The physical structure of planetary nebulae around sdO stars: Abell 36, DeHt 2, and RWT 152

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ABSTRACT
We present narrow-band Hα and [O III] images, and high-resolution, long-slit spectra of the planetary nebulae (PNe) Abell 36, DeHt 2, and RWT 152 aimed at studying their morphology and internal kinematics. These data are complemented with intermediate-resolution, long-slit spectra to describe the spectral properties of the central stars and nebulae. The morphokinematical analysis shows that Abell 36 consists of an inner spheroid and two bright point-symmetric arcs; DeHt 2 is elliptical with protruding polar regions and a bright non-equatorial ring; and RWT 152 is bipolar. The formation of Abell 36 and DeHt 2 requires several ejection events including collimated bipolar outflows that probably are younger than and have disrupted the main shell. The nebular spectra of the three PNe show a high excitation and also suggest a possible deficiency in heavy elements in DeHt 2 and RWT 152. The spectra of the central stars strongly suggest an sdO nature and their association with PNe points out that they have most probably evolved through the asymptotic giant branch. We analyse general properties of the few known sdOs associated with PNe and find that most of them are relatively or very evolved PNe, show complex morphologies, host binary central stars, and are located at relatively high Galactic latitudes.

Key words: subdwarfs – ISM: jets and outflows – planetary nebulae: individual: Abell 36 – planetary nebulae: individual: DeHt 2 – planetary nebulae: individual: RWT 152.

1 INTRODUCTION
Planetary nebulae (PNe) represent the last stage of low- and intermediate-mass stars (0.8 ≤ M/M⊙ ≤ 8) before ending their lives as white dwarfs. It is well known that PNe show varied morphologies that should be closely related to the mass-loss history of their progenitor stars. According to Méndez (1991), most of the central stars (CSs) can be divided in two different groups: the H-rich and the H-poor CSs. However, within these two wide groups, different classes can be found as, e.g. PG 1159, O, Wolf–Rayet type, and hot subdwarfs CSs.

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Table 1. Common names, PN G designations, coordinates, and atmospheric parameters of the CSPNe for the objects discussed in this work.

| Object        | PN G   | $\alpha$ (2000.0) | $\delta$ (2000.0) | $\ell$ | $b$ | $T_{\text{eff}}$ (K) | $\log g$ (cm s$^{-2}$) |
|---------------|--------|------------------|------------------|--------|----|----------------------|------------------------|
| Abell 36      | PN G 318.4+41.4 | 13h40m41.3s | -19°52'55.3" | 318:4 | 41:4 | 93 000$^d$–113 000$^d$ | 5.3$^d$–5.6$^d$ |
| DeHt 2        | PN G 027.6+16.9 | 17h41m40.9s | +03°00'57.3" | 027.6 | 16:9 | 117 000$^d$ | 5.64$^d$ |
| RWT 152       | PN G 219.2+07.5$^c$ | 07h29m58.5s | -02°06'37.5" | 219.2 | 07:5 | 45 000$^d$ | 4.5$^d$ |

$^a$Designation proposed in this work for the designation for Galactic PNe by Acker et al. (1992). $^b$Herrero, Manchado & Mendez (1990). $^c$Traulsen et al. (2005). $^d$Napiwotzki (1999). $^e$Ebbets & Savage (1982).

analysis of the object revealed an extremely faint, double-shell PN, possibly deficient in heavy elements, and hinted to complex ejection processes in the formation of the nebula. Another well-analysed PN+sdO system is Abell 41, a bipolar PN with a prominent equatorial ring, also around a binary sdO (Bruch, Vaz & Diaz 2001; Shimanskii et al. 2008; Jones et al. 2010). Similar analyses of more PN+sdO systems may provide important clues about the formation and evolution of these objects.

Abell 36 and RWT 152 are two faint PNe with sdO CSs and neither their morphology nor their kinematics have previously been analysed in detail. Abell 36 was discovered by Abell (1966) using the Palomar Observatory Sky Survey (POSS) plates and was later imaged by Hua & Kwok (1999). Its bright ($B \approx 11.3$ mag) CS was initially classified as O(H) by Acker et al. (1992) and as sdO by Kilkenny et al. (1997). Later, it was incorporated to the Subdwarf Database by Östensen (2006), the most complete published compilation of hot subdwarfs to date. RWT 152 is also included in this data base as an sdO, although it was previously classified as an O5 star by Chromey (1980). The PN around RWT 152 was discovered by Pritchet (1984) who found a slightly elongated nebulosity after subtracting the image of a nearby star from the image of RWT 152 itself. We have also noticed that the CS of DeHt 2 has similar spectral features to those found in sDs (see Napiwotzki & Schönberner 1995, their fig. 3) and, therefore, we included it in this investigation. DeHt 2 was discovered by Dengel, Hartl & Weinberger (1980) after inspecting the POSS plates. Its CS was classified as an O-type star by Acker et al. (1992) and as a hybrid-high luminosity object by Napiwotzki (1999).

In this work, we present narrow-band, optical images and high-resolution, long-slit spectroscopy of Abell 36, DeHt 2, and RWT 152, which allow us, for the first time, to describe in detail their morphology and internal kinematics. These data are complemented with intermediate-resolution, long-slit spectroscopy of the three objects to describe the nebular and CS spectra. In the case of DeHt 2, our data allow us to classify its CS as a very probable sdO. Table 1 lists a summary of the three objects: the common names and PN G designations, the equatorial and Galactic coordinates, together with the atmospheric parameters (effective temperature and surface gravity) of their CSs.

2 OBSERVATIONS

2.1 Optical imaging

Narrow-band H$\alpha$, [O III], and [N II] images of Abell 36 were obtained with the Mexman filter-wheel at the 0.84 m telescope on San Pedro Mártir Observatory (OAN-SPM). The [N II] image was taken on 2013 February 19 with a seeing of $\approx 2.8$ arcsec, and the [O III] and H$\alpha$ images were obtained on 2013 April 7 with a seeing of $\approx 2.8$ arcsec. A Marconi (e2v) CCD with 2048 $\times$ 4612 pixels each of 15 $\mu$m in size, was used as detector in both campaigns. A 2 $\times$ 2 binning was employed providing a field of view (fov) of $\approx 8.2 \times 18.4$ arcmin$^2$ and a plate scale of 0.468 arcsec pixel$^{-1}$. Total exposure time was 3600 s in the [N II] filter ($\lambda_{\text{eff}} = 6585$ Å, FWHM = 10 Å), 4800 s in the [O III] filter ($\lambda_{\text{eff}} = 5009$ Å, FWHM = 52 Å), and also 4800 s in the H$\alpha$ filter ($\lambda_{\text{eff}} = 6565$ Å, FWHM = 11 Å).

