referred to in the text. Cross-section 0 arcsec defines where the central star is found.

nebulae, where instabilities have begun to structurally deform the shell (Guerrero & Miranda 2012), and clearly show that A70 is not simply an inclined ring but instead has ‘bubbles’ extending in the line of sight. It is reasonable to assume that these bubbles form a closed (as the velocity ellipses are closed along both axes) and axisymmetric (the blue- and red-shifted components are roughly symmetrical) structure. The bright emission at the extremes of each slit indicate that the nebula may have a cusped waist, with slits 1 and 2 showing the ‘crow’s foot’-like structure typical of narrow-waisted nebulae viewed along their symmetry axis (Jones et al. 2012a). However, there is a clear brightening in these regions and those of slits 3 and 4, consistent with a bright ring. We therefore deduce that A70 comprises of such a bright ring, encircling the waist of a disrupted and faint bipolar shell.

Using the same spectra, a polar expansion velocity $V_{\text{exp}}$ for A70 was calculated to be $39 \pm 10$ km s$^{-1}$. This is in agreement with the value for expansion velocity of $V_{\text{exp}} = 38$ km s$^{-1}$ given by Meatheringham, Wood & Faulkner (1988), although no error was quoted. A $V_{\text{sys}}$ of $-73 \pm 4$ km s$^{-1}$ was determined for the nebula, which is consistent with the value of $-72 \pm 3$ km s$^{-1}$ by Miszalski et al. (2012). The kinematical age of A70 was determined to be $2700 \pm 950$ yr kpc$^{-1}$. Taking the distance to the nebula to be 5 kpc,
The planetary nebula LoTr 1

2.3 WeBo 1

2.3.1 Imaging

The deep Hα+[N II]λ6584 Å image shown in Fig. 11(a) is the result of coadding 2 × 120 s exposures, each with seeing better than 1.2 arcsec, acquired as part of the INT/WFC Photometric Hα Survey (Drew et al. 2005) using the Wide Field Camera on the 2.5 m Isaac Newton Telescope based at the Observatorio Roque de los Muchachos, La Palma. The [O III]λ5007 Å image shown in Fig. 11(b) was acquired using the same instrument on 2010 September 9, with an exposure time of 1200 s and under seeing of 1.4 arcsec.

The images show another ring-like morphology, although structurally different to A70 (see Section 2.2), with a pronounced inner edge and fainter, more extended emission around its entire circumference – the ring is particularly diffuse in [O III]λ5007 Å, as shown by the lack of a visible inner edge. Similar extended emission is also found in SuWt 2 (Jones et al. 2010a) and HaTr 10 (Tajitsu et al. 1999), where the ring is actually the waist of an extended bipolar structure, possibly indicating that WeBo 1 may display the same morphology but with as yet undetected, very faint lobes. In SuWt 2, Jones et al. (2010a) attribute this extended material to structural and brightness variations across an irregular toroidal structure; however (particularly in the light of the Hα+[N II] spectra acquired – see Fig. 12), WeBo 1 shows a much more regular and even ring-like shape, indicating that this is more likely an intrinsic structural property (i.e. a teardrop rather than circular-shaped cross-section).

Smith, Bally & Walawender (2007) deprojected the ring of WeBo 1, determining that it is seen almost edge-on with an inclination of 75° ± 3° with an inner-ring radius of ∼25 arcsec, which is consistent with the dimensions of the ring as cited by Bond et al. (2003) (64 arcsec × 22 arcsec) and as measured from the images presented here (65 arcsec × 20 arcsec ± 4 arcsec).
2.3.2 Nebular spectroscopy

On 2010 December 10, spectra were acquired of WeBo 1 in both \(H\alpha\) and \([\text{O III}]\lambda 5007\) Å using SPM-MES. The maximum slit length of 5 arcmin was used with a slit width of 150 \(\mu\)m (\(=\) 2 arcsec, \(R \sim 30\) 000) for each filter. The data were 2 \(\times\) 2 binned to give a spatial scale of 0.75 arcsec pixel\(^{-1}\). Slit 1 was taken at a PA of 353\(^\circ\) and slit 2 was taken at a PA of 263\(^\circ\) to cover the major and minor axes of the nebula, respectively. The seeing was \(\sim 1.5\) arcsec. Due to the \(H\alpha\) profiles having high galactic background emission, only the background-subtracted \([\text{N II}]\) and \([\text{O III}]\) emissions from slit 1, (c) and (d) from slit 2 (see Fig. 11). North is to the top of the array. The velocity axis is heliocentric velocity, \(V_{\text{hel}}\). The display scale has been modified to highlight the spatiokinematic features referred to in the text. Cross-section 0 arcsec defines where the central star is found. The continuum of a field star is visible at cross-section +15 arcsec in figures (a) and (b).

