J-PLUS: Tools to identify compact planetary nebulae in the Javalambre and southern photometric local Universe surveys

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ABSTRACT

Context. From the approximately 3500 planetary nebulae (PNe) discovered in our Galaxy, only 14 are known to be members of the Galactic halo. Nevertheless, a systematic search for halo PNe has never been performed.

Aims. In this study, we present new photometric diagnostic tools to identify compact PNe in the Galactic halo by making use of the novel 12-filter system projects, Javalambre Photometric Local Universe Survey (J-PLUS) and Southern-Photometric Local Universe Survey (S-PLUS).

Methods. We reconstructed the Isaac Newton Telescope Photometric Hα Survey of the Northern Galactic Plane diagnostic diagram and propose four new ones using (i) the J-PLUS and S-PLUS synthetic photometry for a grid of photo-ionisation models of halo PNe, (ii) several observed halo PNe, as well as (iii) a number of other emission-line objects that resemble PNe. All colour–colour diagnostic diagrams are validated using two known halo PNe observed by J-PLUS during the scientific verification phase and the first data release (DR1) of S-PLUS and the DR1 of J-PLUS.

Results. By applying our criteria to the DR1s (~1190 deg2), we identified one PN candidate. However, optical follow-up spectroscopy proved it to be a H ii region belonging to the UGC 5272 galaxy. Here, we also discuss the PN and two H ii galaxies recovered by these selection criteria. Finally, the cross-matching with the most updated PN catalogue (HASH) helped us to highlight the potential of these surveys, since we recover all the known PNe in the observed area.

Conclusions. The tools here proposed to identify PNe and separate them from their emission-line contaminants proved to be very efficient thanks to the combination of many colours, even when applied – like in the present work – to an automatic photometric search that is limited to compact PNe.

Key words. surveys – planetary nebulae: general – binaries: symbiotic – ISM: lines and bands – techniques: photometric

1. Introduction

Planetary nebulae (PNe) represent the final stage of the evolution of low-to-intermediate mass stars (0.8–8.0 M⊙), when the ejected asymptotic giant branch (AGB) and post-AGB material is ionised by the UV radiation field of the hot and luminous descendant. Due to the high temperature of the central star, a typical PN spectrum shows a great variety of emission lines: not only the recombination lines of the Balmer series and He, but also collisionally excited lines from several elements like O, N, S, Ne, and Ar (e.g. Fig. 1 of Kwitter & Henry 2001). Given the wide range of temperatures of the central stars
(50–250)×10^5 K, some PNe are lower-excitation nebulae, and their spectral characteristics can be very similar to those of H II regions (Osterbrock & Ferland 2006).

The AGB and post-AGB ejecta enrich the interstellar medium (ISM) with heavy elements that were produced during the evolution of the progenitor star. Thus, PNe provide important information about the production and evolution of chemical elements in the local Universe, and even more locally in the Milky Way (for reviews, see Magrini et al. 2012 and Gonçalves 2019).

In the recent past, several surveys have contributed to the discovery of new PNe. The AAO/UKST Hα Survey (Parker et al. 2005), later called Macquarie/AAO/Strasbourg Hα Planetary Nebula Catalogue (MASH catalogue, Parker et al. 2006), Southern Hα Sky Survey Atlas (SHAASSA; Gaustad et al. 2001), Wisconsin Hα Mapper (WHAM; Haffner et al. 2003), and the Isaac Newton Telescope (INT) Photometric Hα Survey of the Northern Galactic Plane (IPHAS; Drew et al. 2005), in which a number of PN candidates have been found in an automated manner (Viironen et al. 2009a,b; Sabin et al. 2010). Small, private surveys have also contributed to the discovery of new Galactic PNe (e.g. Boumis et al. 2003, 2006). The most recent compilation of PNe is published in the Hong Kong/AAO/Strasbourg/Hα PN catalogue (HASH; Parker et al. 2016). To date, HASH contains 2401 true, 447 likely, and 692 possible Galactic PNe. More genuine PNe candidates have been recently reported in the UKIRT Wide-Field Imaging Survey (UWISH2) of the Northern Galactic Plane (Gledhill et al. 2018) and in the CORNISH catalogue (Irabor et al. 2018; Fragkou et al. 2018).

So far, only 14 PNe are confirmed members of the Galactic halo (Otsuka et al. 2015). These are low-metallicity objects, since they come from the oldest population of the Galaxy, with log(O/H) + 12 < 8.1 (Peimbert 1978). Their height above the Galactic plane and their kinematics are additional criteria to locate them in the halo. Thus, halo PNe (hPNe) show large vertical distances from the Galactic plane, ~7.2 kpc (Otsuka et al. 2015). The understanding of the chemical evolution of the Galaxy can be improved by studying the old and metal-poor PNe located in the halo of our Galaxy, since these stars were born in the earlier phases of Galactic evolution (Otsuka et al. 2015).

The Javalambre Photometric Local Universe Survey (J-PLUS¹, Cenarro et al. 2019) and the Southern-Photometric Local Universe Survey (S-PLUS², Mendes de Oliveira et al. 2019) provide observations of the Galactic halo covering both northern and southern celestial hemispheres in a systematic way with twin telescopes using the same set of multi-band filters. In addition to the Hα filter, which is already vastly applied to systematically searching for Hα emitters such as PNe and symbiotic stars (SySt), the telescopes offer 11 more filters. In this work, we present and discuss new colour–colour diagnostic diagrams based on the available filters from J-PLUS and S-PLUS projects to identify halo planetary nebulae. Our main goal is to validate these tools, in addition to applying them to very first J-PLUS and S-PLUS data covering about 1190 deg² of the sky. We show that the J-PLUS and S-PLUS filter configuration provide a characterisation of the whole optical spectra of the sources and their potential to such an end with the completion of the surveys, thus opening new horizons for the search of PNe and SySt and other emission line systems.

