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IPHAS and the symbiotic stars*,**,***

III. New discoveries and their IR spectral energy distributions

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ABSTRACT

Context. The IPHAS Hα survey provides a rich database to search for emission-line sources in the northern Galactic plane.
Aims. We are systematically searching for symbiotic stars in the Milky Way using IPHAS. Our final goal, a complete census of this class of objects in the Galaxy, is a fundamental figure for discussing their overall properties and relevance to other classes of stars.
Methods. Candidate symbiotic stars were selected using a refined combination of IPHAS and 2MASS photometric colours. Optical spectroscopy, together with the analysis of their spectral energy distribution in the IR, were obtained to confirm their nature and determine their main properties.
Results. Five new symbiotic stars have been confirmed from spectroscopy at the 10.4 m GTC telescope. In one case, confirming the presence of a red giant star required near infrared spectroscopy. In another case, its symbiotic nature was adopted based on the strong similarity of its optical spectrum and spectral energy distribution to those of other genuinely symbiotic stars. The spectral energy distribution of the two S-types found is well fitted by red-giant model atmospheres up to 22 μm without evidence of IR excesses due to dust. In contrast, the three D-types mostly show emission from hot dust with a temperature around 1000 K. We also present the spectroscopic and photometric monitoring of the symbiotic star IPHASJ190832.31+051226.6 that was originally discovered in outburst, and it has now returned to a lower luminosity status. The spectra of thirteen other sources, all classified as young stellar objects except for a new compact planetary nebula, are also presented.
Conclusions. The refinement of our discovery method, the completion of the IPHAS survey and photometric calibration, and the start of the twin survey in the south, VPHAS+, provide excellent perspectives for completing a reliable census of symbiotic stars in the Galaxy in the next few years.

Key words. binaries: symbiotic – surveys – stars: pre-main sequence – planetary nebulae: individual: IPHASJ191942.91+162128.0 – stars: AGB and post-AGB

1. Introduction

The study of symbiotic stars is relevant to a number of astrophysical subjects. They are excellent laboratories for studying physical processes, such as quasi-steady nuclear burning and thermonuclear outbursts (Munari 1997), the powering mechanism of supersoft X-ray sources (Jordan et al. 1996), the collimation of stellar winds and the formation of jets (Tomov 2003), and their connection with bipolar planetary nebulae (Corradi 2003). Most importantly, symbiotic stars are possibly related to the formation of Type Ia supernovae (SNe Ia). The detection of circumstellar matter around some of these supernovae (Patat et al. 2007; Dilday et al. 2012) provides support to this hypothesis, as originally proposed by Munari & Renzini (1992).

Testing the possible roles of symbiotic stars involves knowing their total population in galaxies, a figure that is very poorly known even in our Galaxy. Before 2008, only ~173 systems were known in the Galaxy (Belczynski et al. 2000), out of an estimated total population between 3000 and 400 000 (Allen 1984; Munari & Renzini 1992; Kenyon et al. 1993; Yungelson et al. 1995; Magrini et al. 2003). To improve the situation, a systematic search for symbiotic stars was started that takes advantage of IPHAS, the "INT Photometric Hα Survey of the northern Galactic plane" (Drew et al. 2005). The description of the

* Appendices are available in electronic form at http://www.aanda.org

** Spectra 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/qcat?J/A+A/567/A49

*** Based on observations obtained with the Gran Telescopio Canarias (GTC) and the 2.6 m Nordic Optical Telescope (NOT) operated by NOTSA, both located on the island of La Palma at the Spanish Observatory of the Roque de Los Muchachos of the Instituto de Astrofísica de Canarias.

photometric method adopted to select symbiotic star candidates was presented by Corradi et al. (2008, 2010a), hereafter Papers I and II. Along with individual studies of other outstanding objects (Corradi & Giammanco 2010; Corradi et al. 2010b, 2011), IPHAS and follow-up spectroscopy allowed us to discover fourteen new symbiotic stars in the 1800 square-degree IPHAS area (covering Galactic latitudes between −5° and +5° in the northern sky), where previously only eleven symbiotic stars were known. In these articles, we also emphasized the need for robust selection criteria to distinguish symbiotic stars from the most problematic mimics, and in particular from T Tauri stars and other young stellar objects (YSOs) that are much more frequent than symbiotic stars in the Galactic plane.

In this paper, we present the spectroscopic observations carried out with the 10.4 m GTC telescope of eighteen symbiotic star candidates. They were selected using new, stricter selection criteria developed by taking advantage of previous results. This work, together with a forthcoming article that will describe the use of IR photometry in detail as a new powerful tool for distinguishing symbiotic stars (Mampaso et al., in prep., Paper IV), will conclude the series of articles about the search of symbiotic stars within IPHAS, providing new constraints on the total number of systems in the Galactic disk. The sample selection is presented in Sect. 2, and observations in Sect. 3. The analysis of the spectra of the new symbiotic stars is included in Sect. 4, where their spectral energy distribution is also presented. Section 5 contains the conclusions. The non-symbiotic objects discovered are briefly discussed in the appendices.

2. Sample selection

Candidate symbiotic stars were selected using a combination of IPHAS and near-IR (2MASS) colours (Paper I). The criteria and list of candidates presented in that paper have now been improved by taking advantage of the results of our follow-up spectroscopic campaign and of the near completion of the IPHAS observations, and its point-source photometric catalogue benefits from a complete photometric calibration that will be presented in the second IPHAS data release (DR2, Barentsen et al., in prep.).

To reduce the contamination of mimics without severely affecting the completeness of the sample of symbiotic star candidates, the selection boxes in the IPHAS and 2MASS colour-colour diagrams defined in Paper I were further restricted as indicated in Fig. 1 (regions labelled with the S and D symbols). The goals are the following. First, we required the selected candidates to have a stronger Hα emission (larger r′-Hα IPHAS colour). This limits the recognition of objects in the rare group of yellow (D′-type) symbiotic stars, but has the advantage of significantly reducing the contamination by YSOs. Second, based on our follow-up spectroscopy, we notice that only some combinations of IPHAS+2MASS selection boxes are effectively populated by symbiotic stars. They are the combinations S/S and D/D, where the first symbol refers to the region labelled as such in the IPHAS colour-colour diagram of Fig. 1 (upper panel), and the second symbol in the 2MASS diagram (lower panel). All other portions of the diagrams defined in Paper I are basically void of symbiotic stars, except a couple of peculiar or active systems in the combination S/D out of a large number of contaminants. More details can be found in Rodríguez-Flores (2012).

By applying the colours cuts corresponding to the combination S/S and D/D to the most recent version of the IPHAS point-source photometric catalogue, which contains ~200 million objects, we have reduced the total number of symbiotic star candidates within IPHAS to 159 objects in S/S and 3 in D/D, after excluding the sources already observed spectroscopically. With this strategy, we are confident that our success rate in detecting symbiotic stars is significantly higher than in our original selection in Paper I, without excluding more than some 10% to 15% of the whole sample of genuine symbiotic stars.