Narrow-band H$\alpha$ and [O III] images of DeHt 2 were obtained on 2010 August 23 with the Wide Field Camera (WFC) at the 2.5 m Isaac Newton Telescope on El Roque de Los Muchachos Observatory (La Palma, Spain). The detector of the WFC consists of four EEV 2k $\times$ 4k CCDs with a plate scale of 0.33 arcsec pixel$^{-1}$ and an fov of $34 \times 34$ arcmin$^2$. Total exposure time was 5400 s in the [O III] filter ($\lambda_{\text{eff}} = 5008$ Å, FWHM = 100 Å), and 3600 s in the H$\alpha$ filter ($\lambda_{\text{eff}} = 6568$ Å, FWHM = 95 Å). We note that the H$\alpha$ filter includes the [N II] $\lambda\lambda6548, 6583$ emission lines. However, these [N II] lines are not detected in the nebular spectra of DeHt 2 (see Section 3.2.3) and, therefore, the H$\alpha$ filter registers only the H$\alpha$ emission line. Seeing was $\approx 1.5$ arcsec.

In the case of RWT 152, narrow-band H$\alpha$ and [O III] images were obtained on 2010 December 16 with the Calar Alto Faint Object Spectrograph (CAFOS) at the 2.2 m telescope on Calar Alto Observatory (Almería, Spain). A SITE 2k $\times$ 2k–CCD was used as detector, with a plate scale of 0.53 arcsec pixel$^{-1}$ and a circular fov of 16 arcmin in diameter. Total exposure time was 900 s in [O III] filter ($\lambda_{\text{eff}} = 5007$ Å, FWHM = 87 Å), and 1900 s in the H$\alpha$ filter ($\lambda_{\text{eff}} = 6563$ Å, FWHM = 15 Å). Seeing was $\approx 1.5$ arcsec.

The images were reduced following standard procedures within the IRAF and MIDAS packages.

2.2 Spectroscopy

2.2.1 High-resolution long-slit spectroscopy

High-resolution long-slit spectra of Abell 36, DeHt 2, and RWT 152 were obtained with the Manchester Echelle Spectrometer (Meaburn et al. 2003) at the 2.1 m telescope on the OAN-SPM during two different campaigns between 2011 and 2012: Abell 36 was observed on 2012 May 12–17, DeHt 2 on 2012 May 11–13, and RWT 152 on 2011 February 17. A 2k $\times$ 2k Marconi CCD was used as detector in 4 $\times$ 4 binning (0.702 arcsec pixel$^{-1}$) in the case of Abell 36 and DeHt 2, and in 2 $\times$ 2 binning (0.338 arcsec pixel$^{-1}$) in the case of RWT 152. Two filters were used: (1) a $\Delta\lambda = 60$ Å filter to isolate the H$\alpha$ emission line (87th order), with a dispersion of 0.11 Å pixel$^{-1}$ (in 4 $\times$ 4 binning) and 0.05 Å pixel$^{-1}$ (in 2 $\times$ 2 binning) and (2) a $\Delta\lambda = 50$ Å filter to isolate the [O III] emission line (114th order), with a dispersion 0.08 Å pixel$^{-1}$ (in 4 $\times$ 4 binning) and 0.04 Å pixel$^{-1}$ (in 2 $\times$ 2 binning). Spectra of Abell 36 and DeHt 2 were obtained with the [O III] filter and an exposure time of 1800 s for each individual spectrum. Spectra of RWT 152 were

1 http://www.ing.iac.es/ds/sddb/
acquired with the Hα and [O iii] filters and exposures times of 1200 and 1800 s, respectively. For all spectra, the slit was centred on the CS of each PN and oriented at different position angles (PAs) to cover relevant morphological structures of each object. The observed PAs for each object and their choice will be described in the corresponding section dedicated to each object. The spectra were wavelength calibrated to an accuracy of ±1 km s$^{-1}$ using a Th-Ar lamp. The resulting spectral resolution [full width at half-maximum (FWHM)] is 12 km s$^{-1}$. Seeing was ≃1.5–2 arcsec during the observations.

The spectra were reduced with standard routines for long-slit spectroscopy within the IRAF and MIDAS packages. Position-velocity (PV) maps have been obtained from these high-resolution, long-slit spectra. The origin of radial velocities in the PV maps is the systemic velocity obtained for each PN (see below), and the origin for projected angular distances is the position of the CS, as given by the intensity peak of the stellar continuum that is detected in all long-slit spectra. Internal radial velocities will be quoted hereafter with respect to the heliocentric systemic velocity of each nebula. The rest wavelengths adopted to rescale the radial velocity are 5006.84 Å for [O iii] and 6562.82 Å for Hα.

### 2.2.2 Intermediate-resolution, long-slit spectroscopy

Intermediate-resolution, long-slit spectra of DeHt 2 and Abell 36 were obtained with the Boller and Chivens spectrograph mounted on the 2.1 m telescope at the OAN-SPM on 2013 June 5 and 6, respectively. The detector was a Marconi CCD with 2k × 2k pixels and a plate scale of 1.18 arcsec pixel$^{-1}$. We used a 400 lines mm$^{-1}$ dispersion grating, giving a dispersion of 1.7 Å pixel$^{-1}$, and covering the 4100–7600 Å spectral range. In the case of DeHt 2, a spectrum with the slit at PA 55° was obtained with the slit centred on the CS. In the case of Abell 36, a spectrum with the slit at PA 90° was obtained covering the CS and the eastern part of the nebula. For both objects, the slit width was 2 arcsec and exposure time was 1800 s for each spectrum. Seeing was ≃3 arcsec.

Intermediate-resolution, long-slit spectra of RWT 152 were obtained using CAFS at the 2.2 m telescope on Calar Alto Observatory on 2010 December 17. The detector was an STTe 2k × 2k–CCD with a plate scale of 0.53 arcsec pixel$^{-1}$. Gratings B-100 and R-100 were used to cover the 3200–6200 Å and 5800–9600 Å spectral ranges, respectively, both at a dispersion of ≃2 Å pixel$^{-1}$. The spectra were taken with the slit at PA 0° and exposure times was 900 s for each grism. The slit width was 2 arcsec and it was centred on the CS. Seeing was ≃2 arcsec. Spectrophotometric standards stars were observed each night for flux calibration.

