Detailed studies of IPHAS sources – II. Sab 19, a true planetary nebula and its mimic crossing the Perseus Arm

M. A. Guerrero 1,‡, R. Ortiz 2,⋆, L. Sabin 3,★, G. Ramos-Larios 4, and E. J. Alfaro 1

1Instituto de Astrofísica de Andalucía, IAA-CSIC, Glorieta de la Astronomía, s/n, E-18008 Granada, Spain
2Escuela de Artes, Ciências e Humanidades, USP, Av. Arlindo Bettio 1000, 03828-000 São Paulo, Brazil
3Instituto de Astronomía, UNAM, Apdo. Postal 877, Ensenada 22860, B.C., Mexico
4Instituto de Astrofísica y Meteorología, CUCEI, Universidad de Guadalajara, Av. Vallarta 2602, Arcos Vallarta, 44130 Guadalajara, Mexico

ABSTRACT

The INT Photometric Hα Survey (IPHAS) has provided us with a number of new emission-line sources, among which planetary nebulae (PNe) constitute an important fraction. Here we present a detailed analysis of the IPHAS nebula Sab 19 (IPHASX J055242.8+262116) based on radio, infrared, and optical images and intermediate- and high-dispersion long-slit spectra. Sab 19 consists of a roundish 0.10 pc in radius double-shell nebula surrounded by a much larger 2.8 pc in radius external shell with a prominent H-shaped filament. We confirm the nature of the main nebula as a PN whose sub-solar N/O ratio abundances, low ionized mass, peculiar radial velocity, and low-mass central star allow us to catalogue it as a Type III PN. Apparently, the progenitor star of Sab 19 became a PN when crossing the Perseus Arm during a brief visit of a few Myr. The higher N/O ratio and velocity shift ≃ 40 km s⁻¹ of the external shell with respect to the main nebula and its large ionized mass suggest that it is not truly associated with Sab 19, but it is rather dominated by a Strömgren zone in the interstellar medium ionized by the PN central star.

Key words: planetary nebulae: general – planetary nebulae: individual: Sab 19 – stars: AGB and post-AGB.

1 INTRODUCTION

The INT Photometric Hα Survey (IPHAS: Drew et al. 2005; Barentsen et al. 2014) has mapped the Northern Galactic Plane within the latitude range b < 5°, discovering hundreds of new emission-line sources. Among those, many can be expected to be planetary nebulae (PNe), and indeed follow-up spectroscopic observations have unveiled a large sample of new PNe. The first release of extended PNe based on the IPHAS catalogue identified 159 true, likely, and possible PNe (Sabin et al. 2014).

We have started a series of detailed analyses of individual IPHAS objects. Sabin et al. (2020) and Rodríguez-González et al. (in preparation) described an evolved bipolar PN and a highly extinguished bipolar PN, respectively. These two sources at an advanced evolutionary stage and found at large distances and affected by large amounts of extinction can be typically expected among IPHAS PNe. Here we have focused our attention on IPHASX J055242.8+262116, the source number #19 in Sabin et al.’s (2014) list, which will be referred to hereafter as Sab 19. This source, classified originally as a likely PN, is located on the Galactic plane along the Galactic anticentre (l = 183°0219, b = +0°0176) and presents an intriguing triple-shell morphology.

We have obtained new images and spectroscopic information for this source and combined this information with archival radio and infrared (IR) observations. Sab 19 is confirmed to be a true small-size PN surrounded by a much larger Strömgren zone in the interstellar medium (ISM), which mimics a PN halo. The article is organized as follows. The imaging and spectroscopic observations are listed in Section 2. The morphokinematics as well as the nebular and stellar properties of Sab 19 are discussed in Section 3. Finally, our discussion on the properties of the PN and its central star and our conclusions are presented in Sections 4 and 5, respectively.

2 OBSERVATIONS

2.1 Optical narrow-band imaging

Narrow-band optical images of Sab 19 in the Hα, [N II] λ6584 Å, and [O III] λ5007 Å emission lines were obtained with the ALhambra Faint Object Spectrograph and Camera (ALFOSC) on the 2.5-m Nordic Optical Telescope (NOT) at the Roque de los Muchachos Observatory (ORM, La Palma, Spain) on 2020 January 26. The detector was an E2V 231-42 2k × 2k CCD with pixel size 15 μm, providing a plate scale of 0.211 arcsec pixel⁻¹ and a field of view (FoV) of 6.3 × 6.3 arcmin². The images were obtained using the Observatorio de Sierra Nevada (OSN) H01 Hα (λc = 6565 Å, full width at half-maximum (FWHM) = 13 Å) and E16 [N II] (λc = 6583 Å, FWHM = 13 Å) filters, and the NOT #90 [O III] (λc = 5007 Å, FWHM = 30 Å) filter.
Three 600-s exposures were obtained for each filter, with a small dithering of a few arcsec between them to improve the image quality and remove cosmic rays. The observing conditions were excellent with a stable seeing of 1.0 arcsec for all the images, as inferred from the FWHM of stars in the FoV. All the images were reduced using standard IRAF routines. After accounting for vignetting caused by the filters, the net FoV is ≈5.2 arcmin.

