A barium central star binary in the Type I diamond ring planetary nebula Abell 70

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ABSTRACT

Abell 70 (PN G038.1−25.4, hereafter A 70) is a planetary nebula known for its diamond ring appearance due to a superposition with a background galaxy. The previously unstudied central star is found to be a binary consisting of a G8IV–V secondary at optical wavelengths and a hot white dwarf at ultraviolet wavelengths. The secondary shows Ba II and Sr II features enhanced for its spectral type that, combined with the chromospheric Hα emission and possible 20–30 km s⁻¹ radial velocity amplitude, firmly classifies the binary as a Barium star. The proposed origin of Barium stars is intimately linked to planetary nebulae (PNe) whereby wind accretion pollutes the companion with dredged-up material rich in carbon and s-process elements when the primary is experiencing thermal pulses on the asymptotic giant branch (AGB). A 70 provides further evidence for this scenario together with the other very few examples of Barium central stars. The nebula is found to have Type I chemical abundances with helium and nitrogen enrichment, which when combined with future abundance studies of the central star, will establish A 70 as a unique laboratory for studying s-process AGB nucleosynthesis. We also discuss guidelines to discover more binary central stars with cool secondaries in large orbits that are needed to balance our knowledge of binarity in PNe against the currently better studied post-common-envelope binary central stars.

Key words: stars: AGB and post-AGB – binaries: general – binaries: symbiotic – stars: chemically peculiar – planetary nebulae: general – planetary nebulae: individual: PN G038.1−25.4.

1 INTRODUCTION

Planetary nebulae (PNe) are the ionized nebulae ejected by low-and intermediate-mass stars that have undergone extensive mass-loss during the asymptotic giant branch (AGB) phase. The central stars of planetary nebulae (CSPN) constitute a rich resource to study the late stages of binary stellar evolution. At least 40 close binary CSPN are known that have orbital periods less than ∼1 d (Miszalski et al. 2011a) and these make up at least 17 ± 5 per cent of all CSPN (Miszalski et al. 2009a). With their short-lived nebulae (∼10⁴ yr) close binary CSPN are assured to have just recently passed through the common-envelope (CE) phase (Iben & Livio 1993). With significantly less time to undergo further angular momentum loss compared to other more evolved post-CE binaries (Schreiber & Gänsicke 2003), the orbital periods of close binary CSPN reflect the true post-CE distribution. This makes them an excellent but relatively unexplored population to constrain CE population synthesis models.

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Miszalski et al. (2009a) showed that there is a drop-off in the post-CE period distribution for periods } \geq 1 \text{ d}, \text{ consistent with more evolved post-CE binaries (Rebassa-Mansergas et al. 2008). While the cause behind this sharp drop-off is not yet understood (Davis, Kolb & Willems 2010), even less is known about intermediate-period binaries in PNe (} \sim 100–1500 \text{ d}) that are predicted by some models (Yungelson, Tutukov & Livio 1993; Han, Podsialkowski & Eggleton 1995; De Marco, Farihi & Nordhaus 2009) and their anticipated connection with the period distribution of post-AGB binaries that precede PNe (Van Winckel 2003a). At present there is essentially no hard evidence to support the existence of these binaries in PNe, primarily because there have been no substantial long-term radial velocity (RV) monitoring campaigns. This is starting to change with some bright central stars included in the survey described by Van Winckel et al. (2010).

The best way to find intermediate-period binaries is to look for giant or subgiant companions whose orbits must be sufficiently large to accommodate their larger radii. As such cool companions are typically more luminous than their white dwarf (WD) companions, these binaries can usually only be found with the aid of ultraviolet (UV) photometry (e.g. Maxted et al. 2009). The arduous UV selection is already done for PNe where the nebula acts as a natural signpost for the presence of a hot WD. All that is left is to identify a suitable CSPN candidate too cool to ionize the PN and to prove that it has a physical connection to the nebula. A small number of CSPN have suspected cool central stars (e.g. Lutz 1977; table 4 of De Marco 2009), but very few have been studied in sufficient detail to rule out a line-of-sight superposition (excluding K 1–6; see Frew et al. 2011). Poor UV sensitivity is a likely explanation for suggestions that some are single CSPN caught momentarily during a born-again phase (Bond & Pollacco 2002).

Perhaps the most studied of the cool central stars are those of the so-called A 35 type (Bond, Ciardullo & Meakes 1993). The initial list included A 35, LoTr 1 and LoTr 5 which have rapidly rotating subgiants or giants accompanied by very hot WDs peaking at UV wavelengths (} T_{\text{eff}} \gtrsim 25 \text{ kK}). The most interesting aspect of these binaries is that the secondaries of A 35 and LoTr 5 both exhibit enhanced barium abundances (Thévenin & Jasniwicz 1997), while this has yet to be demonstrated for LoTr 1. Since these initial discoveries Bond, Pollacco & Webbink (2003) added WeBo 1 to the list, and Frew (2008) raised suspicions that the nebula of A 35 may not be a bona fide PN. Additional observations of the AGB star then evolved into a WD, which may have produced a PN, while the contaminated star evolved to become a red giant with chemical anomalies: a Barium star. This accounts for the few known PNe caught exactly during this phase, but there remains much work to identify and characterize further examples. None of the three known PNe caught exactly during this phase, but there remains much work to identify and characterize further examples. None of the three firm examples, A 35, LoTr 5 and WeBo 1, have determined orbital periods, while photometric monitoring has revealed the cool components to be rapid rotators with rotation periods of a few days. The rapid rotation could possibly have been caused by mass accretion (Jeffries & Stevens 1996; Theuns, Boffin & Jorissen 1996).