The spectra were reduced using standard procedures for long-slit spectroscopy within the IRAF and MIDAS packages. For each PN, the observed emission line fluxes were dereddened using the extinction law of Seaton (1979) and the corresponding logarithmic extinction coefficient $c$(Hβ), as obtained from the Hα/Hβ observed flux ratio, assuming Case B recombination ($T_e = 10^4$ K, $N_e = 10^4$ cm$^{-3}$) and a theoretical Hα/Hβ ratio of 2.85 (Brocklehurst 1971).

### 3 RESULTS

#### 3.1 Abell 36

##### 3.1.1 Imaging

Fig. 1 shows our Hα and [O iii] images of Abell 36. Our [N ii] image does not show nebular emission and is not presented here. Abell 36 presents an elliptical morphology with the major axis oriented at PA ≃ 350°, and a size of ≃7.4 × 5.3 arcmin$^2$. Two particularly bright point-symmetric knotty arcs are observed, giving a spiral appearance to Abell 36, as already noted by Hua & Kwok (1999). Our images also suggest that a faint elliptical envelope could encircle the rest of components. The nebular emission is dominated, particularly in [O iii], by a distorted ring-like structure of ≃3.3 × 5.3 arcmin$^2$ in size, that appears displaced towards the south with respect to the CS. Several bright knots are also observed inside this ring. Towards the north, a bubble-like structure can be recognized inside the elliptical

![Figure 1](https://academic.oup.com/mnras/article-abstract/446/1/317/2907956/figure1)

**Figure 1.** Grey-scale reproductions of the Hα (left) and [O iii] (middle and right) images of Abell 36. Grey levels are linear on the left- and right-hand panels and logarithmic on the middle one. Slit positions used for high-resolution, long-slit spectroscopy are drawn in the right-hand panel (slit width not to scale).
shell, that apparently emanates from the ring. The bubble extends up to $\pm 2.6$ arcmin from the CS and is orientated at PA $\pm 12^\circ$ that is different from the orientation of the major axis of the ellipse.

3.1.2 High-resolution, long-slit spectroscopy

Spectra of Abell 36 were obtained at PAs $35^\circ$, $80^\circ$, $305^\circ$, and $350^\circ$. The slit positions are shown in Fig. 1 (right-hand panel) imposed on the [O III] image of the nebula, and are denoted from S1 to S4 starting at PA $350^\circ$ counterclockwise. The slit PAs were chosen to cover the major and minor axis (S1 and S3, respectively) of the ellipse as well as two intermediate PAs (S2 and S4). It should be noted that in the cases of PAs $35^\circ$, $305^\circ$, and $350^\circ$, two spectra were secured with the slit on the CS but displaced from each other along the corresponding PA to cover the whole nebula. These two spectra were combined during the reduction process into a single long-slit spectrum. Fig. 2 shows the PV maps of the [O III] emission line at the four observed PAs. From the radial velocity centroid of the [O III] emission feature, we derive a heliocentric systemic velocity $V_{\text{HEL}} = +34.8 \pm 1.4 \text{ km s}^{-1}$, in agreement with the value obtained by Bohuski & Smith (1974).

The PV maps show a velocity ellipse with maximum velocity splitting of $\pm 74 \text{ km s}^{-1}$ at the stellar position and with no particular tilt with respect to the angular axis. The spatio-kinematical properties of the velocity ellipse vary with PA. In addition, other structures are also distinguished. We describe below the PV maps in more detail.

The velocity ellipses at PAs $35^\circ$ and $80^\circ$ (S2 and S3 in Figs 1 and 2) present similar properties to each other. They extend up to $\pm 130$ arcsec towards the north-east (NE) and $\pm 105$ arcsec towards the south-west (SW). The size of the velocity ellipses fits very well the size of the bubble and the southern part of the distorted ring (see Fig. 1), suggesting a spatio-kinematical relationship between both structures.

The PV map at $350^\circ$ (S1 in Fig. 1) reveals a more complex kinematics. The velocity ellipse extends between $\pm 130$ arcsec from the CS. Two bright knots are observed close to its tips with radial velocities of $\pm 20 \text{ km s}^{-1}$ (NW knot redshifted). A comparison of the images in Fig. 1 shows that these knots correspond to cuts of slit S1 with the bright edge of the northern bubble and with the southern edge of the distorted ring. This result reinforces those obtained at PAs $35^\circ$ and $80^\circ$ that the northern bubble and the southern half of the observed ring form a unique spatio-kinematic structure that may be defined as a spheroid. It is noteworthy that this spheroid has been identified through an analysis of PV maps based on high-resolution spectra and that it can be hardly recognized in the direct images. In addition, these spectra also demonstrate that the distorted ring observed in the direct images is a projection effect and does not correspond to a real nebular structure. We also note that the velocity ellipse appears to be open at two point-symmetric locations on the PV map, with the north-west (NW) ‘hole’ mainly blueshifted and the south-east (SE) one mainly redshifted. Moreover, towards the NW, faint emission, with an arcuate shape in the PV map, and radial velocities up to $\pm 55 \text{ km s}^{-1}$, connects the velocity ellipse with emission from the NW point-symmetric arc. The NW arc itself presents two radial velocity components centred at the systemic velocity, with the brightest component being slightly blueshifted. The emission feature due to the SE arcs is similar to that of the NW arcs, but fainter and slightly redshifted.

At PA $305^\circ$ (S4 in Fig. 1), the velocity ellipse may also be recognized, although it appears open at its tips and connected to emission from the point-symmetric arcs. This velocity ellipse is also compatible with the spheroidal structures identified at the other PAs. Emission from the NW arc present two velocity components, although it is centred close to the systemic velocity. Emission from
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Figure 3. Sketch of Abell 36 as derived from our morphokinematical analysis. The spheroidal shell is displayed in red and the bright arcs are represented by thick blue lines.

The SE arc shows a single velocity component at the systemic velocity.

Some of the bright knots observed in the inner nebular regions have been covered by the slits (see Fig. 1). These knots do not appear as separated entities in the PV maps but share the kinematics of the velocity ellipses, suggesting that they are a part of the spheroidal structure.

The PV maps (Fig. 2) reveal that the [O iii] emission is noticeable stronger in the blueshifted part of the nebula than in the redshifted one, as observed in other PNe (e.g. IC 2149; Vázquez et al. 2002). This could be related to dust absorption of the redshifted emission. Alternatively, interaction of the front (blueshifted) half of Abell 36 with the interstellar medium (ISM) could be causing this effect. To test this possibility, we compare the radial velocity of the local ISM at the position of Abell 36 with that of the nebula itself, assuming a distance of 150–770 pc (see Abell 1966; Cahn & Kaler 1971; Cahn, Kaler & Stanghellini 1992; Acker et al. 1998; Phillips 2005) and a standard rotation curve of the Galaxy. Following the formulation by Nakanishi & Sofue (2003), we obtain a heliocentric radial velocity of $\simeq 26 \text{ km s}^{-1}$ for the ISM around Abell 36, that is lower than that of the nebula ($\simeq 35 \text{ km s}^{-1}$). These values suggest that Abell 36 is encroaching on the ISM, although one would expect that the rear (redshifted) half of Abell 36 was the brighter one, while the opposite is observed.