Our paper is organised as follows: in Sect. 2, we summarise the observations related to J-PLUS and S-PLUS projects, as well as important information of the first data release for each survey.

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¹ https://www.j-plus.es
² http://www.splus.iag.usp.br

In Sect. 3, the synthetic photometry of the different emission-line sources are explored. Section 4 describes our selection method and the new diagnostic diagrams. Section 5 presents the validation of the colour–colour diagrams, using known hPNe observed by J-PLUS, and in terms of sources we recovered within the DR1 area, the PN candidate selected with our methodology. In Sect. 6 the results obtained after cross-match the J-PLUS and S-PLUS data with the HASH catalogue are discussed. In Sect. 7, we provide a general discussion and conclusions.

2. Observations

J-PLUS is a multi-filter imaging survey, which is being carried out from the Observatorio Astrofísico de Javalambre (OAJ, Cenarro et al. 2014), using the 83 cm Javalambre Auxiliary Survey Telescope (JAST/T80) and the T80Cam camera. This survey, which maps the northern sky, has a southern counterpart, the S-PLUS. The latter uses a twin telescope, the T80-South, located at the Cerro Tololo Interamerican Observatory (CTIO), in Chile. Both telescopes are equipped with cameras that provide a ~2.0 deg² field of view (FoV) of the sky, and each covers an area of around 8500 deg² in total. Their filter systems are made up of 12 filters spanning the optical range from 3000 to 10 000 Å, approximately. Although the prime goal of the J-PLUS survey is to perform the photometric calibration for the Javalambre Physics of the Accelerating Universe Astrophysical Survey (J-PAS; Benítez et al. 2015), it also provides a rich set of photometric data allowing the investigation of many classes of objects in the Galactic halo and in the local Universe. For example, given their multi-filter configuration, they can be used to search for emission-line sources as done by previous narrow-band surveys. J-PLUS and S-PLUS filter sets are formed of seven narrow-band filters; J0378, J0395, J0410, J0430, J0515, J0660 and J0861. They also include five broad-band Sloan Digital Sky Survey (SDSS) like filters (u, g, r, i and z, Fukugita et al. 1996), which are designed to detect the continuum of the sources. Tables 3 and 2 of J-PLUS and S-PLUS Papers 0 (Cenarro et al. 2019; Mendes de Oliveira et al. 2019) specify the characteristics of the filters of the surveys, and the features targeted by the narrow-band ones. The data used here come from J-PLUS scientific verification data, the first J-PLUS data release, and the first S-PLUS data release.

The J-PLUS survey is growing at ~1000 deg² yr⁻¹. Given the present rate of completion of the S-PLUS tiles, we anticipate that 4500 deg² may be covered by the end of 2020, and the full survey should be completed by the middle of 2023.

2.1. J-PLUS scientific verification data

These scientific verification data (SVD) comprise a group of well-known objects to test and challenge the scientific capabilities of J-PLUS (Cenarro et al. 2019). The J-PLUS SVD published observations of the galaxy clusters A2589 and A2593, M101, M49, the Arp313 triplet of galaxies, and a few nearby galaxies, including NGC 4470 and the Coma cluster. The Galactic PNe H 4–1 (Miller 1969) and PNG 135.9+55.9 (Tovmassian et al. 2001) were also included within these data.

2.2. First J-PLUS data release

The J-PLUS first data release (DR1) is composed of 511 fields observed with the 12 narrow- and broad-band filters, and it

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3 https://www.j-plus.es/datarereleases/data_release_dr1
covered 1022 deg$^2$ of the sky. DR1 is based on images collected by the JAST/T80 telescope from November 2015 to January 2018. Around nine million objects are included in this first data release. The limiting magnitudes (5′r, 3′′ aperture) in each filter are presented in Table 4 of Cenarro et al. (2019). The median point spread function (PSF) in the DR1 $r$-band images is 1.1″. The detection of the sources was done in the $r$-band using SEXTRACTOR (Bertin & Arnouts 1996), and the photometry in the 12 J-PLUS bands at the position of the detected sources was made using the aperture defined in the $r$-band image. Different types of apertures were used to perform the photometry: (i) circular aperture photometry (SEXTRACTOR’S MAG_APER) with apertures of different sizes (3′′ and 6′′), (ii) isophotal photometry (SEXTRACTOR’S MAG_ISO), (iii) Kron photometry (SEXTRACTOR’S MAG_AUTO), (iv) Petrosian photometry (SEXTRACTOR’S MAG_PETRO), (v) photometry after degrading the images of all the bands to the worst PSF, (vi) photometry after convolving all the images with a Gaussian kernel of $\sigma = 1.5″$, and (vii) photometry applying a PSF correction as that applied in Molino et al. (2014). In the present work, we use the 6′′ aperture. This choice follows the automatic method used by IPHAS photometry to find compact PNe, with a small angular diameter (typically $\leq 5″$), Viironen et al. (2009b). The 6′′ aperture chosen also follows Akras et al. (2019a), who found that PNe with angular sizes larger than 6′′ exhibit very low $(r-H\alpha)$ colour index.