In this work we present UV and optical observations of the diamond ring\(^2\) PN A 70 (PN G038.1–25.4, Abell 1966) that prove the existence of a Barium star binary CSPN. The Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006) recorded an unusually red \(J - H = +0.70\) mag colour for the CSPN which suggested a subgiant or giant classification. This prompted our investigation of the object, even though it may have been possible to reach this conclusion from the original photographic magnitudes on blue (18.6 mag) and red (17.4 mag) plates. More recent studies of the Abell sample lacked colour information for the CSPN of A 70 and mostly repeated earlier measurements (Kaler 1983; Kaler & Jacoby 1989; Kaler, Shaw & Kwittner 1990). Narrow-band imaging of the nebula was acquired by Jewitt, Danielson & Kupferman (1986), Schwarz, Corradi & Melnick (1992) and most notably Hua, Dopita & Martinis (1998).

2 THE BINARY CENTRAL STAR

2.1 Observations

We obtained spectroscopic observations of A 70 with Gemini South under programme GS-2009A-Q-35 and the VLT under programmes 083.D-0654(A) and 085.D-0629(A). Table 1 summarizes the 0.7 arcsec-wide slitlet observations made using the Multi-Object Spectrograph (GMOS; Hook et al. 2004) and the focal reducer and low-dispersion spectrograph (FORS2; Appenzeller et al. 1998) that had the blue-optimized E2V detector installed. Basic data reduction was performed using the Gemini IRAF package and the ESO FORS pipeline after which the IRAF task APALL was used to trace and extract one-dimensional spectra. In all cases, the surrounding nebula emission was subtracted close to the central star. Flux calibration was also applied using spectrophotometric standard stars observed during the respective programmes in the usual fashion. The signal-to-noise ratio (S/N) reached in the continuum near \(5130 \text{ Å}\) was measured using the SPLAT task in IRAF to range between 19 (FORS2 2009) and 30 (GMOS B). Some narrow-band images were also observed by GMOS (see Section 3.1).

2.2 An s-process-enhanced G8IV-V companion

Fig. 1 shows the GMOS R spectrum dereddened with \(c(H\beta) = 0.07\) (Acker et al. 1992). The He II and H I absorption lines expected for...
Table 1. Summary of Gemini South and VLT observations.

| Spectrum | MJD     | Grating | λ (Å)  | Resolution (FWHM, Å) | Dispersion (Å pix$^{-1}$) | Position angle (°) | Exptime (s) |
|----------|---------|---------|--------|----------------------|---------------------------|-------------------|-------------|
| GMOS B   | 54944.83| B1200   | 4085–5550 | 1.6                  | 0.23                      | 90                | 1800        |
| GMOS R   | 54944.85| R400    | 4650–8890 | 5.3                  | 0.68                      | 90                | 1800        |
| FORS2 2009 | 55026.40 | 1200g   | 4088–5555 | 1.5                  | 0.72                      | 107               | 2400        |
| FORS2 2010A | 55364.41 | 1200g   | 4088–5559 | 1.5                  | 0.36                      | 108               | 1800        |
| FORS2 2010B | 55366.40 | 1200g   | 4088–5559 | 1.5                  | 0.36                      | 87                | 1800        |

$^{a}$Affected by clouds.

Figure 1. Dereddened GMOS R spectrum of A 70.

Table 2. Observed ($m$) and dereddened ($m_0$) magnitudes of the G8IV-V component of the CSPN.

| Waveband | $m$ | $m_0$ | Reference |
|----------|-----|-------|-----------|
| B        | 18.6 | 18.3  | Abell (1966) |
| R        | 17.4 | 17.3  | Abell (1966) |
| Johnson V| 17.82| 17.67 | This work  |
| Cousins R| 17.33| 17.22 | This work  |
| Gunn i   | 16.85| 16.77 | Epchtein et al. (1999) |
| J        | 16.16| 16.12 | Skrutskie et al. (2006) |
| H        | 15.46| 15.43 | Skrutskie et al. (2006) |
| Ks       | 15.30| 15.29 | Skrutskie et al. (2006) |

2.3 Chromospheric Hα emission

A notable feature in Fig. 1 is the residual Hα emission. The spatial resolution of the GMOS R spectrum (0.145 arcsec pixel$^{-1}$) allowed for the nebula to be accurately subtracted from small windows either side of the CSPN. Table 3 verifies that the emission is real with traces of the Hα, [N II] λ6584 and [O III] λ5007 emission lines along the spatial direction. The stellar contribution was removed with adjacent traces of the same width (6.8 Å). Excess emission remains only in the Hα line, leaving no doubt that it is real. The origin is chromospheric in nature and probably originates from a hotspot on the cool star (Thévenin & Jasiewicz 1997). Stellar Hα emission is also seen in A 35 where its RV variations seem to follow the rotational period of the cool star as derived from photometric...
2.4 Radial velocities

