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Catalogue of the central stars of planetary nebulae

Expanded edition[⋆]

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ABSTRACT

Planetary nebulae represent a potential late stage of stellar evolution, however, their central stars (CSPNe) are relatively faint and, therefore, pertinent information is available for merely <20% of the Galactic sample. Consequently, the literature was surveyed to construct a new catalogue of 620 CSPNe featuring important spectral classifications and information. The catalogue supersedes the existing iteration by 25% and includes physical parameters such as luminosity, surface gravity, temperature, magnitude estimates, and references for published spectra. The marked statistical improvement enabled the following pertinent conclusions to be determined: the H-rich/H-poor ratio is 2:1, there is a deficiency of CSPNe with types [WC 5-6], and nearly 80% of binary central stars belong to the H-rich group. The last finding suggests that evolutionary scenarios leading to the formation of binary central stars interfere with the conditions required for the formation of H-poor CSPN. Approximately 50% of the sample with derived values of $\log L_\star$, $\log T_{\rm eff}$, and $\log g$, exhibit masses and ages consistent with single stellar evolutionary models. The implication is that single stars are indeed able to form planetary nebulae. Moreover, it is shown that H-poor CSPNe are formed by higher mass progenitors. The catalogue is available through the Vizier database.

Key words. catalogs – planetary nebulae: general – stars: evolution

1. Introduction

Catalogues are an important tool in astrophysics, helping researchers in their pursuit of discoveries. For example, Majaess et al. (2007) looked for a link between planetary nebulae (PNe) an open cluster, which led in part to the discovery of PN PHR 1315−6555 in the cluster Andrews-Lindsay 1 and a 4% distance solution (Majaess et al. 2014). Miszalski et al. (2009a) discovered 21 periodic binaries at the center of planetary nebulae by cross-matching PNe and OGLE microlensing survey catalogues. They also established that the close binary fraction was 10–20% in a independent sample of binary PNe and, in a follow up work (Miszalski et al. 2009b), they concluded that a fraction of at least 60% of post-common-envelope PNe are bipolar nebulae. Thus changing the fact that NGC 2346 being the only post-common-envelope canonical bipolar. More recently, Stanghellini et al. (2020) matched the astrometry of PNe with DR2 *Gaia* parallaxes, thus providing the parallax to 430 objects. Using these parallaxes, they located the CS of the PNe and, together with the effective temperatures and magnitudes from the literature, determined their masses. These catalogs were the starting points for some important determinations.

Regarding the central star of planetary nebulae (CSPNe), a complete catalogue but with limited information is Weidmann & Gamen (2011b). It has proven to be a useful tool for the astronomical community. However, ever the last nine years there has been an increase in the number of CSPNe with new determined spectral types (or improved through spectra with better quality and resolution, such as in Weidmann et al. 2018), an upgrade of that catalogue becomes necessary. In addition, during these years many new developments have been published concerning the CSPNe. There are spectral types that no longer apply, for example the wels (Weidmann et al. 2015). Moreover, several [WN] stars could be confirmed, that is IC 4663 (Miszalski et al. 2012a), A 48, and probably at PB 8 (Todt et al. 2010). Also, NGC 5189, a binary system whose primary star is of the [WR] type (Manick et al. 2015). With regard to the multiplicity of the CSPNe, it was possible to identify a triple system at the nucleus of the planetary nebula NGC 246 (Adam & Mugrauer 2014). This situation, which is speculated to be common, might happen in LoTr 5 and SuWt 2.

A catalogue would allow statistical analysis and provide observational limits to evolutionary models, such as the progenitor's mass of PNe. Although the range of masses of the

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[⋆] Tables D.1 and D.2 are only available at the CDS via anonymous ftp to `cdsarc.u-strasbg.fr` (`130.79.128.5`) or via `http://cdsarc.u-strasbg.fr/viz-bin/cat/J/A+A/640/A10`

Table 1. Key optical lines to spectral classification of CSPNe.

Spectral classif.	Example	Ion/wavelength [Å]											
		H I 4340	He I 4471	C III 4649	C III 5696	He II 4686	He II 5412	C IV 5806	C IV 4650	N V 4603	N V 4945	O VI 3822	O VI 5290
Early O(H)	NGC 5307	A	A	–	–	A	A	E	–	A	–	E?	E
Late O(H)	Cn 3−1	A	A	A	–	A	A	A	–	–	–	–	–
Early Of(H)	M 1−53	A	A	E	–	E	A	E	–	A	–	?	E
Late Of(H)	IC 4593	A	A	A	–	E	A	?	–	–	–	–	?
Of-WR(H)	NGC 6543	A	?	–	–	E (1)	E	E	–	E	–	–	E
O(He)	Hen 2−64	–	–	–	–	A	A	–	–	E	E	–	–
PG 1159	Jn 1	–	–	–	–	A	A	E	A	–	–	E	E
[WO]	NGC 2867	–	–	–	–	E	E	E	E	–	–	E	E
[WC]	NGC 40	–	–	E	E	E	E	E	–	–	–	–	–
[WN]	IC 4663	–	–	–	–	E	E	–	–	E	E	–	E
DA	DeHt 5	A	–	–	–	–	–	–	–	–	–	–	–
DAO	HDW 3	A	–	–	–	A	–	–	–	–	–	–	–
DO	KPD (2)	–	A	–	–	A	A	–	–	–	–	–	–

Notes. The A represents absorption lines, while the E represents the emission ones. Upper panel represents narrow features, and lower, wide features. The ions are arranged by excitation potential. In the second column we propose a prototype with published spectrum. (1)Wide line. (2)KPD 0005+5106.

progenitor star which would result in a PN is frequently estimated to be between 1–8 $M_\odot$, the observational evidence in support of this point is limited. Nevertheless, the confirmation of a PN associated to an open cluster, has a direct implication on the upper limit on the progenitor's mass. Fragkou et al. (2019a,b) have proved that the PNe PHR 1315−6555 and BMP J1613−5406 are physically linked to an open cluster. Consequently, we have, for the first time, observational evidence that the upper limit of the initial stellar mass for the formation of a PN can be as high as $M_* \lesssim 5.0\,M_\odot$. Another important step forward in the study of the formation of PNe came from the study of Hen 2−428, whose central star was found by Santander-García et al. (2015) to be composed of a double-degenerate core with a combined mass above the Chandrasekhar limit. Although later studies have put such high mass into question, favouring a much lower mass for the central stars (e.g. García-Berro et al. 2016; Reindl et al. 2018). Specifically, the detailed analysis of Reindl et al. (2020) indicates that the system might be composed of a 0.66 $M_\odot$ post-AGB and a reheated 0.42 $M_\odot$ post-RGB star. The study of this peculiar object will certainly shed light on the formation process of PNe through common envelope events.

To establish an evolutionary sequence involving the spectral types of the CSPNe was not a simple task, and certainly, we still have a lot to learn about this topic. Proof of this is the case of Hen 3−1357. Reindl et al. (2017) observed that the CSPN of this object is evolving quickly, changing from B-type ($T_{\rm eff} \sim 21$ kK) object in 1971 to a $T_{\rm eff} \sim 60$ kK peak in 2002. Since then, it seems to have begun cooling and expanding back to the AGB at a rate of $770 \pm 580\,{\rm K\,yr^{-1}}$, similarly to FG Sge ($350\,{\rm K\,yr^{-1}}$; Jeffery & Schönberner 2006) and providing further evidence of the existence of late helium flashes in the post-AGB evolution.

In summary, in the last years a series of extreme phenomena has been found in PNe that increase the complexity of these objects. Undoubtedly, the less understood stage of stellar evolution for low and intermediate mass stars is precisely the last one, that is from post-AGB to pre-WD. This is the main motivation to update and expand the catalogue of CSPNe. Thus, in this work we present a new catalogue of spectral types of CSPNe which supersedes the Weidmann & Gamen (2011b).

This paper is structured as follows: in Sect. 2, we present a summary of the different spectral types of CSPNe. An evolutionary sequence is described in Sect. 3. We detail the main body of the catalogue in Sect. 4.

Results are presented in Sect. 5, while in Sect. 6 there is a summary of this work and we lay our conclusions. Finally, in the Appendix we focus on peculiar CSPNe.

2. Review of spectral classification

It is well known that the CSPNe are divided into two large groups. Those that present hydrogen absorption lines (H-rich) and those that do not (H-poor). One of the pioneering work in compiling CSPNe spectral information was Aller (1975). He reported the following types: O-type, WC, OVI (currently called [WO]), Of + WR, sdO and continuum.

There are few spectral types that are specific of CSPNe such as O(C), [WC]-PG 1159, and Of-WR(H). For the [WR], O and Of-type, the classification criteria for massive WC stars (or massive O-type stars) is used. Implementing an appropriate criteria for CSPNe requires a large number of good quality spectra.

It is appropriate to point out that this is a qualitative classification system in which the unknown stellar spectrum is compared with a grid of standard stars. In this sense, Dreizler (1999) and Napiwotzki et al. (1998) present a collection of spectra of different spectral types of evolved objects which represents a useful tool. In Table 1 we mention some key lines of each spectral type. Nevertheless, these do not replace the proper classification criteria of every type. Below we present a guide, with bibliographic references, that describes the spectrum (in the optical range) of each type of object mentioned in our catalogue.

- [WR] (subtype [WN], [WC] and [WO]): Crowther et al. (1998), Acker & Neiner (2003) and Miszalski et al. (2012a). The spectral type VL was implemented by Górny et al. (2009), which is in fact consistent with a late [WC].
- O(H): Although these objects follow the classification criteria for massive O-type stars, in Weidmann et al. (2018) some characteristics of the O-type stars that are CSPNe are described. In this type of stars it is possible to improve the spectral classification with qualifiers (Sota et al. 2011, 2014;

Maíz Apellániz et al. 2016). Based on the ions identified in the spectrum, the CSPNe could be classified as O(H), O or H-rich (Weidmann et al. 2018).
- Of(H): This includes the O-type stars with emission lines. Historically, there was a distinction between the O-type and Of-type stars. Nevertheless, not all O-type star with emission lines are in fact an Of-type. To clarify this see Mendez et al. (1990), Smith & Aller (1969). In Sota et al. (2011) these objects are indicated with the qualifiers: f, f*, fc and f+.
- O(C): This type of star appears only in one member, that is K 3−67. Previously, Lo 4, wray 17−1, and IsWe 1 were included in this spectral type (Mendez et al. 1991). Nowadays, these last three objects were reclassified as PG 1159.
- O(He): Reindl et al. (2014b), Rauch et al. (2008, 2006, 1998).
- Of−WR(H): Mendez et al. (1990, 1991).
- WD (subtype DA, DAO and DO): Napiwotzki (1999), McCook & Sion (1987), and McCook & Sion (1999).
- hgO(H): The classification hgO(H) was used exclusively for CSPNe (Mendez et al. 1986), these objects are essentially evolved objects like sdO or WD stars. For example Sh 2−68 have three classifications i.e. hgO(H), WD, and PG 1159 (Napiwotzki & Schoenberner 1995).
- sdO, sdB: Jeffery et al. (1997) and Ahumada et al. (2019).
- PG 1159 (subtype A, E and lg E): Werner et al. (1992), Dreizler & Heber (1998) and Hügelmeyer et al. (2005).
- [WC]−PG 1159: Previously called Of-WR(C) (Mendez et al. 1991). There are only two objects with this spectral type, A 30 and A 78.
- hybrid: Dreizler et al. (1996) and Napiwotzki (1999).
- symbiotic star (SySt): This is not strictly a spectral type (see Appendix A).
- B[e]: Oudmaijer & Miroshnichenko (2017) and Lamers et al. (1998).
- cont.: Weidmann et al. (2018). This is not strictly a spectral type. In general, objects with this designation are O-type stars.
- B2-M9: Objects later that a B1 does not have the required temperature to ionize the nebula. In this sense, objects classified with a late type are, in fact, candidates for binary systems whose hot component is hitherto undiscovered.
- wels: Classification implemented by Tylenda et al. (1993). This designation has been shown not to correspond to an independent spectral type. In general it contemplates hot O(H)-type stars (Weidmann et al. 2015).
- EL (Emission Line): Few objects in which the presence of emission lines of stellar origin have been reported. These objects do not always satisfy the wels criterion.
- Blue: The MASH catalogue identified CSPNe of some objects. Photometric observations indicate that these objects are blue. None of these objects have spectroscopic information.

3. Review of stellar evolution

The main parameter that defines the stellar evolution is the mass. It is commonly accepted that the mass range of a main sequence star that gives birth to a PN is $1.0\,M_\odot \lesssim M_* \lesssim 8.0\,M_\odot$. However, this mass range is not a strict limit.

Firstly, the minimum mass required to form a star is $0.07\,M_\odot$, the hydrogen burning mass limit (Chabrier & Baraffe 2000). Therefore, stars with mass in the range between $0.07\,M_\odot \lesssim M_* \lesssim 1.0\,M_\odot$ do not evolve to a PN. In fact, these stars did not have enough time to leave the main sequence (Miller Bertolami et al. 2019). Saracino et al. (2016) estimated the globular cluster turn-off mass in about $0.88\,M_\odot$ for NGC 6624. In this sense, it should not have progenitor CSPN with masses lower than $0.88\,M_\odot$.

A PN is obtained when the gas expelled in the AGB phase is ionized by the remaining object at its core. This requires a star with a certain minimum progenitor mass M_χ. Objects with a mass that is lower than M_χ will not result in a nebula. Observational data must be used to obtain M_χ. Globular clusters are the oldest objects in the galaxy and the lifetime of a PN is about 20 000 years. Hence, if it is possible to determine the progenitor mass of a PN that is physically linked to a globular cluster, this will be a good estimation for M_χ. Jacoby et al. (2017) showed that the progenitor mass of the PN JaFu 1 (planetary nebulae linked to the globular cluster Pal 6) is $0.8\,M_\odot$.

On the other hand, finding observational evidence for the upper limit on the stellar mass that is required to originate a PN is not so straightforward. One option is to determine the mass of the progenitor star of a PN linked to an open cluster. Fragkou et al. (2019b) showed that the progenitor mass of the planetary nebula BMP J1613−5406 (object linked to the open cluster NGC 6067) is $5\,M_\odot$.

Now, take into account evolutionary sequence for a main sequence star with mass between 0.8–$5.0\,M_\odot$, nowadays, it is not clear which is the spectral-type sequence that passes through. Iben (1991) developed a convincing theoretical model, but it does not contemplate the spectral types. Perhaps the sequence shown in Fig. 1 is the most classical picture (see e.g. Leuenhagen & Hamann 1998; Zijlstra et al. 1994; Peña et al. 2001; Koesterke 2001; Werner & Herwig 2006). In addition, a more complex and complete (including several speculations) evolutionary path is presented by Danehkar (2014). The stellar post-AGB evolution divides into two major channels of H-rich and H-poor stars (Löbling et al. 2019). However, other evolutionary pathways exist (see e.g. Fig. 14 of Frew et al. 2014). Nevertheless, it is necessary to clarify that these sequences are valid only for a single star. The CSPNe with spectral type sdO, B[e], O(He), [WN], hybrid and Of−WR(H) are not included in this classical evolutionary picture.

The origin of the sdO is yet not clear. This object probably comes from low mass progenitors (Reindl et al. 2014a), and could end up as a WD (Aller et al. 2013). Aller et al. (2015a) observed that the sample of PNe with a sdO nucleus are faint and can be found at relatively high Galactic latitudes, which would suggest they are in a moderate or evolved stage and evolving from low-mass progenitors. In the work of Heber (2009), several evolutionary paths are considered.