2.3 First S-PLUS data release

The S-PLUS DR1$^4$ includes 80 fields of the Stripe-82 area, a rectangular area with coordinates $4° < RA < 20°$ and $-12.6° < Dec < 1.26°$. These fields were observed during the scientific validation process of the survey. DR1 contains about one million sources, and the limiting magnitude of each filter is presented in Table 8 of the S-PLUS presentation paper (Mendes de Oliveira et al. 2019). Sources were detected using SEXTRACTOR. Photometry was performed by adopting three types of aperture: (i) a circular aperture of 3′′ in diameter (SEXTRACTOR’S APER), (ii) Kron photometry (SEXTRACTOR’S AUTO), and (iii) Petrosian photometry (SEXTRACTOR’S PETRO). Similarly to the case of J-PLUS, we use the circular aperture of 3′′. This aperture is the best within the three possibilities, since – in addition to the arguments given in Sect. 2.2 – it ensures that large objects with high surface brightness, like emission-line galaxies or H II regions, are not recovered (with this automated method).

The tools we use to identify PNe in the two surveys are synthetic photometry and colour–colour diagrams, which we describe in detail in the following sections.

3. Synthetic photometry

In order to recover the synthetic photometry of PNe and their contaminants, we follow the procedure developed by Aparicio Villegas et al. (2010), who characterised the ALHAMBRA photometric system. The magnitudes of any photometric system are defined by a set of AB magnitudes (Oke & Gunn 1983):

\[ AB = -2.5 \log f_\lambda - 48.6, \]

where the constant is obtained from the equation

\[ 48.6 = -2.5 \log F_0 \]

\[ F_0 = 3.63 \times 10^{-20} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1} \text{ being the flux of Vega at } \lambda = 5500 \text{ Å}. \]

The term $f_\lambda$ is the flux per unit of frequency (erg s$^{-1}$ cm$^{-2}$ Hz$^{-1}$).

The synthetic photometry is obtained from the convolution of the observed or modelled spectra with the transmission function or pass-band of a specific photometric system. The transmission function accounts for the transmission filter, the reflectivity of the telescope mirror, the transmission of the camera optics and the quantum efficiency of the detector used (Bessell 2005). By considering these characteristics of the photometric system, Eq. (1) turns to

\[ AB = -2.5 \log \frac{1}{c} \int f_\lambda S_\lambda d\lambda - 48.6, \]

where $c$ is the light speed, $S_\lambda$ is the transmission function, and the units of $f_\lambda$ are (erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$). Therefore, Eq. (3) makes it possible to estimate the synthetic photometry (AB magnitude) in a specific photometric system.

The synthetic photometry or photo-spectra of several emission-line sources – PNe, SySt, cataclysmic variables (CVs), quasi-stellar objects (QSO), extragalactic H II regions, young stellar objects (YSOs), B[e] stars, and star-forming galaxies (SFGs) – were obtained through the convolution of the theoretical transmission curves of the J-PLUS and S-PLUS systems with the available optical spectra, as in Eq. (3).

The same procedure was also applied to a grid of photoionisation models for hPNe to obtain their synthetic magnitudes. For the hPN modelling, we adopted the photoionisation code, CLOUDY (Ferland et al. 2013). The initial parameters used to compute the models reflect the typical properties of the PN population located in the Galactic halo. They represent different sets of nebular abundances, with electron densities of 1000, 3000 and 6000 cm$^{-3}$, of a spherically symmetric nebula with a radius of 2.7″, at distance of 10 kpc. Central star (black body) effective temperatures from 50 000 to 250 000 K, in steps of $10 \times 10^3$ K, and luminosities of 500, 1000, 5000 and 10 000 $L_\odot$ were considered. We reddened the modelled spectra applying the reddening curve by Fitzpatrick (1999), and using two different colour excesses, $E(B-V) = 0.1$ and 0.2, following the J-PLUS and S-PLUS average extinction of $E(B-V) = 0.1$ (Cenarro et al. 2019; Mendes de Oliveira et al. 2019).

Figure 1 comprises all synthetic photo-spectra recovered as explained above. Panels a and b display the photo-spectra of the Galactic hPN DiDm 1 (Kwitter & Henry 1998), and of an extragalactic PN located in NGC 205 (Gonçalves et al. 2014), as examples. Both objects show strong H\alpha emission, with a continuum a little more intense in the blue than in the red part of the spectrum. Panels c and d show two CLOUDY modelled hPNe. Both have the same chemical abundance (equivalent to that of the hPN DiDm 1), and the same luminosity of $10^4 L_\odot$. The effective temperature and density of the model in panel c are of $60 \times 10^3$ K and 1000 cm$^{-3}$ and for the model in panel d of $200 \times 10^3$ K and 6000 cm$^{-3}$, respectively. So, the first model (panel c) corresponds to a low-excitation PN. The ionising star is not hot enough to produce such an [OIII] emission able to stand out significantly in the $g$ broad-band magnitude. The second model (panel d) represents a high-excitation PN. In this case, the magnitude of the $g$ broad-band filter is impacted by the strong [OIII] and [HeII] emission lines. Note that the $g$-band also includes the H\beta line, therefore it is not possible to disentangle the H\beta and [OIII] emission lines in the J-PLUS and S-PLUS photo-spectra and to quantify the level of excitation more precisely. The hPNe (modelled or observed) differ

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$^4$ https://datalab.noao.edu/splus/
from Galactic-disc PNe in size, velocity, distance, and extinction (Howard et al. 1997; Otsuka et al. 2015). All the properties—high distances implying small angular sizes, poor in metals and low extinction—of hPNe, with the exception of the large velocities, make them occupy a specific locus in the colour-colour diagrams, significantly different to that of the disc PNe.