### 2.2 Intermediate-dispersion spectroscopy

Intermediate-resolution spectra were obtained with the 10.4-m Gran Telescopio Canarias (GTC) of the ORM with the Optical System for Imaging and low-Intermediate-Resolution Integrated Spectroscopy (OSIRIS, Cepa et al. 2000) on 2018 January 2. OSIRIS was used with two Marconi 2048 × 4096 pixels CCD detectors with a 2 × 2 binning, leading to a spatial scale of 0.254 arcsec pixel$^{-1}$. The R1000B grism was used, providing a spectral coverage from 3650 to 7500 Å and a dispersion of 2.12 Å pixel$^{-1}$.

The observations consisted of four exposures of 450 and 750 s for a total exposure time of 4800 s. The slit was set at a position angle (PA) of 47° with a length of 7.4 arcmin. The slit width of 0.8 arcsec resulted in a spectral resolution $R = 900$. The data reduction, which includes wavelength calibration with HgAr and Ne lamps and flux calibration with the spectroscopic standard star Feige 110, was performed using standard IRAF routines.

### 2.3 High-dispersion spectroscopy

A long-slit high-dispersion optical spectrum of Sab 19 was obtained with the Manchester Echelle Spectrometer (MES, Meaburn et al. 2003) mounted on the 2.12-m telescope at the Observatorio Astronómico Nacional, San Pedro Mártir (OAN-SPM, Mexico). The observations were obtained on 2016 April 17 with a 2048 × 2048 pixels E2V CCD Marconi detector with a pixel size of 13.5 μm pixel$^{-1}$. An on-chip 4 × 4 binning was applied, resulting in a spatial scale of 0.702 arcsec pixel$^{-1}$ and a spectral scale 0.11 Å pixel$^{-1}$.

MES provides a slit length of 6.5 arcmin and the slit width was set to 150 μm, corresponding to 1.9 arcsec. The slit width and spatial scale were suitable for the non-optimal weather conditions, with a seeing of 1.8 arcsec, providing a spectral resolution $R = 1000$. The slit was arranged at PA 0° and one exposure of 1800 s was obtained with an Hα filter with $Δλ = 90$ Å to isolate the 87th echelle order. This order also contains the [N II] $λλ 6548,6584$ Å emission lines. A calibration frame of a Th–Ar lamp was obtained immediately after the science exposure to perform the wavelength calibration. The data were reduced using standard IRAF routines.

### 2.4 IR archival images

#### 2.4.1 Spitzer IRAC images

Sab 19 was observed on 2010 April by the Spitzer Space Telescope under the programme GLIMPSE360: Completing the Spitzer Galactic Plane Survey (PI: Barbara A. Whitney). Images were obtained in the 3.6- and 4.5-μm channels of the InfraRed Array Camera (IRAC, Fazio et al. 2004), a four-channel camera that provides simultaneous imaging at 3.6, 4.5, 5.8, and 8 μm with a similar 5.2 × 5.2 arcmin$^2$ field of view (FoV). The two short-wavelength channels use InSb detector arrays consisting of 256 × 256 pixels and a nearly same pixel scale of 1.2 arcsec pixel$^{-1}$. Images were retrieved from the Spitzer Heritage Archive.

#### 2.4.2 WISE imaging

Wide-field Infrared Survey Explorer Space Telescope (WISE, Wright et al. 2010) observations of Sab 19 in the mid-IR W2 4.6-μm, W3 12-μm, and W4 22-μm bands were retrieved from the NASA/IPAC Infrared Science Archive (IRSA). The angular resolutions of these observations were 6.4, 6.5, and 12.0 arcsec, respectively. The cryogenically cooled telescope uses 1024 × 1024 detector arrays of HgCdTe and Si:As with a plate scale of 2.75 arcsec pixel$^{-1}$.

### 3 RESULTS

#### 3.1 Morphology

The optical images in Fig. 1 reveal an [O III] and Hα bright round main nebula with a double-shell morphology and an H-shaped feature of diffuse emission brighter in [N II] and Hα. The main nebula consists of a 6.4 × 6.0-arcsec$^2$ roundish inner shell and a concentric 16.4 × 15.6-arcsec$^2$ outer shell. The outer shell has a notable brightness enhancement towards the north–north-east direction with its apex along PA $≈ 25°$, whereas the nebular emission along the opposite direction fades smoothly. The morphology of this outer shell is reminiscent of a bow shock as caused by the motion of the nebula through the ISM. This suggestion is reinforced by the offset of the central star PN (CSPN) with respect to the centre of the outer shell by $≈ 0.6$ arcsec along the direction of the apex of the bow shock.

The bright main optical nebula is surrounded by low-surface-brightness emission with an H-shaped morphology. This emission is not centred at the main nebula, but displaced towards the south–south-east with a filamentary and fuzzy appearance. The emission is brighter in Hα, with some bright filaments in [N II] particularly towards the south-west direction. The emission in these different emission lines is clearly stratified, with the lower ionization [N II] emission farther away from the main nebula.