The evolutionary state of B[e] CSPNe is unknown too. The nebulae that contain these stars are compact and with high-density. These nebulae are often classified as protoplanetary nebulae (PPNe) or young PNe (Clegg et al. 1989). These objects have stellar hydrogen emissions and are therefore considered to belong to the H-rich group. The O(He) stars are even more complicated, (see e.g. Reindl et al. 2014b; Rauch et al. 1998) as they are speculated to have multiple possible evolutionary paths. One possible evolutionary path is Merger(CO WD + He WD)→ RCrB → EHe → O(He) → DO (Reindl et al. 2014b). It is necessary to identify more objects of this type in order to clarify this point.

The same happens with the [WN] type. There are only three well-known objects. Consequently, the evolutionary state is not clear. One possibility is that [WN] → O(He) (Todt et al. 2017).

The hybrid objects (or hybrid PG 1159-type) are strange objects (Löbling et al. 2019). This type include four objects,

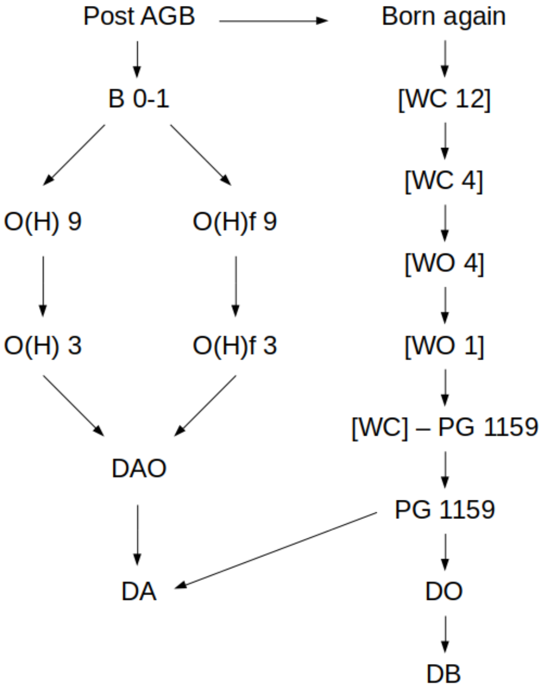

Fig. 1. Evolutionary sequence model, the classical picture.

being one of them not in the core of a PN. Dreizler et al. (1996) suggest two possibilities: [WC 12] → hybrid → PG 1159 or [WC 12] → hybrid → DAO.

Finally, the Of–WR(H) CSPNe belong to the H-rich group. There are not references regarding its evolutionary status. They may be binary objects.

4. The catalogue of CSPNe

This new version of the catalogue contains 620 galactic objects, representing an increase of 25% compared to the previous version. However, it is not only in the number of objects that the real impact of the new version lies. We also report many spectral type changes. For example, the core of He 2−47 that was previously classified as a [WC], has now been catalogued as an O(H)-type star based on newer, better quality spectra. Besides, new high-quality spectra made possible to improve and refine the previous classification, as is the case of Sa 1−8 (from OB type to O(H)4−8 III). In addition, some objects were rejected in the new version because we currently know that they are not PNe. This is the case, for example, of Sh 2−128 (Bohigas & Tapia 2003). Moreover, in this new version, we include physical parameters such as temperature, luminosity, and surface gravity, which were obtained from the available literature. On the other hand, we added the apparent magnitude (a key parameter for planning an observation), and a bibliography reference where the stellar spectrum is shown. This allows future researchers to re-evaluate the spectral classification or to obtain a better quality spectrum. In this sense, it is important to note that there are few spectra available in the literature, in particular of [WR]-type. Also, in general, the spectral classification of these objects has not been confronted with new observations. Crowther et al. (1998) and Acker & Neiner (2003) are perhaps the two most important works dealing with spectral classification of [WR]. Both works include important object samples however the published spectra do not allow to properly check the spectral classification. The catalogue is divided into two tables. The former with the spectral type and the second one with physical parameters. In the following sections, we describe each column of the two main tables.

4.1. Table D.1: spectral types

- c1: The PN G designation, taken from SECGPN.
- c2: The flag indicates that the object could not be a PN.
- c3: The common name of the object, taken from SECGPN and MASH.
- c4–5: The equatorial coordinates (J2000.0). Frequently, it is not clear which is the CSPN either because the star is not at the geometric center of the nebula, due to the interaction with the ISM or because of the object lies in crowded star fields. For example the PN Sh 2−71 (Močnik et al. 2015) or K 4−37 (Miranda et al. 2017). The problem worsens when the PN has a large angular size, which may lead to incorrect identification of the CSPN (e.g. Szyszka et al. 2009; Kwitter et al. 1988). A couple of articles that may be useful in identifying the position of a central star are Kerber et al. (2003) and Chornay & Walton (2020).
- c6-9: Spectral classification (SpT) of the CSPNe and reference (t.w. means this work). We use the most current SpTs, unless there is a large discrepancy. In that case, we include both classifications. All of them are described in Sect. 2. We maintain the notation given by different authors, in this context we keep the classification wels. Nevertheless, the spectrum can change in a short period of time. Bond (2014) showed that the CSPN of Lo 4 had a short-time mass loss episode, manifested by the appearance of new emission lines.
- c10: Reference of multiplicity, taken from the actual web of Dr. David Jones[1]. We do not included binaries detected by J or I-band excess.
- c11: Reference of the optical spectra.

4.2. Table D.2: physical parameters

- c1: PN G designation. The first nine objects do not have PN G, then we use the *recno* number of Table D.1.
- c2–3: Surface gravity (log g, cm s^{-2}) and reference. t.w. means this work. We computed log g according to Eq. 17 of Zhang & Kwok (1993) with data take from Gesicki & Zijlstra (2007).
- c4: The method by which the temperature was determined. We prefer the effective temperature ($T_{\rm eff}$). Nevertheless, in the catalogue we include other temperatures, Zanstra temperatures T_Z(He I) or T_Z(He II) (Phillips 2003) or the photoionization (equivalent black-body) temperature (Gesicki et al. 2006). Hoare et al. (1995) show the different results obtained for CSPN temperature using different methods.
- c5–6: Temperature and reference. In the case of the H-rich group, it is possible to estimate the temperature inspecting the spectra and looking for He I absorption lines. The absence of these lines indicates that the central star is hotter than 70 k (Kepler et al. 2016).
- c7–8: Bolometric luminosity (log($L_\star/L_\odot$)) and reference (e.g. Zhang & Kwok 1993).
- c9–10: The apparent magnitude and reference. We indicate the band in which the magnitude is reported. When available, the visual magnitude was preferred. For those objects catalogued as photometric variables, we report an average magnitude. For binary systems, it is probable that the reported magnitude corresponds to the bright source, which is not

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[1] `http://www.drdjones.net/bCSPN/`

Table 2. Summary of the spectral types of CSPNe compiled in our catalogue, grouped by their atmospheric hydrogen abundance.

H-rich				H-poor	
SpT	Sample	SpT	Sample	SpT	Sample
O3-B1	133	cont.	22	[WC 4–12]	68
Of	31	hybrid	3	[WO 1–4]	37
Of-WR(H)	3	SySt	11	[WN]	8
B2-M9	40	Blue	50	[WR]	10
DA, WD	14	EL	8	PG 1159	17
DAO	28	wels	77	[WC]-PG 1159	2
sdO	12			O(He)	5
hgO(H)	12			O(C)	1
B[e]	6			DO	4
H-rich	11			H-poor	1
Total	290	Total	171	Total	153

Notes. We include confirmed and probable spectral types. Here, we have discarded 6 objects without any specific spectral type. The O3-B1 group include objects classified as O(H), O and OB. [WR] group include the two objects classified as [WN/C] and [WO]-[WC 8].

necessary the ionizing source. Moreover, when the CSPN is binary, it is usual that it presents photometric variations.

The physical parameters that we report in the tables are the most up-to-date and post 1982. In addition, we include the uncertainty, only in cases where the original author published them. Nevertheless, there are objects that undergo a fast evolution of their physical parameters. For example He 3−1357 (Reindl et al. 2014a). In this sense, the physical parameters of the CSPN have importance from a statistical viewpoint.

4.3. Multiplicity vs. spectral type

CSPNe confirmed to be part of a binary system are described in Table D.1 (Col. 10). It is known that many stars are binary, but in a few cases, it is possible to have the spectrum of the two stars separately. The criterion for describing the spectral type in these cases is $SpT_1 + SpT_2$. Where the first star is the brightest, not necessarily the ionizing star of the nebula. In the case in which the spectral type of a star is not known, it is indicated as SpT_1+?.

The fact that recently the number of CSPNe that are binary systems have increased considerably means that we have to rethink which component would be considered the CSPN. An appropriate response would be: the star of the binary system responsible for the ionisation of the nebula. Nevertheless, it is possible that both stars of the binary system have as high-enough temperature to ionise the nebula. This is the case of He 2−428, where the first star has $T_{\rm eff} = 48 \pm 7$ kk and the second star has $T_{\rm eff} = 46 \pm 7$ kk (Reindl et al. 2018).

Two objects require clarification because there are no references reporting its binarity: (i) Cn 1−1: there is evidence indicating that this object is a D′-type symbiotic star (Gutierrez-Moreno et al. 1995). (ii) PHR J0905−4753: in the MASH catalogue the central star is identified with a spectral type A8. If this is correct, then it is indeed a binary system.

5. Results

5.1. Dichotomy between H rich and poor CSPNe

We separate the CSPNe of our sample according to their atmospheric hydrogen abundance into H-rich and H-poor (see Table 2). The ratio H-rich/H-poor in the present catalogue is 2:1, which is greater than the one found by Weidmann & Gamen (2011b). Nevertheless, it is still far from the value determined by Mendez et al. (1991). The large number of objects included in our present catalogue reinforce the idea that the H-poor population is larger than previously thought.

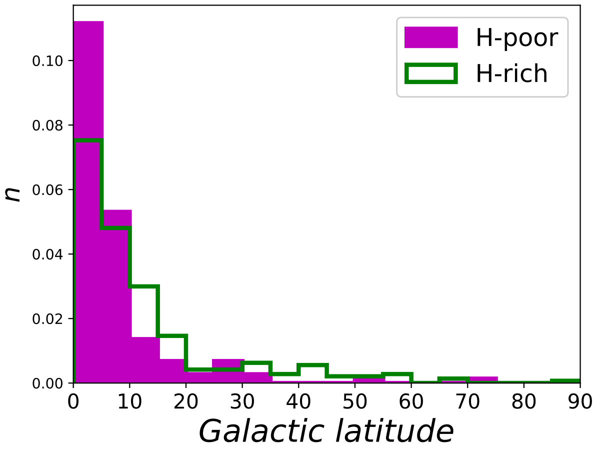

Fig. 2. Normalised distributions in Galactic latitude of CSPNe (of confirmed and possible PNe) that belong to H-rich and H-poor group. Each bin has a width of 5 deg.

Applying the Kolmogorov-Smirnov test to compare the Galactic latitude distributions of H-rich and H-poor populations, we find $D = 0.2$ and a p-value = 0.00049. This is in agreement with the results found by Weidmann & Gamen (2011b), which implies that the distribution in Galactic latitudes of H-rich and H-poor stars are different (Fig. 2). This is an indication that the progenitors masses and ages of both populations are different. The progenitors of H-deficient stars expected to be more massive and younger than those of their H-rich counterparts. It would be interesting to analyse whether this can be related to the observed dearth of H-deficient white dwarfs in old globular clusters (Moehler et al. 2004; Davis et al. 2009), as the reasons behind this feature are still not clear (Williams et al. 2018).

The physical parameters that we have collected from the literature allow us to characterize the CSPNe population (Table 3). Although it is generally accepted that hydrogen requires a minimum temperature of 10 000 K to ionise, the minimum temperature of a CSPN is 13 000 K. This value agrees with what was expected.

According to the values presented in Table 3 (Figs. 3–5), the H-poor population appears to have greater surface gravity than the H-rich one, except for the most evolved objects. With regard to the effective temperature, the H-poor group is clearly hotter. Luminosity shows a more complex situation. Still a trend can be appreciated in which more evolved H-poor objects display a higher luminosity.

Moreover, Fig. 6 shows the [WR] subtype distribution, where a dearth of objects with subtypes 5–7 is apparent. This feature is seen both in our restricted sample with definite spectral types (our “pure” sample), as well as in the complete sample that includes also uncertain spectral types. This result is consistent with previous results in the literature Todt (2009). Even more, given that our sample is significantly larger than that discussed by Todt (2009), we consider this result as a confirmation that the lack of subtypes 5–7 in [WR]-CSPNe is a real feature. In principle this gap could be explained in two different ways. On the one hand, it could be the consequence of faster evolutionary speeds at that particular stage and, on the other, it could be the

Table 3. Average physical parameter of our catalogue.

Population	$\overline{\log g}$	$\overline{T_{\rm eff}} \times 10^3$	$\overline{(L_\star/L_\odot)} \times 10^3$
[WC4−12]	4.17 (33)	50 (41)	6.3 (36)
[WO1−4]	5.37 (20)	110 (23)	4.2 (21)
PG 1159	6.68 (10)	117 (14)	0.7 (13)
O8–B0	3.51 (13)	38 (16)	10 (14)
O3–7	4.52 (26)	71 (29)	5.9 (29)
hgO(H), DA, DAO	6.93 (31)	99 (33)	0.1 (25)

Notes. We only included objects with accurate SpT, and exclude objects with confirmed binary nucleus. Between parentheses the number of objects is indicated.

consequence that specific photospheric conditions are necessary for [WR]-CSPNe to be classified as [WC 5–7]. Interestingly, a concomitant gap is not apparent in the sample of H-deficient CSPNe with derived effective temperatures, suggesting that the latter might be the right explanation. This hypothesis will need to be teste by future studies tailored to this subject.

Regarding Of-type CSPNe, within these objects early subtypes are predominant, with the coolest object being Hen 2−138, classified as O(H)7-9 f. Mendez et al. (1990) propose that O stars are less luminous than the Of stars. However, we do not find a significant difference between both groups. We find that O-type CSPNe have $\overline{(L_\star/L_\odot)} = 5.3 \times 10^3$ and $\overline{(L_\star/L_\odot)} = 5.7 \times 10^3$ for Of-type.

A peculiar situation can be observed by comparing the number of objects with different spectral types. The number of objects classified as [WC 4–12] is larger than [WO 1–4]. We interpret this as a difference in evolutionary speeds. That is, these objects spend more time in its earliest evolutionary stage than in the subsequent ones. Interestingly, this is in clear contradiction with what is expected from the late thermal pulse scenario. Stellar evolution models are predicted to slow their evolution as they reach their maximum effective temperature (i.e. the knee of the evolutionary tracks in the HR-diagram, see the supplementary material in Guerrero et al. 2018). Alternatively, this could be a consequence of the larger luminosity expected during the earlier stellar evolution, which leads to a larger volume in which these stars can be detected. Volume limited samples are required to solve this issue. On the other hand, the distributions of the O-type CSPNe over the subtypes is different (Fig. 7). This distribution is in general flat, but with a remarkable number of objects classified as O3. This may be due to a selection effect. Since for the O-type CSPNe the spectral classification is more qualitative that in case of the [WR], many objects have doubtful classifications. But, in the case of the O3 CSPNe, these are easily identifiable by the absorption of the N V. Nevertheless, this might be due to the saturation of a qualitative classification scheme, originally constructed for main sequence object, when applied to the much hotter CSPNe.

Finally, Figs. 8 and 9 display the distribution of spectral subtypes for both the H-poor and H-rich populations. According to the evolutionary sequence described in Fig. 1, stars are thought to evolve along evolutionary tracks, first increasing their effective temperature and then becoming dimmer and entering the white dwarf cooling sequence.