In addition to PNe, we also computed the photo-spectra of a number of other emission-line sources that mimic PNe. Panel e of Fig. 1 shows the photo-spectrum of an extragalactic H II region located in the dwarf galaxy NGC 55 (Magrini et al. 2017), in which the H ε emission is also perceptible. The low-excitation PN (on panel c) and the H II region show very similar photo-spectra, which will make them hard to distinguish within the J-PLUS and S-PLUS catalogues. Merrett et al. (2006) have shown that for low-luminosity objects, it is hard to distinguish PNe and H II regions, using the ratio between [O III] and Hα+[N II] emission lines. We encounter the same problem here, even using a wider range of wavelengths. We further investigate this issue, including morphological criteria, in Sect. 5. With the exception of the morphology, the same difficulty occurs for H II galaxies, as is shown in panel g, for a SDSS H II galaxy. At this point, it should be noted that the synthetic photometric magnitudes are below the limiting magnitudes for all the filters bluer than 4500 Å, in the case of the extragalactic PN (panel b), and for r and J0378 filters in the case of the extragalactic H II region (panel e).

Panel f of Fig. 1 presents the photo-spectrum of the SySt LMC1 (Munari & Zwitter 2002), displaying a clear H α emission with an increasing continuum to the longer wavelengths. The resolution of the J-PLUS and S-PLUS photometry allows to perceive undoubtedly the reddened nature of the SySt. As PNe, symbiotic stars are also constituted by an evolved star, in most cases a white dwarf (WD). They are interacting binary systems with a cold giant companion (red giant or Mira star) and an evolved hot star. The wind of the giant is ionized by the UV radiation from the evolved companion, thus resulting in a spectrum composed by both absorption features from the stellar photo-sphere of the giant (e.g. TiO and VO), and emission line features from the excited ions (Munari & Zwitter 2002; Corradi et al. 2003; Rodriguez-Flores et al. 2014; Ilikiewicz & Mikolajewska 2017; Akras et al. 2019b; Angeloni et al. 2019). The photo-spectrum of a cataclysmic variable (CV) selected from the SDSS catalogue is also presented in Fig. 1 (panel i). Cataclysmic variables are interacting binary systems, in which a white dwarf accretes gas from a main-sequence star, via Roche lobe overflow, forming an accretion disc. The Balmer lines are produced in the optically thin outer regions of the disc (Williams 1980). It is simple to notice that based on their photo-spectra, PNe of high and low excitation could be mistaken for CVs. Panel h brings the convolution results for a YSO, from Alcalá et al. (2014). An accretion disc, from where the Hα emission emerges, is also present in this type of (pre-main-sequence) stars. The YSO’s photometry shows a continuum that is stronger in the red part of the spectrum. Panel j displays a B[e] star (Lamers et al. 1998). B[e] stars have a surrounding nebula produced by large-scale mass loss involving one or more eruptions (Marston & McCollum 2006). Its photo-spectrum resembles that of both SySt and YSOs.

The J-PLUS and S-PLUS synthetic spectra of several SDSS QSOs, in specific redshift (z) ranges, were also included in our selection of emission-line objects. The QSOs in the redshift ranges \(1.3 < z < 1.4\), \(2.4 < z < 2.6\), and \(3.2 < z < 3.4\) possess features that resemble those of PNe, in other words, they could be misinterpreted as Hα line emission at \(z = 0\). At these
4. Synthetic colour–colour diagrams: selection criteria

The photo-spectra of the emission-line sources just discussed in Figs. 1 – for PNe, SySt, CVs, B[e], QSOs, extragalactic H II regions, YSOs, and SFGs – are now used to build diagnostic colour–colour diagrams. Our goal is to pinpoint the most relevant ones to discriminate PNe from the above systems.

4.1. IPHAS equivalent colour–colour diagram

Drew et al. (2005) designed the IPHAS survey (see Sect. 1) showing that the (r′ – Hα) vs. (r′ – i′) diagram is an optimal tool to select strong Hα emission-line sources (Witham et al. 2008). IPHAS PNe candidates were selected using the above colour–colour diagram as well as the common (J – H) vs. (H – Ks) 2MASS diagram. Their true nature was confirmed later on, spectroscopically (Corradi et al. 2008; Viironen et al. 2009a; Rodriguez-Flores et al. 2014; Sabin et al. 2014).

Given that the J-PLUS and S-PLUS filter systems include the three IPHAS filters, we reconstructed the IPHAS equivalent diagram in Fig. 2. The (r′ – J0660) colour clearly indicates an increasing excess of the Hα emission line, while the (r′ – i) one increases with the reddening, as previously stated in Corradi et al. (2008). Modeled PNe are found to display (r′ – J0660) > 0.6 due to their strong Hα emission lines as well as (r′ – i) < 0. It should be noted that Fig. 1 of Viironen et al. (2009a) shows that Galactic disc PNe have (r′ – i) < 1, so they are redder than the hPNe. The empirical (black) lines delimit the selection criteria for being PNe (PNe zone) and are meant to include most of the modelled hPNe and exclude the majority of the contaminants. The definition of the selection criteria or zones has been made visually. This holds for the IPHAS equivalent as well as the new colour–colour diagrams of the present study. The PNe zone is contaminated by extragalactic H II regions, especially for moderately lower (r′ – J0660) colour indices or, equivalently, low-excitation nebulae. Therefore, our lists of PN candidates are not characterised by high purity. The distribution of main sequence (MS) and giant stars (purple and brown symbols in the inset figures) in the library of stellar spectral energy distributions (SEDs, Pickles 1998) are represented by the purple and brown symbols, and the loci of white dwarf stars observed by S-PLUS (DR1, Mendes de Oliveira et al. 2019) are represented by the light green symbols. The limiting region applied in the candidate selection is shown by black lines for hPNe. The arrow indicates the reddening vector with AV ≃ 2 mag. It was estimated by comparing the locus of unreddened models of PNe with the reddened ones.