A comparison with Spitzer IRAC images in the available 3.6- and 4.5-μm bands in Fig. 2 reveals that the optical H-shaped feature is not only particularly prominent in these IR bands, but it is the brightest feature of a larger structure, a roundish shell with a diameter $≈ 7.5$ arcmin. This external shell is quite filamentary and, as the outer shell of the main nebula, it is brighter towards the north-east direction and fainter and smoother towards the opposite direction. This might be indicative of the interaction with the ISM as the nebula moves through it, and actually the noticeable displacement of the main nebula towards the brightest north-east rim of this external shell lends support to this idea. The IR emission in the H-shaped feature also follows the excitation structure revealed in the optical emission lines, thus suggesting that the emission from this H-shaped feature arises from an atomic, molecular, or dusty component at lower excitation than the material responsible for the emission of the optical [N II] lines.

The parallax of Sab 19 is $0.35 ± 0.13$ mas (Gaia Collaboration et al. 2018). Adopting the Bayesian inference method of Baier-Jones et al. (2018), it implies a distance of 2.6$^{+1.3}_{-0.7}$ kpc. Accordingly, the main nebula of Sab 19 has a radius of 0.10$^{+0.08}_{-0.03}$ pc, whereas its external shell has a radius of 2.8$^{+1.4}_{-0.1}$ pc.

#### 3.2 Physical conditions and chemical abundances

The GTC OSIRIS long-slit spectra along PA 47° have been used to extract one-dimensional spectra of the different structural components of Sab 19, namely the CSPN, the inner and outer shells of the main nebula, and the external shell. The spectrum of the latter
corresponds to the only region detected, the bright filament of the H-shaped feature ≃ 70 arcsec south-west of the main nebula (marked by the label H in Fig. 2, right-hand panel). The one-dimensional spectra presented in Fig. 3 generally show a small number of emission lines, with very faint or even absent emission lines of low-ionization species in the main nebula (e.g. [S II]), which become brighter in the external shell. We notice that the He II $\lambda$4686 emission line is not detected throughout the nebula, neither in the higher excitation main nebula nor in the lower ionization external shell.

The intensity of the emission lines in these spectra relative to H$\beta$ and their $1\sigma$ uncertainties was determined and dereddened using the extinction law by Fitzpatrick & Massa (2007) for RV = 3.1 described by the coefficients $f_\lambda$ listed in Table 1 and the logarithmic extinction coefficient $c(H\beta)$ also listed in Table 1 derived from the observed H$\alpha$-to-H$\beta$ line ratio adopting case B recombination. The $1\sigma$ uncertainties of these logarithmic extinction coefficients imply that they have a similar value through the different nebular components, with marginal evidence for a higher extinction in the external shell.

These relative intensities were analysed using the nebular analysis tool ANNEB (Olguín et al. 2011) based on the IRAF nebular package (Shaw & Dufour 1995). Unfortunately, the spectra display very few temperature or density diagnostic emission lines; only a temperature $T_e$ ≃ 11 200 K can be determined from the relative intensities of the auroral-to-nebular [O III] optical emission lines in the spectrum extracted at the CSPN, and a density $N_e$ ≃ 300 cm$^{-3}$ from the relative intensities of the [S II] doublet in the spectrum of the brightest feature of the external shell.

The determination of the ionic and elemental abundances listed in Table 2 is thus affected by the small number of emission lines in the spectra, but also by the uncertain determination of the physical conditions. For the main nebula, we have assumed a density of 4000 cm$^{-3}$ as derived from radio observations (see Section 3.4) and adopted a temperature of 11 200 K, whereas for the external shell, we have adopted a density of 300 cm$^{-3}$ and assumed a typical value of 10 000 K for the temperature. Besides H$^+$ and He$^+$, the main species in the main nebula is O$^{++}$, which is almost 90 times more abundant than O$^+$. Yet the He II $\lambda$4686 emission line is not detected, indicating the lack of species of high excitation, including O$^{3+}$ and above. The nebula has thus a peculiar ionization balance, with most of the oxygen atoms as O$^{++}$ ions. The He and O abundances are
typical of Type III and IV PNe, with sub-solar N/O ratios \([\text{N/O}]_0 = 0.25 \pm 0.04\), Asplund et al. 2009\). Although the N/O ratio relies on the determination of the O$^+$ ionic abundances based on the [O II] $\lambda\lambda$7320,7330 doublet, which is more sensitive to $T_e$ than the determination of the N$^+$ ionic abundances, a solar value for this ratio would require an electronic temperature $\lesssim 8000$ K, which seems unlikely for the observed nebular excitation. On the other hand, the N/O ratio of the external shell is higher and marginally consistent with the solar value.