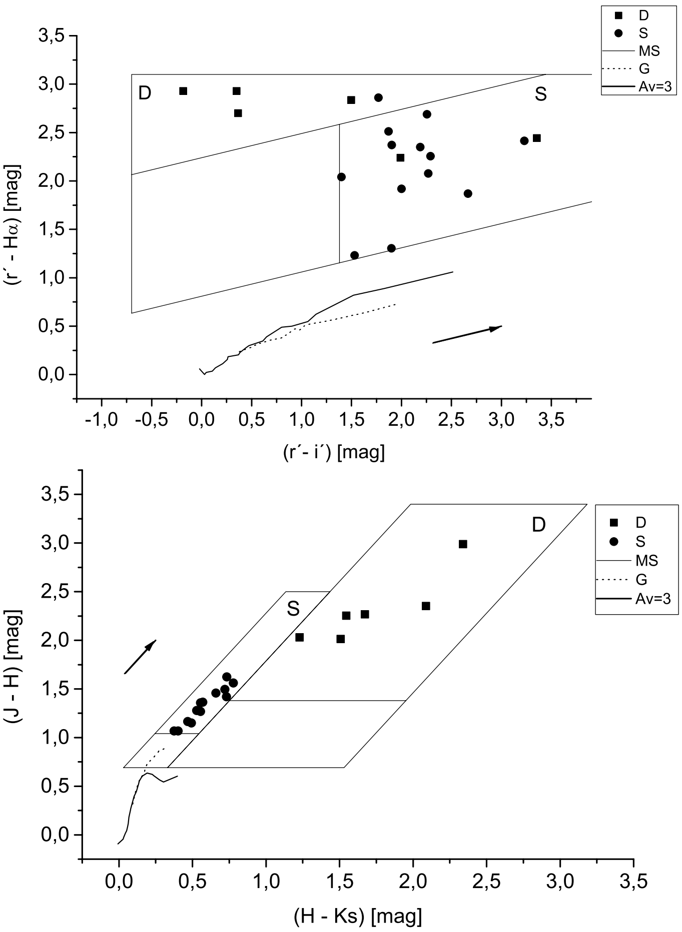

Fig. 1. Definition of new regions for the selection of symbiotic stars in the IPHAS (*upper panel*) and 2MASS (*lower panel*) colour−colour diagrams. Circles and squares indicate the location of the S and D-type systems, respectively, discovered so far by the IPHAS survey. The location of the unreddened main-sequence (MS), giants sequence (G), and the reddening vector for A_V = 3 mag (arrow), are also shown (see Paper I and Drew et al. 2005 for more details).

3. Observations

We obtained spectra for 18 candidate symbiotic stars in May, June, and December 2012 at the 10.4 m Gran Telescopio Canarias (GTC) at the Observatorio del Roque de los Muchachos (La Palma, Spain). The OSIRIS instrument was used in its long-slit mode. The combination of grism R1000B and a slit width of 1″ provides a spectral dispersion of 2.1 Å per (binned ×2) pixel, a resolution of 7 Å, and a spectral coverage from 3650 to 7850 Å. Exposure times ranged between 100 s and 800 s, depending of the magnitude of each object. The observations were obtained in photometric nights, and generally the airmasses of the objects and standard stars were smaller than 1.5. Flux calibration was performed by observing spectrophotometric standard stars from Oke (1990). Reduction of all spectra was carried out with standard routines in IRAF *V2.16*[1]. In addition, a spectrum of the symbiotic star IPHASJ190832.31+051226.6 (discovered in Corradi et al. 2010b) was obtained with the same telescope and configuration as above.

Finally, a 4 min IR-spectrum in the K band of IPHASJ193943.36+262933.1 (see below) was obtained at the 2.6 m Nordic Optical Telescope (NOT) on 7 September 2012. The NOTCAM spectrograph was used in combination with grism #1 and a 0.128 mm wide slit (0.5″ arcsec projected on the plane of the sky). This setup covers a useful spectral range from 2.12 to 2.36 μm with a dispersion of 4.2 Å pix^{-1}. Seeing was 0.5″, and both the A0V standard star, Hipparcos 95560, and the target were observed at an airmass between 1.24 and 1.26 using a nodding ABBA pattern along the slit. Data were reduced following standard IRAF procedures, except for the telluric-correction and flux-calibration stages, which were performed using the `xtellcor-general` task from the `Spextool` package (Vacca et al. 2003).

4. Analysis

Similarly to Papers I and II, the original criterion by Allen (1984) was adopted to identify a source as a genuine symbiotic star. This requires both high ionization conditions (emission lines from at least HeII) and the presence of a cool giant. The O VI Raman scattered lines at 6825, 7088 Å are a feature seen only in symbiotic stars, and they also provide a firm classification criterion when the red giant continuum is not directly observed. In three of the objects observed spectroscopically, the high ionization nebular spectrum, the red giant continuum, and the Raman features are clearly observed. In another object, IPHASJ193943.36+262933.1, the presence of a red giant is revealed by a near infrared (NIR) spectrum. A fifth object, IPHASJ224834.32+582908.4, is also classified as a symbiotic star because its nebular spectrum and NIR colours are virtually identical to IPHASJ193943.36+262933.1. Three new symbiotic stars are of D-type, and two are S-type systems. Figure A.1 shows the spectrum of these symbiotic stars. The standard IAU nomenclature for IPHAS point sources ("IPHASJ" followed by the J2000 coordinates, Drew et al. 2005) was adopted. Details of individual objects are presented in Sect. 4.2.

4.1. Spectral energy distributions

Compared to our previous articles on IPHAS symbiotic stars, in this work we add the information about the optical and IR spectral energy distribution (SED) of the newly discovered sources. This allows some basic properties of the cool components to be estimated, highlights the differences between the S and D types at longer wavelengths than generally considered, and provides additional information to separate symbiotics from their most common mimics, namely young stars and planetary nebulae.

SEDs were built using our spectra and all other relevant photometric information available on the web via VizieR[2]. Additionally, the `VOSpec` and `VOSA` tools of the ESAC and Spanish virtual observatories, respectively, were used for SED analysis and stellar model fitting. For the visible range, we used our observed spectrum and the IPHAS photometry because available catalogued data are generally only photographic. For