![Fig. 2. J-PLUS and S-PLUS (r′ – J0660) vs. (r′ – i) colour–colour diagram, equivalent to IPHAS (r′ – Hα) vs. (r′ – i′)]. The big yellow and green stars with error-bars are the J-PLUS observations for H 4–1 and PNG 135.9+55.9, respectively. Included in the diagrams, there are families of clouds modelled hPNe spanning a range of properties (density map region). Cyan circles represent hPNG 135.9+55.9 spectrum from SDSS, DdDM-1 (Kwitter & Henry 1998), NGC 2022, BB-1, H4-1 (Kwitter et al. 2003), and MWC 574 (Pereira & Miranda 2007). Grey diamonds represent H II regions in NGC 55 (Magrini et al. 2017). Red boxes display Munari & Zwitter (2002) and Munari & Jurdana-Sepe (2002) SySt, this group also includes external SySt from NGC 205 (Gonçalves et al. 2015), IC 10 (Gonçalves et al. 2008) and NGC 185 (Gonçalves et al. 2012), and red triangles correspond to IPHAS symbiotic stars (Rodriguez-Flores et al. 2014). Yellow circles correspond to cataclysmic variables (CVs) from SDSS. Orange triangles refer to SDSS star-forming galaxies (SDSS SFGs). SDSS QSOs at different redshift ranges are shown as light blue diamonds, and YSOs from Lupus and Sigma Orionis (Rigliaco et al. 2012; Alcalá et al. 2014) are represented by salmon stars. Blue stars refer to B[e] stars from Lamers et al. (1998). In the inset plot, the synthetic main sequence and giant stars loci from the library of stellar spectral energy distributions (SEDs, Pickles 1998) are represented by the purple and brown symbols, and the loci of white dwarf stars observed by S-PLUS (DR1, Mendes de Oliveira et al. 2019) are represented by the light green symbols. The limiting region applied in the candidate selection is shown by black lines for hPNe. The arrow indicates the reddening vector with AV ≃ 2 mag. It was estimated by comparing the locus of unreddened models of PNe with the reddened ones.

4.2. New J-PLUS and S-PLUS colour–colour diagrams

Studying the photo-spectra of the PNe and their contaminants (Sect. 3), four new colour–colour diagrams were defined.
(J0515 − J0660) vs. (J0515 − J0861), (g − J0515) vs. (J0660 − r), (z − J0660) vs. (z − g), and (J0410 − J0660) vs. (g − i) to search for PN candidates in the J-PLUS and S-PLUS catalogues.

In the first diagnostic diagram, high- and low-excitation PNe occupy distinct regions within the PNe zone. For instance, H 4–1, a moderate high-ionisation PN, exhibits (g − J0515) ≈ −2, with $T_{\text{eff}}$ around 132 $\times 10^3$ K (Henry et al. 1996), and MWC 574, a very low-excitation PN with (g − J0515) ≈ 0.0, exhibits an [O III] emission even weaker than Hβ (Sanduleak & Stephenson 1972; Pereira & Miranda 2007). The (J0515 − J0861) colour index is associated with the continuum of the sources. Neither of these two filters contains strong emission lines. The (J0515 − J0660) colour provides an estimation of the Hα excess.

Regarding the second diagnostic diagram, the (g − J0515) colour index yields the excess of the [O III] lines. Therefore, the higher the (g − J0515) colour, the higher the excitation of the nebula. This can be seen from the photo-spectra of two CLOUDY models with different stellar temperatures (panels c and d in Fig. 1). We remind the reader, however, that the g broad-band filter is also affected by the Hβ and other emission lines down to about 4000 Å. The (J0660 − r) colour is to illustrate the Hα emission as it has been explained in the previous section.

The (z − J0660) colour index also gives us an estimation of the Hα excess, by taking into account the continuum at the very red part of the spectrum, while the (z − g) colour is directly related to the shape of the continuum from the blue to the red part of the spectrum. The QSOs and SFGs are concentrated in a very small area ($-2 < (z − J0660) < 1$ and $-2 < (z − g) < 1$), well separated from PNe.

Finally, (g − i) is another colour index associated with the shape of the continuum, and the (J0410 − J0660) colour reflects the Hα excess, though using different parts of the spectrum in contrast with the previous diagrams. From panel d in Fig. 3, we find that QSOs and SFGs show an increase in the (J0410 − J0660) colour as a function of the (g − i) colour, while PNe appear to have a more restricted range of (g − i) values between −2 and 0, and (J0410 − J0660) values from 0 to 4. Hence, the
(J0410 – J0660) vs. (g – i) colour–colour diagram can distinguish PNe from galaxies. The SySt and YSOs are found to lie in the right part of the plot ((g – i) > 2), which is indicative of their stronger emission in the near-IR. This last diagnostic diagram turns out to be very useful to assure low contamination by B[e] stars, differing from the first three diagrams.