**3.3 Kinematics**

The MES echelle data provide kinematic information of the main nebular shell and the bright southern region and northern filament of the H-shaped feature intersected by the slit with PA = 0° (regions H$_S$ and H$_N$ in Fig. 2, right-hand panel, respectively). The position–velocity (PV) map of the H$_\alpha$ line shown in Fig. 4 reveals a lenticular shape for the main nebula of Sab 19 with brighter emission in the innermost region associated with its inner shell. Meanwhile, the line profile of the H$_\alpha$ emission associated with the regions of the H-shaped feature to the south of the main nebula (the northern filament is much fainter) is narrower than that of the main nebula and is basically consistent with a unique velocity, i.e. it does not show any velocity structure along the spatial extent $\sim 60$ arcsec of the line.

The H$_\alpha$ line profile extracted from the main shell (Fig. 5, top panel) is not resolved, but it is broader than the instrumental spectral resolution. The line can be fitted with two Gaussian components with radial velocities in the local standard of rest (LSR) $+81.8 \pm 2.1$ and $+101.0 \pm 2.1$ km s$^{-1}$, implying an LSR radial velocity $V_{\text{LSR}} = +91.4 \pm 1.3$ km s$^{-1}$ and an expansion velocity $V_{\text{exp}} \approx 9.6 \pm 3.0$ km s$^{-1}$. Adapting this expansion velocity for the outer shell, its $0.10^{+0.05}_{-0.05}$ pc radius implies a kinematic age $10^{4000}_{+5000} - 3000$ yr.

The line profile of the H$_\alpha$ emission associated with the H-shaped feature is shown in the middle and bottom panels of Fig. 5. As described above, it is narrow and it can indeed be fitted with a single Gaussian component with radial velocity $V_{\text{LSR}} = +51.1 \pm 1.5$ km s$^{-1}$ for the southern region H$_S$ and $+49.4 \pm 3.2$ km s$^{-1}$ for the northern region H$_N$. As illustrated in Figs 4 and 5, there is a remarkable $\sim 40$ km s$^{-1}$ shift between the radial velocities of the H-shaped feature and the main nebula of Sab 19.

**3.4 Nebular masses**

The ionized mass $M_{\text{ion}}$ of a PN can be estimated from its total H$\beta$ flux using, for instance, the relationship

$$M_{\text{ion}} = 11.06 \times F(\text{H}\beta) d^2 10^{0.88} N_e^{-1},$$

where $M_{\text{ion}}$ is given in solar masses, $F(\text{H}\beta)$ is the extinction-corrected H$\beta$ flux in units of $10^{-11}$ erg cm$^{-2}$ s$^{-1}$, $d$ is the distance in kpc, $\tau$ is the electron temperature in units of 10,000 K, and $N_e$ is the electron density (Pottasch 1983).

The H$\beta$ flux can be derived from the measured H$\alpha$ flux and the extinction derived from the nebular spectra $\epsilon(\text{H}\beta)$ of 1.9, as listed in Table 1. The H$\alpha$ flux from the main nebula and the external shell has been derived from the NOT ALFOSC H$\alpha$ image, computing the star-subtracted photon count rate within apertures encompassing the main nebular shell and the external shell (after excising the main nebular shell) and using the GTC OSIRIS spectra to flux calibrate them by comparing the image count rate within the nebular area covered by the GTC OSIRIS slit and the H$\alpha$ flux derived from this spectrum. The observed flux of the main and external nebulae are $1.6 \times 10^{-12}$ and $3.6 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$, respectively. The extinction-corrected intrinsic H$\beta$ fluxes would be $2.9 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ for the main nebula and $6.4 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ for the external shell. The corresponding intrinsic H$\beta$ fluxes would be $1.0 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ for the main nebula and $2.2 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ for the external shell. Therefore, the external shell intrinsic fluxes in these emission

\[\text{1}\] Accounting for the uncertainties in image count rate, cross-calibration of the NOT images with the OSIRIS spectra, and extinction, the total uncertainties for these intrinsic H$\beta$ fluxes are $<10$ per cent for the main nebula and $<15$ per cent for the external shell.
Figure 3. GTC OSIRIS one-dimensional spectra of the H-shaped feature of the external shell, the outer and inner shells, and the central star of Sab 19 (see the position of the long slit overlaid on Fig. 2, right-hand panel). Two different intensity scales are used to show both the bright (left-hand column) and faint (right-hand column) emission lines. Spectral regions with low signal-to-noise ratio are shown as dotted lines.

lines are approximately twice that of the main nebula, although its average surface brightness is \( \approx 100 \) times lower. We note that the H\( \beta \) intrinsic flux can also be derived from the radio flux at 5 GHz using the relationship

\[
\frac{F_{5 \text{ GHz}}}{F(\text{H}\beta)} = 2.82 \times 10^9 \rho^{0.53} \left(1 + \frac{n(\text{He}^+)}{n(\text{H}^+)}\right)
\]

(2)
given in Pottasch (1983). The radio flux at this frequency of 44 ± 4 mJy (Gregory & Taylor 1986) implies an H\( \beta \) flux of \( 10^{-11} \) erg cm\(^{-2}\) s\(^{-1}\), in general agreement with the previous estimate for the main nebula.