5.2. Binary CSPNe

While there are continuous efforts focused on the search for new binary in PNe (e.g. Douchin et al. 2015), the fraction of PNe with binary nuclei is still relatively small[2]. In our catalogue, there are 117 PNe with a confirmed binary system at its nuclei. We do not include the SySt stars. Eleven of them belong to the H-poor group ([WR], DO, H-poor, O(He), PG 1159, and [WN]), plus an

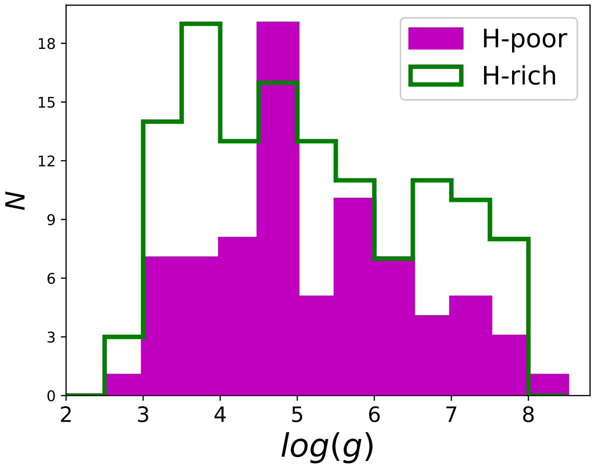

Fig. 3. Distribution in surface gravity of CSPNe.

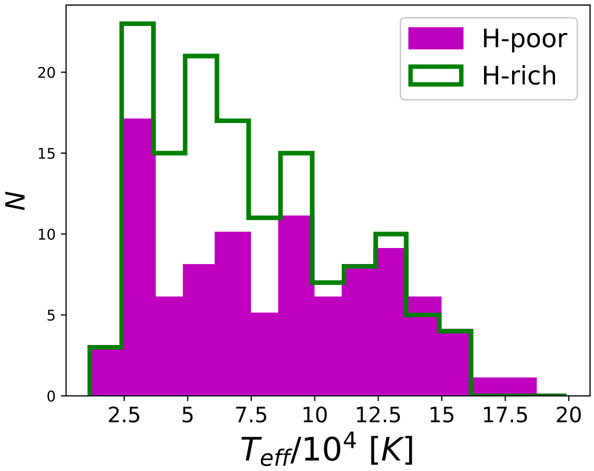

Fig. 4. Distribution in temperature of CSPNe.

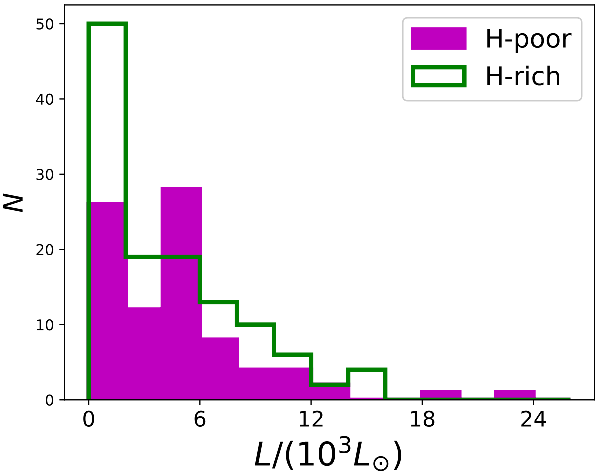

Fig. 5. Distribution in luminosity of CSPNe.

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[2] A regularly updated catalogue of binary CSPNe is mantained by David Jones can be found at `http://www.drdjones.net/bcspn/`.

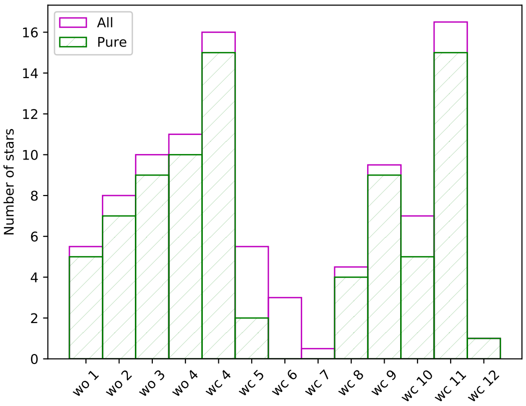

Fig. 6. Distributions of the [WR] type CSPN over the subtype. The sample "Pure" exclude objects with imprecise classification (e.g. [WC 5–6]). The sample "All" includes these objects with the criteria: an object with classification [WC 5–6], adds 0.5 to the frequency of [WC 5] and adds 0.5 to the frequency of [WC 6].

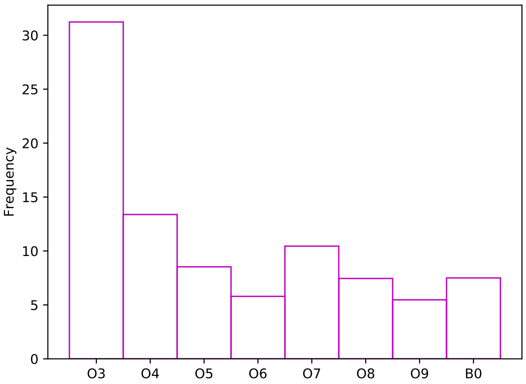

Fig. 7. Distributions of the O-type CSPN over the subtype. Criterion used for objects with dubious classifications (e.g. O5–9) is the same as that described in Fig. 6.

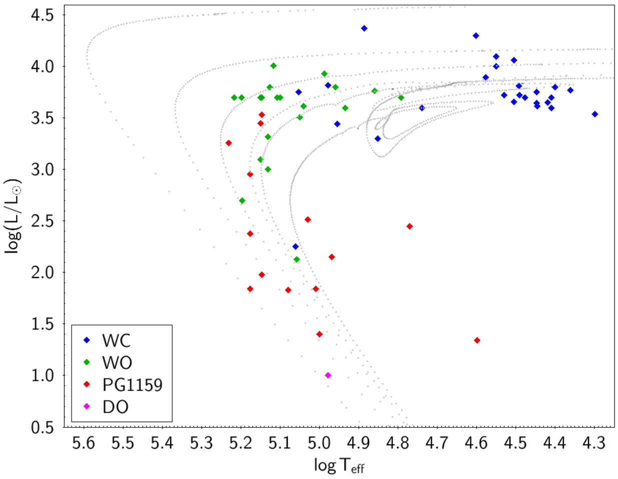

Fig. 8. HR diagram of H-poor CSPNe, according subtype. H-deficient tracks correspond to the post-VLTP sequences computed by Miller Bertolami & Althaus (2006), which display He, C, and O photospheric abundances similar to those of [WR]-CSPNe and PG 1159 stars ($M_{\rm CSPN}$ = 0.515, 0.542, 0.584, 0.664 and 0.870 $M_\odot$, from right to left).

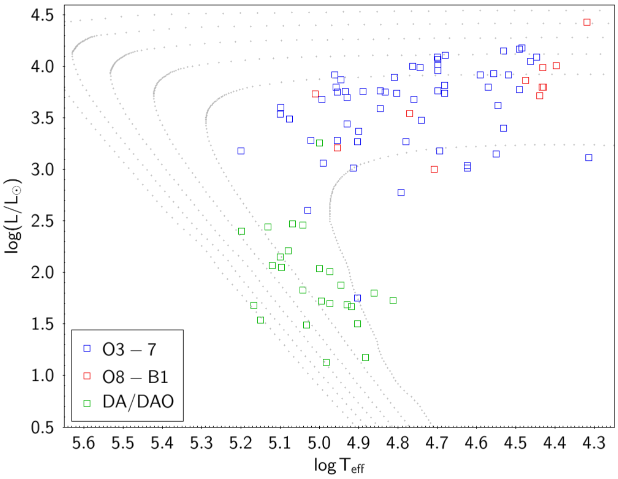

Fig. 9. HR diagram of H-rich CSPNe, according subtype. H-rich track are described in Sect. 5.3.

object classified as [WR]/wels (Vy 1–2). The O, O(H), O(H)f, sdO, H-rich, DAO, and hgO(H) stars totalize 62 objects, together with nine objects that do not have a specific spectral type. In addition, there are 34 objects with late spectral types.

For the vast majority of binary systems there are only spectroscopic data for the brightest star, so there are few systems in which we know the spectral type of the two stars of the system. No binary systems composed by stars with different H abundances in its atmosphere (i.e. H-rich + H-poor) are currently known. In this sense, and for statistical purposes, we adopt the criterion of using the H abundance of the brightest star.

With the above clarifications, we found that 10.3% of confirmed binaries belong to the H-poor group and 82.1% to the H-rich group. Consequently, there is a pronounced tendency, even more so considering that the H-rich ones are twice as many in the general population, for binary stars to occur more frequently in stars with hydrogen in their atmosphere.

The lack of H-deficient central stars in binary systems is a natural expectation from the proposed scenarios for their formation, namely the merger and the late thermal pulse. This is particularly true given that close binary systems are much easier to be detected than wide binaries. Mass transfer in a close binary system is expected to prevent the natural occurrence of the TP-AGB phase, making the late thermal pulse scenario unlikely. And, while a merger after a common envelope phase is a possible outcome, if this merger leads to a H-deficient star it will be a single H-deficient star unless the original system was triple and set in a specific configuration.

5.3. Comparison with stellar evolution models. Stellar masses and ages

From the comparison of the surface $\log L_\star$, $\log g$, and $\log T_{\rm eff}$ values of our catalogue stars with those predicted by stellar evolution models (Miller Bertolami 2016) it is possible to derive ages and masses for the CSPNe. Due to the absence of a grid of appropriate stellar evolution models for H-deficient stars, this can only be done for those with normal H/He surface compositions (i.e. those with solar-like H/He compositions). A comparison of 213 of our H-rich catalogue stars with the $Z = 0.01$ models of Miller Bertolami (2016) is shown in Fig. 10 both for the $\log L_\star - \log T_{\rm eff}$ (i.e. HR diagram) diagram and the $\log g - \log T_{\rm eff}$ (i.e. Kiel diagram). From the total of 213 objects only 175 have values of all three surface parameters and can be plotted in both diagrams.

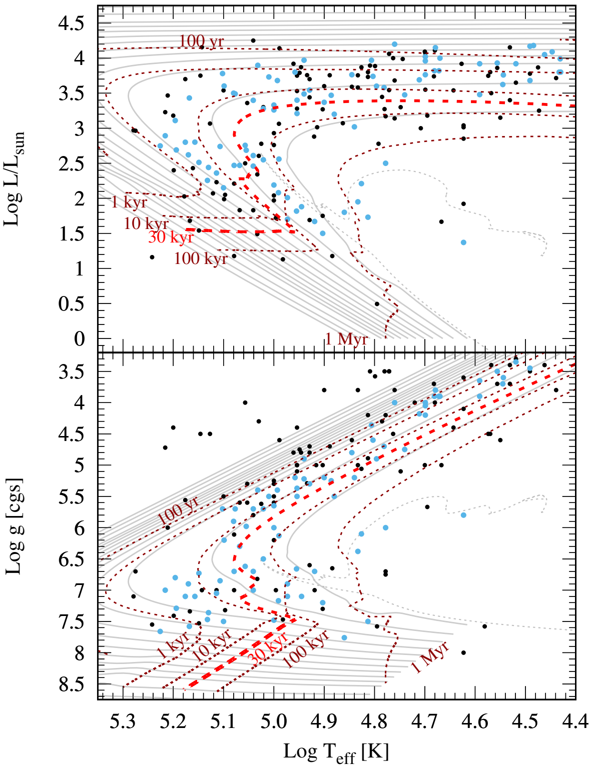

Fig. 10. Location of the selected sample of H-rich stars (213 objects in total) in both the HR (*upper panel*) and Kiel (*lower panel*) diagrams. Light blue points symbols show the location of the subsample for which interpolation in both diagrams indicate a consistent age and mass (88 objects, see text). Grey continuous lines show the location of interpolated tracks for different masses (0.5, 0.55, 0.6, 0.65, 0.7, 0.75, 0.8, 0.85, 0.9, 0.95, 1, 1.1, 1.2, 1.3 $M_{\odot}$, and $Z_0 = 0.01$, from right to left). Brown and red lines show isochroned in the post-AGB evolution. The doted grey line indicates a typical post-EHB evolution.

In this sample we exclude doubtful PNe, SySt, hybrid and objects classified as "O?". Also there were excluded those objects where two contradictory spectral classifications are reported, i.e. H-rich and H-poor (e.g. IC 4776).

By interpolating the location of our sample stars in both the HR and Kiel diagrams we can estimate their masses (Fig. 11) and ages (Fig. 12). A couple of things are particularly noteworthy in the full H-rich sample shown in Fig. 10. On the one hand the masses of CSPNe inferred from the Kiel and HR diagram interpolations agree quite well with our current expectations from single post-AGB stellar evolution (see histograms in Fig. 11), with peaks around (~0.55 $M_{\odot}$). Both diagrams show, however, slightly different pictures, while interpolation in the HR diagram shows a double peak, the Kiel diagram shows a wider peak between 0.525 $M_{\odot}$ and 0.600 $M_{\odot}$. On the other hand, some features are clearly at variance with expectation from stellar evolution models. One is the group of objects at low surface gravities, well beyond the most massive model (Fig. 10, lower panel). Such object would have masses well beyond the Chandrasekhar mass if they were post-AGB stars and should not be there. In addition, there is a rather large number of stars with inferred masses below 0.5 $M_{\odot}$, something that is not expected from the point of view of single stellar evolution. Finally, interpolated/extrapolated ages and masses in the full H-rich sample show a relatively large number of objects beyond the 30 Kyr isochrone, that is well beyond the expected lifetime for true PNe, as well as a large number of young objects with interpolated ages below 100 yr (Fig. 12).

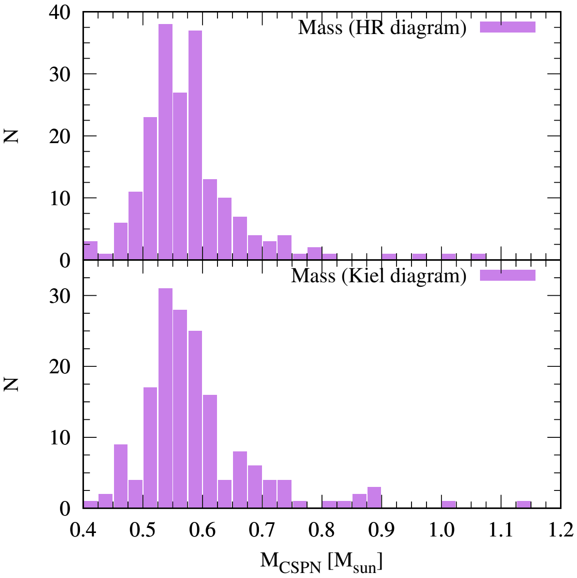

Fig. 11. Masses derived from interpolation of the full H-rich sample (213 objects, see Fig. 10) with the $Z = 0.01$ model grid of Miller Bertolami (2016). *Upper panel*: masses derived from interpolation in the HR diagram. *Lower panel*: masses derived from interpolation in the Kiel diagram ($\log g - \log T_{\rm eff}$).

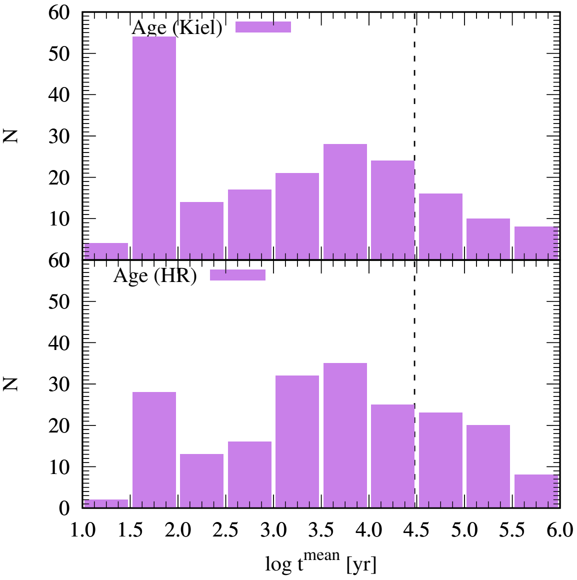

Fig. 12. Ages derived from interpolation of the full H-rich sample (213 objects, see Fig. 10) with the $Z = 0.01$ model grid of Miller Bertolami (2016). *Upper panel*: masses derived from interpolation in the HR diagram. *Lower panel*: masses derived from interpolation in the Kiel diagram ($\log g - \log T_{\rm eff}$). The vertical dashed line indicates the canonical value of 30 Kyr value beyond which PNe are not expected to survive.