The higher resolution blue spectra in Table 1 are well suited to determine whether the RV of the nebula matches the G8IV–V star and to probe variations that may be due to orbital motion. As the GMOS B spectrum was the only one observed with a contemporaneous arc lamp exposure, it served as our reference spectrum. We re-extracted all spectra to contain both the CSPN and nebula emission so that features from both components could be measured from the same spectrum. From both [O III] emission lines in the GMOS B spectrum, we measured a heliocentric nebula RV of $V_{\text{neb}} = -72 \pm 3$ km s$^{-1}$ with the RVS AO task EMSAO (Kurtz & Mink 1998). This value is in good agreement with $-79 \pm 18$ km s$^{-1}$ found by Meatheringham, Wood & Faulkner (1998). The RVs of the [O III] emission lines were also measured in the FORS2 spectra, which were then used to shift the FORS2 spectra to the same wavelength scale as that of the GMOS B spectrum. The H$\beta$ line was excluded from this process given its weak strength and the potential influence of H$\beta$ absorption from the G8IV–V star on its measured velocity.

Table 3 lists the RVs of the G8IV–V star as measured from the mean velocity of three Mg i absorption lines $\lambda 5167$, $\lambda 5172$ and $\lambda 5183$ Å. The errors are the standard deviation of the three measurements with the largest error expectedly belonging to the lowest S/N FORS2 2009 spectrum. Within the errors, the FORS2 data were consistent with $V_{\text{neb}}$, proving that the G8IV–V star is physically connected to the nebula. The 24 km s$^{-1}$ difference between $V_{\text{neb}}$ and the GMOS B measurement was originally suspected to arise from the fact that the Mg i absorption lines lie on a different CCD to the [O III] emission lines; however, a careful manual re-reduction of the data per CCD proved this not to be the case. If the one discrepant measurement is indeed true, then it would be consistent with typical Barium star amplitudes of 20–30 km s$^{-1}$ (McClyre & Woodsworth 1990). Such an amplitude may be rather high for what should be a low-inclination object (Section 3.1), so we consider the amplitude to be an upper limit. The apparent constancy of the FORS2 measurements is consistent with a few hundred days orbital period and the most suitable progenitor for the system would be a post-AGB binary (Van Winckel 2003a,b).

### Table 3. RVs of the G8IV–V star.

| Spectrum   | MJD      | HRV (km s$^{-1}$) |
|------------|----------|-------------------|
| GMOS B     | 54944.83 | -96 ± 2           |
| FORS2 2009 | 55026.40 | -67 ± 18          |
| FORS2 2010A| 55364.41 | -69 ± 8           |
| FORS2 2010B| 55366.40 | -70 ± 8           |

2.5 Detection of the WD and spectral energy distribution

To rule out the possibility that the G8IV–V star is a single CSPN caught momentarily during a ‘born-again’ phase (Bond & Pollacco 2002), the WD of A 70 must be detected. Fortunately, A 70 lies at a high enough Galactic latitude to be covered by the All Sky Imaging Survey (AIS) of the Galaxy Evolution Explorer (GALEX) (Martin et al. 2005; Morrissey et al. 2007). The far-ultraviolet (FUV, $\sim$154 nm) and near-ultraviolet (NUV, $\sim$232 nm) images (Section 3.1) have corresponding pipeline AB magnitudes of 16.48 ± 0.04 and 16.63 ± 0.03, respectively. These were however unsuitable since they included extended nebula emission. We performed aperture photometry on the images with a sky aperture radius incorporating most of the nebula to find FUV = 18.00 ± 0.05 mag and NUV = 18.9 ± 0.1 mag. Table 4 lists the GALEX AB magnitudes alongside estimated Vega-based magnitudes of the WD. These magnitudes were calculated by convolving a spectrum of NGC 7293 (Oke 1990), scaled to the GALEX magnitudes, through the filters listed using SYNPHOT. Values of $A$(NUV) = 2$A$(V) and $A$(FUV) = 2.3$A$(V) were inferred from fig. 4 of Cardelli, Clayton & Mathis (1989) to deredden the GALEX photometry, while standard wavelength-specific corrections were used at other wavelengths (Cardelli et al. 1989). As before $c$(H$\beta$) = 0.07 or $A$(V) = 0.15 mag was used (Acker et al. 1992).

To demonstrate that the GALEX magnitudes belong to the WD, we present the spectral energy distribution (SED) in Fig. 4. Fluxes were calculated using the relation $F_{\nu} [\mu$Jy] = $-0.4m + 9.56,3$ for GALEX magnitudes and standard flux at magnitude zero from Fouqué et al. (2000) for the $i$ magnitude (Table 2). The cool component is shown by the dereddened GMOS R spectrum and is accompanied by a Pickles (1998) G8IV spectrum scaled to best fit the observed spectrum, while the hot component is the scaled NGC 7293 spectrum used to estimate the WD magnitudes. Note the clear UV excess that confirms the presence of the hot WD primary to the $x$-process enhanced G8IV–V secondary that dominates at optical wavelengths. The intrinsic faintness of the WD ($V = 20.4$ mag) and large magnitude difference ($\Delta V = 2.6$ mag) explains why it was not seen in our spectroscopy.