The analysis of the PV maps implies a physical structure for Abell 36 that is quite different from what could be expected from the images. Fig. 3 shows a sketch of the nebula overimposed on the [O iii] image. As already mentioned, the velocity ellipse observed at all PAs is compatible with a spheroidal structure. Its major axis should be almost perpendicular to the line of sight, as indicated by the lack of tilt of the velocity ellipse in the PV maps, and oriented at PA around $12^\circ$, as suggested by the orientation of the northern bubble. The arcs resemble the point-symmetric structures observed in other PNe (e.g. NGC 6309; Vázquez et al. 2008). Hua & Kwok (1999) compared Abell 36 with NGC 6543 and our results strengthen this comparison and extend it to IC 4364 as well. These three PNe show a/spheroidal/ellipsoidal shell that is accompanied by outer and extended point-symmetric regions [components DD’ in NGC 6543 (Miranda & Solf 1992) and in IC 4364 (Guerrero et al. 2008) and point-symmetric arcs in Abell 36], which appear twisted with respect to the orientation of the spheroidal shell. Following these authors, the point-symmetric arcs of Abell 36 may be interpreted as due to a collimated bipolar outflow that has been ejected along a rotating axis. If so, the axis has rotated mainly in a plane (the plane of the sky) as indicated by the low radial velocity of the arcs, while a relatively large rotation angle of $\simeq 100^\circ$ is inferred from the images.

The velocity ellipses appear disrupted at PAs $305^\circ$ and $350^\circ$, where the bright arcs are observed, but not at PAs $35^\circ$ and $80^\circ$, where the bright arcs do not extend. This strongly suggests a relationship between the bright arcs and the disrupted regions of the spheroid. In particular, this disruption could be originated by a collimated outflow that is able to go through the spheroid, perforating parts of it. The kinematics of the faint emission connecting the velocity ellipse and the emission features from the arcs observed in the PV map at PA $305^\circ$ strongly suggests an acceleration of material from the spheroid followed by a more or less sudden deceleration that could be due to interaction with the faint elliptical envelope. It is worth noting that, if this interpretation is correct, the collimation degree of the bipolar outflow should have been very high because only ‘relatively’ small portions of the spheroid are disrupted at each PA and a velocity ellipse can still be recognized in the PV maps at PAs $305^\circ$ and $350^\circ$.

The equatorial expansion velocity of the spheroid ($\simeq 37 \text{ km s}^{-1}$), its equatorial radius ($\simeq 1.7 \text{ arcmin}$), and the distance ($150–770 \text{ pc}$; see above) yield a kinematical age of $\simeq 2–10 \times 10^3 \text{ yr}$, a broad range of ages given by the uncertainty in the distance, that is compatible with a relatively young or very evolved PN. Finally, if our interpretation of the bright arcs is correct, the corresponding collimated outflows should be younger than the spheroid. However, their kinematical age is impossible to obtain because their original velocity as well as the changes that their velocity may have suffered through collimated outflow–shell interaction are unknown.

3.1.3 Intermediate-resolution, long-slit spectroscopy

The intermediate-resolution, long-slit nebular spectrum of Abell 36 is presented in Fig. 4. A logarithmic extinction coefficient $c(\text{H} \beta)$ of $\simeq 0.17$ was obtained (see Section 2.2.2). The dereddened line intensities and their Poissonian errors are listed in Table 2. In addition to the hydrogen and [O iii] $\lambda\lambda 4959, 5007$ emission lines, strong high excitation emission lines are observed as He ii $\lambda 4686$ and [Ar iv] $\lambda\lambda 4711, 4740$. We note that [O iii] $\lambda 4363$ and [Ar v] $\lambda 7005$ line emissions could also be present but deeper spectra are needed to confirm them. The spectrum indicates a high-excitation nebula, which is compatible with the non-detection of the nebula in the [N ii] filter.

The normalized spectrum of the CS of Abell 36 is shown in Fig. 5. As already mentioned, this star is included in the Subdwarf Database by Østensen (2006). The presence of narrow He ii

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noticeable in [O iii] than in Hα. Two bright filaments are observed in [O iii] (much weaker in Hα) at the NE tip of the shell. They are parallel to each other, separated by 0.1 arcmin, and oriented perpendicular to the major nebular axis. Furthermore, the images reveal the existence of an (elliptical) ring embedded in the elliptical shell, that is mainly distinguished by its relative brightness. The size of the ring is $\geq 1.5 \times 0.7$ arcmin$^2$ and its minor axis is oriented E–W approximately. This ring is drawn in Fig. 6. The orientations of the ring and the elliptical shell are quite different from each other, indicating that the ring does not trace the equatorial plane of the elliptical shell.

### 3.2 DeHt 2

#### 3.2.1 Imaging

Fig. 6 shows our Hα and [O iii] images of DeHt 2 that reveal more details than previous ones (Manchado et al. 1996). They show an elliptical shell with a size of $\approx 1.9 \times 1.5$ arcmin$^2$ and major axis oriented at PA $\approx 55^\circ$, although the polar regions seem to protrude and deviate from a ‘pure’ elliptical geometry, in particular at the SW region. The shell shows a limb-brightening that is more noticeable along the northern edge. This could be a result of interaction of the nebula with the ISM (Wareing, Zijlstra & O’Brien 2007), an idea that is supported by the fact that the limb-brightening is more}

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**Figure 4.** Nebular spectrum of Abell 36 obtained by integrating the emission lines between 77 and 124 arcsec eastern from the CS along the slit position. The emission lines are labelled.

**Figure 5.** Normalized optical spectrum of the CS of Abell 36. Poorly subtracted sky lines and nebular emission lines are marked as well as some absorption lines (specially He ii $\lambda 4686$) as well as the atmospheric parameters (Table 1) are indeed compatible with an sdO nature.