To analyse which of the previous features are real and which ones are artifacts due to poor determinations of the stellar parameters of individual stars, we restricted to those stars that have independent determinations of all three surface parameters ($\log L_{\star}$, $\log T_{\rm eff}$ and $\log g$). From these we selected the subsample for which both the HR and Kiel diagram interpolations give consistent values of age and mass[3]. This smaller sample is shown

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[3] Which we arbitrarily set to be in agreement within an order of magnitude for age and a difference of less than a 10% for mass.

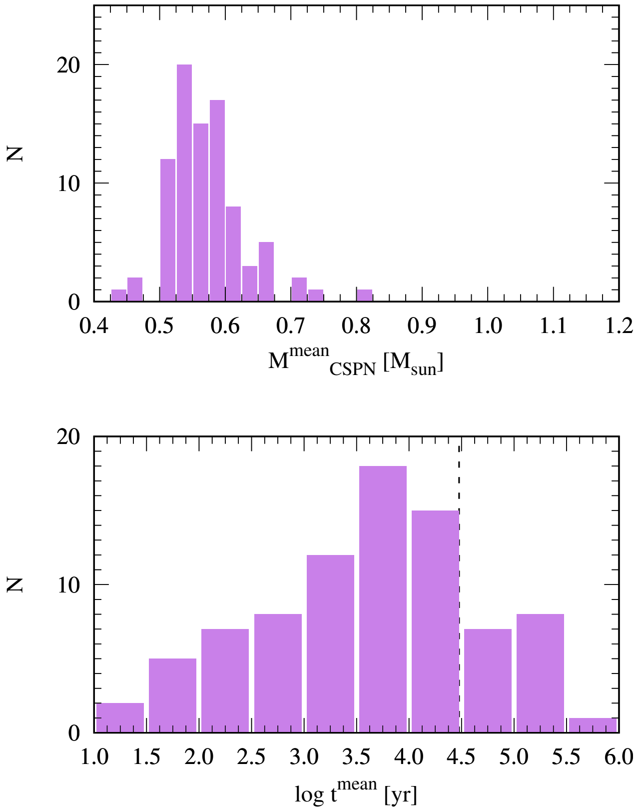

Fig. 13. Mean values of the ages and masses for the reduced sample of 88 objects (blue dots in Fig. 10) for which interpolation in the Kiel and HR diagrams yield consistent results. Age (mass) of each object is calculated as the geometric (arithmetic) mean of the values yield by the interpolation in each diagram. The vertical dashed line indicates the canonical value of 30 Kyr value beyond which PNe are not expected to survive.

as light blue dots in Fig. 10. Consists of 88 objects out of the 175 objects (i.e. 50%) that have values of $\log L_\star$, $\log T_{\rm eff}$ and $\log g$. The consistency of the values of $\log L_\star$, $\log T_{\rm eff}$ and $\log g$ gives us confidence that no large errors are present in the derived masses and ages. Figure 13 shows the masses and ages of this reduced sample. Remarkably, many of the weird features seen in the full sample (Figs. 11 and 12) disappear when we restrict ourselves to our internally consistent sample. Specifically, no low gravity objects remain, and the number of young CSPNe is strongly reduced. Also, the mass values of the smaller, and consistent, sample show a sharp cut-off at $\sim$0.5 $M_\odot$ much consistent with the expectations from stellar evolution theory. Similarly, the post-AGB age distribution of CSPNe in this smaller sample shows a steady rise until the typical timescales of PNe (10 to 30 Kyr) and a clear drop afterwards.

Interestingly, we see that in this reduced sample a small group of objects with inferred low masses persist ($M_\star < 0.5\,M_\odot$). As such low masses, the objects cannot be post-AGB stars, and these extrapolated masses cannot be taken at face value but just as an indication of a different evolutionary origin. These low-mass objects correspond to the high-gravity or low-luminosity blue points in Fig. 10. These objects are in fact located where post extreme horizontal branch (EHB) stars (a.k.a. “AGB-manqué” stars) should be (e.g. Moehler et al. 2019). This alternative evolutionary path is displayed by the dotted grey line in Fig. 10. If these objects are indeed post-EHB stars then their masses should be close to 0.5 $M_\odot$, and due to the long timescale of this evolutionary stage the “PN” around them is probably ionized interstellar gas that was not ejected by the star.

We conclude that, when we restrict our sample to those stars for which $\log L_\star$, $\log T_{\rm eff}$ and $\log g$ yield a consistent picture, the derived masses and ages are in good agreement with the expectations of single star post-AGB evolution theory. We conclude that a 50% of our sample with values of $\log L_\star$, $\log T_{\rm eff}$ and $\log g$ (88 out of 175 objects) show masses and ages consistent with single stellar evolution models. Although some of this objects seem to have derived ages too large to host a PN, we believe that in view of the ongoing debate of whether single stars can form PNe (Jones & Boffin 2017; Boffin & Jones 2019), this is a remarkable result. This should not be taken as a claim that multiple systems do not form PNe or that companions do not play any role in the shaping of the PNe. Rather, it should be taken as a hint that stars in isolation or in wide binaries are able to form PNe as well. As mentioned before, common envelope events are the reason for the formation of PNe with close binary central stars (Ivanova & Nandez 2018; Boffin & Jones 2019). There have been suggestions that substellar companions (Sabach & Soker 2018) or triple systems (Soker 2016) might be involved in the formation or shaping of non-spherical PNe.

6. Summary and conclusions

In this paper we present a new CSPNe catalogue comprising 620 stars that could be spectrally classified in a reliable way. This catalogue represents an expansion of the first version (Weidmann & Gamen 2011b) with the inclusion of 128 new objects. In addition to updating all available information, this version includes new physical parameters for the CSPNe, as well as the visual magnitude and the corresponding bibliographic reference of the spectra used for spectral classification. The information collected and processed in this catalogue represents an essential contribution both in theoretical studies and in the planning of future observations. Based on this evaluation, we understand that it constitutes a fundamental tool both for the field of planetary nebula research in particular and for stellar evolution studies in general.

In relation to the completeness of the information included in this catalogue, of the total number of objects: 56.3% have log g, 69.8% have log T, 60.5% have log $L_\star$, and 74.4% have magnitude. It is important to note that the objects reported in this catalogue represent less than 20% of the total PNe known to date. Furthermore, almost 30% of these objects do not have any specific physical parameter determined. The origin of this lack of information is probably related to the low brightness of these objects, if we consider that 50% of the sample has a visual magnitude lower than 17. This reveals an important information gap in this area of research, a gap that can only be overcome with new large-scale studies using 8–10 m class telescopes.

The main conclusions can be summarised as follows:

- When we separate the CSPNe between H-rich and H-poor we find that the ratio H-rich/H-poor is 2:1. This value is greater than the one found by Weidmann & Gamen (2011b) but lower than the value determined by Mendez et al. (1991).
- According to the distribution in galactic latitude we find evidence that the CSPNe H-rich and H-poor come from different populations, suggesting that H-deficient stars are preferentially formed in younger populations by higher mass progenitors.
- Our larger sample confirms the existence of a deficiency of [WR]-CSPNe with [WC 5-7] spectral types found by previous authors Todt (2009).

- Upper 80% of binary CSPNe belong to the H-rich group. We find a significant dearth of H-deficient stars in binary systems. This result suggests that evolutionary scenarios leading to the formation of binary central stars interfere with the conditions required for the formation of H-deficient CSPNe. This is in agreement with the expectations from both merger and late thermal pulse scenarios.
- We find that 50% of our sample with derived values of $\log L$, $\log T_{\rm eff}$, and $\log g$ (88 out of 175 objects) shows masses and ages consistent with single stellar evolution models. This suggests that some single stars are indeed able to form PNe.

The task of building large catalogues is hard and time-consuming, but it is the only way to organize the knowledge achieved by the astronomical community and to promote new studies that will make progress in any area of research. We hope that the work presented here will constitute a mobilizer of ideas and a driving force for new projects that will result in an increase in our understanding of the final stages of ordinary mass stars.

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References

Acker, A., & Neiner, C. 2003, A&A, 403, 659
Acker, A., Marcout, J., Ochsenbein, F., et al. 1992, The Strasbourg-ESO Catalogue of Galactic Planetary Nebulae. Parts I, II (Garching: European Southern Observatory)
Adam, C., & Mugrauer, M. 2014, MNRAS, 444, 3459
Ahumada, J. A., Weidmann, W. A., Miller Bertolami, M. M., & Saker, L. 2019, ApJ, 882, 171
Akras, S., Boumis, P., Meaburn, J., et al. 2015, MNRAS, 452, 2911
Akras, S., Clyne, N., Boumis, P., et al. 2016, MNRAS, 457, 3409
Akras, S., Guzman-Ramirez, L., Leal-Ferreira, M. L., & Ramos-Larios, G. 2019a, ApJS, 240, 21
Akras, S., Leal-Ferreira, M. L., Guzman-Ramirez, L., & Ramos-Larios, G. 2019b, MNRAS, 483, 5077
Akras, S., Monteiro, H., Aleman, I., et al. 2020, MNRAS, 493, 2238
Aleman, I., Leal-Ferreira, M. L., Cami, J., et al. 2019, MNRAS, 490, 2475
Ali, A., & Dopita, M. A. 2017, PASA, 34, e036
Ali, A., & Dopita, M. A. 2019, MNRAS, 484, 3251
Ali, A., Dopita, M. A., Basurah, H. M., et al. 2016, MNRAS, 462, 1393
Allen, D. A. 1984, PASA, 5, 369
Aller, L. H. 1975, Mem. Soc. Roy. Sci. Liège, 9, 271
Aller, L. H., & Keyes, C. D. 1985, PASP, 97, 1142
Aller, L. H., & Keyes, C. D. 1987, ApJS, 65, 405
Aller, L. H., Keyes, C. D., & Feibelman, W. 1988, PASP, 100, 192
Aller, A., Miranda, L. F., Ulla, A., et al. 2013, A&A, 552, A25
Aller, A., Miranda, L. F., Olguín, L., et al. 2015a, MNRAS, 446, 317
Aller, A., Montesinos, B., Miranda, L. F., Solano, E., & Ulla, A. 2015b, MNRAS, 448, 2822
Aller, A., Lillo-Box, J., Jones, D., Miranda, L. F., & Barceló Forteza, S. 2020, A&A, 635, A128
Amnuel, P. R., Guseinov, O. K., Novruzova, K. I., & Rustamov, I. S. 1985, Ap&SS, 113, 59
Angeloni, R., Contini, M., Ciroi, S., & Rafanelli, P. 2007, A&A, 472, 497
Arkhipova, V. P., Esipov, V. F., & Iudin, B. F. 1985, Astrophys. Lett., 24, 205
Arkhipova, V. P., Noskova, R. I., Esipov, V. F., & Sokol, G. V. 1999, Astron. Lett., 25, 615
Arkhipova, V. P., Esipov, V. F., Noskova, R. I., Ikonnikova, N. P., & Komissarova, G. V. 2008, Astron. Lett., 34, 839
Arkhipova, V. P., Ikonnikova, N. P., Kniazev, A. Y., & Rajoelimanana, A. 2013, Astron. Lett., 39, 201
Arrieta, A., & Torres-Peimbert, S. 2002, Rev. Mex. Astron. Astrofis., 12, 154
Arrieta, A., & Torres-Peimbert, S. 2003, ApJS, 147, 97
Balick, B. 1989, AJ, 97, 476
Barría, D., Kimeswenger, S., Kausch, W., & Goldman, D. S. 2018, A&A, 620, A84
Barstow, M. A., Holberg, J. B., Marsh, M. C., et al. 1994, MNRAS, 271, 175
Basurah, H. M., Ali, A., Dopita, M. A., et al. 2016, MNRAS, 458, 2694
Bateson, F. M., & Dodson, A. W. 1982, R. Astron. Soc. New Zealand Publ. Variable Star Sect., 10, 1
Belczyński, K., Mikołajewska, J., Munari, U., Ivison, R. J., & Friedjung, M. 2000, A&AS, 146, 407
Benetti, S., Cappellaro, E., Ragazzoni, R., Sabbadin, F., & Turatto, M. 2003, A&A, 400, 161
Bhatt, H. C., & Mallik, D. C. V. 1986, A&A, 168, 248
Bilíková, J., Chu, Y.-H., Gruendl, R. A., Su, K. Y. L., & De Marco, O. 2012, ApJS, 200, 3
Boffin, H. M. J., Jones, D., Wesson, R., et al. 2018, A&A, 619, A84
Boffin, H. M. J., & Jones, D. 2019, The Importance of Binaries in the Formation and Evolution of Planetary Nebulae
Boffin, H. M. J., Miszalski, B., & Jones, D. 2012a, A&A, 545, A146
Boffin, H. M. J., Miszalski, B., Rauch, T., et al. 2012b, Science, 338, 773
Bohigas, J. 2008, ApJ, 674, 954
Bohigas, J., & Tapia, M. 2003, AJ, 126, 1861
Bond, H. E. 2014, AJ, 148, 44
Bond, H. E., & Ciardullo, R. 1999, PASP, 111, 217
Bond, H. E., & Pollacco, D. L. 2002, Ap&SS, 279, 31
Bond, H. E., O'Brien, M. S., Sion, E. M., et al. 2002, ASP Conf. Ser., 279, 239
Bond, H. E., Pollacco, D. L., & Webbink, R. F. 2003, AJ, 125, 260
Bond, H. E., Ciardullo, R., Esplin, T. L., et al. 2016, ApJ, 826, 139
Brown, A. J., Jones, D., Boffin, H. M. J., & Van Winckel, H. 2019, MNRAS, 482, 4951
Cahn, J. H. 1984, ApJ, 279, 304
Cazetta, J. O., & Maciel, W. J. 2000, Rev. Mex. Astron. Astrophys., 36, 3
Cerruti-Sola, M., & Perinotto, M. 1985, ApJ, 291, 237
Chabrier, G., & Baraffe, I. 2000, ARA&A, 38, 337
Chen, X., Han, Z., & Tout, C. A. 2011, ApJ, 735, L31
Chiotellis, A., Boumis, P., Nanouris, N., Meaburn, J., & Dimitriadis, G. 2016, MNRAS, 457, 9
Chornay, N., & Walton, N. A. 2020, A&A, 638, A103
Chromey, F. R. 1980, AJ, 85, 853
Chu, Y.-H., Gruendl, R. A., Guerrero, M. A., et al. 2009, AJ, 138, 691
Ciardullo, R., Bond, H. E., Sipior, M. S., et al. 1999, AJ, 118, 488
Cidale, L., Zorec, J., & Tringaniello, L. 2001, A&A, 368, 160
Clayton, G. C., Kerber, F., Pirzkal, N., et al. 2006, ApJ, 646, L69
Clayton, G. C., De Marco, O., Nordhaus, J., et al. 2014, AJ, 147, 142
Clegg, R. E. S., Hoare, M. G., & Walsh, J. R. 1989, IAU Symp., 131, 443
Cohen, M., & Jones, B. F. 1987, ApJ, 321, L151
Corradi, R. L. M. 1995, MNRAS, 276, 521
Corradi, R. L. M., Mikolajewska, J., & Mahoney, T. J. 2003, ASP Conf. Ser., 303
Corradi, R. L. M., Rodríguez-Flores, E. R., Mampaso, A., et al. 2008, A&A, 480, 409
Corradi, R. L. M., Sabin, L., Miszalski, B., et al. 2011, MNRAS, 410, 1349
Corradi, R. L. M., Rodríguez-Gil, P., Jones, D., et al. 2014, MNRAS, 441, 2799
Costa, R. D. D., de Freitas Pacheco, J. A., & Maciel, W. J. 1993, A&A, 276, 184
Crowther, P. A., De Marco, O., & Barlow, M. J. 1998, MNRAS, 296, 367
Cudworth, K. M. 1973, PASP, 85, 401
Cuisinier, F., Acker, A., & Koeppen, J. 1996, A&A, 307, 215
Danehkar, A. 2014, Ph.D. Thesis, Macquarie University, Australia
Danehkar, A., Parker, Q. A., & Ercolano, B. 2013, MNRAS, 434, 1513
Davis, D. S., Richer, H. B., Rich, R. M., Reitzel, D. R., & Kalirai, J. S. 2009, ApJ, 705, 398
de Araújo, F. X., Marcolino, W. L. F., Pereira, C. B., & Cuisinier, F. 2002, AJ, 124, 464
De Marco, O. 2006, IAU Symp., 234, 111
De Marco, O. 2009, PASP, 121, 316
De Marco, O., Crowther, P. A., Barlow, M. J., Clayton, G. C., & de Koter, A. 2001, MNRAS, 328, 527
De Marco, O., Bond, H. E., Harmer, D., & Fleming, A. J. 2004, ApJ, 602, L93
De Marco, O., Passy, J.-C., Frew, D. J., Moe, M., & Jacoby, G. H. 2013, MNRAS, 428, 2118
De Marco, O., Long, J., Jacoby, G. H., et al. 2015, MNRAS, 448, 3587
DePew, K., Parker, Q. A., Miszalski, B., et al. 2011, MNRAS, 414, 2812
Di Stefano, R. 2010, ApJ, 719, 474
Douchin, D., De Marco, O., Frew, D. J., et al. 2015, MNRAS, 448, 3132
Downes, R. A., Liebert, J., & Margon, B. 1985, ApJ, 290, 321
Dreizler, S. 1999, Rev. Mod. Astron., 12, 255
Dreizler, S., & Heber, U. 1998, A&A, 334, 618
Dreizler, S., & Werner, K. 1996, A&A, 314, 217
Dreizler, S., Werner, K., Heber, U., & Engels, D. 1996, A&A, 309, 820
Drilling, J. S. 1983, ApJ, 270, L13