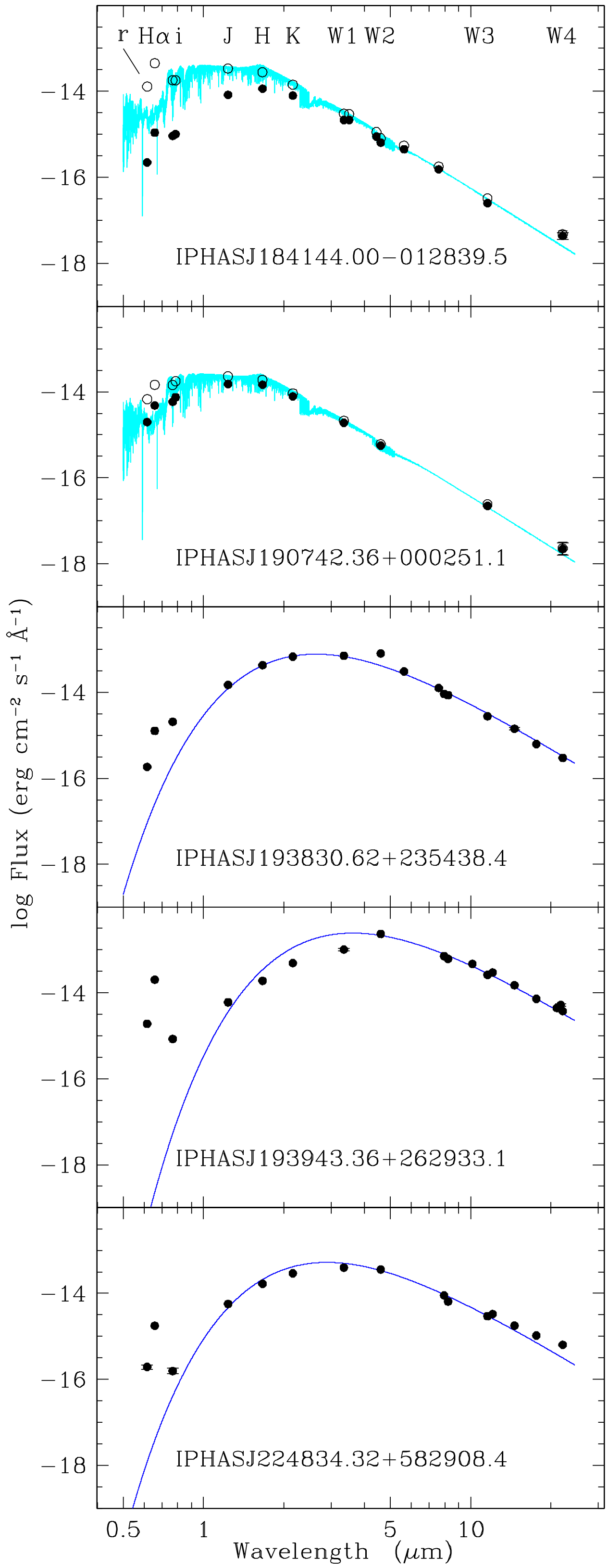

Fig. 2. Spectral energy distribution for the two S-type (*top two panels*) and the three D-type (*bottom panels*) new symbiotic stars. Filled circles are the observed fluxes from 0.6 to 22 μm, whereas open circles are fluxes dereddened with values of A_V determined from the best fit photospheric modelling (cyan line in the S-type objects). Errors are plotted when larger than the size of the symbol. The blue curves represent blackbody fits to the 2.2 → 22 μm data for the D-type symbiotics. See text for details.

[1] IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under cooperative agreement with the National Science Foundation.

[2] http://vizier.u-strasbg.fr/

Table 1. Optical and IR magnitudes of the new symbiotic stars. Errors are indicated in parentheses.

IPHAS	r	i	Hα
184144.00-012839.5	17.561 (0.006)	15.225 (0.004)	15.483 (0.004)
190742.36+000251.1	15.338 (0.002)	13.402 (0.002)	13.987 (0.002)
193830.62+235438.4	17.840 (0.010)	14.479 (0.003)	15.403 (0.005)
193943.36+262933.1	15.342 (0.002)	15.538 (0.007)	12.424 (0.001)
224834.32+582908.4	17.709 (0.006)	17.344 (0.013)	15.009 (0.003)

Table 2. Main spectral features in the GTC spectra of the new symbiotic stars.

IPHASJ	Main spectral features
184144.00–012839.5	TiO, H I, He I, He II, [Ca V], [Fe VII], O VI
190742.36+000251.1	TiO, H I, He I, He II, O VI
193830.62+235438.4	TiO, H I, He I, He II, [O III], [Ca V], [Fe VII], [Ar III], [Ar IV], [Fe II], O VI
193943.36+262933.1	rich nebular spectrum[a]
224834.32+582908.4	rich nebular spectrum[a]

Notes. [(a)] See text.

Table 3. Other properties of the new symbiotic stars.

IPHASJ	Type	$T_{\rm cool}$	$A_{V({\rm fit})}$ [mag]	$A_{V({\rm Bal})}$ [mag]	$T_{\rm hot}$ [10^3 K]
184144.00–012839.5	S	M5.6 ± 1	5.0 ± 0.6	≤8.3	114
190742.36+000251.1	S	M5.0 ± 0.5	1.6 ± 0.2	2.6 ± 0.8	114
193830.62+235438.4	D	≥M7.5	≤7.4	≤10.1	114
193943.36+262933.1	D	–	–	3.2 ± 0.5	99
224834.32+582908.4	D	–	–	3.2 ± 0.2	99

the IR range, we have mainly used the data from 2MASS and WISE, supplemented with fluxes from DENIS, MSX, IRAS, and AKARI databases when available. The SEDs of the five new IPHAS symbiotic stars are shown in Fig. 2. Simple blackbody fits to the IR fluxes indicate that the two S-type symbiotics exhibit their reddened photospheres with almost no dust emission, whereas the three D-symbiotics mostly show emission from hot dust with a typical temperature around 1000 K. Also included in Fig. 2 are synthetic stellar spectra fitted to the SEDs of the S-symbiotics. We have used the `BT-Settl` model library (Allard et al. 2012) as implemented in `VOSA`, given its wide range of parameters $T_{\rm eff}$, metallicity, and surface gravity (log g). Results for individual objects are discussed below.

4.2. Description of individual objects

In Table 1, we provide the IPHAS magnitudes of the new symbiotic stars, and Table 2 lists the main features identified in their spectra. In Table 3, the properties derived from the analysis of their spectra are given: first, the IR type of the system (S or D) is indicated. Then, for the three objects where the continuum of the red giant is clearly visible, a fit of the spectrum as in Paper II was attempted. We used the Fluks et al. (1994) spectral library of red giants and nebular continua from Osterbrock & Ferland (2006). The R_V = 3.1 extinction law by Fitzpatrick (2004) was adopted, and the same amount of reddening was assumed to affect both the cool giant and the nebular region. The spectral type of the cool component $T_{\rm cool}$ estimated and the visual extinction $A_{V({\rm fit})}$ derived in this way are indicated in Table 3. We then list the extinction value $A_{V({\rm Bal})}$ from the Balmer decrement of the emission-line spectrum. If available, all the main Balmer lines down to Hδ were used. The theoretical Balmer line ratios from Brocklehurst (1971) for electron temperature $T_{\rm e}$ = 10^4 K and density $N_{\rm e}$ ∼ 10^6, and the extinction law by Fitzpatrick (2004) with R = 3.1, were adopted. For symbiotic stars, self-absorption of the Hβ line due to the large optical depth of the dense inner nebulae often makes the Balmer decrement deviate from the standard case B. In the cases where significant optical depth effects are suspected in the analysis of the Balmer decrement, an upper limit to $A_{V({\rm Bal})}$ is indicated. Finally, we indicate in Table 3 the temperature of the hot component $T_{\rm hot}$, estimated from the highest ionization stage observed in our spectra (Mürset & Nussbaumer 1994).