Figure 12. PV arrays showing reduced \([\text{N II}]\) and \([\text{O III}]\) SPM-MES spectra of WeBo 1. Figures (a) and (b) show the \([\text{N II}]\) and \([\text{O III}]\) emission from slit 1, (c) and (d) from slit 2 (see Fig. 11). North is to the top of the array. The velocity axis is heliocentric velocity, \(V_{\text{hel}}\). The display scale has been modified to highlight the spatiokinematic features referred to in the text. Cross-section 0 arcsec defines where the central star is found. The continuum of a field star is visible at cross-section +15 arcsec in figures (a) and (b).

A \(V_{\text{sys}}\) of \(-6 \pm 4\) \(\text{km s}^{-1}\) was calculated for the nebula. The kinematical age of WeBo 1 was determined to be of the order of 7300 \(\pm\) 3700 yr kpc\(^{-1}\). Taking the distance to the nebula to be 1.6 kpc (Bond et al. 2003), this gives an overall age for WeBo 1 of 11 700 \(\pm\) 5900 yr.\(^6\)

No clear evidence of lobes or extended nebular structure are detected in the spectra, unlike for A70 (see Section 2.2.2); however, faint material detected inside the ring on the \([\text{N II}]\) \(\lambda 6584\) Å PV array of slit 1 could be consistent with such a structure. Deeper, higher resolution spectra are required to confirm the nature of this emission, but it is safe to say that if any lobes are present they are significantly fainter than those of A70, as its lobes were still clearly detected by SPM-MES spectra (see Fig. 10).

3 DISCUSSION

3.1 The A35 group and PN mimics

A35 – the archetype of the class of PNe discussed in this paper – has recently been shown to be a PN mimic. It is, therefore, critical to establish the true nature of the objects considered here before beginning a comparison. We restrict our analysis to the three PNe presented in this work and exclude both A35 (which is no longer considered a true PN) and LoTr 5 (which is a considerably more complex case and discussed in more detail in Frew 2008; see also Graham et al. 2004).

Frew & Parker (2010) present a ‘recipe’ for determining whether we can classify an object as a true PN or not, parts of which we can apply to the nebulae presented here.

(i) Presence of a hot, blue central star: all three nebulae present here show evidence of excess UV flux that point towards the

\(^{6}\) Bond et al. (2003) assume an expansion velocity of 20 \(\text{km s}^{-1}\) to derive a similar age of 12 000 \(\pm\) 6000 yr.
existence of a hot companion – see Fig. 5(a) for LoTr 1, Miszalski et al. (2012) for A70 and Siegel et al. (2012) for WeBo 1.

(ii) Nebular morphology: each PN possesses what we would classify as a ‘typical’ PN shape, with rings (A70 and WeBo 1) and shells (LoTr 1). A mimic is often more diffuse.

(iii) Systemic velocity: the $V_{\text{sys}}$ of the central star is consistent with the $V_{\text{sys}}$ of the nebula for both LoTr 1 and A70 (see Section 2.1.4 and Miszalski et al. 2012), and so we can say that the observed emission comes from a true PN. No $V_{\text{sys}}$ for the central star of WeBo 1 has been published.

(iv) Nebula expansion: all three nebulae have been shown to have an expansion velocity typical for a PN (see Table 1).

(v) Nebular diameter: using the values stated in this paper, the physical diameters of LoTr 1, A70 and WeBo 1 are all of the order of 1 pc (see Table 1); a sensible value for a PN.

(vi) Galactic latitude: two of the three nebulae are found at high galactic latitudes of $-22^\circ$ and $-25^\circ$ for LoTr 1 and A70, respectively (WeBo 1 is at $+1^\circ$). PNe are more likely to be found away from the Galactic plane than isolated Strömgren spheres.

We can thus be confident that the three objects studied in this paper show the characteristics of bona fide PNe, although, as mentioned earlier, their link with the class of symbiotic stars should also be investigated further.

### 3.2 Conclusions

From the study conducted in this paper, we have been able to show that LoTr 1 possesses a double-shelled, slightly elliptical morphology of the age of 35 000 ± 7000 yr for the outer shell and 17 000 ± 5500 yr for the inner. We have been able to infer the presence of a K1 III-type giant ($T_{\text{eff}} \sim 4500$ K) and hot WD ($T_{\text{eff}} \sim 123$ K, $R = 0.017R_\odot$) binary system at its core. The cool star has been shown to be kinematically associated with the nebula and to have a rotation period of 6.4 d. Although it was not possible to accurately determine the [Ba/Fe] value for the central star system, we were able to say with confidence that LoTr 1 does not show any evidence for an overabundance of Ba compared to Fe. LoTr 1 also presents double-peaked emission lines, which have been seen in the other PNe with cool central stars.

