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Exploitation of the IPHAS to Investigate Planetary Nebulae

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Similar to other classes of astronomical objects, there is a large discrepancy between the total count of theoretically predicted planetary nebulae (PNe) and the number of those actually observed. This discrepancy introduces bias in our attempt to globally understand and characterize the PNe population. Major efforts have been made to find the *missing PNe*. In particular, the INT Photometric Hα Survey (IPHAS) has, since its debut, provided a whelm of new (candidate) PNe, some of which have been studied in depth using various methodologies such as deep imaging and low- and high-resolution spectroscopy. Here, we present the outcome of the analysis of a first group of these well-investigated *IPHAS PNe* with a focus on the extended ones. We show that, in general, the missing objects that were expected to be unveiled by the survey (low density, evolved, and distant) are indeed discovered, but the survey also allows the retrieval of "simply" overlooked PNe.

Keywords: survey, optical, planetary nebulae, IPHAS, census

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1 INTRODUCTION

Planetary nebulae (PNe) are ionized shells of gas and dust that represent the late stage of the evolution of low- and intermediate-mass stars (~1–8 M⊙). Their importance in terms of chemical enrichment of the Galaxy, distance estimators, and plasma laboratories is well known, and a full review can be found in Kwitter and Henry (2022).

In order to improve our knowledge of PNe, a good census of this population is needed, if not crucial. Actually, the ~3,500 currently known Galactic PNe[1] only represent a fraction of the total estimated number of ~25,000 objects (Jacoby et al., 2010; Frew, 2017). Several surveys, particularly with narrowband Hα filters, have been conducted to unveil the missing PNe, that is, those with low surface brightness, compact, and located in crowded areas, obscured by dust, for example (Sabin, 2008; Frew et al., 2016).

We focus on the outcome of the INT Photometric Hα Survey (IPHAS) by Drew et al. (2005), which scanned the northern Galactic plane over 1800 deg^2 and allowed the discovery of various new PNe. The subsequent deep analysis of these objects will be the center of our discussion, so we can see the characteristics of PNe unveiled by this survey.

This article is organized as follows. In **Section 2**, we present the IPHAS. In **Section 3**, we present the different works conducted on specific PNe and a comparative analysis based on various parameters. Our discussion and conclusions are presented in **Section 4**.

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[1] They are compiled in the Hong Kong/AAO/Strasbourg Hα planetary nebula database (HASH) (Parker et al., 2016).

2 INT PHOTOMETRIC Hα SURVEY

As aforementioned, IPHAS scanned the northern part of the Galactic plane in the restricted galactic latitude range ±5°. The survey was conducted in the Hα, using r' and i' filters with a wide-field camera mounted on the 2.5-m Isaac Newton Telescope (La Palma, Spain). One of the advantages of this CCD survey compared to previous ones is the depth reached. Indeed, IPHAS can target compact sources down to ~21 mag in r' and ~20 mag in Hα and extended sources down to 2.5×10^{-16} erg cm^{-2} s^{-1} arcsec^{-2} at binning 1 (0.33 arcsec/pixel) and ~10^{-17} erg cm^{-2} s^{-1} arcsec^{-2} at binning 15 (5 arcsec/pixel).

The survey produced various general photometric and imaging catalogs (González-Solares et al., 2008; Barentsen et al., 2014; Sale et al., 2014; Scaringi et al., 2018; Monguió et al., 2020; Fratta et al., 2021; Greimel et al., 2021), but it also focused on dedicated astronomical objects such as PNe for instance.

Hence, within the IPHAS consortium, several articles and catalogs reporting the detection of new PN candidates have been presented by Corradi et al. (2005), Viironen et al. (2009a), Sabin et al. (2010), and Sabin et al. (2014), and some still have to be introduced (see Ritters et al. submitted).

The first results of these searches indicated 781 compact PNe candidates and 157 true, likely, and possibly extended PNe. In addition to the detection reports, studies directed toward distance determination using the extinction method (Giammanco et al., 2011; Dharmawardena et al., 2021), the H_2 molecular content (Ramos-Larios et al., 2017), a classification system (Akras et al., 2019), and deep imaging of a sample of PNe (Sabin et al., 2021a) were conducted.

Detailed characteristics of the *IPHAS PNe* need to be studied in order to better understand the type of objects that would preferentially be detected using the survey and to identify how it is contributing to the increase of our knowledge of these evolved stars.