IPHASJ184144.00-012839.5. No object is listed in the SIMBAD database at this source coordinate. The source is quite reddened, with no signal below He II 4686 Å in the spectrum. The symbiotic nature of the object is revealed by the strong TiO bands and the presence of high excitation emission lines (Fig. A.1, upper plot, and Table 2), including the presence of prominent O VI Raman scattered emission at 6825 Å. The Hα line shows extended wings with a full-width-at-zero intensity *FWZI* ∼ 3500 km s^{-1}, as commonly observed in symbiotic stars.

The SED of the object, displayed in Fig. 2, shows a reddened photosphere typical of a giant in S-type symbiotics. We have fitted to the observed SED different model photospheres with a broad range of parameters corresponding to normal K0 to M9 giants: $T_{\rm eff}$ was varied from 2500 to 4500 K and log g from −0.5 to 2.5, whereas A_V was allowed to vary between 0 and 10 mag.

The metallicity was assumed to be solar in all cases. The IPHAS Hα and r′ fluxes (which include the line emission) and the WISE W3 and W4 data (potentially affected by dust emission) have been excluded from the fits. The resulting best model fit is shown in Fig. 2 and corresponds to a giant star with $T_{\rm eff}$ = 3300 K and log g = 0, (i.e. an M6 III star; cf. Houdashelt et al. 2000), reddened by A_V = 5.0 mag.

On the other hand, the fit to the GTC spectrum yields a spectral type M5.6 III and A_V = 5 mag, with a possible range between M4.5 and M6.5 III, and A_V between 5.6 and 4.3, respectively (Table 3). Assuming an M5.6 III star, the observed 2MASS K magnitude implies a distance of 7.6 kpc, which in turn yields a luminosity-integrated under the observed SED of ∼915 $L_\odot$, in agreement with the value expected from an M5.6 III star.

IPHASJ190742.36+000251.1. This source was previously known as the emission-line star HBHA-0201-01 and variable star NSV 11749. Its symbiotic nature was independently discovered by Bond & Kasliwal (2012) who proposed that it is a symbiotic nova based on the historical light curve that showed an outburst in 1903 followed by a slow photometric decline. An M1–2 III classification of its cool component reddened by 0.75 mag in the visual was determined by these authors from the optical and NIR spectra.

Our deeper spectrum, also obtained in 2012, shows several H I lines of the Balmer series, and strong TiO bands longwards of 7000 Å. The depth of these absorption bands indicate a later spectral type than estimated by Bond & Kasliwal (2012). The fit to our spectrum indicates an M5.0 ± 0.5 III type for the red giant of the system. This is also supported by modelling the SED: the best model fitted to the SED is for a moderately reddened (A_V = 1.5 mag) giant with $T_{\rm eff}$ = 3300 K and log g = −0.5, i.e. an M6 III star. Adopting the spectral type deduced from the optical spectrum, M5.0 III, a distance of 8.0 kpc and a total luminosity (from the SED) of 660 $L_\odot$ are determined.

IPHASJ193830.62+235438.4. This highly reddened object, projected on the sky in a zone of faint and diffuse H II emission, shows the clear signatures of a symbiotic star: a red giant continuum with prominent TiO bands, an exceptionally strong Hα line with an equivalent width around −1700 Å, several high excitation emission lines, and the Raman feature. According to its 2MASS colours, it should be classified as a D-type symbiotic star.

The SED of IPHASJ193830.62+235438.4 is shown in Fig. 2 and includes a wealth of measurements from the optical up to 22 μm, in particular fluxes from *Spitzer*/IRAC *I3* and *I4*, MSX *A* and *D*, and AKARI/IRC 9 and 18 μm bands, besides the 2MASS and WISE measurements. No photosphere model can fit the observed SED, not even between 0.6 and 2.2 μm, with any reasonable set of parameters. Clearly, the circumstellar dust and gas emission dominate the observed SED already from the NIR, something that is typical of D-type symbiotics. In fact, a blackbody with T = 1100 K fits the observed SED very well up to 22 μm, again something characteristic of D-type objects (Angeloni et al. 2010). It is interesting to note that in many D symbiotics a second colder dust component with T ∼ 400 K is present at longer IR wavelengths, dominating the observed emission from 20 to 1000 μm (Angeloni et al. 2010). Unfortunately, no data beyond 22 μm is available for IPHASJ193830.62+235438.4 to see whether such a colder component is present.

The total flux integrated from the SED, F = 3.58 × 10^{-9} erg cm^2 s^{-1}, implies a high luminosity of ≈3300 $L_\odot$ for a distance D = 5.4 kpc (see Sect. 5), consistent with a giant star in the AGB phase, and therefore confirming the D-type nature of this source.

IPHASJ193943.36+262933.1. Also named Hen 2-442, this object is listed as a possible symbiotic in both the catalogue of Belczynski et al. (2000) and the atlas of Munari & Zwitter (2002). According to Belczynski et al. (2000), the source consists of two PN-like sources: Hen 2-442A and Hen 2-442B. The latter, located 7 arcsec to the NE of Hen 2-442A, is an emission-line, B-type star according to Arkhipova et al. (1985). Its IPHAS colours, however, do not indicate the presence of Hα emission. This source is most likely unrelated to Hen 2-442A so is not discussed further here.

Yudin (1983) suggested a symbiotic nature for Hen 2-442A based on weak evidence for TiO bands. Arkhipova et al. (1985) obtained an optical spectrum and detected a number of emission lines with ionization potential up to 100 eV. The NIR excess of this source is remarkable.

Our observations with GTC show a very rich emission line nebular spectrum, nearly identical to the well known D-type symbiotic star H 1-36 (cf. Fig. 60 in the atlas of Munari & Zwitter 2002). More than a hundred narrow emission lines are present in our spectrum. They include permitted and forbidden lines from a variety of atomic species in highly different ionization and excitation status – e.g. N, O, Ne, S, and Ar up to triply ionized – but also a number of Fe lines at all stages from [Fe II] to [Fe VII] and other less abundant species. See Allen (1983) for line identification in the spectrum of the similar symbiotic star H 1-36. The spectrum in Munari & Zwitter (2002) shows a remarkably intense [Ne V]3426 emission line. All other emission lines of IPHASJ193943.36+262933.1 in the atlas of Munari & Zwitter (2002) closely match the intensities displayed in the spectrum presented in this article, indicating long-term stability (20 years) in the radiation from the ionization source and the photoionized gas.

The continuum is weak and slowly rising, with no evidence of the absorption bands of a red giant. No Raman feature is observed either. This is indeed a case where proving its symbiotic nature is not straightforward. The nebular spectrum highly resembles that of a planetary nebula, and the only hint of the presence of a cool giant is provided by the 2MASS colours. For this reason, we have obtained a NIR spectrum at the NOT. It is presented in Fig. 3 and shows faint absorption features that can be attributed to the band heads of CO at 2.29 μm and 2.32 μm (the latter with marginal evidence) from a red giant photosphere. We consider this as proof of the symbiotic nature of this source, but additional data (deeper NIR spectra and photometric monitoring in the IR to search for Mira pulsations) would be desirable. Another D-type symbiotic star whose continuum is dominated by hot dust emission and where the red giant only shows up at a NIR wavelength is Hen 2-104 (Santander-García et al. 2008).