**Table 2.** Emission line intensities in Abell 36.

| Line          | $f(\lambda)$ | $f(H\beta/\lambda 100)$ |
|---------------|--------------|--------------------------|
| Hα $\lambda 4340$ | 0.129        | 46.5 ± 0.7               |
| He II $\lambda 4686$ | 0.042        | 123.0 ± 1.0              |
| He I $\lambda 4711$ | 0.036        | 16.7 ± 0.3               |
| [Ar II] $\lambda 4740$ | 0.029        | 8.4 ± 0.4                |
| Hβ $\lambda 4861$ | 0.000        | 100.0 ± 1.0              |
| [O II] $\lambda 4959$ | $-0.023$     | 96.9 ± 1.0               |
| [O III] $\lambda 5007$ | $-0.034$     | 278.6 ± 2.2              |
| He II $\lambda 5411$ | $-0.118$     | 9.5 ± 0.3                |
| Hα $\lambda 5863$ | $-0.323$     | 285.0 ± 1.4              |
| $c(H\beta) = 0.17$ |              |                          |
| $\log F_{H\beta}(\text{erg cm}^{-2}\text{s}^{-1}) = -13.34$ | | |

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### 3.2.2 High-resolution, long-slit spectroscopy

Spectra of DeHt 2 were obtained at PAs 0°, 50°, 90°, and 140°. These slit positions (denoted S1 to S4, respectively) are plotted in Fig. 6 (right-hand panel), on the [O iii] image of the nebula. Slits S1 and S3 were chosen to cover the major and minor axes of the ring, respectively, while S2 covers the main axis of the elliptical shell and S4 its minor axis. Fig. 7 shows the PV maps of the [O iii] emission line at the four observed PAs. From the radial velocity centroid of the line emission feature, we derive a heliocentric systemic velocity $V_{HEL} = +47 \pm 2$ km s$^{-1}$.

The PV maps at PAs 0° and 140° mainly show a velocity ellipse. The ellipse does not appear tilted on these PV maps, although some asymmetries with respect to the velocity axis are observed. At PA 50° the emission line feature shows a spindle-like shape slightly tilted in the PV map such the NE (SW) regions present an excess of blueshifted (redshifted) radial velocities. At PA 90° the emission line feature shows a shape halfway between that observed at PA 50° and PA 140°. Maximum line splitting of $\pm 100$ km s$^{-1}$ is observed at the stellar position at all PAs. The PV maps also show that the CS is displaced from the nebular centre $\approx 3$ arcsec towards the SW at PA 50° and PA 140°. Maximum line splitting of $\pm 100$ km s$^{-1}$ is observed at the NE tip of the shell. They show an elliptical shell with a size of $\approx 1.9 \times 1.5$ arcmin$^2$ and major axis oriented at PA $\approx 55^\circ$, although the polar regions seem to protrude and deviate from a ‘pure’ elliptical geometry, in particular at the SW region. The shell shows a limb-brightening that is more noticeable along the northern edge. This could be a result of interaction of the nebula with the ISM (Wareing, Zijlstra & O’Brien 2007), an idea that is supported by the fact that the limb-brightening is more

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**Figure 4.** Nebular spectrum of Abell 36 obtained by integrating the emission lines between 77 and 124 arcsec eastern from the CS along the slit position. The emission lines are labelled.

**Figure 5.** Normalized optical spectrum of the CS of Abell 36. Poorly subtracted sky lines and nebular emission lines are marked as well as some absorption lines (specially He ii $\lambda 4686$) as well as the atmospheric parameters (Table 1) are indeed compatible with an sdO nature.

**Table 2.** Emission line intensities in Abell 36.
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Figure 6. Grey-scale reproductions of the Hα (left) and [O III] (middle and right) images of DeHt 2. Grey levels are linear. Slit positions used for the high-resolution, long-slit spectroscopy are drawn on the right-hand panel (slit width not to scale). The small nebulosity towards the north-western of DeHt 2 could be a galaxy.

Figure 7. Grey-scale, PV maps derived from the high-resolution, long-slit [O III] spectra of DeHt 2 at four different PAs (upper left, see also Fig. 6). The bright features related to the ring-like structure are indicated by ‘R’.

as indicated by the maximum radial velocity splitting of the velocity ellipse.

The spatio-kinematical properties of DeHt 2 indicate that its formation has been complex with at least two different ejection processes being involved. In Fig. 8, we show a schematic representation of the structures that compose DeHt 2, as inferred from the analysis of the PV maps. We suggest that the original structure of this PN was a spheroid on which a bright, ring-like region defined its equatorial plane. The fact that the expansion velocity of the ring (36 km s⁻¹) is lower than that measured at the stellar position (50 km s⁻¹, at some latitude above the equator), strongly suggests that the original structure was not spherical but probably an ellipsoid with the major axis oriented approximately E–W. Taken into account the spatio-kinematical properties of the ring and assuming a distance of 1.9–3.2 kpc (Dengel et al. 1980; Napiwotzki 1999, 2001), its kinematical age results to be 1.3–1.9 × 10⁴ yr, compatible with an evolved PN. Probably later, another bipolar ejection has taken place, that interacted with and deformed the original spheroid, as suggested by the protruding regions that are now observed as the polar regions of the apparent elliptical shell. The second ejection should have been collimated and along a bipolar axis oriented at PA ≃ 50°, that is different from the orientation of the previous structure.

3.2.3 Intermediate-resolution, long-slit spectroscopy

Fig. 9 shows the intermediate-resolution, long-slit spectra of the NE filaments of DeHt 2. Only the Hα, Hβ, [O III]4959, 5007, and He i4686 emission lines are detected. A logarithmic extinction
The spheroidal shell (dashed blue line), the ring-like structure (solid blue line), and the bipolar outflow (solid red line) are drawn.

The spectrum corresponds to the bright filaments at the northeastern (see Fig. 6). The spectrum indicates a very high excitation although other high-excitation emission lines (as in the case of Abell 36) are not observed. The same emission lines are detected in other nebular regions (spectra not shown here), suggesting a somewhat lower excitation than in the NE filaments.

The stellar spectrum is shown in Fig. 10. It shows strong He II absorptions some of which can be blended with the Balmer absorptions. Although the spectrum of DeHt 2 does not have enough spectral resolution to resolve the Pickering and Balmer absorption lines, most probably the absorptions present in this spectrum mainly correspond to the Pickering ones, due to the high effective temperature of this CS (117 000 K, see Table 1). These spectral features and the atmospheric parameters (Table 1) are compatible with a very hot sdO star. To provide more support for this classification, we compare in Fig. 10 the normalized blue spectrum of the CS with that of BD+28°4211, a well-known sdO with $T_{\text{eff}} \simeq 82 000$ K and logg $\simeq 6.2$ cm s$^{-2}$ (Latour et al. 2013). The spectrum of BD+28°4211 was obtained with the CAFOS spectrograph in 2011 July. Spectra of both stars are also shown in Napiwotzki & Schonberner (1995, their fig. 3). Both spectra are remarkably similar to each other, being the observed differences probably due to the signal to noise in each spectra and to the different atmospheric parameters of the stars. In any case, the spectral similarities strongly suggest an sdO nature for the CS of DeHt 2.