### Table 4. Observed (m) and dereddened ($m_0$) magnitudes of the WD component of the CSPN.

| Waveband | m     | $m_0$ | Source |
|----------|-------|-------|--------|
| FUV      | 18.0  | 17.6  | GALEX  |
| NUV      | 18.9  | 18.6  | GALEX  |
| Johnson U| 18.9  | 18.6  | Scaled NGC 7293 |
| Johnson B| 20.2  | 19.9  | Scaled NGC 7293  |
| Johnson V| 20.4  | 20.3  | Scaled NGC 7293  |
| Johnson R| 20.5  | 20.4  | Scaled NGC 7293  |
| Johnson I| 20.7  | 20.6  | Scaled NGC 7293  |
Figure 4. SED of the binary nucleus of A 70. The UV excess of the hot component (represented by a scaled spectrum of NGC 7293) is clearly visible against the rapidly diminishing flux of the G8IV–V secondary towards UV wavelengths. Solid points mark fluxes obtained from photometric observations (see the text).

3 THE NEBULA

3.1 Morphology

GMOS acquisition images of 60 s each were taken in the OIII, OIIIC, Ha and HaC filters whose central wavelengths and FWHMs are 499.0/4.5 nm, 514.0/8.8 nm, 656.0/7.2 nm and 662.0/7.1 nm, respectively. An average stellar FWHM of \( \sim 0.65 \) arcsec was measured from the images which are sampled at 0.145 arcsec pixel\(^{-1}\). No other stars besides the CSPN are detected within the nebula whose dimensions at 10 per cent of peak intensity are 45.2 \( \times \) 37.8 arcsec (Tylenda et al. 2003). The Ha filter includes H\( \alpha \) and both [N II] lines, while the HaC filter is an [N II] \( \lambda 6584 \) filter. The [O III] and H\( \alpha + [N II] \) images are depicted in Fig. 5 together with the GALEX FUV and NUV images whose 4–6 arcsec (FWHM) resolution was smoothed by a 2 \( \times \) 2 pixel Gaussian.

The apparent morphology of A 70 is that of a ring nebula (e.g. NGC 6720). On closer inspection, the [O III] image shows a ridged appearance similar to Sp 1 which is a bipolar nebula viewed close to pole-on (Bond & Livio 1990; Jones et al. 2011). Multiple knots of low-ionization (Gonçalves, Corradi & Mampaso 2001) are also seen which are common in post-CE nebulae (Miszalski et al. 2009b). It is unlikely however that A 70 is the outcome of a CE interaction, although we cannot discard this possibility outright since the orbital period and eccentricity are not yet determined. While it is possible for the shortest period Ba stars to go through a CE phase, such occurrences are rare since the eccentricity distribution of Ba stars is explained by a combination of wind accretion and tidal evolution, rather than CE evolution or stable Roche-lobe overflow which tends to circularize orbits (Karakas, Tout & Lattanzio 2000).

The Barium star nucleus of A 70 tells us that wind interaction in a long orbital period binary has happened, and since bipolar nebulae can be produced under such circumstances (Mastrodemos & Morris 1999; Gawryszczak, Mikołajewska & Różycka 2002), we can conclude that the nebula of A 70 may have been shaped in this fashion. The ring morphology of A 70 further strengthens the apparent trend seen already in similar PNe such as WeBo 1 (Bond et al. 2003), and the probably related Me 1-1 (Shen, Liu & Danziger 2004; Pereira et al. 2008), which both display bipolar morphologies. Pereira et al. (2008) suggested the barium abundance of Me 1-1 may have been diluted to explain the lack of barium enhancement; however, its K(1–2) II nucleus does show a high rotation velocity of 90 km s\(^{-1}\) in common with other Barium stars.

Also seen in our images is the external feature outside the main nebula at a position angle (PA) of 108\( ^\circ \), as first remarked by Hua et al. (1998), that is also visible in earlier images taken by Jewitt et al. (1986). The nature of this feature remains uncertain since its
velocity (consistent with the main nebula) and [O III]/Hβ ratio (4.4) are both lower than would be expected for a shocked collimated outflow. It may be related to loop-like structures seen outside the main nebulae of bipolar PNe (e.g. K 3-17; Miranda, Ramos-Larios & Guerrero 2010).

3.2 Chemical abundances and plasma parameters

Earlier studies of the chemical properties of A 70 by Kaler et al. (1990) and Perinotto et al. (1994) showed an enhancement of helium. However, their spectra were taken only at bright parts of the nebula and were not deep enough to measure the weak diagnostic lines needed to derive accurate abundances. The greater depth of our spectra allows for a greatly improved abundance analysis, which benefits from both [O III] λ4363 and [N II] λ5755 measured at S/N ~20. We perform our analysis using the red GMOS spectrum and the FORS2 2010B spectrum which is slightly deeper than the blue GMOS spectrum and is taken essentially at the same PA (87° instead of 90°). In order to measure the faintest lines in our spectra we separately extracted an inner zone, from a 18.5 arcsec wide region centered on the central star that emphasizes the highest ionization species, and an outer zone, being the average of two 9 arcsec zones either side of the inner zone extraction. Fig. 6 shows the four extracted spectra where the bottom part of each panel highlights the faintest lines. Emission-line intensities from these two extractions were combined to form an average spectrum for the whole nebula, such that the brighter emission-line intensities matched those recovered from a separate extraction of the whole nebula. Table 5 records our measurements for the inner zone and the combined average or total spectrum. The VLT and GMOS spectra were merged by rejecting lines bluer than λ5600 Å in the GMOS spectrum and by scaling the spectra to obtain Hα/Hβ = 3.0 [i.e. c(Hβ) = 0.07; Acker et al. 1992]. Line intensities were dereddened using the Howarth (1983) extinction law. An unidentified emission line at λ7738 Å is associated with the lower ionization O+ region.