Figure 3 and the colour–colour diagrams also show the loci of main sequence, giant and white dwarf stars, which clearly do not affect the PN selection criteria. Leaving aside the H II regions, all the colour–colour diagrams turned out to be very useful for identifying good PN and SySt candidates (a detailed analysis for SySt is to be presented in a forthcoming paper). The combination of several narrow- and broad-band filters to construct colour–colour diagrams allows characterising the whole optical spectrum of every source type. If a source simultaneously satisfies all the criteria of being a PN, the possibility of false positive identification, though not negligible, is small.

5. Validation of the colour–colour diagrams

Aiming to validate the tools to search for PNe in J-PLUS and S-PLUS, we followed two different methods. The first is to use the J-PLUS SVD (Sect. 2.1) and the second is by applying the previously presented selection criteria (Sect. 4) to the DR1 (very limited in area) of each of these surveys.

5.1. SVD validation

Two hPNe, H 4–1 and PNG 135.9+55.9, were observed during the scientific verification phase of the J-PLUS, as described in Sect. 2.1. The instrumental magnitudes were calculated for each object using IRAF\(^5\). In order to find the calibrated magnitudes, we used the zero point provided by the unit of processing and data analysis (UPAD) inside the J-PLUS collaboration. The resulting photo-spectra are shown in Fig. 15 of the J-PLUS presentation paper (Cenarro et al. 2019). In Table 1, we compare the synthetic and observed magnitudes of these hPNe. For H 4–1, the two magnitudes are very compatible, with a difference smaller than 0.07, except for the \( u \) and J0378 filters, whose differences are 0.4 and 0.23, respectively. As for PNG 135.9+55.9, the synthetic and observed magnitudes are found to be in very good agreement, with, on average, a difference smaller than 0.1 mag. The only discrepant magnitude is the one of the J0660 filter, for which the difference reaches 0.35 mag.

The positions of H 4–1 and PNG 135.9+55.9 in the colour–colour diagrams – based on their J-PLUS observations – are shown in Figs. 2 and 3 as yellow and green stars, respectively. H 4–1 satisfies all five criteria of being a PN (see Figs. 2 and 3), while PNG 135.9+55.9 passes four of them, violating the \((g-J0515)\) colour criterion given in panel b of Fig. 3. We note, however, that this PN is located close to the border of the PN zone. This border was defined in a conservative way, to avoid more contamination of H II regions and SySt, since low-excitation PNe and H II regions are extremely hard to differentiate.

5.2. DR1 validation

In order to apply the colour–colour diagrams to the J-PLUS and S-PLUS data releases, there are a few cleaning instructions (FLAGS) that need to be considered, since they avoid artefacts. For J-PLUS, we used two FLAGS. One responsible for excluding the objects that have neighbours, bright and close enough to significantly affect the photometry, or that have bad pixels (more than 10% of the integrated area affected). The other FLAG allows us to exclude objects originally blended with another one. In the case of S-PLUS, only one FLAG was applied, which avoids the objects for which the aperture photometry is likely biased by neighbour sources or by more than 10% of bad pixels. Note that not considering the sources flagged with these known issues affects the selection, because of the quality of the photometry.

To encounter the best way of applying all five selection criteria described in Sect. 4, we follow a few validating steps, using the J-PLUS data set. To ensure the recovery of the largest amount of potential candidates due to lack of detection in some filters, we explore how the limiting magnitude errors for different sets of filters affect the results: (i) by limiting the error associated with the magnitudes corresponding to IPHAS-like magnitudes (\(i, r\) and J0660), and admitting any error for the other 9 photometries, (ii) by limiting the magnitude errors of the J0660 and broadband filters, and finally, (iii) by limiting the magnitude errors of all narrow- and broadband filters. Whenever it applies, the limiting magnitude error is ±0.2. All the procedure was performed with the 6′′ aperture.

To test whether further limitations would minimise the number of contaminates, we use step (ii) of the validation process. This option accounts for the fact that the continuum of PNe is usually faint, with the consequence of uncertain photometry (large errors) in the narrow-band filters. Therefore, this time we limited the errors in the H\(\alpha\) and broad-band magnitudes. Four sources are returned in this case, they are the two known

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Table 1. Synthetic and observed magnitudes of H 4–1 and PNG 135.9+55.9, for the 12 J-PLUS filters.

| Filter | Synt. | Obs. | Synt. | Obs. |
|--------|-------|------|-------|------|
| \( u \) | 15.74 | 16.14 ± 0.13 | 17.37 | 17.22 ± 0.10 |
| J0378 | 15.54 | 15.77 ± 0.02 | 17.36 | 17.31 |
| J0395 | 17.01 | 16.97 ± 0.06 | 17.35 | 17.28 ± 0.12 |
| J0410 | 17.14 | 17.11 ± 0.03 | 17.43 | 17.43 ± 0.10 |
| J0430 | 16.61 | 16.68 ± 0.07 | 17.48 | 17.48 ± 0.13 |
| g | 15.59 | 15.61 ± 0.04 | 17.62 | 17.74 ± 0.07 |
| J0515 | 17.63 | 17.62 ± 0.04 | 17.86 | 17.80 ± 0.07 |
| J0660 | 13.45 | 13.47 ± 0.04 | 17.02 | 16.66 ± 0.08 |
| i | 17.28 | 17.24 ± 0.05 | 18.47 | 18.40 ± 0.07 |
| J0861 | 17.44 | 17.60 ± 0.03 | 18.69 | 18.55 ± 0.07 |
| z | 17.23 | 17.30 ± 0.09 | 18.72 | 18.61 ± 0.10 |
5.3. Photometry and spectroscopy of the PN candidate

The location of the PN candidate, with ID in J-PLUS DR1 26063-6129, (J2000 RA: J09 50 20.92, Dec: 31 29 11.02) is represented by the blue circle in Figs. 4 and 5. The source displays a clear Hα excess (see Fig. 6). Also, from the b, c, and d diagrams of Fig. 5, it is possible to argue that this candidate has moderate [O III] and/or Hβ emission. In fact, the (g − J0515), (z − g) and (z − i) colours have approximate values of −0.5, 0.5, and −0.6, respectively, indicating low to moderate contribution of the [O III] and/or Hβ lines to the g-band magnitude.