3.3 RWT 152

3.3.1 Imaging

Fig. 11 shows the H$\alpha$ and [OIII] images of RWT 152, in which details of the nebular morphology can be distinguished for the first time. Both images reveal a very faint PN. While in the H$\alpha$ image the nebula presents a diffuse, although non-spherical appearance, a more defined nebula can be discerned in the [OIII] image. At low-intensity levels, the nebula seems to be almost circular whereas at higher intensity levels, it appears slightly bipolar with a size of $\simeq 17 \times 21$ arcsec$^2$, major axis oriented at PA $\simeq 40°$, and a rather uniform intensity distribution. It is worth noting that the CS is clearly displaced towards the NW with respect to the centre of the nebula (see also below).

3.3.2 High-resolution, long-slit spectroscopy

Spectra of RWT 152 were obtained at PA 45° (in H$\alpha$ and [OIII]) and PA 135° (in [OIII]) to cover the major and minor axis (S1 and S2, respectively, in Fig. 11) of the bipolar shell. Fig. 12 shows the two PV maps in the [OIII] emission line. We note that the [OIII] emission line feature presents a much more knotty appearance in the PV maps than in the image. The PV map of H$\alpha$ emission line at PA 45° (not shown here) is very similar to that of the [OIII] emission line at the same PA, but the large thermal width in the H$\alpha$ line does not allow us a detailed analysis of the kinematics.
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Figure 11. Grey-scale reproductions of the H$\alpha$ and [O\textsc{iii}] images of RWT 152. Grey-levels are linear. A $3 \times 3$ box smooth was used for the representation. The slit positions used for the high-resolution, long-slit spectroscopy (S1 and S2) are drawn in the right-hand panel.

Figure 12. Grey-scale, PV maps derived from the high-resolution, long-slit [O\textsc{iii}] spectra of RWT 152. Grey-levels are linear. The continuum of the CS has been removed (using the background task) and its position is marked with a dashed horizontal line. A $3 \times 3$ box smooth was used for the representation.

From the velocity centroid of the line emission features, we derive a heliocentric systemic velocity of $V_{\text{HEL}} = +134.5 \pm 1.8$ km s$^{-1}$.

In the PV map at PA 45$^\circ$, the [O\textsc{iii}] emission feature presents an hour-glass like shape with a size of $\simeq 22$ arcsec, although deviations from a pure hour-glass shape are noticed, particularly in the NE lobe. Radial velocity at the tips of the emission feature is $\simeq \pm 7$ km s$^{-1}$. Two bright knots can be distinguished in the central region, that are symmetric in radial velocity but not centred on the CS: the redshifted knot presents a radial velocity of $\simeq +14$ km s$^{-1}$ and is located $\simeq 0.12$ arcsec NE from the CS; the blueshifted one has a radial velocity of $\simeq -14$ km s$^{-1}$ and is located $\simeq 1.8$ arcsec SW from the CS. The PV map at PA 135$^\circ$ presents a velocity ellipse with a maximum line splitting of $\simeq 34$ km s$^{-1}$ at the stellar position and a size of $\simeq 18$ arcsec as measured between the intensity peaks at the systemic velocity. The centre of the velocity ellipse is displaced $\simeq 1.2$ arcsec towards the SE with respect to the CS.
The displacements of nebula’s centre with respect to the CS as measured in the PV maps are consistent with the off-centre position of the CS observed in the direct images. Taken into account the two observed PAs, a shift of $\pm 1.4$ arcsec towards PA $\simeq 348^\circ$ is obtained.

Both images and PV maps are compatible with a bipolar PN. The two bright knots observed in the central regions in the PV map at PA $45^\circ$ suggest the existence of an equatorial enhancement. If we assume circular cross-section for the equator, the equatorial plane of the nebula is tilted by $\pm 6^\circ$ with respect to the line of sight. Assuming homologous expansion, a polar velocity of $19$ km s$^{-1}$ is obtained. There is no reliable determination for the distance of RWT 152 and estimates are 1.4 and 6.5 kpc (Ebbets & Savage 1982; Pritchet 1984). In consequence, only a lower limit of $\leq 4 \times 10^3$ yr can be obtained for its kinematical age, which suggests (at least) a relatively evolved PN.

3.3.3 Intermediate-resolution, long-slit spectroscopy

The intermediate-resolution nebular spectrum of RWT 152 is presented in Fig. 13. Only the H$\alpha$, H$\beta$, and [O i] $\lambda\lambda 4959, 5007$ emission lines are identified. A logarithmic extinction coefficient $c$(H$\beta$) of $\pm 0.46$ was derived (see Section 2.2.2). Table 4 lists the dereddened line intensities and their Poissonian errors. The [O i]/H$\beta$ line intensity ratio is $\simeq 8$ (Table 4), suggesting a relatively high excitation.

The normalized spectrum of the CS is shown in Fig. 14. In contrast to the CS spectrum of DeHt 2, the CS spectrum of RWT 152 is dominated by hydrogen Balmer lines. The narrowness of the absorption lines, and the presence of He I ($\lambda\lambda 4386, 4471$) and He II absorption lines (specially He II $\lambda 4686$) confirm the sDO nature of the CS. The CS was analysed by Ebbets & Savage (1982) who determined a relatively low (for an sDO) $T_{eff}$ of $\simeq 45\,000$ K (see Table 1) that is compatible with the presence of He I $\lambda 4471$.

4 DISCUSSION

The data presented and analysed in the previous sections have allowed us to deduce the basic physical structure and emission properties of Abell 36, DeHt 2, and RWT 152 and their CSs. Moreover, the spatio-kinematical analysis has been able to recover relevant information about the processes involved in the formation of the three objects. In addition, the spectra of the three CSs show characteristics that allow us to classify them as sDOs. In particular, the narrowness of the absorption lines and the presence of prominent He II absorption are typical of sDOs. This classification is corroborated by the atmospheric parameters of the CSs (Table 1), that are within the range of the sDOs atmospheric parameters (see Heber 2009).

RWT 152 seems to be a result of a typical bipolar ejection as observed in many PNe. The formation of Abell 36 and DeHt 2 appears more complex and requires multiple ejection events, changes in the orientation of main ejection axis between events, and a different collimation degree of the ejections. In Abell 36, the bright arcs indicate a very large and ‘continuous’ change in the collimated ejection axis, whereas in DeHt 2 the bipolar outflows seem to have acted along a constant direction that is different from the main axis of the previous shell. Interestingly, evidence is found in both PNe that the collimated outflows might have been ejected after the main nebular shell was formed. Moreover, in both cases, the collimated outflows seem to have disrupted or deformed the previous shell. This situation is similar to that found in other PNe (e.g. Guerrero & Miranda 2012; Ramos-Larios et al. 2012; Güillén et al. 2013) in which young collimated outflows seem to have disrupted a previous nebular structures. The origin of collimated outflows in PNe after the formation of the main nebular shell is difficult to explain within current scenarios for PN formation and is still matter of debate (see Tocknell, De Marco & Wardle 2014).