Drilling, J. S. 1985, ApJ, 294, L107
Duerbeck, H. W., & Benetti, S. 1996, ApJ, 468, L111
Exter, K. M., Pollacco, D. L., & Bell, S. A. 2003, MNRAS, 341, 1349
Exter, K. M., Pollacco, D. L., Maxted, P. F. L., Napiwotzki, R., & Bell, S. A. 2005, MNRAS, 359, 315
Feibelman, W. A. 1994, PASP, 106, 56
Feibelman, W. A. 1996, PASP, 108, 664
Feibelman, W. A., & Kaler, J. B. 1983, ApJ, 269, 592
Feibelman, W. A., & Kondo, Y. 2001, ApJS, 136, 735
Feibelman, W. A., Hyung, S., & Aller, L. H. 1994, ApJ, 426, 653
Ferguson, D. H., Liebert, J., Green, R. F., McGraw, J. T., & Spinrad, H. 1981, ApJ, 251, 205
Ferguson, D. H., Liebert, J., Cutri, R., et al. 1987, ApJ, 316, 399
Ferguson, D. H., Liebert, J., Haas, S., Napiwotzki, R., & James, T. A. 1999, ApJ, 518, 866
Fragkou, V., Parker, Q. A., Zijlstra, A., Shaw, R., & Lykou, F. 2019a, MNRAS, 484, 3078
Fragkou, V., Parker, Q. A., Zijlstra, A. A., Crause, L., & Barker, H. 2019b, Nat. Astron., 357
Frew, D. J. 2008, PhD Thesis, Department of Physics, Macquarie University, NSW 2109, Australia
Frew, D. J., & Parker, Q. A. 2010, PASA, 27, 129
Frew, D. J., Parker, Q. A., & Russeil, D. 2006, MNRAS, 372, 1081
Frew, D. J., Madsen, G. J., O'Toole, S. J., & Parker, Q. A. 2010, PASA, 27, 203
Frew, D. J., Bojičić, I. S., Parker, Q. A., et al. 2014, MNRAS, 440, 1345
Frew, D. J., Parker, Q. A., & Bojičić, I. S. 2016, MNRAS, 455, 1459
García-Berro, E., Soker, N., Althaus, L. R. G., Ribas, I., & Morales, J. C. 2016, New A, 45, 7
García-Díaz, M. T., González-Buitrago, D., López, J. A., et al. 2014, AJ, 148, 57
García-Hernández, D. A., & Górny, S. K. 2014, A&A, 567, A12
Gathier, R., & Pottasch, S. R. 1988, A&A, 197, 266
Gauba, G., & Parthasarathy, M. 2003, A&A, 407, 1007
Gauba, G., Parthasarathy, M., Nakada, Y., & Fujii, T. 2001, A&A, 373, 572
Gesicki, K., & Zijlstra, A. A. 2007, A&A, 467, L29
Gesicki, K., Zijlstra, A. A., Acker, A., et al. 2006, A&A, 451, 925
Gesicki, K., Hajduk, M., & Zijlstra, A. A. 2008, ASP Conf. Ser., 391, 107
Gesicki, K., Zijlstra, A. A., Hajduk, M., & Szyszka, C. 2014, A&A, 566, A48
Giammanco, C., Sale, S. E., Corradi, R. L. M., et al. 2011, A&A, 525, A58
Gianninas, A., Bergeron, P., Dupuis, J., & Ruiz, M. T. 2010, ApJ, 720, 581
Gillett, F. C., Jacoby, G. H., Joyce, R. R., et al. 1989, ApJ, 338, 862
Gómez-Muñoz, M. A., Manchado, A., Bianchi, L., Manteiga, M., & Vázquez, R. 2019, ApJ, 885, 84
González-Santamaría, I., Manteiga, M., Manchado, A., Ulla, A., & Dafonte, C. 2019, A&A, 630, A150
Górny, S. K. 2014, A&A, 570, A26
Górny, S. K., & Tylenda, R. 2000, A&A, 362, 1008
Górny, S. K., & Siódmiak, N. 2003, IAU Symp., 209, 43
Górny, S. K., Stasińska, G., & Tylenda, R. 1997, A&A, 318, 256
Górny, S. K., Stasińska, G., Escudero, A. V., & Costa, R. D. D. 2004, A&A, 427, 231
Górny, S. K., Chiappini, C., Stasińska, G., & Cuisinier, F. 2009, A&A, 500, 1089
Grauer, A. D., & Bond, H. E. 1983, ApJ, 271, 259
Green, R. F., Liebert, J., & Wesemael, F. 1984, ApJ, 280, 177
Guerrero, M. A., & De Marco, O. 2013, A&A, 553, A126
Guerrero, M. A., Miranda, L. F., Ramos-Larios, G., & Vázquez, R. 2013, A&A, 551, A53
Guerrero, M. A., Fang, X., Miller Bertolami, M. M., et al. 2018, Nat. Astron., 2, 784
Gutierrez-Moreno, A. 1988, ASP Conf. Ser., 1, 12
Gutierrez-Moreno, A., Moreno, H., & Cortes, G. 1995, PASP, 107, 462
Guzmán, L., Gómez, Y., & Rodríguez, L. F. 2006, Rev. Mex. Astron. Astrophys., 42, 127
Hachisu, I., Kato, M., & Nomoto, K. 1999, ApJ, 522, 487
Hajduk, M., Zijlstra, A. A., & Gesicki, K. 2010, MNRAS, 406, 626
Hajduk, M., van Hoof, P. A. M., & Zijlstra, A. A. 2015, A&A, 573, A65
Hamann, W. R. 1996, ASP Conf. Ser., 96, 127
Handler, G. 1999, A&AS, 135, 493
Handler, G. 2003, IAU Symp., 209, 237
Harrington, J. P., & Paltoglou, G. 1993, ApJ, 411, L103
Harris, H. C., Dahn, C. C., Canzian, B., et al. 2007, AJ, 133, 631
Heap, S. R. 1977, ApJ, 215, 609
Heap, S. R., & Augensen, H. J. 1987, ApJ, 313, 268
Heber, U. 2009, ARA&A, 47, 211
Heber, U., Werner, K., & Drilling, J. S. 1988, A&A, 194, 223
Henden, A., & Munari, U. 2008, Baltic Astron., 17, 293
Henry, R. B. C., Kwitter, K. B., Dufour, R. J., & Skinner, J. N. 2008, ApJ, 680, 1162
Henry, R. B. C., Balick, B., Dufour, R. J., et al. 2015, ApJ, 813, 121
Henry, R. B. C., Stephenson, B. G., Miller Bertolami, M. M., Kwitter, K. B., & Balick, B. 2018, MNRAS, 473, 241
Herald, J. E., & Bianchi, L. 2004, PASP, 116, 391
Herald, J. E., & Bianchi, L. 2011, MNRAS, 417, 2440
Herbig, G. H. 1999, PASP, 111, 1144
Herrero, A., Méndez, R. H., & Manchado, A. 1990, Ap&SS, 169, 183
Hewett, P., & Irwin, M. 2004, The Newsletter of the Isaac Newton Group of Telescopes, 8, 6
Hillwig, T. C., Bond, H. E., & Afsar, M. 2006, IAU Symp., 234, 421
Hillwig, T. C., Bond, H. E., Afsar, M., & De Marco, O. 2010, AJ, 140, 319
Hillwig, T. C., Margheim, S. J., De Marco, O., & Frew, D. 2013, Am. Astron. Soc. Meeting Abstr., 221, 249.09
Hillwig, T. C., Frew, D. J., Louie, M., et al. 2015, AJ, 150, 30
Hillwig, T. C., Bond, H. E., Frew, D. J., Schaub, S. C., & Bodman, E. H. L. 2016a, AJ, 152, 34
Hillwig, T. C., Jones, D., De Marco, O., et al. 2016b, ApJ, 832, 125
Hillwig, T. C., Frew, D., Jones, D., & Crispo, D. 2017a, Am. Astron. Soc. Meeting Abstr., 229, 148.10
Hillwig, T. C., Frew, D. J., Reindl, N., et al. 2017b, AJ, 153, 24
Hoard, D. W., Debes, J. H., Wachter, S., Leisawitz, D. T., & Cohen, M. 2013, ApJ, 770, 21
Hoare, M. G., Barstow, M. A., Werner, K., & Fleming, T. A. 1995, MNRAS, 273, 812
Høg, E., Fabricius, C., Makarov, V. V., et al. 2000, A&A, 355, L27
Hsia, C. H., Ip, W. H., & Li, J. Z. 2006, AJ, 131, 3040
Hsia, C.-H., Kwok, S., Zhang, Y., Koning, N., & Volk, K. 2010, ApJ, 725, 173
Hsia, C.-H., Zhang, Y., Kwok, S., & Chau, W. 2019, Ap&SS, 364, 32
Hu, J. Y., Slijkhuis, S., Nguyen-Q-Rieu, & de Jong, T. 1993, A&A, 273, 185
Hubeny, I., Heap, S. R., & Lanz, T. 1994, Am. Astron. Soc. Meeting Abstr., 185, 47.10
Huckvale, L., Prouse, B., Jones, D., et al. 2013, MNRAS, 434, 1505
Hügelmeyer, S. D., Dreizler, S., Werner, K., et al. 2005, A&A, 442, 309
Hultzsch, P. J. N., Puls, J., Méndez, R. H., et al. 2007, A&A, 467, 1253
Hyung, S., & Aller, L. H. 1997, ApJ, 491, 242
Hyung, S., Aller, L. H., & Feibelman, W. A. 1994, ApJS, 93, 465
Hyung, S., Aller, L. H., & Feibelman, W. A. 1999a, ApJ, 525, 294
Hyung, S., Aller, L. H., & Feibelman, W. A. 1999b, ApJ, 514, 878
Hyung, S., Aller, L. H., Feibelman, W. A., & Lee, W.-B. 2001a, AJ, 122, 954
Hyung, S., Aller, L. H., & Lee, W.-B. 2001b, PASP, 113, 1559
Iben, I., Jr 1991, ApJS, 76, 55
Iłkiewicz, K., & Mikołajewska, J. 2017, A&A, 606, A110
Ivanova, N., & Nandez, J. 2018, Galaxies, 6, 75
Jacoby, G. H., De Marco, O., Davies, J., et al. 2017, ApJ, 836, 93
Jasniewicz, G., Thevenin, F., Monier, R., & Skiff, B. A. 1996, A&A, 307, 200
Jeffery, C. S., & Hambsch, F. J. 2019, MNRAS, 487, 4128
Jeffery, C. S., & Schönberner, D. 2006, A&A, 459, 885
Jeffery, C. S., Drilling, J. S., Harrison, P. M., Heber, U., & Moehler, S. 1997, A&AS, 125, 501
Jones, D., & Boffin, H. M. J. 2017, Nat. Astron., 1, 0117
Jones, D., Boffin, H. M. J., Miszalski, B., et al. 2014, A&A, 562, A89
Jones, D., Boffin, H. M. J., Rodríguez-Gil, P., et al. 2015, A&A, 580, A19
Jones, D., Van Winckel, H., Aller, A., Exter, K., & De Marco, O. 2017, A&A, 600, L9
Jones, D., Boffin, H. M. J., Sowicka, P., et al. 2019a, MNRAS, 482, L75
Jones, D., Pejcha, O., & Corradi, R. L. M. 2019b, MNRAS, 489, 2195
Jones, D. H. P., Evans, D. S., & Catchpole, R. M. 1969, Observatory, 89, 18
Jordan, S., Schmutz, W., Wolff, B., Werner, K., & Muerset, U. 1996, A&A, 312, 897
Kaler, J. B., & Feibelman, W. A. 1985, ApJ, 297, 724
Kaler, J. B., & Jacoby, G. H. 1991, ApJ, 372, 215
Kaler, J. B., Shaw, R. A., & Kwitter, K. B. 1990, ApJ, 359, 392
Kaler, J. B., Stanghellini, L., & Shaw, R. A. 1993, A&A, 279, 529
Kastner, J. H., Balick, B., Blackman, E. G., et al. 2003, ApJ, 591, L37
Kawka, A., Vennes, S., O'Toole, S., et al. 2015, MNRAS, 450, 3514
Keller, G. R., Bianchi, L., & Maciel, W. J. 2014, MNRAS, 442, 1379
Kepler, S. O., Pelisoli, I., Koester, D., et al. 2016, MNRAS, 455, 3413
Kerber, F., Mignani, R. P., Guglielmetti, F., & Wicenec, A. 2003, A&A, 408, 1029
Kilkenny, D., Spencer Jones, J. H., & Marang, F. 1988, Observatory, 108, 88
Kilkenny, D., O'Donoghue, D., Worters, H. L., et al. 2015, MNRAS, 453, 1879
Kingsburgh, R. L., & Barlow, M. J. 1994, MNRAS, 271, 257
Kleinman, S. J., Kepler, S. O., Koester, D., et al. 2013, ApJS, 204, 5
Kniazev, A. Y. 2012, Astron. Lett., 38, 707
Koesterke, L. 2001, Ap&SS, 275, 41
Koesterke, L., & Hamann, W. R. 1997b, A&A, 320, 91
Koesterke, L., & Hamann, W. R. 1997a, IAU Symp., 180, 114
Koller, J., & Kimeswenger, S. 2001, ApJ, 559, 419