The density of the bright filament of the H-shaped feature of the external shell south-west of the main nebula has been estimated to be \( \approx 300 \) cm\(^{-3}\) (Table 1), which is certainly an upper limit to its average density. If this density is assumed to be the same for all ionized material in this shell, then equation (1) implies it has an ionized mass \( \approx 0.5 \) M\(_{\odot}\), which would be a lower limit for the ionized mass according to equation (1). On the other hand, the density of the main nebula is unknown. Since its H\( \beta \) flux is known, we can use the
recently, the AMI Galactic Plane Survey (AMIGPS, Perrott et al. 2018) detected an unresolved 5-GHz source at 17 arcsec from the central star of Sab 19, showing a flux of 44 $\mu$Jy. The stellar spectrum shows the broad spectral feature of $C IV$ at $\lambda 5806$, $\lambda 5770$, and $\lambda 5608$ from the intensity of the $[O III]$ line. The linear size of this emission, 0.91 pc by 7.5 arcmin or 5.7 pc at 2.6 kpc, it would imply an average electron temperature of $70000$ K, regardless of the optical thickness of the nebula ($\alpha < 0.005$). The density of the main nebula would be in the range from 2600 to $5600$ cm$^{-3}$, which is consistent with the estimate of the rms density for values of the filling factor $\epsilon$ in the range 0.02–0.10, that would result in ionized masses in the range $0.016$–$0.035$ $M_\odot$.

Assuming that the radio source associated with Sab 19 has the same dimensions at 1.4, 4.5, and 15.7 GHz, we can estimate the spectral index $\alpha$, considering $F(\nu) \propto \nu^\alpha$. The spectral index between 1.4 and 5 GHz is $-0.027$ and that between 5 and 15.7 GHz is $-0.25$. Therefore, at 1.4 GHz the radio continuum is near the turnover point between the optically thin and thick regimes, and the optical depth equals unity at this frequency (Pottasch 1983):

$$\tau_\nu = \int k_\nu dS = 8.24 \times 10^{-2} T_e^{-1.35} \nu^{-2.1} \int N_e N_\rho dS = 1,$$

where $\tau_\nu$ is the optical depth at the frequency $\nu$, $k_\nu$ is the absorption coefficient, $T_e$ is the electron temperature (K), and $N_e$ and $N_\rho$ are the proton and electron density (cm$^{-3}$), respectively, integrated along the line of sight $S$ (in pc). Assuming that $\tau_\nu$ equals the unity at 1.4 GHz, $T_e = 10000$ K, and $N_\rho = N_e$, we obtain the emission measure (EM):

$$EM = \int N_e^2 dS = 6.18 \times 10^6,$$

where EM is given in cm$^{-6}$ pc$^{-1}$.

An inspection of the radio emission shown in Fig. 6 reveals that the 3$\sigma$ contour levels of the emission at 1.4 GHz spread over an area about $72 \times 54$ arcsec$^2$. The linear size of this emission, 0.91 pc by 6.8 pc, would correspond to electron densities 2600–3000 cm$^{-3}$. If we assume instead that this radio emission uniquely arises from the main nebula of Sab 19, with a diameter of 16 arcsec or 0.20 pc at 2.6 kpc, then the emission measure in equation (5) implies an average electron density $N_e \approx 5600$ cm$^{-3}$. Alternatively, if the emission were uniquely associated with the external shell, with a diameter of 7.5 arcmin or 5.7 pc at 2.6 kpc, it would imply an average electron density $N_e \approx 1000$ cm$^{-3}$, which is unphysical because it is notably larger than the value derived from the [S II] line ratio. Most likely, the emission measure in equation (5) is a combination of those of the main nebula and external shell. The density of the main nebula would be in the range from 2600 to $5600$ cm$^{-3}$, which is consistent with the estimate of the rms density for values of the filling factor $\epsilon$ in the range 0.02–0.10, that would result in ionized masses in the range $0.016$–$0.035$ $M_\odot$.

### Table 2. Ionic and elemental abundances of Sab 19.

<table>
<thead>
<tr>
<th>Ratio</th>
<th>Main nebula</th>
<th>External shell</th>
</tr>
</thead>
<tbody>
<tr>
<td>$He^+ / H^+$</td>
<td>0.096 ± 0.008</td>
<td>...</td>
</tr>
<tr>
<td>$O^+ / H^+$</td>
<td>(6.8 ± 0.9) × 10$^{-6}$</td>
<td>(1.1 ± 0.3) × 10$^{-4}$</td>
</tr>
<tr>
<td>$O^{++} / H^+$</td>
<td>(2.9 ± 0.1) × 10$^{-6}$</td>
<td>(2.1 ± 0.3) × 10$^{-4}$</td>
</tr>
<tr>
<td>$N^+ / H^+$</td>
<td>(3.2 ± 0.5) × 10$^{-7}$</td>
<td>(1.6 ± 0.3) × 10$^{-5}$</td>
</tr>
<tr>
<td>$S^+ / H^+$</td>
<td>...</td>
<td>(1.6 ± 0.3) × 10$^{-6}$</td>
</tr>
<tr>
<td>$Ar^{+++} / H^+$</td>
<td>(5.8 ± 0.7) × 10$^{-7}$</td>
<td>(1.3 ± 0.4) × 10$^{-6}$</td>
</tr>
<tr>
<td>$He/H$</td>
<td>≥0.096</td>
<td>...</td>
</tr>
<tr>
<td>$O/H$</td>
<td>3.0 × 10$^{-6}$</td>
<td>3.3 × 10$^{-4}$</td>
</tr>
<tr>
<td>N/O</td>
<td>0.05 ± 0.01</td>
<td>0.15 ± 0.05</td>
</tr>
</tbody>
</table>