As in the case of IPHASJ193830.62+235438.4, this object has been detected in several mid-IR surveys, namely WISE, MSX, AKARI, and IRAS up to 60 μm. The best fit to the observed SED corresponds to a single blackbody with T = 680 K (Fig. 2) with no evidence of a colder dust component up to 60 μm. The integrated flux (0.6 to 60 μm) is F = 1.24 × 10^{-8} erg cm^2 s^{-1}, corresponding to a total luminosity L ≈ 3500 $L_\odot$ for a distance D = 3.0 kpc (see Sect. 5).

D-type symbiotic stars often show extended nebulae (Corradi 2003). A careful analysis of the point-spread function in the IPHAS Hα and GTC r-band images of IPHASJ193943.36+262933.1 shows that the source is moderately extended with *FWHM* ≈ 0.2 arcsec after seeing

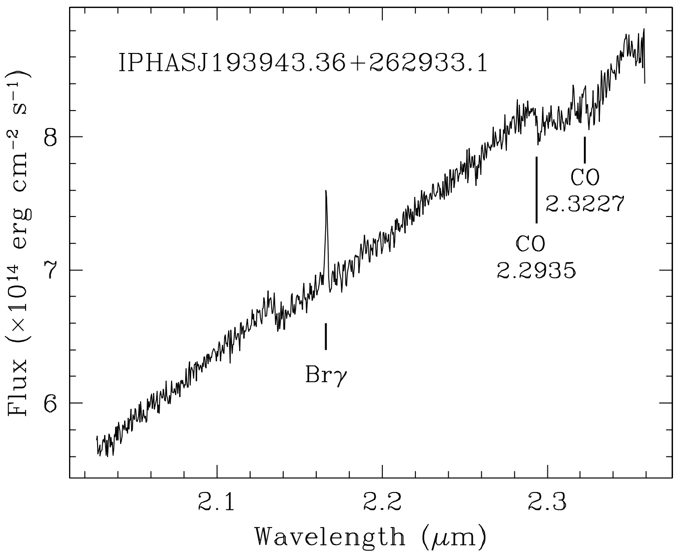

Fig. 3. *K*-band NIR spectrum of IPHASJ193943.36+262933.1. Two CO band heads are identified.

deconvolution. We have searched in the HST archive and found that Hen 2-442 was observed through ten narrow- and two broad-band filters from 3750 to 8140 Å in 1997 with WFPC2 (proposal 6943). The object appears extended in the filters corresponding to [O I], [O III], and [N II] lines with $FWHM$ = 0.12 arcsec. This would correspond to a very compact nebula of size 180 AU around IPHASJ193943.36+262933.1.

IPHASJ224834.32+582908.4. The source is included in the catalogue of PNe by Acker et al. (1992) with name PN G107.4-00.6 (K 4-57), but our photometric criteria make it a promising symbiotic star candidate of D type. Only low-resolution spectra from Kazarian et al. (2000) are available in the literature. Our GTC spectrum is dominated by nebular lines of low to high ionization species, with a faint, slowly rising continuum. The spectrum is virtually identical to IPHASJ193943.36+262933.1 but is fainter, with no detection of the Raman feature either. Even if in this case we do not have a NIR spectrum to prove the existence of the cool star, by analogy with the previous source and other known symbiotic systems such as H 1-36, we classify IPHASJ224834.32+582908.4 as a D-type symbiotic star. The location of the source in the [O III]4363/Hγ vs. [O III]5007/Hβ diagram from Gutiérrez-Moreno et al. (1995), in the high-density locus typical of symbiotic stars, reinforces our classification. The SED of IPHASJ224834.32+582908.4 (Fig. 2) includes fluxes from the optical up to 22 μm (IPHAS, 2MASS, WISE, MSX, and AKARI data). The best fit to the SED from 0.8 to 22 μm corresponds to a blackbody with T = 1000 K, although significant excess emission due to colder dust grains is also present in the range 12–22 μm. As mentioned above, this type of SED is very different to those from S-type symbiotics, giving more weight to our classification as a D-type object. The total luminosity, when adopting the distance of 7.4 kpc (Sect. 5), is 3950 $L_\odot$.

IPHASJ190832.31+051226.6. We also present the monitoring of IPHASJ190832.31+051226.6[3], whose discovery was presented in Corradi et al. (2010b) based on spectra obtained in 2006 and 2009. In the latter, the source was almost ten times brighter than in the former, the continuum turned bluer, the He I lines had disappeared, and several low ionization [Fe II] lines appeared with a strong NIR Ca II triplet. This was interpreted as the onset of an outburst. Our 2012 GTC spectrum and new photometric data obtained at the 2.5 m INT show that the system has returned to the same lower luminosity status as in 2006. This deeper spectrum also confirms a marginal detection of the [O III]5007 line, and the absence of He II4686. The [Fe II] lines from multiplet #42 persist, as do the several strong diffuse interstellar bands (DIBs) and the Na I D interstellar absorption lines.

Corradi et al. (2010b) used model fit to the optical spectrum to determine a spectral type for the giant between M4.0 III and M6.0 III with A_V = 4.8 and 5.2 mag, respectively. As in previous objects, we have fitted reddened photospheres to the SED of IPHASJ190832.31+051226.6 finding that a M6.0 III star with A_V = 6 mag provides the best fit in the range of possible types from Corradi et al. (2010b). For the distance of 5.4 kpc quoted by those authors, a luminosity of 1070 $L_\odot$ is obtained, in good agreement with the value expected for an M6 III star.

5. Discussion and conclusions

From the analysis of the IPHAS data we have discovered another five symbiotic stars in the Galactic plane, making a total of 19 new sources found by the survey, compared to 11 objects previously known in this area. The spectroscopic follow-up of candidates also allowed us to improve the selection criteria, thereby reducing the total number of candidates to slightly more than a hundred, compared to the more than thousand of objects listed in Paper I. In addition, we used the recently released WISE All-Sky mid-IR catalogue (Cutri et al. 2012), which in combination with other IR databases and IPHAS and 2MASS data, allowed us to build a SED covering the bulk of emission from the star and dust components of the systems, providing the final information needed for a robust selection of symbiotic stars in IPHAS.

The discussion of the SED also provides valuable information about the cool components of the systems. For the two S-type systems, the SEDs are reasonably well fit by red-giant models up to 22 μm, and no significant dust excess is present. For D-types, the IR SED is dominated by the dust. Angeloni et al. (2010) studied the SED of a sample of D-type symbiotic stars in detail and found that in most of them two dust shells with temperatures of ~1000 K and ~400 K are present. The hotter shell corresponds to the normal circumstellar envelope around the AGB star, whereas the colder one would be a more external, circumbinary envelope surrounding the whole system.