Kondrat'eva, L. N. 1994, Astron. Lett., 20, 644

Kramida, A., Ralchenko, Yu, Reader, J., & NIST ASD Team 2019, NIST Atomic Spectra Database (ver. 5.7) [Online] (Gaithersburg, MD: National Institute of Standards and Technology), Available: `https://physics.nist.gov/asd` [2017, April 9]

Kraus, M., Borges Fernandes, M., de Araújo, F. X., & Lamers, H. J. G. L. M. 2005, A&A, 441, 289

Kudritzki, R. P., Mendez, R. H., Puls, J., & McCarthy, J. K. 1997, IAU Symp., 180, 64

Kwitter, K. B., Jacoby, G. H., & Lydon, T. J. 1988, AJ, 96, 997

Lamers, H. J. G. L. M., Zickgraf, F.-J., de Winter, D., Houziaux, L., & Zorec, J. 1998, A&A, 340, 117

Latour, M., Fontaine, G., Green, E. M., & Brassard, P. 2015, A&A, 579, A39

Law, W. Y., & Ritter, H. 1983, A&A, 123, 33

Lee, S. J., & Hyung, S. 2013, A&A, 549, A65

Lee, T.-H., Stanghellini, L., Ferrario, L., & Wickramasinghe, D. 2007, AJ, 133, 987

Leone, F., Corradi, R. L. M., Martínez González, M. J., Asensio Ramos, A., & Manso Sainz, R. 2014, A&A, 563, A43

Leuenhagen, U., & Hamann, W. R. 1994, A&A, 283, 567

Leuenhagen, U., & Hamann, W.-R. 1998, A&A, 330, 265

Liebert, J., Fleming, T. A., Green, R. F., & Grauer, A. D. 1988, PASP, 100, 187

Liebert, J., Tweedy, R. W., Napiwotzki, R., & Fulbright, M. S. 1995, ApJ, 441, 424

Liebert, J., Bond, H. E., Dufour, P., et al. 2013, ApJ, 769, 32

Lisker, T., Heber, U., Napiwotzki, R., et al. 2005, A&A, 430, 223

Liu, X. W., Storey, P. J., Barlow, M. J., et al. 2000, MNRAS, 312, 585

Löbling, L., Rauch, T., Miller Bertolami, M. M., et al. 2019, MNRAS, 489, 1054

Lü, G., Zhu, C., Wang, Z., & Wang, N. 2009, MNRAS, 396, 1086

Lutz, J. H. 1977, A&A, 60, 93

Lutz, J. H. 1984, ApJ, 279, 714

Lutz, J. H., & Kaler, J. B. 1983, PASP, 95, 739

Lutz, J. H., & Kaler, J. B. 1987, BAAS, 19, 1090

Lutz, J., Fraser, O., McKeever, J., & Tugaga, D. 2010, PASP, 122, 524

Lykou, F., Chesneau, O., Zijlstra, A. A., et al. 2011, A&A, 527, A105

Maíz Apellániz, J., Sota, A., Arias, J. I., et al. 2016, ApJS, 224, 4

Majaess, D. J., Turner, D. G., & Lane, D. J. 2007, PASP, 119, 1349

Majaess, D., Carraro, G., Moni Bidin, C., et al. 2014, A&A, 567, A1

Mal'Kov, Y. F. 1997, Astron. Rep., 41, 760

Mampaso, A., Corradi, R. L. M., Viironen, K., et al. 2006, A&A, 458, 203

Manick, R., Miszalski, B., & McBride, V. 2015, MNRAS, 448, 1789

Marcolino, W. L. F., & de Araújo, F. X. 2003, AJ, 126, 887

McCarthy, J. K., Rich, R. M., Becker, S. R., et al. 1991, ApJ, 371, 380

McCook, G. P., & Sion, E. M. 1987, ApJS, 65, 603

McCook, G. P., & Sion, E. M. 1999, ApJS, 121, 1

Medina, S., Peña, M., Morisset, C., & Stasińska, G. 2006, Rev. Mex. Astron. Astrophys., 42, 53

Méndez, R. H. 1989, IAU Symp., 131, 261

Mendez, R. H. 1991, IAU Symp., 145, 375

Mendez, R. H., Kudritzki, R. P., & Simon, K. P. 1985, A&A, 142, 289

Mendez, R. H., Groth, H. G., Husfeld, D., Kudritzki, R. P., & Herrero, A. 1988a, A&A, 197, L25

Mendez, R. H., Kudritzki, R. P., Herrero, A., Husfeld, D., & Groth, H. G. 1988b, A&A, 190, 113

Mendez, R. H., Herrero, A., & Manchado, A. 1990, A&A, 229, 152

Mendez, R. H., Herrero, A., Manchado, A., & Kudritzki, R. P. 1991, A&A, 252, 265

Mendez, R. H., Kudritzki, R. P., & Herrero, A. 1992, A&A, 260, 329

Mendez, R. H., Miguel, C. H., Heber, U., & Kudritzki, R. P. 1986, IAU Colloq.: Hydrogen Deficient Stars and Related Objects, 87, 323

Méndez, R. H., Kudritzki, R.-P., & Urbaneja, M. A. 2016, ApJ, 829, 73

Menzies, J. W., & Wolstencroft, R. D. 1990, MNRAS, 247, 177

Mikolajewska, J. 2010, ArXiv e-prints [arXiv:1011.5657]

Miller Bertolami, M. M. 2016, A&A, 588, A25

Miller Bertolami, M. M. 2019, IAU Symp., 343, 36

Miller Bertolami, M. M., & Althaus, L. G. 2006, A&A, 454, 845

Miranda, L. F., Torrelles, J. M., Guerrero, M. A., Vázquez, R., & Gómez, Y. 2001, MNRAS, 321, 487

Miranda, L. F., Vázquez, R., Guerrero, M. A., Pereira, C. B., & Iñiguez-Garín, E. 2010, PASA, 27, 199

Miranda, L. F., Guillén, P. F., Olguín, L., & Vázquez, R. 2017, MNRAS, 466, 2151

Miranda, L. F., Vazquez, R., Torrelles, J. M., Eiroa, C., & Lopez, J. A. 1997, MNRAS, 288, 777

Miszalski, B., & Mikołajewska, J. 2014, MNRAS, 440, 1410

Miszalski, B., Parker, Q. A., Acker, A., et al. 2008, MNRAS, 384, 525

Miszalski, B., Acker, A., Moffat, A. F. J., Parker, Q. A., & Udalski, A. 2009a, A&A, 496, 813

Miszalski, B., Acker, A., Parker, Q. A., & Moffat, A. F. J. 2009b, A&A, 505, 249

Miszalski, B., Corradi, R. L. M., Boffin, H. M. J., et al. 2011a, MNRAS, 413, 1264

Miszalski, B., Jones, D., Rodríguez-Gil, P., et al. 2011b, A&A, 531, A158

Miszalski, B., Mikołajewska, J., Köppen, J., et al. 2011c, A&A, 528, A39

Miszalski, B., Crowther, P. A., De Marco, O., et al. 2012a, MNRAS, 423, 934

Miszalski, B., Boffin, H. M. J., Frew, D. J., et al. 2012b, MNRAS, 419, 39

Miszalski, B., Boffin, H. M. J., & Corradi, R. L. M. 2013a, MNRAS, 428, L39

Miszalski, B., Boffin, H. M. J., Jones, D., et al. 2013b, MNRAS, 436, 3068

Miszalski, B., Mikołajewska, J., & Udalski, A. 2013c, MNRAS, 432, 3186

Miszalski, B., Woudt, P. A., Littlefair, S. P., et al. 2016, MNRAS, 456, 633

Miszalski, B., Manick, R., Mikołajewska, J., et al. 2018a, MNRAS, 473, 2275

Miszalski, B., Manick, R., Mikołajewska, J., Van Winckel, H., & Iłkiewicz, K. 2018b, PASA, 35, e027

Miszalski, B., Manick, R., Van Winckel, H., & Escorza, A. 2019a, PASA, 36, e018

Miszalski, B., Manick, R., Van Winckel, H., & Mikołajewska, J. 2019b, MNRAS, 487, 1040

Mitchell, D. L., O'Brien, T. J., Pollacco, D., & Bryce, M. 2007a, IAU Symp., 240, 429

Mitchell, D. L., Pollacco, D., O'Brien, T. J., et al. 2007b, MNRAS, 374, 1404

Moehler, S., Koester, D., Zoccali, M., et al. 2004, A&A, 420, 515

Moehler, S., Landsman, W. B., Lanz, T., & Miller Bertolami, M. M. 2019, A&A, 627, A34

Montez, R. J., Kastner, J. H., Balick, B., et al. 2015, ApJ, 800, 8

Moreno-Ibáñez, M., Villaver, E., Shaw, R. A., & Stanghellini, L. 2016, A&A, 593, A29

Morgan, D. H., Parker, Q. A., & Russeil, D. 2001, MNRAS, 322, 877

Morgan, D. H., Parker, Q. A., & Cohen, M. 2003, MNRAS, 346, 719

Motch, C., Werner, K., & Pakull, M. W. 1993, A&A, 268, 561

Močnik, T., Lloyd, M., Pollacco, D., & Street, R. A. 2015, MNRAS, 451, 870

Muerset, U., Schild, H., & Vogel, M. 1996, A&A, 307, 516

Munari, U. 1997, Physical Processes in Symbiotic Binaries and Related Systems, ed. J. Mikołajewska, 37

Munari, U., & Zwitter, T. 2002, A&A, 383, 188

Munari, U., Siviero, A., Tamajo, E., et al. 2012, Balt. Astron., 21, 180

Muthumariappan, C., Parthasarathy, M., & Ita, Y. 2013, MNRAS, 435, 606

Napiwotzki, R. 1998, Rev. Mod. Astron., 11, 3

Napiwotzki, R. 1999, A&A, 350, 101

Napiwotzki, R., & Schonberner, D. 1993, IAU Symp., 155, 495

Napiwotzki, R., & Schoenberner, D. 1995, A&A, 301, 545

Napiwotzki, R., Heber, U., & Koeppen, J. 1994, A&A, 292, 239

Napiwotzki, R., Tovmassian, G., Richer, M. G., et al. 2005, AIP Conf. Ser., 804, 173

Neiner, C., Acker, A., Gesicki, K., & Szczerba, R. 2000, A&A, 358, 321

Otsuka, M., & Hyung, S. 2020, MNRAS, 491, 2959

Otsuka, M., Kemper, F., Hyung, S., et al. 2013, ApJ, 764, 77

Otsuka, M., Kemper, F., Cami, J., Peeters, E., & Bernard-Salas, J. 2014, MNRAS, 437, 2577

Otsuka, M., Hyung, S., & Tajitsu, A. 2015, ApJS, 217, 22

Öttl, S., Kimeswenger, S., & Zijlstra, A. A. 2014, A&A, 565, A87

Oudmaijer, R. D., & Miroshnichenko, A. S. 2017, ASP Conf. Ser., 508, 3

Parker, Q. A., Acker, A., Frew, D. J., et al. 2006, MNRAS, 373, 79

Parker, Q. A., & Morgan, D. H. 2003, MNRAS, 341, 961

Parker, Q. A., Bojičić, I. S., & Frew, D. J. 2016, J. Phys. Conf. Ser., 728, 032008

Parthasarathy, M., Garcia-Lario, P., de Martino, D., et al. 1995, A&A, 300, L25

Parthasarathy, M., Acker, A., & Stenholm, B. 1998, A&A, 329, L9

Peña, M. 2005, Rev. Mex. Astron. Astrophys., 41, 423

Peña, M., & Medina, S. 2002, Rev. Mex. Astron. Astrophys., 38, 23

Peña, M., & Ruiz, M. T. 1998, ApJ, 504, L103

Peña, M., Ruíz, M. T., Maza, J., & González, L. E. 1989, Rev. Mex. Astron. Astrophys., 17, 25

Peña, M., Stasińska, G., & Medina, S. 2001, A&A, 367, 983

Peña, M., Medina, S., & Stasińska, G. 2003, Rev. Mex. Astron. Astrofis. Conf. Ser., 18, 84

Peña, M., Rechy-García, J. S., & García-Rojas, J. 2013, Rev. Mex. Astron. Astrophys., 49, 87

Pena, M., Torres-Peimbert, S., & Ruiz, M. T. 1992, A&A, 265, 757

Pena, M., Ruiz, M. T., Bergeron, P., Torres-Peimbert, S., & Heathcote, S. 1997, A&A, 317, 911