The measured line intensities were analysed with the plasma diagnostics program HOPPLA (Acker et al. 1991; Köppen, Acker & Stenholm 1991; see also Girard, Köppen & Acker 2007). Electron temperatures in the O+ and O++ zones were derived from the [N II] and [O III] line ratios in a consistent way with the electron density (see Table 6). The [S II] line ratio is in its low-density limit, while both [Cl III] and [Ar IV] yielded substantially higher densities. We have therefore determined the chemical composition for two density values in Table 7, where the usual ionization correction factors yield the elemental abundances expressed in the usual 12+log(n(X)/n(H)) format. Table 7 also includes our HOPPLA re-analysis of Perinotto et al. (1994) and Kaler et al (1990),4 the average values for Type I and non-Type I PNe from Kingsburgh & Barlow (1994) and the solar abundances from Asplund, Grevesse & Sauval (2005). Values in parentheses are results without proper correction for unseen ionic stages, and should be considered strictly as lower limits, while colons in Table 7 indicate quantities with greater uncertainty.

Due to the lower critical density collisional de-excitation for the [N II] lines, the two assumptions for the electron density affect only the nitrogen abundance. In any case, the He/H and N/O ratios

4 Note that the previously published line intensities for A 70 do not include the weak diagnostic and auroral lines required to derive meaningful abundances.
Table 5. The measured and dereddened emission-line intensities.

| Identification | Inner | Total |
|----------------|-------|-------|
|                | $F_2$ | $I_2$ | $F_3$ | $I_3$ |
| Hα 4340        | 51.6  | 52.7  | 50.4  | 51.4  |
| [O III] 4363   | 19.1  | 19.5  | 13.7  | 14.0  |
| He I 4388      | –     | –     | 1.0   | 1.0   |
| He I 4472      | –     | –     | 6.2   | 6.3   |
| He II 4542     | 5.1   | 5.2   | 3.2   | 3.2   |
| He II 4686     | 115.2 | 116.0 | 56.2  | 56.6  |
| [Ar IV] 4711   | 5.1   | 5.1   | 1.2   | 1.2   |
| He I 4713      | –     | –     | 1.0   | 1.0   |
| [Ne IV] 4720   | 2.4   | 2.4   | 0.6   | 0.6   |
| [O III] 4740   | 4.3   | 4.3   | 1.0   | 1.0   |
| Hα 4821        | 100.0 | 100.0 | 100.0 | 100.0 |
| [O III] 4959   | 349.2 | 347.9 | 336.2 | 334.9 |
| [O III] 5007   | 1036.9| 1031.0| 992.8 | 987.1 |
| He I 5015      | –     | –     | 2.7   | 2.6   |
| [N II] 5200    | –     | –     | 4.8   | 4.8   |
| He II 5412     | 8.1   | 7.9   | 3.9   | 3.8   |
| [Cl II] 5518   | –     | –     | 0.4   | 0.4   |
| [Cl II] 5538   | –     | –     | 0.4   | 0.4   |
| [N II] 5754    | –     | –     | 14.3  | 13.9  |
| He I 5876      | 7.9   | 7.6   | 19.4  | 18.7  |
| [O I] 6300     | –     | –     | 13.7  | 13.1  |
| [S II] 6312    | –     | –     | 3.4   | 3.2   |
| [O I] 6346     | –     | –     | 5.4   | 5.1   |
| [N II] 6548    | 19.0  | 18.0  | 221.8 | 210.7 |
| Hα 6563        | 300.0 | 284.9 | 300.0 | 284.9 |
| [N II] 6583    | 59.8  | 56.8  | 673.5 | 639.4 |
| He I 6678      | –     | –     | 5.7   | 5.4   |
| [S II] 6716    | 7.4   | 7.0   | 60.6  | 57.3  |
| [S II] 6731    | 6.7   | 6.3   | 42.7  | 40.4  |
| He I 7065      | –     | –     | 4.3   | 4.0   |
| [Ar II] 7316   | 13.3  | 12.5  | 17.3  | 16.2  |
| [O II] 7320    | –     | –     | 3.8   | 3.6   |
| [O II] 7330    | –     | –     | 3.8   | 3.6   |
| ?? 7738        | –     | –     | 5.5   | 5.1   |

Table 6. The derived plasma parameters.

| Parameter                  | Inner | Total |
|----------------------------|-------|-------|
| c(Hβ) (Acker et al. 1992)  | 0.07  | 0.07  |
| $T_e$([O III]) (K)         | 14900 | 13200 |
| $T_e$([N II]) (K)          | –     | 12400 |
| $n_e$([S II]) (cm$^{-3}$)  | 300   | ≤100  |
| $n_e$([Cl II]) (cm$^{-3}$) | –     | 2700  |
| $n_e$([Ar IV]) (cm$^{-3}$) | 1700  | 1600  |

both exhibit a strong enhancement which, together with the overall abundance pattern, makes A 70 a genuine Type I object (Peimbert & Torres-Peimbert 1983; Kingsburgh & Barlow 1994). As highly evolved nebulae are expected to be low-density objects, we attach a greater importance to the analysis made with $n_e = 100$ cm$^{-3}$. It may well be that [Ar IV] and [Cl II] emission originates in denser clumps, but in either analysis the contribution of Ar$^{3+}$ to the elemental abundance is only 10 per cent. Hence, the argon abundance is essentially determined by [Ar II]. Similarly, sulphur is derived in almost equal terms from [S II] and [S III], for which the low density deduced from the [S II] line ratio is more representative.