3 COMPARATIVE STUDY OF INVESTIGATED INT PHOTOMETRIC Hα SURVEY PLANETARY NEBULAE

Among all PNe identified with IPHAS, few have been thoroughly investigated, that is, in terms of morphological structure, physical parameters, abundances, and kinematics (**Figure 1**). We cite a group of ten extended PNe (with the nomenclature *IPHASX J*) that have been studied by the following teams:

- IPHASX J191104.8+060845 (Rodríguez-González et al., 2021)
- IPHASX J055242.8+262116 (Guerrero et al., 2021)
- IPHASX J193718.6+202102 (Sabin et al., 2021b)
- IPHASX J211420.0+434136 Corradi et al. (2014)
- IPHASX J194226.1+214522, IPHASX J195248.8+255359, and IPHASX J232713.1+650923 (Hsia and Zhang, 2014)
- IPHASX J194359.5+170901 (Corradi et al., 2011)
- IPHASX J052531.2+281945.1 Viironen et al. (2011)
- IPHASX J221118.0+552841.0 (Viironen et al., 2009b)

All the investigations were not conducted under the same circumstances. For instance, they did not use the same facilities/instruments, and therefore, while some spectroscopic analyses were realized with 2-m class telescopes (e.g., INT), others were conducted with the 10-m class GranTeCan (La Palma). Although this would affect the precision and accuracy of the emission line detection and measurement, it will still be possible to compare some basic characteristics, as shown in **Table 1**.

Hence, most of the PNe analyzed were either bipolar or round, which should be regarded as a selection bias rather than a trend. Indeed, the first objects to be investigated were the "brightest" (particularly for the spectroscopic analysis) and the most interesting and intriguing ones from a morphological point of view. The objects are small-to-medium sized with a maximum extent of 1 arcmin. The

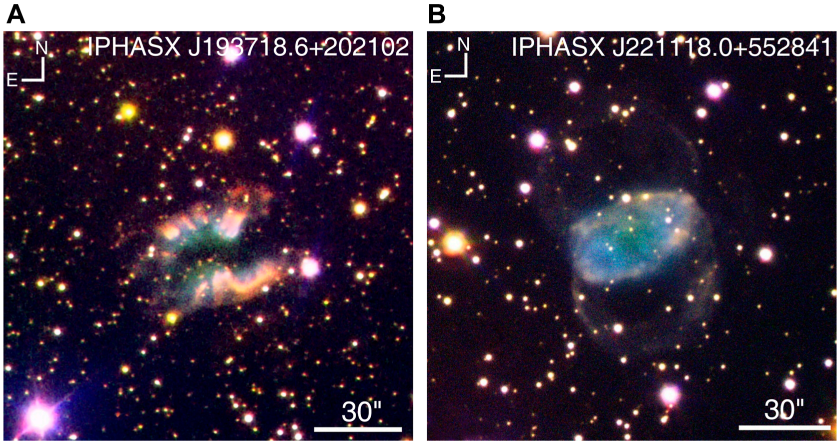

FIGURE 1 | Nordic Optical Telescope RGB-composite pictures of the IPHAS sources IPHASX J193718.6+202102 **(A)** and IPHASX J221118.0+552841 **(B)**, respectively, where the color red was assigned to the [N II] λ_c = 6,583 Å, green for the Hα λ_c = 6,563 Å, and blue for the [O III] λ_c = 5,007 Å filters. Faint bipolar lobes are barely visible in IPHASX J221118.0+552841 at the north and south of the main nebula, while IPHASX J193718.6+202102 was extensively studied by Sabin et al. (2021b), reporting chemical abundances typical of Type II PNe.

TABLE 1 | Optical physical parameters reported for the group of 10 IPHAS PNe.

PN IPHASX	Main Morph.	Size (")	Distance (kpc)	c (Hβ)	T_e (K)	n_e (cm^{-3})	Age (yrs)	Ref
J191104.8	B	30	<4.9 ± 0.6 >	3.36 ± 0.16	8,000 ± 1800	260 ± 20	11,000 ± 1,500	a
J055242.8	R	16.4	$2.6^{+1.3}_{-0.7}$	<1.84 ± 0.07 >	†	†	10400^{+5000}_{-3000}	b
J193718.6	B	60	$7.1^{+0.8}_{-0.3}$	<2.54 ± 0.18 >	<9600 >	<380 >	26,000	c
J211420.0	B	60	≤5.0 ± 1.0	0.95 ± 0.25	13,050 ± 850	125 ± 40	—	d
J194226.1	B	23	4.76 ± 2.38	*	*	2700^{+4100}_{-1400}	9,900 ± 4,950	e
J195248.8	B	26	5.56 ± 2.78	*	*	400^{+430}_{-290}	10,400 ± 5,300	e
J232713.1	R	18	–	1.63 ± 1.01	*	300^{+150}_{-180}	—	e
J194359.5	B	21	4.6 ± 1.1	0.55 ± 0.06	11000^{+2000}_{-2000}	360^{+380}_{-240}	13,000 (‡)	f
J052531.2	R	10	12.8 ± 3.7	0.8 ± 0.1	<11800 ± 600 >	190 ± 120	17,800	g
J221118.0	B	79	6.1 ± 1.1	1.19 ± 0.15	—	—	—	h