Figure 6 displays the PN candidate photo-spectrum, whose shape is very similar to that of typical PNe in the J-PLUS and S-PLUS configurations (see, for instance, panels a and b of Fig. 1), with strong emission lines and relatively flat continuum. From its J-PLUS Hα image, we derived an angular radius of ~1.5 arcsec. This figure also presents a composite g, r, and i image centred on the candidate. It clearly shows another object, a diffuse emission, which we identified as the UGC 5272 galaxy, at 7 Mpc (Garrido et al. 2004; Karachentsev et al. 2014). If the candidate was at the distance of UGC 5272, it would have a size of 40–50 pc, and it would be a H II region. It could also be a Milky Way halo source, at 30 to 40 kpc, for instance, displaying a 0.2 to 0.3 pc size.

The PN candidate was observed with the 2.54-m INT at Roque de los Muchachos observatory in La Palma (Spain), on November 15 2018, using the Intermediate Dispersion Spectrograph (IDS). The spectrum of the candidate, together with the J-PLUS photometry, is presented in Fig. 7. The fluxes of the emission lines detected in our spectrum are presented in Table 2. Based on the Hα, Hβ, and Hγ lines, its extinction is 0.35. From the observed central wavelength of the detected lines, we also derived the heliocentric velocity of the source, 515 km s⁻¹. This value agrees with the heliocentric velocity of the galaxy (S13 ± 2 km s⁻¹; Garrido et al. 2004), and it confirms that our J-PLUS PN candidate belongs to UGC 5272.
The [S II] λλ6716/6731 diagnostic ratio of 1.75 suggests a very tenuous H II region.

5.4. Recovering DR1 known Hβ emitters

One PN and two H II galaxies were recovered applying our selection methodology to the J-PLUS catalogue.

PN Sp 4-1 (J2000 RA: 19 00 26.5, Dec: 38 21 07.99), also called PN G068.7+14.8, is a previously confirmed compact Galactic PN (Acker et al. 1992; Moreno-Ibáñez et al. 2016). In the diagrams of Figs. 4 and 5, Sp 4-1 is represented by the green circle. The colours (J0515 – J0660) and (g – J0515) are estimated to be 3.4 and −1.6, respectively. The former colour clearly indicates a strong Hβ emitter, while the latter implies a significant contribution from the [O III] and Hβ lines to the g-band. The upper panel of Fig. 8 displays its photo-spectrum and corresponding image. There is no doubt that these data correspond to those of a typical PN photo-spectrum, of a roundish and compact object with full width at half maximum (FWHM) ~ 1.3 arcsec.

LEDA 2790884 (J2000 RA: 20 00 25.50, Dec: 35 32 32.01) is a H II galaxy (blue compact galaxy) at z ~ 0.0024 (Moiseev et al. 2010). The loci where the system is represented in the diagrams of Figs. 4 and 5 (one of the red diamonds) corresponds to that of a low-excitation PN, in agreement with the expectations from the H II regions. The photo-spectrum and image of this source are shown in the middle panel of Fig. 8.

LEDA 101538 (J2000 RA: 16 16 23.51, Dec: 47 02 02.64), the red diamond in Fig. 5, is a H II galaxy (blue compact dwarf galaxy) at z ~ 0.002, with a very blue colour, which indicates that it is likely a starburst (Ann et al. 2015). The photo-spectrum of this galaxy is presented in the lower panel of Fig. 8. The spectra of the H II galaxies are very similar to those of giant extragalactic H II regions (Sargent & Searle 1970). For this reason, LEDA 101538 lies in the PN zone, even though it is not a PN.

6. DR1 vs. the complete PNe catalogue – HASH

We cross-matched the J-PLUS and S-PLUS data with the HASH catalogue (Parker et al. 2016). We remind the reader that this catalogue contains all known PNe, which are classified as true, likely and possible PNe. We found four matches with J-PLUS, and one with S-PLUS. The J-PLUS ones appear in the colour–colour diagrams as purple (1 true PN), brown (1 likely PN), and orange (2 possible PNe) circles, while the S-PLUS match is the
dark magenta (1 possible PN) circle in Figs. 4 and 5. It is simple to see from these diagnostic diagrams that, following our selection criteria, none of these sources are classified as PNe, all being located outside the PN zone. Four of these HASH sources are located in the zone of very blue WDs. Why does this happen? Below, we describe each source, thus highlighting that their sizes preclude their automatic recovery by our criteria.

6.1. J-PLUS

Jacoby 1 (J2000 RA: 15 23 46.56, Dec: 52 22 04.05) is classified as a true (tHASH) PN, previously reported by Jacoby & van de Steene (1995). The low (r ~ J0660) and (J0515 ~ J0660) colour indices are indicative of very weak, or totally absent, Hα line-emission. The first panel of Fig. 9 displays the photo-spectrum, which turns out to be typical for white dwarfs (e.g. Fig. 14 of Cenarro et al. 2019) and its combined image (right inset image of the figure). Following Tweedy & Kwitter (1996), Jacoby 1 is a highly evolved PN of ~11 arcmin in size. Such large sizes cannot be recovered/found by automatic photometric criteria, this is only possible by visual inspection of the fields (e.g. Sabin et al. 2014). We managed to detect the Hα emission from the PN by applying a Gaussian smoothing filter of 10 pixels to the combined RGB – J0660, r, and i – as shown in the left inset in Fig. 9.