To estimate the errors in our abundance analysis, we performed Monte Carlo simulations. This involved 100 iterations of adding wavelength-independent noise to our spectra and re-performing our analysis each time. The noise level selected was 0.5 per cent of Hβ as judged from the measurement of our spectra. From the standard deviation of values derived in our simulations, we find an error of 200 K for $T_e$([O III]) and $T_e$([N II]), 0.009 dex for the He abundance, 0.018 dex for O, 0.034 dex for N, 0.028 dex for Ar and 0.049 dex for S. These are however formal errors since uncertainties concerning the ionization correction factor and ‘averaging’ $T_e$([O III]) give a lower limit to the actual error of at least 0.1 dex for the oxygen abundance. Since weak emission lines were used to determine the Ne and Cl abundances, and the [Ar IV] and [Cl II] densities, these values may only be seen as indicative. Since the spectra did not cover the [Ne III] lines, we could only estimate the neon abundance from the [Ne IV]/Hβ ratio obtained from our extraction of the inner nebula.

A number of consistency checks were also applied to the total spectrum. The intensities of the three Balmer lines match within 8 percent and we checked whether all lines of the same ion should give the same ion abundance. The He I lines give the same isotopic abundance within about 10 per cent, if one excludes $\lambda$5015 Å which is underestimated by a factor of 1.4, and the very weak lines $\lambda$4713 and $\lambda$4388 Å. Among the three He II lines, $\lambda$4541 Å is overestimated by a factor of 1.7. The three lines of [N II] and [O III] have the same isotopic abundances within 3 per cent.

3.3 Distance

Table 8 lists two distance estimates of 2.4 kpc (Stanghellini, Shaw & Villaver 2008, hereafter SSV08) and 5.0 kpc from the mean trend of the Hα surface brightness–radius relation (SBR) of Frew & Parker (2006). The SBR calculation adopted an integrated Hα flux of log $F$(Hα) = −11.85, the mean of fluxes measured by Kaler (1983) and Hua et al. (1998), angular dimensions from Tylenda et al. (2003) and the reddening from Acker et al. (1992). Also given in Table 8 are distance-dependent luminosities of the central star components, the nebula ionized mass $M_{\text{ion}}$ (assuming a filling factor of 0.3), the height below the Galactic Plane $z$ and the expansion age $t_{\text{exp}}$ of the nebula (using 40 km s$^{-1}$ measured by Meatheringham et al. 1988).

Further distances imply a higher $z$, higher $M_{\text{ion}}$, higher stellar luminosities and an older $t_{\text{exp}}$, while shorter distances imply a lower $z$, lower $M_{\text{ion}}$, lower stellar luminosities and a younger $t_{\text{exp}}$. If the SSV08 distance were adopted, the stellar luminosities would imply an implausibly massive ionizing star for the small associated $t_{\text{exp}}$ and $M_{\text{ion}}$ would be unusually low for a Type I PN (Peimbert 1997) and the empirical finding that most bipolar Type I PNe are found at very low $z$ (Corradi & Schwarz 1995). Whether the binary nature of A 70 could explain this incongruity remains to be proven. Irrespective of the adopted distance, we can say that the WD has turned on to the WD cooling track (e.g. Frew et al. 2006) and that the luminosity of the companion is less certain. It could be either G8V
Table 7. Chemical abundances and plasma parameters of A 70.

| Quantity | Inner | Total | KSK1990 | P1994 | Type I | Non-type I | Sun |
|----------|-------|-------|---------|-------|--------|------------|-----|
| $n_e$ (cm$^{-3}$) | 301 | 100 | 3000 | 40 | 2000 | – | – | – |
| $T_e(O^+)$ (K) | 8900±1240 | 11800 | 10200 | 15000 | – | – | – |
| $T_e(O^{++})$ (K) | 14900 | 13200 | 13100 | 9700 | 15000 | – | – |
| $T_e(He^{++})$ (K) | 14900 | 12800 | 12400 | 9700 | 15000 | – | – |
| He | 11.19 | 11.28 | 11.23 | – | 11.26 | 11.11 | 11.05 | 10.93 |
| N | (6.97) | 8.68 | 8.96 | >8.41 | >7.52 | 8.72 | 8.14 | 7.78 |
| O | 8.51 | 8.43 | 8.42 | 8.68 | 7.98 | 8.65 | 8.69 | 8.66 |
| Ne | 7.84±(7.68) | (7.71) | – | – | 8.09 | 8.10 | 7.84 |
| S | (5.44) | 6.82 | 7.04 | – | 8.69 | 7.91 | 7.14 |
| Cl | – | 4.61 | 4.69 | – | – | – | 5.5 |
| Ar | (5.87) | 6.11 | 6.25 | – | 6.42 | 6.38 | 6.18 |
| log(N/O) | – | +0.25 | +0.54 | >0.27 | >0.34 | +0.07 | –0.55 | –0.88 |
| log(Ne/O) | −0.58 | – | – | – | −0.56 | −0.59 | −0.82 |
| log(S/O) | −1.61 | −1.38 | – | – | −1.74 | −1.78 | −1.52 |
| log(Ar/O) | −2.32 | −2.17 | – | – | −2.23 | −2.31 | −2.28 |