Angeloni et al. (2010) also find an empirical relation between the peak flux of the blackbody emission fitted to the SED and the distances to the D-type symbiotics. We can use their relation to provide a rough estimation of the distances D for the three new D-type symbiotics. Using the peak blackbody fluxes from Fig. 2, we obtain $D \approx$ 3.0, 5.4, and 7.4 kpc for IPHASJ193943.36+262933.1, IPHASJ193830.62+235438.4, and IPHASJ224834.32+582908.4, respectively.

In a forthcoming and final article in the series, we will take advantage of IPHAS DR2 to apply the photometric criteria discussed above to estimate the total number of symbiotic stars in this area of the sky, and extrapolate it to the whole disk of the Galaxy. At the same time, progress of the twin survey in the southern sky, VPHAS+ (Drew et al., in prep.), will provide new data for the southern portion of the Galactic plane and, most importantly, the bulge, where a large number of systems are expected to be found (Whitelock & Munari 1992; Miszalski et al. 2013). All together, we can conclude that we are on the

[3] Its coordinates, hence its IPHAS name, have changed in IPHAS DR2 to IPHASJ190832.31+051226.5.

way towards largely improving the census of symbiotic stars in the Galaxy, a figure that is fundamental to understanding this class of objects and their viability as progenitors of type Ia supernovae.

Finally, we have set up a dedicated page on symbiotic stars in the web of the IPHAS consortium[4], where we will maintain an updated list of systems discovered by the survey. We encourage all interested researchers to check it from time to time for additional symbiotic stars that we might discover in the future and to find useful information, such as the existing spectra, or finder charts helpful for planning follow-up observations.

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Pages 8 to 13 are available in the electronic edition of the journal at http://www.aanda.org

[4] http://www.iphas.org/symbiotic-stars

Appendix A: Symbiotic stars

The spectra of the new symbiotics stars are presented in Fig. A.1, and their fit files can be accessed from the CDS.

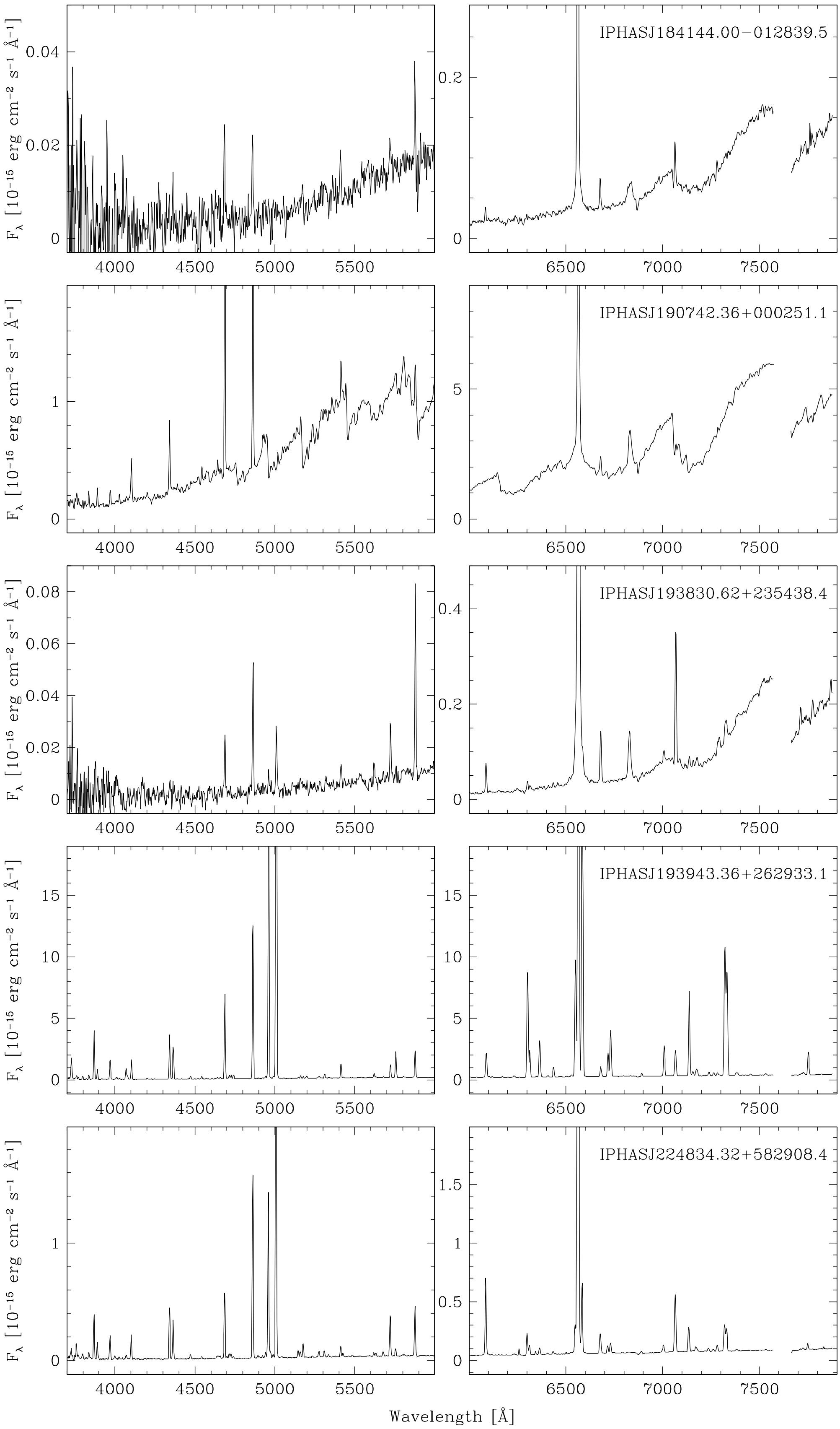

Fig. A.1. GTC spectra of the new IPHAS symbiotic stars. The region at 7600 Å with the strong oxygen atmospheric absorption band is not plotted.

Appendix B: Non-symbiotic systems

For the other 12 sources observed with the GTC telescope, spectra and SEDs reveal their nature as YSOs (Fig. B.1). In addition, one very compact planetary nebula, IPHASJ191942.91+162128.0, was also discovered. These 13 objects are listed in Table B.1 and their SEDs displayed in Fig. B.2. Their fit files can also be accessed from the CDS. The new planetary nebula IPHASJ191942.91+162128.0, which is discussed in some detail in Appendix C, is displayed at the top of Fig. B.2, whereas all other objects are shown to be young stars of different types (see Table B.1). Criteria for their spectral classification follow what was already discussed in Paper II.

Compared to both S- and D-type symbiotic stars (Fig. 2), the SED of YSOs are typically flatter, showing strong excesses beyond 12 μm. A 2000 K blackbody function is fitted to the 0.6 $\rightarrow$ 4.6 μm fluxes of the classical TTau star IPHASJ012539.29+613630.4 (bottom SED, blue solid curve) to illustrate this. The mid-IR colours are in this respect a very useful tool for distinguishing between symbiotic stars, YSOs, and other kinds of common mimics, such as compact planetary nebulae, even when lacking optical spectra, a fact that will be explored in detail in Paper IV.