Multiple ejection events, as those identified in Abell 36 and DeHt 2, are observed in many PNe. The idea that complex PNe are related to the evolution of binary CSs has been present during many years and it has received strong support with recent detections of new binary CSs in PNe with multiple structures and jets (see Miszalski et al. 2009 and references therein). Within this context, it could be suggested that the CSs of Abell 36 and DeHt 2 are also binaries, although, to the best of our knowledge, no direct evidence exists for such binaries. It is interesting to note that both Abell 36 and DeHt 2 contain off-centre CSs, which could be considered as an indirect evidence for a binary CS (e.g. Soker, Rappaport & Harpaz 1998). Although it is true that some binary CSs appear off-centre, inferring a binary CS from its off-centre position only should be
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seen with caution. Given that DeHt 2 and, perhaps, Abell 36 are evolved PNe, the off-centre CSs could be caused by deformation in the shell due to, for instance, interaction with the ISM (Jones et al. 2010; Frew et al. 2014), and/or amplification through evolution of (originally small) asymmetries in the ejection process. In the case of Abell 36, interaction shell-collimated outflows could also contribute to create asymmetries in the shell. The case of the off-centre CS of RWT 152 looks different because of the more symmetric shell. However, RWT 152 may be a very distant PN and a higher spatial resolution is necessary to investigate possible asymmetries in the shell, which are already suggested by the distortions in the kinematics. In any case, these three PNe are good candidates to host binary CSs (see also below), and dedicated observations of their CSs should be obtained to search for possible companions.

The nebular spectra of Abell 36 indicate high excitation, as shown by the presence of [Ar iv] and strong He ii λ4686 emission lines. The nebular spectra of DeHt 2 and RWT 152 also indicate high excitation but no emission lines from heavy elements (except [O iii]) are detected. If other emission lines exist in these two PNe, they should be very faint. The CSs of Abell 36 and DeHt 2 present very similar atmospheric parameters (Table 1). Therefore, similar emission lines could be expected, unless the physical conditions and/or chemical abundances are very different in both PNe. The CS of RWT 152 has a relatively low Teff and, in principle, low-excitation emission lines should be present in the nebula. The nebular spectra of DeHt 2 and RWT 152 are very similar to that of PN G 075.9+11.6 (Aller et al. 2013), in which only [O ii] and Balmer emission lines have been detected. Following these authors, a probable explanation for the peculiar nebular spectra of DeHt 2 and RWT 152 is a deficiency in heavy elements in the nebula. Such a deficiency may be expected in PNe that originate from low-mass progenitors (see e.g. IC 2149; Vázquez et al. 2002), and it would be consistent with the idea that sdOs evolve from low-mass progenitors (see e.g. Heber 2009). Deep spectroscopy of these PNe is crucial to detect faint emission lines and to obtain their chemical abundances.

It is interesting to compare the properties of PN+sdO systems. A search in the literature suggests 33 PNe with sdO CS, although in several cases this classification is doubtful or not confirmed (see Weidmann & Gamen 2011). For instance, the CS of NGC 2371 is classified as sdO in SIMBAD but as WR-PG 1159 by Herald & Bianchi (2004); the CS of NGC 6026 is classified as WD/sdO by de Marco (2009), as a pre-WD/WD by Hillwig et al. (2010) but as OB by Weidmann & Gamen (2011); in the case of NGC 1514, the hot star in its binary CS has been classified as sdO (Kohoutek 1967) but a recent spectral analysis (Aller et al., in preparation) does not allow us to establish a firm classification. If we restrict to those objects with a more confident classification, the number of PN+sdO systems is 18. Table 5 lists these PNe (columns 1 and 2), their morphology and some comments about nebular structures present in them (column 3), the binary nature of the CSs (column 4), and the corresponding references (column 5). We emphasize that the discussion below does not critically depend on whether some of the possible PN+sdO systems are added to the list and/or whether some of the objects in Table 5 are removed. We note that our Table 5 shares several objects with table 1 by Miszalski et al. (2009). These authors analyse the morphology of PNe with close binary CSs while we focus in the morphology and presence of binaries in sdO CSs.

An inspection of the properties of PN+sdO systems reveals that most of these PNe are very faint, suggesting that they are in a moderately or very evolved stage. A noticeable exception is the Stingray nebula (Hen 3−1357), a very young PN (Parthasarathy et al. 1995) whose CS (SAO244567) has recently been identified as an sdO (Reindl et al. 2014). If we attend to the morphology, the sample is dominated by elliptical and bipolar shapes with only an object (DS 2) presenting a round morphology. Moreover, many of these PNe show multiple structures, jet-like outflows or point-symmetric structures that could be related to the action of bipolar collimated

Table 5. Properties PN+sdO systems.

| PN G       | Name      | Morphology/Comments                      | Binary CS | References |
|------------|-----------|------------------------------------------|-----------|------------|
| 009.6+10.5 | Abell 41  | Bipolar                                  | Y         | (1), (2), (3) |
| 009.8−07.5 | GHJC 1    | Irregular/Cometary-like                  | ?         | (4), (5)   |
| 027.6+16.9 | DeHt 2    | Elliptical/Spheroidal shell and bipolar outflows at different orientations | ?         | (6)        |
| 053.8−03.0 | Abell 63  | Bipolar/Jets                             | Y         | (7), (9), (10) |
| 055.4+16.0 | Abell 46  | Elliptical-Bipolar                       | Y         | (9), (11), (12), (13) |
| 065.0−27.3 | K 648     | Elliptical/Two elliptical shells and halo | ?         | (14)       |
| 075.9+11.6 | 2M1931+4324 | Multishell/Bipolar and elliptical shell at different orientations | Y         | (15), (16) |
| 136.3+05.5 | HFG 1     | Irregular                                | Y         | (17), (18) |
| 215.6+03.6 | NGC 2346  | Bipolar                                  | Y         | (9), (12), (19) |
| 219.2+07.5 | RWT 152   | Bipolar                                  | ?         | (6), (20)  |
| 272.1+12.3 | NGC 3132  | Elliptical                               | Y         | (21), (22) |
| 273.6+06.1 | LSS 1362  | Elliptical-irregular                    | N         | (23), (24) |
| 279.6−03.1 | He 2−36   | Elliptical/Point-symmetry                | ?         | (25), (26) |
| 283.9+09.7 | LSS 2018 (DS 1) | Bipolar-irregular/Low-ionization structures | Y         | (9), (27)  |
| 318.4+41.4 | Abell 36  | Elliptical/Spheroidal shell and point-symmetric arcs | ?         | (6), (20)  |
| 331.3−12.1 | Hen 3−1357 | Multishell/Bipolar and elliptical shells and jets | ?         | (28), (29) |
| 335.5+12.4 | LSE 125 (DS 2) | Round                                    | N         | (27), (30) |
| 339.9+88.4 | LoTr 5    | Bipolar                                  | Y         | (31), (32) |