Table 8. Distance estimates for A 70 and distance-dependent quantities.

| $d$ (kpc) | $M_V$ | $M_V$ hot | $M_{cool}$ | $M_0$ | $z$ | $t_{exp}$ | Method |
|-----------|-------|-----------|-----------|-------|-----|---------|--------|
| 2.4 | 5.8 | 8.4 | 0.05 | −1.0 | 5700 | SSV08 |
| 5.0 | 4.2 | 6.8 | 0.29 | −2.1 | 12000 | SBR |

(for shorter distances) or G8IV (for larger distances; see Sandage, Lubin & VandenBerg 2003). Improved central star magnitudes and spectroscopy are required to decide between each luminosity class, so for now we adopt G8IV–V.

4 Discussion

4.1 Evolutionary status

The G8IV–V star with Ba ii and Sr ii enhancements, chromospheric Hα emission and negligible to low RV amplitude, coupled with the GALEX UV detection of the WD, all strongly support the presence of a Barium star nucleus in A 70. Having detected a PN around a Barium star is quite rare; however, A 70 may represent an even more process-rich wind contaminated its nebula. Similar to A 70, WeBo 1 is chromospherically active and enhanced late-type giant star surrounded by a ring-like planetary nebula. A 70 starts with the slightly more massive component of a binary system with a mass ratio near unity evolving through the AGB, and after experiencing thermal pulses, becomes a subgiant (Sandage et al. 2003). The evolutionary history of A 70 involves a greater frequency of twins. This would foster a greater overlap concerning the potential presence of Mira secondaries in PNe. Schwarz (1991) discovered inner and outer nebulae around one of these, AS 201, of which the outer nebula is likely to be a PN (ejected by the WD). Barium stars with PNe and barium-enhanced D’-type symbiotic stars.

Given the present state of the system, we can also consider how A 70 will evolve, although the final state will depend on many parameters. In a few thousand years, the nebula will disappear and the hot star will gradually cool off. Soon after this the cool star will ascend the red giant branch (RGB) and the system will appear as a common Barium star with a peculiar red giant and no visible companion. At the tip of the RGB, the star will experience heavy mass-loss by transferring matter to the WD. During this time, it may be observed as a symbiotic system where accreting matter will heat the WD and ionize the wind of the cool giant.

The Barium stars have close ties with symbiotic stars as well as with PNe. Several extrinsic S stars have been found to exhibit symbiotic-like features (e.g. Ake, Johnson & Ameen 1991), while several symbiotic stars are also known to present overabundances of s-process elements (Smith et al. 1996, 1997; Pereira et al. 2005). The D’-type symbiotic stars are the closest relatives to Barium stars (Schmid & Nussbaumer 1993; Jorissen et al. 2005; Pereira et al. 2005), especially considering some of them are surrounded by apparently PNe. Schwarz (1991) discovered inner and outer nebulae around one of these, AS 201, of which the outer nebula is likely to be a PN (ejected by the WD). Miszalski et al. (2011c) found symbiotic characteristics in the Galactic Bulge PN M 2-29, which also exhibits inner and outer nebulae; however, the secondary has yet to be observed against the glare of the primary. Appendix A describes the discovery of a bipolar nebula around HD 330036 (Cn 1–1), which if considered to be a planetary nebula would add further evidence to the link between Barium stars with PNe and barium-enhanced D’-type symbiotic stars.

Observing a system such as A 70 implies that the initial mass ratio must have been close to unity. The rarity of such a configuration may be used as an argument against the present formation scenario, and indeed an identical approach was taken by Corradi (2003) concerning the potential presence of Mira secondaries in PNe. Such an A 70-like configuration can, in principle, occur since Lucy (2006) found an excess of so-called twins, i.e. systems with mass ratios between 0.98 and 1. As further binaries similar to A 70 and WeBo 1 are found, these probabilities may have to be revised in favour of a greater frequency of twins. This would foster a greater overlap between symbiotic stars (at least those of yellow or D’-type) and PNe (Jorissen et al. 2005), with the formal difference becoming notional. Wide binaries will interact and produce genuine PNe in...
a wide variety of cases; however, only a relatively narrow range is currently observed (e.g. De Marco 2009).

### 4.2 A 70 as a probe of AGB nucleosynthesis

The measurement of nebular $s$-process abundances in PNe has considerable potential to improve AGB nucleosynthesis models (e.g. Sterling & Dinerstein 2008, hereafter SD08; Karakas et al. 2009; Karakas & Lugaro 2010). These abundances are a valuable constraint upon the number of third dredged-up episodes experienced during the thermally pulsing AGB phase. Of particular interest are Type I PNe whose He- and N-rich abundances are well reproduced in models that require a progenitor mass $>4 M_\odot$ to achieve hot bottom burning. Quantifying the stellar $s$-process abundances of A 70 via high-resolution spectroscopy will therefore be of great interest to compare against the Type I nebula abundance. The high surface brightness of A 70 compared to e.g. WeBo 1 may also allow nebula $s$-process abundances to be measured via near-infrared spectroscopy.