a-Rodríguez-González et al. (2021); b-Guerrero et al. (2021): (†)T_e = 11200K from CSPN, n_e = 4,000 cm–3 from radio data; c-Sabin et al. (2021b); d-Corradi et al. (2014); e-Hsia and Zhang (2014): (*)No Hβ detected, Te = 10,000 K; f-Corradi et al. (2011):‡ for the polar caps, 5,000 years for the inner ring; g-Viironen et al. (2011); and h-Viironen et al. (2009b).

distances were measured either with a statistical method (e.g., Hα surface brightness method; Frew et al., 2016) or *via* the extinction method (Giammanco et al., 2011). The results indicate distances greater than 2 kpc in general and up to ~13 kpc with an average of ~6 kpc. The spectroscopic analysis points toward a large range of logarithmic extinction values c (Hβ), from 0.55 to 3.36, indicating a wide variety of nebular environments. While electronic temperatures (T_e) can be described as low to typical for PNe (with values between ~8000 K and ~13000 K), the electronic densities (n_e) are particularly low, with a mean of ~290 cm^{-3} if we remove the only high-density PN IPHASX J194226.1+214522. Finally, in various cases, it was possible to derive the (kinematic) ages of the nebulae and all indicated values ≥10,000 years, that is, evolved PNe. Joint analysis of the elemental abundances (helium, oxygen, and nitrogen in particular) and velocities of the PNe revealed a wide range of Peimbert's types (Peimbert, 1978; Peimbert and Serrano, 1980), therefore implying a range of masses for the progenitors. In the small sample of investigated IPHAS PN, we found Type I (J191104.8 and maybe J194359.5), Type II (J193718.6 and J052531.2), and Type III (J055242.8) objects. When a larger number of IPHAS PNe will have their elemental abundances determined and investigated, it will be possible to have a better global understanding of the chemistry of these objects.

4 DISCUSSION AND CONCLUSION

We can infer from **Table 1** and the main points described earlier that IPHAS is indeed more prone to detect (very) evolved and low surface brightness objects (some have no detectable Hβ or the emission lines needed for electron temperature and density calculations). This ultimate stage of the nebular evolution is moreover underlined by the very low nebular densities that characterize the objects that were studied.

It is also worth noticing first that the PNe detected with IPHAS are not necessarily very extinguished, as new PNe with low-to-moderately high c (Hβ) are found. There is no doubt, however, that the survey can allow us to unveil very extinguished objects, as shown with IPHASX J191104.8+060845 (Rodríguez-González et al., 2021) and its c (Hβ) value of 3.36 ± 0.16. In this regard, IPHAS is relatively complete in terms of the distance that can be reached through the interstellar medium. Then, we note that several objects show the presence of the HeII λ4686 Å emission line, which indicates an excitation degree (or class) from moderate (e.g., IPHASX J193718.6+202102; Sabin et al., 2021b) to high (e.g., IPHASX J194359.5+170901; Corradi et al., 2011).

The extended PNe detected and studied with IPHAS are mostly located at large distances, that is, from ~5 kpc to 12.8 kpc. We are likely to trace objects at larger galactocentric distances which can therefore be used to trace the chemical distribution. Indeed, this would have some impact on the determination of the Galactic abundance gradient.

Finally, it does not seem that IPHAS is targeting a particular (Peimbert's) type of PNe in terms of chemical abundances, and we would therefore have a spread in terms of progenitor's masses and characteristics. But a caveat is, as stated before, the general faintness of the PNe which makes difficult not only the estimation of the abundances but also the accuracy of the measurements.

In conclusion, based on the data collected for this first reduced sample of IPHAS extended PNe, we can therefore infer that IPHAS is fulfilling its objective as a discovery tool for the missing PNe. Indeed, it is targeting mostly evolved PNe (in terms of kinematic age), distant with low electronic density. In addition, while it can detect highly extinguished objects, IPHAS is also uncovering overlooked more "extinction-free" PNe. There is no doubt that the survey will strongly contribute to the understanding of the PNe population as a whole, but more complete analyses of IPHAS PNe, which implies observing and pushing the limits of the instrumentation, are needed for a stronger statistical view.

AUTHOR CONTRIBUTIONS

LS, JT, and MG contributed to the conception of the study. LS wrote the first draft of the manuscript. GR-L prepared the figure. All authors contributed to manuscript revision, read, and approved the submitted version.

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