Pena, M., Stasińska, G., Esteban, C., et al. 1998, A&A, 337, 866

Pereira, C. B. 2004, A&A, 413, 1009

Pereira, C. B., & Miranda, L. F. 2005, A&A, 433, 579

Pereira, C. B., Smith, V. V., & Cunha, K. 2005, A&A, 429, 993

Pereira, C. B., Miranda, L. F., Smith, V. V., & Cunha, K. 2008, A&A, 477, 535

Pereira, C. B., Baella, N. O., Daflon, S., & Miranda, L. F. 2010, A&A, 509, A13

Pereyra, M., Richer, M. G., & López, J. A. 2013, ApJ, 771, 114

Pereyra, M., López, J. A., & Richer, M. G. 2016, AJ, 151, 53

Perinotto, M. 1983, IAU Symp., 103, 323
Phillips, J. P. 2003, MNRAS, 344, 501
Phillips, J. P. 2005a, MNRAS, 357, 619
Phillips, J. P. 2005b, MNRAS, 362, 847
Phillips, J. P. 2007, MNRAS, 376, 1120
Phillips, J. P., Cuesta, L., & Kemp, S. N. 2005, MNRAS, 357, 548
Pierce, M. J., Frew, D. J., Parker, Q. A., & Köppen, J. 2004, PASA, 21, 334
Pinheiro, M. C., Copetti, M. V. F., & Oliveira, V. A. 2010, A&A, 521, A26
Pollacco, D. 1999, MNRAS, 304, 127
Pollacco, D. L., & Bell, S. A. 1994, MNRAS, 267, 452
Pottasch, S. R. 1984, Astrophys. Space Sci. Libr., 107
Pottasch, S. R. 1996, A&A, 307, 561
Pottasch, S. R., Wesselius, P. R., Wu, C.-C., Fieten, H., & van Duinen, R. J. 1978, A&A, 62, 95
Pottasch, S. R., Beintema, D. A., & Feibelman, W. A. 2005, A&A, 436, 953
Pottasch, S. R., Bernard-Salas, J., & Roellig, T. L. 2007, A&A, 471, 865
Preite-Martinez, A., Acker, A., Koeppen, J., & Stenholm, B. 1989, A&AS, 81, 309
Preite-Martinez, A., Acker, A., Koeppen, J., & Stenholm, B. 1991, A&AS, 88, 121
Ramos-Larios, G., & Phillips, J. P. 2005, MNRAS, 357, 732
Ratag, M. A., Pottasch, S. R., Dennefeld, M., & Menzies, J. 1997, A&AS, 126, 297
Rauch, T., Koeppen, J., & Werner, K. 1994, A&A, 286, 543
Rauch, T., Koeppen, J., & Werner, K. 1996, A&A, 310, 613
Rauch, T., Dreizler, S., & Wolff, B. 1998, A&A, 338, 651
Rauch, T., Köppen, J., Napiwotzki, R., & Werner, K. 1999, A&A, 347, 169
Rauch, T., Heber, U., & Werner, K. 2002, A&A, 381, 1007
Rauch, T., Reiff, E., Werner, K., et al. 2006, ASP Conf. Ser., 348
Rauch, T., Reiff, E., Werner, K., & Kruk, J. W. 2008, ASP Conf. Ser., 391, 135
Reindl, N., Rauch, T., Parthasarathy, M., et al. 2014a, A&A, 565, A40
Reindl, N., Rauch, T., Werner, K., Kruk, J. W., & Todt, H. 2014b, A&A, 566, A116
Reindl, N., Rauch, T., Miller Bertolami, M. M., Todt, H., & Werner, K. 2017, MNRAS, 464, L51
Reindl, N., Finch, N., Schaffenroth, V., et al. 2018, Galaxies, 6, 88
Reindl, N., Schaffenroth, V., Miller Bertolami, M., et al. 2020, A&A, 638, A93
Reynolds, R. J. 1987, ApJ, 315, 234
Rodríguez, M., Corradi, R. L. M., & Mampaso, A. 2001, A&A, 377, 1042
Rodríguez-Flores, E. R., Corradi, R. L. M., Mampaso, A., et al. 2014, A&A, 567, A49
Sabach, E., & Soker, N. 2018, MNRAS, 473, 286
Sabbadin, F., Falomo, R., & Ortolani, S. 1987, A&AS, 67, 541
Santander-García, M., Rodríguez-Gil, P., Corradi, R. L. M., et al. 2015, Nature, 519, 63
Saracino, S., Dalessandro, E., Ferraro, F. R., et al. 2016, ApJ, 832, 48
Saurer, W., Werner, K., & Weinberger, R. 1997, A&A, 328, 598
Schaffenroth, V., Barlow, B. N., Geier, S., et al. 2019, A&A, 630, A80
Schmeja, S., & Kimeswenger, S. 2001, A&A, 377, L18
Schreiber, M. R., & Gänsicke, B. T. 2003, A&A, 406, 305
Shaw, R. A., & Kaler, J. B. 1989, ApJS, 69, 495
Shen, Z. X., Liu, X. W., & Danziger, I. J. 2004, A&A, 422, 563
Shimanskii, V. V., Borisov, N. V., Pozdnyakova, S. A., et al. 2008, Astron. Rep., 52, 558
Smith, L. F., & Aller, L. H. 1969, ApJ, 157, 1245
Smith, N., Bally, J., & Walawender, J. 2007, AJ, 134, 846
Soker, N. 2016, MNRAS, 455, 1584
Soker, N., & Zucker, D. B. 1997, MNRAS, 289, 665
Sota, A., Maíz Apellániz, J., Walborn, N. R., et al. 2011, ApJS, 193, 24
Sota, A., Maíz Apellániz, J., Morrell, N. I., et al. 2014, ApJS, 211, 10
Stanghellini, L., & Pasquali, A. 1995, ApJ, 452, 286
Stanghellini, L., Corradi, R. L. M., & Schwarz, H. E. 1993, A&A, 276, 463
Stanghellini, L., Kaler, J. B., & Shaw, R. A. 1994, A&A, 291, 604
Stanghellini, L., Kaler, J. B., Shaw, R. A., & di Serego Alighieri, S. 1995, A&A, 302, 211
Stanghellini, L., Villaver, E., Manchado, A., & Guerrero, M. A. 2002, ApJ, 576, 285
Stanghellini, L., Bucciarelli, B., Lattanzi, M. G., & Morbidelli, R. 2020, ApJ, 889, 21
Steffen, M., Hubrig, S., Todt, H., et al. 2014, A&A, 570, A88
Stenholm, B., & Acker, A. 1987, A&AS, 68, 51
Sterling, N. C., Porter, R. L., & Dinerstein, H. L. 2015, ApJS, 218, 25
Surendiranath, R. 2002, A&A, 390, 667
Szyszka, C., Walsh, J. R., Zijlstra, A. A., & Tsamis, Y. G. 2009, ApJ, 707, L32
Tamura, S., & Shaw, R. A. 1987, PASP, 99, 1264
Thorstensen, J. R., & Skinner, J. N. 2012, AJ, 144, 81
Toalá, J. A., Guerrero, M. A., Todt, H., et al. 2015, ApJ, 799, 67
Toalá, J. A., Ramos-Larios, G., Guerrero, M. A., & Todt, H. 2019, MNRAS, 485, 3360
Todt, H. 2009, PhD Thesis, Universitat Potsdam
Todt, H., Miszalski, B., Toalá, J. A., & Guerrero, M. A. 2017, IAU Symp., 323, 174
Todt, H., Peña, M., Hamann, W. R., & Gräfener, G. 2010, A&A, 515, A83
Tomov, T. 2003, ASP Conf. Ser., 303, 376
Torres-Peimbert, S., Arrieta, A., & Bautista, M. 2010, Rev. Mex. Astron. Astrophys., 46, 221
Tovmassian, G., Yungelson, L., Rauch, T., et al. 2010, ApJ, 714, 178
Tovmassian, G. H., Napiwotzki, R., Richer, M. G., et al. 2004, ApJ, 616, 485
Traulsen, I., Hoffmann, A. I. D., Rauch, T., et al. 2005, ASP Conf. Ser., 334, 325
Tylenda, R., & Stasińska, G. 1994, A&A, 288, 897
Tylenda, R., Acker, A., Gleizes, F., & Stenholm, B. 1989, A&AS, 77, 39
Tylenda, R., Acker, A., Stenholm, B., Gleizes, F., & Raytchev, B. 1991, A&AS, 89, 77
Tylenda, R., Acker, A., & Stenholm, B. 1993, A&AS, 102, 595
Tyndall, A. A., Jones, D., Boffin, H. M. J., et al. 2013, MNRAS, 436, 2082
Tyne, V. H., Evans, A., Geballe, T. R., et al. 2002, MNRAS, 334, 875
Ueta, T., Ladjal, D., Exter, K. M., et al. 2014, A&A, 565, A36
van der Hucht, K. A., Conti, P. S., Lundstrom, I., & Stenholm, B. 1981a, Space Sci. Rev., 28, 307
van der Hucht, K. A., Conti, P. S., Lundstrom, I., & Stenholm, B. 1981b, Space Sci. Rev., 28, 227
Van Winckel, H., Jorissen, A., Exter, K., et al. 2014, A&A, 563, L10
Walborn, N. R., & Fitzpatrick, E. L. 1990, PASP, 102, 379
Walsh, J. R., & Walton, N. A. 1996, A&A, 315, 253
Walton, N. A., Walsh, J. R., & Pottasch, S. R. 1993, A&A, 275, 256
Wang, W., & Liu, X. W. 2007, MNRAS, 381, 669
Wassermann, D., Werner, K., Rauch, T., & Kruk, J. W. 2010, A&A, 524, A9
Weidmann, W. A. 2009, PhD Thesis, Universidad Nacional de Cordoba, Spain
Weidmann, W. A., & Gamen, R. 2011a, A&A, 531, A172
Weidmann, W. A., & Gamen, R. 2011b, A&A, 526, A6
Weidmann, W. A., Méndez, R. H., & Gamen, R. 2015, A&A, 579, A86
Weidmann, W., Gamen, R., Mast, D., et al. 2018, A&A, 614, A135
Weinberger, R., Kerber, F., & Groebner, H. 1997, A&A, 323, 963
Werner, K. 1992, Analysis of PG 1159, eds. U. Heber, & C. S. Jeffery, 401, 273
Werner, K. 1995, Balt. Astron., 4, 340
Werner, K., & Herwig, F. 2006, PASP, 118, 183
Werner, K., & Koesterke, L. 1992, in NLTE analysis of the hydrogen-deficient centralstar of the planetary nebula Abell 78, eds. U. Heber, & C. S. Jeffery, 401, 288
Werner, K., & Rauch, T. 1994, A&A, 284, L5
Werner, K., Dreizler, S., & Wolff, B. 1995, A&A, 298, 567
Werner, K., Rauch, T., & Kruk, J. W. 2016, A&A, 593, A104
Werner, K., Rauch, T., & Reindl, N. 2019, MNRAS, 483, 5291
Wesemael, F., Green, R. F., & Liebert, J. 1985, ApJS, 58, 379
Wesson, R., Jones, D., García-Rojas, J., Boffin, H. M. J., & Corradi, R. L. M. 2018, MNRAS, 480, 4589
Whelan, J., & Iben, I., Jr 1973, ApJ, 186, 1007
Williams, K. A., Canton, P. A., Bellini, A., et al. 2018, ApJ, 867, 62
Wlodarczyk, K., & Olszewski, P. 1994, Acta Astron., 44, 407
Wright, N. J., Barlow, M. J., Ercolano, B., & Rauch, T. 2011, MNRAS, 418, 370
Yuan, H. B., & Liu, X. W. 2013, MNRAS, 436, 718
Yudin, B. F. 1983, Astronomicheskij Tsirkulyar, 1250, 7
Zacharias, N., Finch, C. T., Girard, T. M., et al. 2012, VizieR Online Data Catalog: I/322A
Zhang, C. Y., & Kwok, S. 1993, ApJS, 88, 137
Zhang, Y., & Liu, X. W. 2002, MNRAS, 337, 499
Ziegler, M., Rauch, T., Werner, K., Köppen, J., & Kruk, J. W. 2012a, A&A, 548, A109
Ziegler, M., Rauch, T., Werner, K., & Kruk, J. W. 2012b, IAU Symp., 283, 211
Zijlstra, A. A., & Walsh, J. R. 1996, A&A, 312, L21
Zijlstra, A., Pottasch, S., & Bignell, C. 1990, A&AS, 82, 273
Zijlstra, A. A., van Hoof, P. A. M., Chapman, J. M., & Loup, C. 1994, A&A, 290, 228
Zuckerman, B., & Aller, L. H. 1986, ApJ, 301, 772

Appendix A: Possibly symbiotic stars

Symbiotic stars (SySt) are binary systems composed by a cold giant (red giant or Mira star) and an evolved hot star (in most cases, a white dwarf), in which the giant transfers material to the white dwarf star via stellar wind (Mikolajewska 2010). The wind is ionized by the UV radiation field from the evolved companion, producing a spectrum with emission-lines typical of PNe. In addition to these emission-lines, SySt generally exhibit absorption features (e.g. TiO and VO) produced in the cool stellar photosphere of the giant (Corradi et al. 2003). Symbiotic stars allow to study physical processes such as the powering mechanism of supersoft X-ray sources (Jordan et al. 1996), the thermonuclear outbursts (Munari et al. 1997), the collimation of stellar winds and formation of jets (Tomov 2003) or their relation with the formation of bipolar PNe (Corradi et al. 2003).

Another important aspect is that SySt are, probably, progenitors of Type Ia supernovae (see e.g. Whelan & Iben 1973; Hachisu et al. 1999; Lü et al. 2009; Di Stefano 2010; Chen et al. 2011). SySt are divided into three categories: (i) The S-type (stellar) in which the giant has a M-spectral type and dominates the emission in the near-IR, showing the presence of stellar photospheres at (3000–4000 K) (Belczyński et al. 2000; Akras et al. 2019a). (ii) The D-type systems (dusty) in which the cool companion is a Mira variable star and the near-IR emission corresponds to the dusty envelope around the systems. And (iii) D′-type symbiotic stars which are characterized by a F, G, or K type cool giant surrounded by a dust shell (Allen 1984). A new type of SySt namely S+IR, a S-type with an infrared excess in the 11.6 and/or 22.1 μm bands, was proposed by Akras et al. (2019a).

Evolutionary links between PNe and symbiotic systems are likely. A kind of symbiotic outflow around D-type symbiotic Miras shows morphological similarities with bipolar PNe, indicating that symbiotic Miras, in an evolutionary phase, are a prelude to formation of genuine PNe. This transition occurs when the Mira variable of SySt loses its envelope and forms a PN (Corradi et al. 2003). Note that nebulae observed around symbiotic Miras are not PNe. On the other hand, many current symbiotic stars may have gone through the PN phase, when the current WD companion was at an early phase in its evolution. Similarly, many PNe with binary central stars may turn-up into symbiotic systems in the future when the companion star evolves into to AGB phase (Frew & Parker 2010).

Symbiotic stars can be discriminated from PNe using either near-IR colours or, in the optical spectra, the presence of the red continuum and strong [O III] λ4363 relative to λ5007 in higher-excitation objects. Given that symbiotic stars are generally much denser than even the youngest PNe, Gutierrez-Moreno (1988) and Gutierrez-Moreno et al. (1995) used the [O III] $\lambda4363/\lambda5007$ line ratio to separate PNe from symbiotics. Colour–colour diagrams using near-IR and optical colours were used (Schmeja & Kimeswenger 2001; Ramos-Larios & Phillips 2005; Corradi et al. 2008). Recently, Iłkiewicz & Mikołajewska (2017) also proposed a number of new diagnostic diagrams in the optical regime for discriminating SySt from PNe. For instance, they used diagnostic diagrams based on the He I recombination lines. Akras et al. (2019b) used machine learning algorithms to develop new near-IR selection criteria that are more efficient in distinguishing SySt from other Hα emitters, including PNe.

Our catalogue has eleven CSPNe classified as SySt, which are presented in Table A.1. Two objects of this list are classified as possible PNe (PM 1−322 and Mz 3) in the Hong Kong/AAO/Strasbourg Hα PNe database (HASH; Parker et al. 2016). The spectroscopy of these possible PNe is insufficiently conclusive due to the combination of low S/N spectra, low surface brightness and insufficient wavelength coverage. The spectrum of PM 1−322 presents the typical forbidden emission lines of a PN as well as the Balmer and Paschen recombination lines. The spectral characteristics indicate that PM 1−322 is a young PN, however, its high density and its position on the diagnostic diagram of Gutierrez-Moreno et al. (1995) suggest a symbiotic nature (Pereira & Miranda 2005). Mz 3 is widely classified as a bipolar PN based on its optical spectral characteristics and morphology (Acker et al. 1992). However, the position of Mz 3 on the near-IR colour diagrams strongly indicates that it has a symbiotic binary nucleus (Schmeja & Kimeswenger 2001).

Table A.1. Sample of CSPNe classified as SySt.

PN G	name	Prev. class.	Akras class.
#8	PM 1−322	?	D′
003.4−04.8	H 2−43	D	D
004.9−04.9	M 1−44	S	S+IR
007.5+04.3	Th 4−1	?	?
044.1+05.8	CTSS 2	?	?
061.8+02.1	Hen 2−442	D	D
107.4−00.6	K 4−57	D	D
275.2−03.7	Hen 2−25	?	D′
289.6−01.6	Hen 2−57	?	D
331.7−01.0	Mz 3	?	D
359.2+01.2	19w32	D	D′

M 1−44 and CTSS 2 are catalogued as true PNe in the HASH catalogue. They are confirmed PNe with multi-wavelength PN-type morphologies and PN spectral features (Parker et al. 2016). For M 1−44 the near-IR photometry indicates the possible presence of a cool component (G–K giant). However, the giant may not be associated with the nebula (Belczyński et al. 2000; Phillips 2007).

The source K 4−57 is presented as a PN candidate in HASH (Parker et al. 2016). It appears in the PNe catalogue by Acker et al. (1992). However, its optical spectrum is similar to a SySt with nebular emission lines of low to high ionization species and a faint slow rising continuum (Rodríguez-Flores et al. 2014). In addition, the location of the source in the high-density region of the optical diagram from Gutierrez-Moreno et al. (1995), which is typical of symbiotic stars, reveals the possible presence of a symbiotic nebula.

Hen 2−442 was previously classified as PN (Acker et al. 1992), however it is now catalogued as a true SySt (Parker et al. 2016). The near-IR spectrum exhibits the presence of a red giant and the optical one is dominated by nebular lines and shows a weak evidence of TiO bands (Yudin 1983), confirming its symbiotic nature (Rodríguez-Flores et al. 2014).

The other five objects: H 2−43, Th 4−1, Hen 2−25, Hen 2−57, and 19w32 are classified as SySt candidates (Parker et al. 2016). Three of these objects (H 2−43, He 2−25, and 19w32) were previously classified as planetary nebulae. They were subsequently found to have near-IR colours which are consistent with symbiotic binary nucleus (Belczyński et al. 2000; Schmeja & Kimeswenger 2001; Pereira & Miranda 2005; Phillips 2007). The spectra of Th 4−1 and Hen 2−57 indicate they are genuine PNe, but this spectroscopic information do not allow to totally rule out the possibility of being a symbiotic nature.