In principle, the $s$-process abundances of Type I PNe should be relatively straightforward to understand; however, no firm patterns have been found so far (Karakas et al. 2009). SD08 noted that binary interactions may be responsible for reducing their measured $s$-process abundances; however, the paucity of known binaries in their sample meant that this remained untested. New discoveries of binary central stars in the SD08 sample should therefore help resolve the issue. Miszalski et al. (2011b) recently found a close binary in NGC 6778 which is a bipolar Type I PN in the SD08 sample with strong He and N enhancements (He/H = 0.155 and N/O = +0.78; Perinotto, Morbidelli & Scatarriz 2004). It is possible that post-CE binaries may reduce $s$-process abundances to a greater extent than wider binary systems, making wider binaries a potentially more reliable probe of $s$-process abundances in PNe. The growing samples of A 70 and WeBo 1 as Barium stars, and perhaps also Me 1-1, therefore, provide a powerful alternative to the analysis of close binaries in the SD08 sample.

### 4.3 Proving a PN has a cool companion

The discovery of the cool CSPN of A 70 has important implications for further survey work to find similar binaries. To establish a physical connection between a cool CSPN candidate and a PN a number of factors must be considered. The two most important being: (i) a UV excess or spectroscopic features of the WD must be detected to rule out the born-again scenario and (ii) the agreement between the RVs of the nebula and the cool star (modulo the expected RV amplitude of a binary). It is also preferable to have a small nebular diameter or equivalently an uncrowded field to help rule out a superposition (e.g. Ciardullo et al. 1999). A favourable spectroscopic distance should also preferably agree well with the approximate statistical nebula distance.

A general lack of deep enough UV observations has made the task of confirming hot components in PNe difficult. Sahai et al. (2008) found 9/21 AGB stars to have FUV excesses which they attribute to a hot companion, but there has not been a systematic UV-excess survey of PNe. The only other object studied so far is K 1-6 (Frew et al. 2011); however, no spectroscopic data were presented in this study. We also advise against searching too hard for a cool companion, especially in large PNe where many candidates may be present. It is certainly possible that an intrinsically very faint $M_V \gtrsim +7$ mag single WD nucleus may be beyond the detection limit of typical optical surveys, and this is especially true for the most distant PNe. This emphasizes the crucial role of UV photometry to confirm such A 70-like binaries if they were located in more crowded stellar fields. On the other hand, the unique spectroscopic signature of a Barium star is also a sound means to secure a binary confirmation and multiobject spectroscopy may be an efficient tool in this respect.

### 5 CONCLUSIONS

We have presented 8-m optical spectroscopic and imaging observations of the unique diamond-ring PN A 70. Combined with GALEX UV photometry, the data prove the binary nature of the central star which is expected to have an orbital period of a few hundred days. Our main conclusions are as follows.

(i) Optical spectroscopy of the central star revealed a G8IV–V star, slightly enhanced in $s$-process elements, with chromospheric He emission. GALEX UV photometry detected the signature of a WD coincident with the central star, therefore providing the first clear proof for a Barium dwarf binary inside a PN. This is firm evidence for the standard formation scenario of Barium stars since Barium dwarfs are generally difficult to observe (e.g. Gray et al. 2011).

(ii) RVs of the G8IV–V secondary were analysed in comparison to the $-72 \pm 3$ km s$^{-1}$ heliocentric nebula velocity of A 70. FORS2 observations are consistent with the nebula velocity proving they are physically connected, while one GMOS observation presented a difference of 24 km s$^{-1}$. Such a difference is of the same magnitude expected for orbital motion, if indeed this one measurement can be trusted. Further observations are required at higher resolution to measure the orbital period and RV amplitude.

(iii) Chemical abundances of the nebula were measured and found to have a Type I composition with strong He and N enrichment. As the G8IV–V companion is also $s$-process enhanced, this makes A 70 an exceptional laboratory for further improving our understanding of AGB nucleosynthesis and the origin of Type I PNe (e.g. Karakas et al. 2009).

(iv) The distance remains uncertain; however, it is clear that the WD has evolved on to the cooling track. A plausible 5 kpc distance would imply a height below the Galactic Plane of $z \sim -2.0$ kpc, in contradiction with the Type I composition and the only slightly subsolar oxygen abundance ($-0.3$ dex cf. solar). It may be possible that a thick-disc origin or binary stellar evolution could explain the Type I composition, but this remains to be proven with improved observations.

(v) A 70 is one of the very few PNe with apparently cool central stars to have the WD detected in the UV. The observations presented here strongly suggest that insensitive UV observations were responsible for the non-detections of Bond & Pollacco (2002) and the conclusion that the companions are single nuclei caught during the ‘born-again’ phase. A 70 also serves as a template to guide future discoveries of similar binary central stars.

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The AAO/UKST SuperCOSMOS Hα Survey (SHS; Parker et al. 2005) is a deep 4000 deg² Hα and broad-band red (Short-Red) photographic survey of the Southern Galactic Plane. Fig. A1 depicts a faint bipolar nebula in the SHS data surrounding HD 330036 (PN G330.7+04.1, also known as Cn 1–1) found during the course of this work. This is an entirely new discovery since previous studies were concerned with the bright emission-line core only and were not sensitive enough to reveal the very low surface brightness lobes (e.g. Kohoutek 1997). The flattened X-shape is uncannily similar to the ‘outer lobes’ of Hen 2-104 (Corradi 2003), suggesting a similar process was responsible for their formation. At the 2.3 kpc distance estimated by Pereira et al. (2005) the lobes would measure 1.2 pc tip to tip.