### 3.5 Properties of the central star

The excitation of the main nebula of Sab 19 is quite intriguing and may shed some light on the properties of its central star. The He II $\lambda 4686$ emission line is not detected with an upper limit at 3$\sigma$ of 1.8 per cent the intensity of the $H\beta$ line. The He II $\lambda 5876$ to $\lambda 5897$ line ratio $< 0.12$ thus indicates an effective temperature of $\leq 60000$ K, regardless of the optical thickness of the nebula (Gruenwald & Viegas 2000). The Stoy and Zanstra H temperatures $\approx 57300$ ± 3400 and $\approx 53000$ ± 10000 K, respectively, derived from the intensity of the [O III] $\lambda 5007$ line using Kaler & Jacoby’s (1991) prescriptions are consistent with the aforementioned upper limit. The stellar spectrum shows the broad spectral feature of C IV $\lambda 1548$, 1550, 5812 (Fig. 3), but neither the C III $\lambda 5696$ nor the O VI $\lambda 5290$ features. The range of effective temperatures proposed above for the central star of Sab 19 is consistent with these Wolf–Rayet (WR) features (Acker & Neiner 2003).

The Lyman luminosity of the central star ($L_{Ly}$) can be used to constrain the stellar radius and luminosity. The nebular recombination $^2$As suggested by the coincidence of the $H\beta$ flux derived from these radio observations and that of the main nebula derived from optical observations.

\[ N_e \epsilon^{1/2} = 2.74 \times 10^4 \left( \frac{F(H\beta) \epsilon^{0.88}}{\theta^3 d} \right)^{1/2}, \]

where $\epsilon$ is the filling factor and $\theta$ is the angular size in arcsec (Pottasch 1983). Then, for the angular size and $H\beta$ flux of the main nebula, an rms density of 800 $\epsilon^{-1/2}$ $cm^{-3}$ is derived. Therefore, according to equation (1), the ionized mass of the main nebula would be 0.10 $\epsilon^{1/2}$ $M_\odot$.
The rate can be obtained from the luminosity in the Hα line by comparing the total recombination rate with the bound–free transitions down to

\[
\int_{v_0}^{\infty} \frac{L_\alpha(\nu)}{h\nu} dv = \frac{L(\alpha)}{h\nu_{\text{Ly}}} \left( \frac{\alpha_\text{B}(T)}{\alpha_{\text{He}^+}(T)} \right),
\]

where \(\alpha_\text{B}(T)\) and \(\alpha_{\text{He}^+}(T)\) are the case B and the \(n = 2\) recombination coefficients, and \(v_0\) is the minimum ionization frequency of the hydrogen. Adopting the values of \(\alpha_\text{B} = 2.59 \times 10^{-13}\) and \(\alpha_{\text{He}^+} = 7.69 \times 10^{-14}\) cm s\(^{-1}\) for a temperature of 10 000 K (Osterbrock & Ferland 2006), the intrinsic Hα luminosities in the main nebula and external shell of 2.4 \(\times\) 10\(^{44}\) and 5.2 \(\times\) 10\(^{44}\) erg s\(^{-1}\), respectively, derived from the extinction-corrected fluxes given in the previous section, imply a total of 8.4 \(\times\) 10\(^{46}\) recombinations s\(^{-1}\).

At frequencies where the nebula is optically thick to the stellar Lyman continuum, the rate of incoming ionizing photons over the entire nebula (\(L_{\text{Ly}}\)) can be related to the free–free emission at the frequency \(v\) by the following relationship (Rubin 1968):

\[
L_{\text{Ly}} = \frac{5.59 \times 10^{48}}{1 + f_\text{e}(\text{He}^+/(\text{H}^+ + \text{He}^+))} \left( \frac{v}{5\text{ GHz}} \right)^{0.1} T_\text{e}^{-0.45} F_d d^2,
\]

where \(d\) is the distance in kpc, \(F_d\) is the total intensity in Jansky, and \(f_\text{e}(\text{He}^+/(\text{H}^+ + \text{He}^+))\) is the fraction of He–recombination photons energetic enough to ionize the hydrogen. Since the He II lines are absent in the optical spectrum, we can assume the latter to be null. Assuming \(T_\text{e} = 10\ 000\text{ K}\), we obtain at a distance of 2.6 kpc Lyman recombination numbers of 2.4 \(\times\) 10\(^{46}\), 2.6 \(\times\) 10\(^{46}\), and 2.2 \(\times\) 10\(^{46}\) s\(^{-1}\) at 1.4, 5, and 15.7 GHz, respectively.