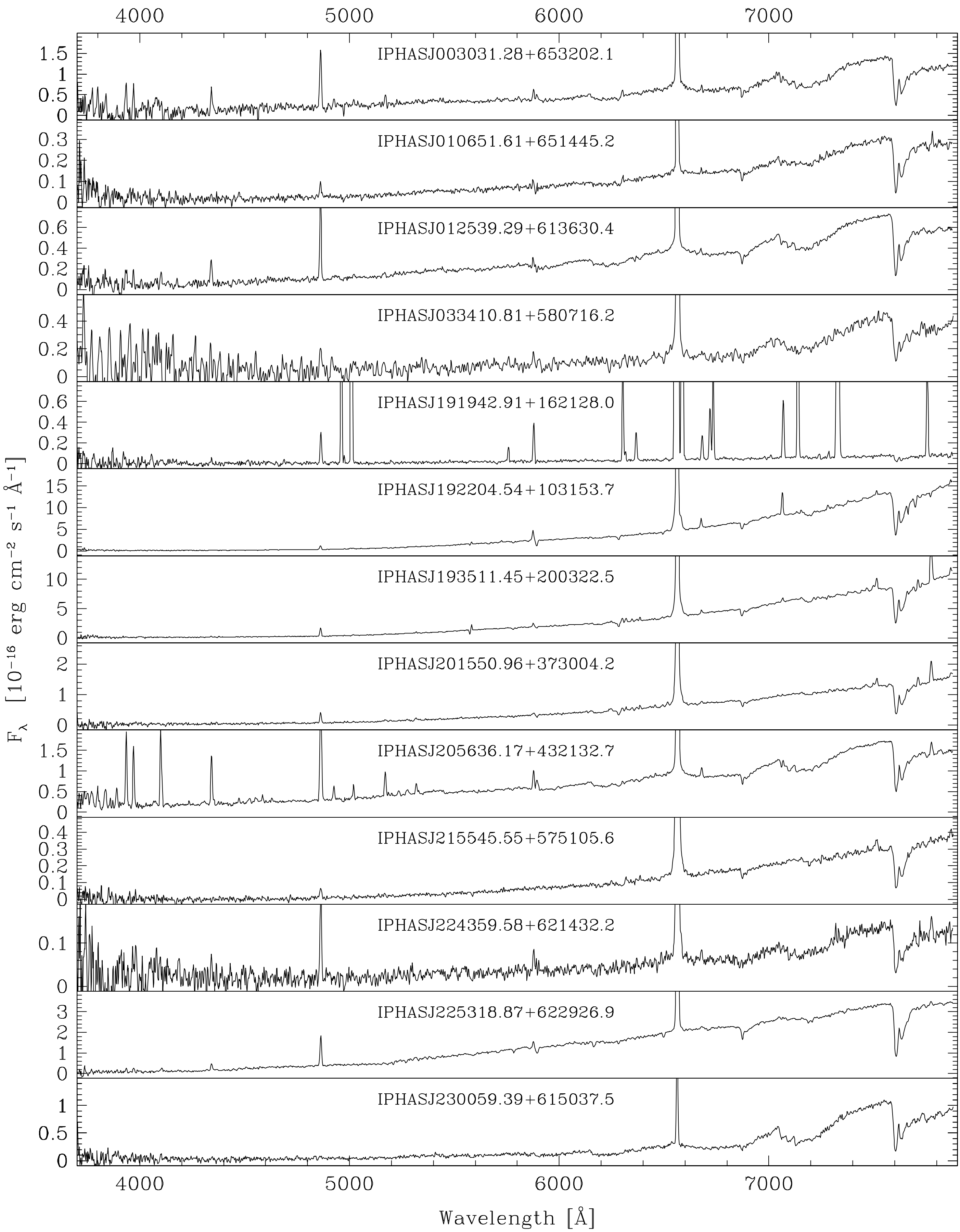

Fig. B.1. GTC spectra of non-symbiotic sources.

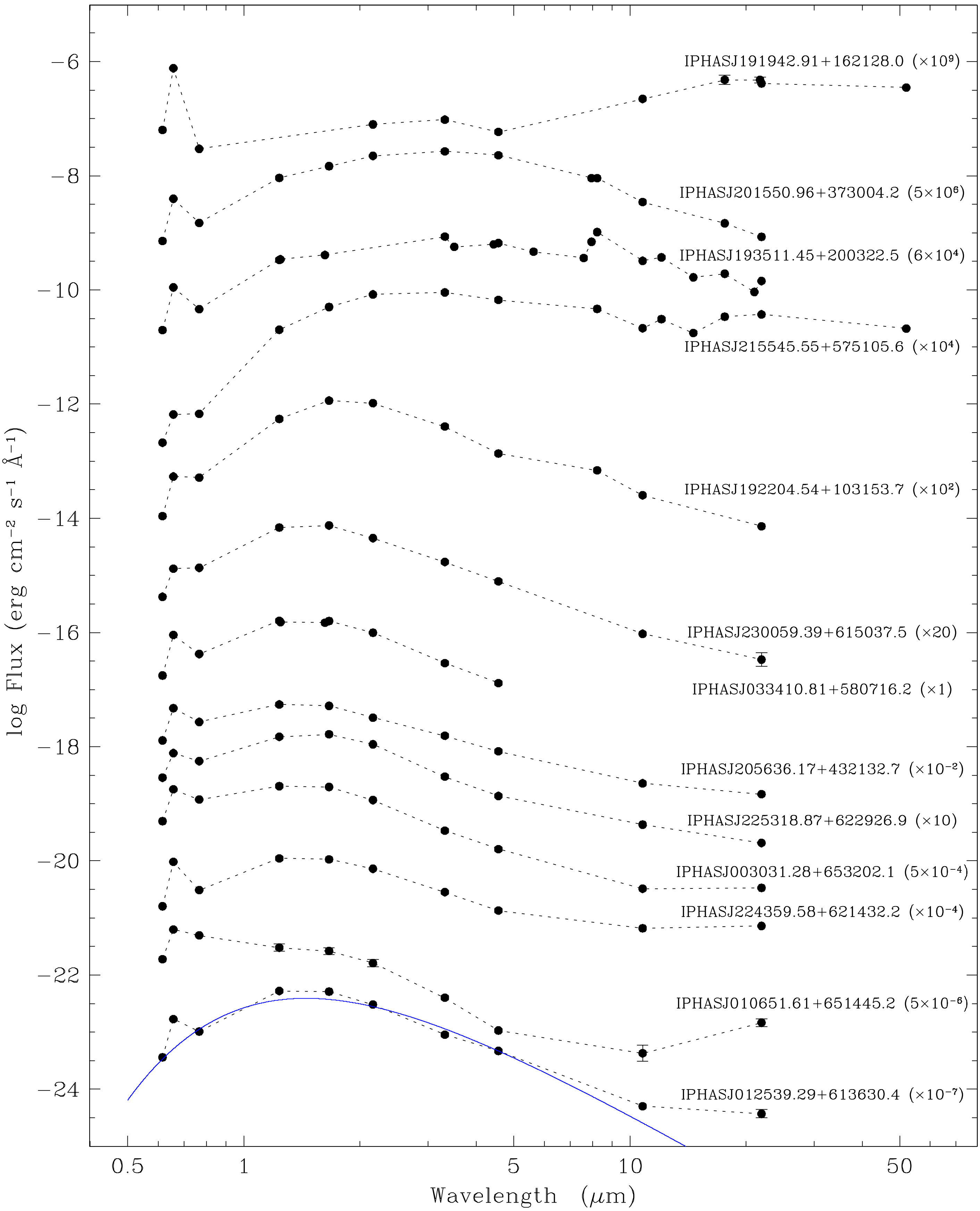

Fig. B.2. Spectral energy distribution of non-symbiotic objects. Numbers in parentheses following the IPHAS names indicate the scale factors used for clarity in the figure. Errors are plotted when larger than the size of the symbols. See text.