TK 1 (J2000 RA: 08 27 05.52, Dec: 31 30 08.10) is a likely (lHASH) PN, of up to 15 arcmin (Tweedy & Kwitter 1996). Its position in our colour–colour diagrams is very close to Jacoby 1 suggesting similar spectral characteristics (see photo-spectrum in the second panel of Fig. 9). So, we suggest that the recovered emission is that of a WD star, in agreement with Rebassa-Mansergas et al. (2015). The above technique that recovered the nebular emission of Jacoby 1 was used, though it could not confirm the nebula that is possibly surrounding this white dwarf.

Kn J1857.7+3931 (J2000 RA: 18 57 42.24, Dec: 39 31 00.13) is a possible (pHASH) PN. It shares the same position in the diagnostic diagrams, as well as an akin photo-spectrum, with Jacoby 1 and TK 1 (see Fig. 9). Nevertheless, when we looked for the extended nebula, this was not detected. We argue that Kn J1857.7+3931 is also a WD star, possibly associated with a nebular emission too faint to be detected by J-PLUS.

KnPa J1848.6+4151 (J2000 RA: 18 48 38.36, Dec: 41 51 02.52), another pHASH PN, is located far from the other HASH objects in our colour–colour diagrams (orange circle with large error bar), and again with no Hα excess. KnPa J1848.6+4151 lies in the regime of SDSS SFG and QSOs (fourth panel of Fig. 9). It is a very faint object with r ~ 19.5 and its estimated angular size is of ~10.3″. KnPa J1848.6+4151 is very likely a galaxy (e.g. Fig. 16 of Cenarro et al. 2019; Alam et al. 2015; Greiss et al. 2012), and less likely to be a genuine PN.

6.2. S-PLUS

Fr 2-21 (J2000 RA: 21 26 21.17, Dec: 00 58 34.22) is also called PHL 4, and previously identified as a hot subdwarf (Kilkenny 1984), in addition to being a pHASH PN. It is located very close to the other HASH objects in the diagnostic diagrams. Its properties (Fig. 10) suggest another WD. No extended nebula was found combining J0660, r and i images.

7. Discussion and conclusions

The results described above highlight the potential of the data provided by J-PLUS and S-PLUS to explore the population of planetary nebulae in the Galactic halo. The developed photometric tools used to identify strong emission-line sources were applied to the very limited area surveyed up to now – in both J-PLUS and S-PLUS – returning promising results.

Our selection criteria were very successful in avoiding all the strong emission-line emitters present in the fields, apart from...
the compact H II regions (H II galaxies), which means that J-PLUS and S-PLUS can really do a good job in terms of searching for PNe, at the same time minimising the list of spectroscopic follow-up candidates. As anticipated in Sect. 3, the ability of photometrically distinguish PNe and H II regions is strongly hampered by the similarities between low-excitation PNe and H II regions. Therefore, our only way of avoiding lots of H II regions among the candidates is by limiting the automatic search to compact PN. For this reason, we adopt apertures up to 6 arcsec. Unfortunately, the first PN candidate identified in these surveys turned out to be a H II region located in the UGC 5271 galaxy, which resembles a compact PN.

The larger planetary nebulae with lower density and corresponding lower surface brightness are more difficult to discover. These objects are essentially undetectable by survey methods. The cross-match between the HASH and J-PLUS/S-PLUS catalogues made this point very clear. The magnitudes of the resultant PNe matches correspond only to the photometry of the central WDs, as can be seen from their photo-spectra with no Hα emission.

As in the case of IPHAS, a parallel study needs to be done in order to find extended PNe (Sabin et al. 2014). It is necessary to bin the images in order to increase the surface brightness of the extended nebula and make their recovery feasible by visually inspecting one by one the images of the surveys.

In conclusion, we considered the photometric systems of two twin imaging surveys (J-PLUS and S-PLUS), by using the synthetic photometry of different types of strong emission-line sources, to select the best combination of filters and construct diagnostic colour–colour diagrams to isolate hPNe. We reproduced the equivalent IPHAS and proposed four new diagnostic colour–colour diagrams to separate hPNe from SySt, CVs, B[e] stars, QSOs, extragalactic H II regions, star-forming galaxies, and young stellar objects. We find that the there is a high probability that a candidate found by our criteria will end up being a genuine PN if it is located well within the PN zones in the IPHAS equivalent and the other four colour–colour diagrams we proposed. It is also true that J-PLUS and S-PLUS are not completely successful at discriminating low-excitation PNe from compact H II regions (H II galaxies). We have validated our colour–colour diagrams through the photometry of the known hPNe H I–I and PNG 135.9+55.9 observed by J-PLUS during the SVD phase, and by applying them to the J-PLUS DR1 and S-PLUS DR1, which make up an observed area of the sky of ~1900 deg².

Having proven that our selection criteria are very effective in selecting PN candidates, even considering the contamination by H II regions/galaxies, we intend to continuously apply these photometric tools to the forthcoming J-PLUS and S-PLUS data releases, to provide a more complete list of hPN candidates for spectroscopic follow-up.

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Fr 2-21

Fig. 10. S-PLUS photo-spectrum of Fr 2-21 and corresponding image. This object is classified as possible PN in the HASH catalogue.