We note that the radio-derived recombinations are about 3.5 times lower than that derived using the Hα line. Several factors might be responsible for this discrepancy. For example, the recombination rate obtained from the Hα image is strongly dependent on the interstellar extinction, whereas the radio value, which is not affected by extinction, assumes that Sab 19 is matter-bounded. If the latter hypothesis is incorrect, then \(L_{\text{Ly}}\) should be considered as a lower limit.

These observed \(L_{\text{Ly}}\) are compared to those computed assuming that the CSPN of Sab 19 emitted like a blackbody for various radii and temperatures in Fig. 7. The grey area in the plot delimits the upper and lower limits for the effective temperature. The plot also shows the Lyman luminosity of evolving CSPNe of 0.546 and 0.565 M\(_\odot\) calculated from the stellar temperatures and luminosities of the theoretical tracks by Schönberner (1983). According to this figure, the observed \(L_{\text{Ly}}\) is compatible with a very low mass CSPN, with \(M_{\text{CSPN}} \leq 0.546\ M_\odot\). The theoretical tracks indicate that \(L_{\text{CSPN}} \leq 1.2 \times 10^4 L_\odot\) and the stellar radius is \(R_{\text{CSPN}}/R_\odot = 0.3–0.4\), as obtained from the Hα flux, or \(\sim 0.2\), as obtained from the radio data.

Zhang & Kwok (1993) obtained various distance-independent parameters of PNe and analysed how they vary as the nebula evolves. Their results were based on the theoretical tracks of the...
Sab 19, a PN crossing the Perseus Arm

Figure 6. Colour-composite WISE picture of Sab 19 in the W2 4.6-μm (blue), W3 12-μm (green), and W4 22-μm (red) bands overlaid with yellow NVSS radio emission contours at 3, 10, 20, 40, and 50σ over the background. The arrows indicate the motion of Sab 19 derived from Gaia’s observations, as described in Fig. 1.

Figure 7. Lyman luminosity of CSPNe as a function of the stellar temperature assuming a blackbody model. Each curve represents a distinct radius (in $R_\odot$). The thick horizontal lines assign the Lyman luminosity obtained from the H$_\alpha$ image and from 1.4-, 5.0-, and 15.7-GHz radio data. The red dotted lines represent two evolutionary tracks calculated by Schönberner (1983), and the quantities along them represent the stellar luminosity. The grey area delimited by the two vertical dashed lines marks the lower and upper limits for the stellar temperature, obtained from the spectrum.

CSPN calculated by Schönberner (1983), but they noted that the evolutionary tracks of the lowest mass CSPNe had to be sped up in order to match the observations, which is in line with the latest evolutionary models of Miller-Bertolami (2016). Fig. 8 illustrates the evolutionary tracks of 0.546-, 0.565-, and 0.598-M$_\odot$ CSPNe by Zhang & Kwok (1993), based on the theoretical models by Schönberner (1983). CSPNe evolve from the left-hand to the right-hand side. The box marks the lower and upper limits of the temperature of the CSPN ($T_{\text{eff}}$) and the brightness temperature of the PN ($T_b$) at 5 GHz, whereas the crosses correspond to the location in this plot of a sample of PNe with measured $T_b$ extracted from Zhang & Kwok (1993).

Figure 8. Evolutionary tracks of CSPNe by Zhang & Kwok (1993), based on the theoretical models by Schönberner (1983). CSPNe evolve from the left-hand to the right-hand side. The box marks the lower and upper limits of the temperature of the CSPN ($T_{\text{eff}}$) and the brightness temperature of the PN ($T_b$) at 5 GHz, whereas the crosses correspond to the location in this plot of a sample of PNe with measured $T_b$ extracted from Zhang & Kwok (1993).

During a rapid evolutionary phase, the brightness temperature ($T_b$) of the nebula reaches its maximum, from which it slowly decreases as the PN evolves. The maximum $T_b$ at 5 GHz reached by a 0.598-, 0.565-, and 0.546-M$_\odot$ nucleus is 200, 120, and 3 K, approximately. This diagram allows the determination of the mass of the CSPN from two quantities: the nebular brightness temperature and the stellar effective temperature.
The average brightness temperature of Sab19 can be calculated using the equation

$$T_b = 0.28 \times \frac{F_{5 \text{GHz}}}{\theta^2}. \quad (8)$$

Assuming the dimensions of the 3σ contour levels at 1.4 GHz shown in Fig. 6 (72 × 54 arcsec$^2$), we obtain a lower limit for $T_b$ of 0.80 K, whereas an upper limit of 12.1 K is obtained assuming that all radiation emitted at 5 GHz originates in the main nebula only. When plotted in Fig. 8, these results indicate $M_{\text{ESPNe}} \approx 0.56 M_\odot$.