(1) Bruch et al. (2001); (2) Shimanskii et al. (2008); (3) Jones et al. (2010); (4) Borkowski, Tsvetanov & Harrington (1993); (5) Rauch, Dreizler & Wolff (1998); (6) This work; (7) Pollacco & Bell (1997); (8) Tsessevich (1977); (9) Miszalski et al. (2009); (10) Mitchell et al. (2007); (11) Stanghellini et al. (2002); (12) Bond & Livio (1990); (13) Ritter & Kolb (2003); (14) Alves, Bond & Livio (2000); (15) Aller et al. (2013); (16) Jacoby et al. (2012); (17) Heckathorn, Fesen & Gull (1982); (18) Grauer et al. (1987); (19) Kohoutek & Senkbeil (1973); (20) Ostensen (2006); (21) Ciardullo et al. (1999); (22) Monteiro et al. (2000); (23) Chu et al. (2009); (24) Heber et al. (1988); (25) Corradi & Schwarz (1993); (26) Mendez (1978); (27) Drilling (1983); (28) Bobrowsky et al. (1998); (29) Reindl et al. (2014); (30) Hua, Dopita & Martinis (1998); (31) Van Winckel et al. (2014); (32) Graham et al. (2004)
outflows. It is also remarkable that many PN+sdO systems host binary CSs, suggesting that binary CSs may play an important role in the formation of PN+sdO systems. Finally, a large fraction of these systems are observed at a relatively high Galactic latitude. In particular, 11 PNe in Table 1 have |b| > 10° and 15 have |b| > 7°. Although the number of objects is small to draw firm conclusions, the relatively high Galactic latitudes are more typical of round PNe evolving from low-mass progenitors (Corradi & Schwarz 1995; Stanghellini et al. 2002). Remarkably, low-mass progenitors are generally expected for sdOs (see above) and, in addition, sdOs are normally located at high Galactic latitudes. However, one would not expect a large fraction of complex PNe resulting from low-mass progenitors. These results and the large fraction of binary CSs in PN+sdO systems point out that the key parameter to form a complex PN is a binary CS rather than the mass of the progenitor. This conclusion is reinforced by recent results by, e.g. Miszalski et al. (2009), Boffin et al. (2012), Corradi et al. (2014), and Jones et al. (2014) who found that most PNe with close binary CS present complex morphologies.

sdOs associated with PNe represent a very small fraction of the ≥800 known sdOs (Ostensen 2006). This number could increase as more CSs may be classified as sdO (e.g. Reindl et al. 2014). In this respect, we note the lack of firm classifications for many CS of PNe, which are crucial to identify new sdO among CSs. On the other hand, a recent image survey of ≥80 ‘classical’ sdOs (Aller et al., in preparation) to search for associated PNe has identified only a new case (Aller et al. 2013). Nevertheless, given the intrinsic faintness of these PNe, much deeper surveys should be carried out to identify more cases. Several evolutionary paths are considered for the formation of sdOs (see Heber 2009) and, in the case of PN+sdO systems, evolution through asymptotic giant branch (AGB) and post-AGB phases appears to be the most suitable one. For the rest of sdOs (those without a PN), other evolutionary paths (post-red giant branch, post-extended horizontal branch evolution, or star mergers) should be considered (Alves et al., 2013). The spectra of the three CSs present narrow absorption lines, beam-splitting and their atmospheric parameters strongly suggest a possible deficiency in heavy elements.

5 CONCLUSIONS

We have presented and analyzed narrow-band direct images, and high- and low-resolution, long-slit spectra of Abell 36, DeHt 2, and RWT 152, three PNe for which detailed spatio-kinematical analysis had not been carried out before. This analysis has been complemented with low-resolution, long-slit spectra that have allowed us to describe the spectral characteristics of the nebula and their CSs. The main conclusions of this work can be summarized as follows.

Abell 36 presents a point-symmetric elliptical morphology but the spatio-kinematical analysis reveals that it consists of a spheroidal shell and two bright point-symmetric arcs, attributable to bipolar, rotating outflows; the collimated outflows seem to have bored parts of the spheroid. DeHt 2 appears as an elliptical PN in direct images but our analysis strongly suggests that it has formed through two different ejection events, with the last one being more collimated than a previous ellipsoidal shell; evidence also exists in DeHt 2 for collimated outflow–shell interaction. RWT 152 is a bipolar PN with an equatorial ring. The complex structures of Abell 36 and DeHt 2 suggest that binary CSs may be involved in their formation.

The nebular spectra of the three PNe indicate a high excitation but only Abell 36 exhibits emission lines different from those due to Balmer, [O ii], and He ii. In DeHt 2 and RWT 152, the nebular spectra suggest a possible deficiency in heavy elements.

The spectra of the three CSs present narrow absorption lines, being the He ii λ4686 absorption particularly prominent. These characteristics, and the published atmospheric parameters strongly suggest an sdO nature for these CSs. Thus, these sdOs have most probably evolved through AGB and post-AGB phases.

The number of sdOs surrounded by PNe is very scarce (~18). This number could be biased by the intrinsic faintness of the associated PNe, and by the lack of a firm classification for many CS of PNe. Very deep images of more sdOs, and analysis of high-quality CS spectra are necessary to identify new PN+sdO systems. On the other hand, if sdOs originate from low-mass progenitors, the non-detection of more PN+sdO systems could be, at least for a certain fraction of sdOs, a consequence of the dissipation of the nebula before being photoionized, due to the slow evolution of the CS.

We have compared properties of the more confident PN+sdO systems and found that most of them are relatively or very evolved PNe, present collimated outflows or signs that collimated outflows have been involved in their formation, host binary CSs, and are observed at relatively high Galactic latitudes. These properties and other published results reinforce the idea that the formation of complex PNe is related to binary stars rather than to the progenitor mass. More studies of PN+sdO systems could provide interesting information about formation of complex PNe and sdO evolution.

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