Table B.1. Other objects.

IPHASJ	Main spectral features	Class	Notes
003031.28+653202.1	TiO, H I, He I, [Fe II], Ca II	CTT	[S]: nothing. $F = 8.9 \times 10^{-12}$
010651.61+651445.2	TiO, H I, He I	YSO	[S]: nothing. $F = 1.3 \times 10^{-12}$
012539.29+613630.4	TiO, H I, He I, Ca II	CTT	[S]: nothing. $F = 1.1 \times 10^{-11}$
033410.81+580716.2	TiO, H I, He I, [Fe II]	YSO	[S]: nothing. $F = 2.3 \times 10^{-12}$
191942.91+162128.0	rich nebular spectrum[1]	PN	[S]: IRAS 19147+1615.
192204.54+103153.7	H I, He I	Be/YSO	[S]: nothing. Very broad Hα line: *FWZI*(Hα) = 66 Å. $F = 2.9 \times 10^{-10}$
193511.45+200322.5	H I, He I, [Fe II]	Be/YSO	[S]: IRAS 19330+1956. $F = 6.0 \times 10^{-9}$. In extended, complex IR nebula. Low-mass YSO[a]
201550.96+373004.2	H I, He I, [Fe II]	Be/YSO	[S]: IRAS 20140+3720. $F = 3.6 \times 10^{-11}$
205636.17+432132.7	TiO, H I, He I, [Fe II], Ca II	CTT	[S]: nothing. $F = 2.1 \times 10^{-11}$. Class II YSO[b]
215545.55+575105.6	H I	Be/YSO	[S]: possible PN? (PM 1-336). Extended: *FWHM*(Hα) = 0.8″. $F = 1.7 \times 10^{-9}$. Massive YSO?[c]
224359.58+621432.2	TiO, H I, He I	YSO	[S]: nothing. $F = 3.5 \times 10^{-12}$
225318.87+622926.9	TiO, Li I, H I, He I, Ca II	CTT	[S]: nothing. X-ray source J225319.1+622926. $F = 3.9 \times 10^{-11}$. YSO in Cyg OB3 complex[d]
230059.39+615037.5	TiO, H I	YSO	[S]: nothing. $F = 2.0 \times 10^{-11}$

Notes. Classification codes are: CTT = Classical T Tauri star; YSO = young stellar object; Be = Be star; PN = planetary nebula. In the Notes, codes are: [S] = SIMBAD data. F = optical–IR integrated flux in erg cm^2 s^{-1}. [1] See Appendix C.

References. [a] Arvidsson et al. (2010); [b] Rebull et al. (2011); [c] Mottram et al. (2011); [d] Littlefair et al. (2010).

Appendix C: The compact planetary nebula IPHASJ191942.91+162128.0

SIMBAD lists at this position an IRAS source (IRAS 19147+1615) detected at 25 and 60 μm. It coincides with an unresolved (size <42″) radio continuum source NVSS J191942+162128 with flux S(1.4 GHz) = 4.3 ± 0.5 mJy. The object is also included in the 2MASS, UKIDSS, WISE, and AKARI-IRC databases.

The IPHAS (Hα+[N II]) and UKIDSS (H and K) images show that IPHASJ191942.91+162128.0 is moderately extended, with deconvolved FWHM of 1.2–1.3″. The UKIDSS H image, taken under excellent seeing conditions (0.6″), shows that the source is elongated in the NE-SW direction.

The SED of IPHASJ191942.91+162128.0 (not including the radio flux) is shown in Fig. B.2, and is rather different than those of YSOs and symbiotic stars, indicating that different contributors to the 1 → 60 μm emission are present: nebular continuum and line emission, dust with a broad range of temperatures, and possibly IR bands from molecules and other solid state features. This SED is typical of planetary nebulae.

Indeed, the optical spectrum of IPHASJ191942.91+162128.0 in Fig. B.1 corresponds to a low-excitation PN, showing a very weak continuum and strong emission lines of intermediate excitation ions. No He II lines are detected. The strongest spectral lines are spatially resolved in the 2D GTC spectrum with deconvolved FWHM of 1.1 and 1.3″ in Hα and [N II]6583 Å, respectively, i.e. in agreement with the values obtained from the images. Table C.1 lists the fluxes of the main emission lines measured in the spectrum.

The PN is heavily reddened, with A_V = 7.3 mag, which is the weighted average obtained from the Hα, Hβ, and Hγ line ratios using the Fitzpatrick (2004) extincton law with R_V = 3.1. The density is N_e([S II]) = 5000 cm^{-3}, and the temperature T_e([N II]) = 12 000 K. In spite of the relatively high electron density and small diameter, it is worth noting the absence in IPHASJ191942.91+162128.0 of the Ca II infrared triplet and [Fe II] emission lines typical of very young PNe (Viironen et al. 2009), indicating that the small apparent size is probably due to a large distance to the object. Total abundances of He/H = 0.11, 12log(S) = 6.6, and 12log(O) = 8.7 were obtained using *ICF* = 1.13 and 1.0 for S and O, respectively (Kingsburgh & Barlow 1994). These values are typical of mainstream Galactic PNe (cf. Pottasch 1983).

IPHASJ191942.91+162128.0 is located at $l_{\rm II}$ = 50.7°, $b_{\rm II}$ = +1.3°, i.e. towards the direction passing through the nearest end of the Galactic bar. Although its distance is undetermined with the data at hand, its size and chemical abundances are consistent with being a distant, relatively evolved PN located in the inner Galaxy near the extreme of the Galactic bar.

Table C.1. Observed line fluxes in IPHASJ191942.91+162128.0, normalized to Hβ = 100.

Line identification	Observed flux
Hγ 4340	17.9
Hβ 4861	100.0
[O III] 4959	701.0
[O III] 5007	2319.6
[N II] 5755	45.0
He I 5876	119.0
[O I] 6300	290.7
[S III] 6312	24.2
[O I] 6364	95.3
[N II] 6548	1719.9
Hα 6563	4662.3
[N II] 6583	5621.9
He I 6678	82.9
[S II] 6716	174.5
[S II] 6731	327.3
He I 7065	189.6
[Ar III] 7136	887.1
[O II] 7319	507.0
[O II] 7330	393.3
[Ar III] 7751	306.3