Table A.1 shows that these objects, in general, belong to the symbiotic class D/D′ (Akras et al. 2019a). D-type SySt are in more evolved phase than S-types. D-types contain AGB stars as the cold components whereas the S-type SySt have RGB stars (Muerset et al. 1996). The intense mass-loss generated during the end of the TP-AGB stage is responsible for the formation of the dusty shell in D-type SySt.

Appendix B: Objects rejected from the catalogue

IRAS 17150−3224 (PN G353.8+02.9), strong evidence that is not PN. Hu et al. (1993) show the optical spectra and classify it as G2 I.

RE 1738+665 (PN G096.9+32.0), it is a faint, irregular HII region in the ISM (Frew 2008).

Zijlstra & Walsh (1996) proved that the PNe He 2−436 (PN G004.8−22.7) and WRAY 16−423 (PN G006.8−19.8) are not linked to our galaxy.

Sh 2−128 (PN G325.8+04.5), Bohigas & Tapia (2003) showed that this is an HII region.

Appendix C: Spectral classification of peculiar CSPNe

Thanks to the identification of certain ions in published spectra, it was possible to improve the spectral classification for several objects. In the cases when two or more different spectral classifications were available, the relevance of each one is discussed in the text.

2MASS J18482874−1237434: This object was classified as PN by Miszalski & Mikołajewska (2014) who reported He II absorption lines at 4540 and 4686 Å. According to our spectral classification system, this CSPN is an O-type.

A 41: This object requires special attention. On one hand, Wlodarczyk & Olszewski (1994) reported that the primary component of the binary system is a sdB (they do not show spectra). On the other hand, Green et al. (1984) classified this CSPN as sdO, and show spectra where Hβ is clearly visible in absorption. As a more probable classification, we prefer a sdO type.

A 46: According to Pollacco & Bell (1994), this CSPN presents Balmer, He II, and N V λ4603−19 lines in absorption. It also shows emission of C IV, C III, and N III. On the other hand, Mitchell et al. (2007b) classified it as M6 V. Moreover, De Marco (2009) report that the secondary star is a M6 V. There exists a possibility that the object is a sdO (Aller et al. 2015a). We classify this CSPN as O(H)3 + M6 V.

CRBB 1: According to the spectra shown by McCarthy et al. (1991) we classify this star as B0 III.

ESO 330–9: This object presents a distorted morphology. The CSPN is not at the geometric center. Hillwig et al. (2017b) show a spectrum where only an absorption of He II at 4686 Å is visible. We classify this CSPN as O.

Fg 1: Figure 1 of Boffin et al. (2012b) shows clear Hydrogen absorption lines, He II and N V (4603–19 Å) together with emission lines of C IV and O V[4]. In addition, the authors report that this planetary nebula nucleus is constituted by a double-degenerate central star. Both stars are responsible for the ionization of the nebula. We classify this CSPN as O(H)3-4.

H 2−1: The CSPN is classified as [WC 11] by Górny et al. (2009), who show a spectrum in the range 5200–7300 Å. However, in the spectrum taken by Mendez et al. (1988b) Hγ is in absorption, He I, and He II are evident. We reclassify this CSPN as O(H)5-9.

Hb 12: Aller & Keyes (1985) suggest that the emission lines equivalent width does not correspond to a [WR]. The Hα line presents broad emission (Arrieta et al. 2002) and the spectrum does not present absorption lines (Arrieta & Torres-Peimbert 2003). This object could be in a previous stage to a PN. We keep both classifications, possible B[e] and possible [WN 7].

Hen 2−11: Górny & Siódmiak (2003) reported non-stellar emission lines, but Górny et al. (2004) classified this object as wels. However, the spectrum showed by Jones et al. (2014) displays subtle He II absorption at 5412 Å. In this context, we prefer an O-type.

Hen 2−108: Górny (2014) classified this CSPN as VL. However, the spectra display clear He II absorption at 5412 Å and subtle C IV absorption at 5806 Å. According to the spectrum shown by Hultzsch et al. (2007), the CSPN shows He I, He II, and Hγ absorption. We classify this object as O(H).

Hen 2−131: Górny (2014) classified this CSPN as VL. However, the spectra display clear He II absorption at 5412 Å and subtle C IV absorption at 5806 Å. Zuckerman & Aller (1986) reported a Of8 spectral type and P Cygni profile. Heap (1977) reported a O7(f)eq spectral type and showed the spectra where Balmer line absorption is visible. While Guerrero & De Marco (2013) reported Of(H) and Tylenda et al. (1993) classified it as wels. We prefer to adopt a spectral type O(H).

Hen 2−138: Mendez et al. (1988b) classified this object as Of(H), but considering these author spectra we propose a reclassification as O(H)7-9f.

Hen 2−146: There are two possible CSPNe in this object. Both display a late spectral type (Jones et al. 1969). To be consistent with this catalogue nomenclature, we prefer a classification K-M.

Hen 2−155: The spectra showed by Jones et al. (2015) display H absorption lines, He II, O V (at 5114 Å), and C IV (at 5801–12 Å). We classify this CSPN as O(H)3-5.

Hen 2−161: The spectra show Balmer absorption lines, He II λ4542 Å, He II λ5412 Å, N V λ4603−1 Å, O V at λ5114, and C IV emission at λ5801–12 Å (Jones et al. (2015) and private communication with Jones). In addition I(4542)~I(4603), in this sense we suggest a spectral type O(H)3-4.

Hen 2−442: Arkhipova et al. (1985) reported that there are two stellar sources separated by 6 arcsec, and both sources produce PN-like emission spectra. A description of this objects is presented by Rodríguez-Flores et al. (2014).

Hen 2−260: According to the spectrum shown by Hultzsch et al. (2007), the CSPN shows He I, He II, and Balmer absorption. I(4471) > I(4542) implies a later star than O(H)7. Nevertheless, the intensity of the He II lines is significant. Si III absorption lines (at 4552, 4567 and 4574 Å) are evident in the spectrum published by Kudritzki et al. (1997). According to this, we classify this star as O(H)7-8.

Hf 2−2: Hillwig et al. (2016a) indicate that Balmer and He II absorption lines are clearly visible in the spectrum. Moreover, in the spectrum shown by the authors, strong N V absorption lines at 4603–19 Å are present. This features are typical of an O(H)3 star.

IC 2149: This CSPN is classified as O4f in SECGPN, and Guerrero & De Marco (2013) classify it as Of(H). Feibelman et al. (1994) reported stellar features at the optical range. We adopt the spectral type O(H)4f.

IC 2553: Ali & Dopita (2017) showed that the emission lines of N III 4631+4641 Å, C III 4650 Å, and O III+O V 5592 Å are

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[4] `https://science.sciencemag.org/content/sci/suppl/2012/11/07/338.6108.773.DC1/Boffin.SM.pdf`

of nebular origin. The only line that could be stellar is 5806 Å. These authors ruled out the wels classification. In this sense, we prefer to classify this CSPN as emission line.

IC 4776: Aller (1975) classified this CSPN as a possible [WC 6]. More recently, Miszalski et al. (2019b) analyzed and presented high resolution spectra. They ruled out a spectral type [WR] neither Of. Moreover, they could not affirm if the CSPN is H-rich or not. According to the strong He II absorption line we prefer an O-type spectral classification.

IC 4846: This CSPN displays Hγ absorption lines and He II (4200, 4541 Å) together with He II emission line at 4686 Å (Hyung et al. 2001b). In addition García-Hernández & Górny (2014) reported C IV emission at 5806 Å. We adopt a classification O(H)3-4 f.

IC 5217: Certainly the central star of this object requires further study. Cerruti-Sola & Perinotto (1985) classified this object as Of-WR, Hyung et al. (2001a) as WC(WNb ?), Tylenda et al. (1993) as wels, and Acker & Neiner (2003) as [WC 8-9]?. There is no spectrum published. Cautiously, we adopt a classification [WC]?.

K 1−2: Exter et al. (2003) described this object but does not show the spectrum or classify it. They detected He II and Hβ stellar features. In addition, they mentioned that Hβ absorption is wide. On the other hand, De Marco (2009) reported that the secondary star of the binary system is a K2 V (or earlier). We classify it as O(H) + K2 V.

M 1−12: Previously, in Weidmann & Gamen (2011b) we classified this CSPN as [WC 10-11]. Nevertheless, in a spectra showed by Kniazev (2012) an absorption at 5412 Å is clear. So, we prefer a classification O-type.

M 1−37: According to the spectrum shown by Hultzsch et al. (2007), the CSPN shows He I, He II, and Hγ absorption. Taking into account that it is a noisy spectrum, we can say that the star is O(H) type. The spectrum presented by Kudritzki et al. (1997) shows strong P Cygni-type profiles at 4471 Å. Although this object was classified as [WC 11] by Gesicki et al. (2006), this classification is discarded because of the Hγ feature. On the other hand, the object was classified as a peculiar star by HP2007.

M 1−38: Górny et al. (2009) classified this object as [WC 11], but its spectra is not conclusive. On the other hand, Hultzsch et al. (2007) showed an spectrum with clear Balmer, He I, and He II absorption lines. Moreover, I(4471) > I(4542). We classify this star as O(H)7-8.

M 1−44: Seemingly the object is not well identified. Lutz & Kaler (1983) did one of the first identifications and mentioned two stars that are separated by 2 arcsec. Later, Stenholm & Acker (1987) classified this star as possible PN, and possible SySt is the conclusion of Belczyński et al. (2000). A deeper investigation is required for this object.

M 1−77: Object classified as possible OB star by SECGPN. De Marco (2009) showed some absorption lines, i.e., Hδ, O II, and He I. This information is not enough to classify it. We assume these are the most intense lines in the spectrum. The O II features are especially important in B1 type star (Walborn & Fitzpatrick 1990). Hence, we classify this star as B1.

M 2−12: According to the spectrum shown by Hultzsch et al. (2007), the CSPN displays He I and He II absorption lines, with I(4471) > I(4542). The presence of Balmer features is not evident. Górny et al. (2004) classified this objects as [WC 11], although the spectrum shown by Hultzsch et al. (2007) discards this classification. We classify this star as an O7-8.

M 2−54: It is a variable star with a magnitude variation amplitude of up to 0.3 mag in Johnson *V* band (Handler 1999). It could also be a post-AGB star (Gauba & Parthasarathy 2003). Nevertheless, the same authors classify it as O9 *V*.

M 3−1: We could not detect any stellar feature in this object (Weidmann & Gamen 2011b). But in the spectra showed by Jones et al. (2019a) absorptions at Hβ and 5412 Å are evident. We classify this CSPN as O(H).

M 3−2: Spectra showed by Kniazev (2012) display clear Balmer absorption lines. We classify this CSPN as H-rich.

My 60: Basurah et al. (2016) classified this CSPN as O(H), however they only observed O VI emission lines at 3811–34 Å. On the other hand, Górny (2014) has classified it as wels. In this situation we prefer to classify it as emission line.

MyCn 18: This object received different types of classifications, Mendez et al. (1991) and Miszalski et al. (2018b) classified the CSPN as Of(H). On the other hand, Peña et al. (2013) report a spectral type [WC]−PG 1159. While Lee et al. (2007) with high quality spectra did not detect Balmer absorption and classified this object as Of(c). Based on the quality of the published spectra we choose the classification Of(c).

NGC 1360: CSPN classified as O(H) by Mendez et al. (1991). Nevertheless, in the spectra showed by Mendez et al. (1988b) strong absorption of He II at 4686 Å is visible. On the other hand, in the spectra presented by Herald & Bianchi (2011) no He I absorption can be appreciated. In this sense, we classified this CSPN as O(H)3-4.

NGC 1535: In the spectrum showed by Mendez et al. (1988b) the H absorption is evident, and it is confirmed by Guerrero & De Marco (2013). According to this, we classify this CSPN as O(H)5.

NGC 3211: Basurah et al. (2016) classified this CSPN as O(H). Nevertheless, they did not observe the Balmer series; they only detected O VI emission lines at 3811–34 Å. In this situation we prefer to classify this object as emission line.

NGC 5979: Basurah et al. (2016) observed this CSPN and classified it as O (H). However, according to the features displayed in their spectra, in particular C IV at 5806 Å and O III at 5592 Å, we prefer to classify this object as O(H)3-4. It is noteworthy that the spectrum obtained by Basurah et al. (2016) shows clear O VI emission lines. These lines are typical of [WO] stars.

NGC 6026: WD2011a reported a spectral type O(H)7. For their part, Hillwig et al. (2010) classified this object as O7 V. So we classify this CSPN as O(H)7 V.

NGC 6058: Object classified previously by Pottasch (1984) as O9, and by Guerrero & De Marco (2013) as O(H). Nevertheless, in the spectra showed by Herald & Bianchi (2011) strong H, He II, and N V absorptions are revealed. We classify this CSPN as O(H)3.

NGC 6210: Object classified by Pottasch et al. (1978) as O6, and as O(H) by Guerrero & De Marco (2013). Nevertheless, in the spectra showed by Herald & Bianchi (2011) strong H, He II, and N V absorption are revealed. We decided to classify this CSPN as O(H)3.

NGC 6629: This CSPN was classified as possible [WC 4] (Acker & Neiner 2003) and as wels by Tylenda et al. (1993). Nevertheless, in the spectra showed by Mendez et al. (1988b) and Leone et al. (2014), the Balmer series together with the He II absorption are present. According to this, we propose a spectral type O(H) for this CSPN.

NGC 6778: Previously classified as cont. by Feibelman (1994). Miszalski et al. (2011b) showed a high quality spectra where the absorptions at Hβ, He II, and N V (4603–19 Å) are evident. We classify this CSPN as O(H)3–4.

Pa 5: García-Díaz et al. (2014) classified the central star of this new PN as PG 1159. They reported He II, Balmer series, and Ca II photospheric lines. On the other hand De Marco et al. (2015) classified the star as O(He). We consider that the lines identified by these authors are insufficient to classify this object as a PG 1159. We prefer a spectral classification O(H).

PRTM 1: Peña & Ruiz (1998) reported that the central star have an O(H) spectral type. Later, the high quality spectra obtained by Boffin et al. (2012a) display absorption lines of He II (5412 and 4686 Å), O V (5114 Å), N V (4603–19 Å), and emission lines of C IV (4658, 5801–12 Å) O V (4930 Å), N V (4945 Å). All of this features are compatible with an O(H)3–4 type. In this sense, it is surprising that the line N IV at 5200–03 Å does not appear. In addition, the authors identified an emission line at 5292 Å, that they associated to O VI. Nevertheless, the NIST Atomic Spectra Database (Kramida et al. 2019) do not include this line for O VI. Instead, we consider that this line better match with Ne IV.

SkAc 1: The CSPN of this object was identified in a WD survey (Kepler et al. 2016). Although the authors did not assign a spectral classification to the spectrum, the Balmer series together with He II absorption at 4686 and 5412 Å are clearly seen. We opt for a spectral classification DAO.

TC 1: SECGPN reported a spectral type Of(H), and in the spectra showed by Mendez et al. (1988b) the He I lines are clear and strong. Zuckerman & Aller (1986) reported P Cygni profile. For this reason, we prefer a classification O(H)5-9f.

TS 01: Tovmassian et al. (2004) classified this CSPN as WD/NS, nevertheless in the spectrum that these author showed, the Balmer series is clear but the He II stellar lines are not. With this evidence, we prefer a classification H-rich. De Marco (2009) reported that the secondary star is a WD/NS or sdB. Finally, Tovmassian et al. (2010) showed a spectra with H and He II, 4686 Å line, detectable in both emission and absorption. According to the log g of the optical component, determined by Tovmassian et al. (2010), the CSPN is indeed a sdO star.