Unlike LoTr 1, the PNe A70 and WeBo 1 have both been previously confirmed to contain a Ba-III-enriched central star system at their core. The two nebulae are also shown here to display morphologies distinct to that of LoTr 1, with both possessing ring-like waists and possible extended lobes. The similar morphologies and chemical enrichment strongly imply that the two have undergone very similar evolutionary or mass-loss processes. It is possible that the wind-accretion process involved in the formation of Ba stars is also responsible for the formation of these ring-like morphologies. Although the CSPN of LoTr 1 does share some common traits with those of A70 and WeBo 1 – namely binarity with hot and cool components, and rapid rotation of the secondary – both the lack of a significant overabundance of Ba-III and the marked difference in nebular morphology would imply a difference in the evolution of this system. The lack of Ba-III enhancement could be explained by a difference in progenitor mass, metallicity or simply quantity of mass transferred via the same wind-accretion process (the amount of material accreted is strongly dependent on orbital separation; Boffin & Jorissen 1988). However, as shown by Boffin & Zacs (1994) only a small amount of matter is needed to be accreted to make a star appear as a barium star and some mass must have been transferred as it is required in order to spin up the secondary to its rapid rotator state. The most obvious explanation, therefore, is that the mass was transferred at an earlier stage in the evolution of the primary, i.e. before the thermally pulsing AGB phase, when the s-process elements are created and brought to the surface. This would allow us to infer that the AGB evolution of the primary was cut short by this mass-transfer episode, signs of which should be detectable in the properties of the WD. We strongly encourage follow-up observations of the system in order to confirm this hypothesis, and in particular it would be crucial to determine the orbital period of these systems. It is, however, important to note that given the inclination of the LoTr 1 nebula (very close to pole-on), any radial velocity variations of the central star system would be very difficult to detect, particularly for the expected period of 1–3 yr, and this therefore requires very high spectral resolution and stable instruments.

Coming back to the nebula, multiple shells are not uncommon in PNe, with 25–60 per cent found to show outer structures (Chu, Jacoby & Arendt 1987). However, it is important to distinguish here between ‘halo-like’ shells (Corradi et al. 2003, 2004), which are extended, generally spherical, structures attached to the inner shell, and detached outer shells, with the latter being far less common. This is critical as the haloes are generally understood to be the ionized remnant of mass lost on the AGB which is now being swept up to form the inner shell, while the formation mechanism for multiple, detached shells is still a mystery. Schönberger et al. (1997) show that this may be possible via a combination of photoionization and wind interaction, or, alternatively, a binary evolution might be responsible for rapid changes in mass-loss that could form two distinct shells, such as with Abell 65 (Huckvale et al. 2013).

LoTr 1 clearly shows a detached outer shell which may have been produced by rapid changes in mass-loss/transfer in the CSPN. The difference in kinematical ages between the two shells, of roughly 18 000–20 000 yr, is much shorter than the single star evolutionary time-scales on which these changes might occur.

Perhaps, the nature of LoTr 5 should also be investigated further, as it too does not have an apparent ring-like morphology despite possessing a rapidly rotating, G5 III-type, Ba-III-rich central star. As mentioned earlier, Montez et al. (2010) have carried out a study into the X-ray emission emanating from this system and concluded that it is most likely chromospheric in origin, implying the presence of a spun-up companion.

### Table 1. Physical parameters of LoTr 1, A 70 and WeBo 1.

| Nebula   | $v_{\text{exp}}$ (km s$^{-1}$) | Kinematical age (yr) | Physical size (pc) | Morphology                  |
|----------|-------------------------------|----------------------|--------------------|----------------------------|
| LoTr 1   | 17 ± 4                        | 17 000 ± 5500        | 0.59 ± 0.05        | Spherical/elliptical       |
| LoTr 1 (outer) | 25 ± 4                      | 35 000 ± 7000        | 1.86$^{+0.05}_{-0.09}$ | Spherical/elliptical    |
| A 70     | 39 ± 10                       | 13 400 ± 4700        | 1.10$^{+0.06}_{-0.04}$ | Ringed-waist with detected lobes |
| WeBo 1   | 23 ± 10                       | 11 700 ± 5900        | 0.50 ± 0.03        | Ringed-waist, no lobes detected |
The results presented here show that we still have some way to go to fully constrain mass-transfer mechanisms in intermediate-period binary and post-AGB systems, and further study of other similar systems would be highly beneficial, in particular with regards to BaII pollution.

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