Considering the uncertainties, this result agrees with the previous estimates obtained using the Hα and radio nebular fluxes shown in Fig. 7.

4 DISCUSSION

4.1 The true and the mimic

The analysis of the observations presented in previous sections has revealed a multicomponent structure for Sab 19 consisting of a main double-shell nebula and a larger and fainter external shell with a prominent H-shaped feature. Their distinct properties suggest a distinct nature for each morphological component.

The main nebula of Sab 19 has a typical double-shell PN morphology. Its spectrum and the physical conditions and chemical abundances derived from it are also typical of PNes. It can be concluded that the main nebula of Sab 19 is a true PN. The nebula has sub-solar N/O abundance ratio, which is suggestive of a Type III or IV PN (Maciel & Koppen 1994), but we reckon that the distance error bar towards Sab 19 exhibits a range of velocities $-13 < V_{\text{LSR}} < +9$ km s$^{-1}$ (Wouterloot & Brand 1989). The radial velocity of the main nebula of Sab 19, however, is notably different, $V_{\text{LSR}} = +91$ km s$^{-1}$.

The discrepancy in radial velocity is also notorious on the tangential component of the velocity, i.e. the velocity on the plane of the sky. The proper motion components of Sab 19 measured by Gaia are $pm_\alpha = 1.234 \pm 0.205$ mas yr$^{-1}$ and $pm_\delta = 0.848 \pm 0.161$ mas yr$^{-1}$, implying a large angle with the Galactic plane. On the other hand, the proper motion module of 1.50 mas yr$^{-1}$ corresponds to a linear velocity on the plane of the sky of $\approx 19$ km s$^{-1}$ for the distance given by Baier-Jones et al. (2018). This confirms that the motion of Sab 19 is dominated by its radial velocity and that it does not corotate with the Perseus Arm, reinforcing the idea that Sab 19 is not actually associated with it, but it is crossing it at a relative velocity $\geq 80$ km s$^{-1}$. Actually, the distance of 2.6 kpc of Sab 19 would place it in the outer border of the Perseus Arm, which it would be ‘leaving’ after a ‘short visit’ of a few Myr (15 Myr if a thickness of 1.5 kpc is adopted for the Perseus Arm according to fig. 3 in Reid et al. 2019), but we reckon that the distance error bar towards Sab 19 makes this claim uncertain.

The complete information on the position of Sab 19 in the phase space has been used to analyse its dynamic properties using the GALPY package (Bovy 2015). The initial values of the orbit are given by the coordinates, distance, proper motion, and radial velocity of Sab 19, though we reckon the large uncertainties in distance and proper motion. The nebula is then assumed to move under the gravitational potential MWPotential2014 included in GALPY, whose structure and physical properties are discussed in detail by Bovy (2015). As for our position and velocity in the Galaxy, the solar motion $[-9.4, 12.6, 6.3]$ km s$^{-1}$ in the ISM, to further reassure this possibility, the relationship between Sab 19 and the local ISM is investigated in the next section.

4.2 Sab 19 and its place in the galaxy

At a distance of 2.6$^{+1.3}_{-0.7}$ kpc along galactic longitude $\approx 183^\circ$ (i.e. mostly at the Galactic anticentre), Sab 19 is located in the outskirts of the Perseus Arm, which extends from 1.4 to 2.9 kpc along this direction, traced by very young high-mass stars (Reid et al. 2019).

This description is consistent with the image in Fig. 6, which shows large-scale patchy emission in the WISE W3 band at 12 μm, revealing a complex ISM along the line of sight of Sab 19. Since the mid-IR emission from the external shell of Sab 19 peaks in the Spitzer 3.6-μm and WISE W2 4.6-μm bands, whereas that of the ISM around it is brighter in the WISE W3 12-μm band (Figs 2 and 6), it can be concluded that the mid-IR emission from the external shell of Sab 19 includes line emission or is indicative of warmer dust than that in the ISM.

The positional coincidence of Sab 19 with the Perseus Arm is, however, in sharp contrast with their respective radial velocities. The LSR velocity at the Galactic anticentre is expected to be null. Actually, LSR velocities in the range from $-20$ km s$^{-1}$ to $+10$ km s$^{-1}$ are measured in the Galactic H I emission and giant molecular clouds along this direction (see fig. 3 in Reid et al. 2019). For instance, WB717 is a CO ($J=1-0$) source detected towards Sab 19 at $V_{\text{LSR}} = -0.2$ km s$^{-1}$, whereas other neighbouring CO sources detected within Galactic longitude $\pm 1^\circ$ from Sab 19 exhibit a range of velocities $-13 < V_{\text{LSR}} < +9$ km s$^{-1}$ (Wouterloot & Brand 1989).

The radial velocity of the main nebula of Sab 19, however, is notably different, $V_{\text{LSR}} = +91$ km s$^{-1}$.

4.3 Just passing by, but leaving a mark

The notable differences between the radial velocity of the main nebula of Sab 19 and the external shell make very unlikely the latter to
be a halo ejected in late phases of the stellar evolution. Interestingly, the radial velocity of the external shell \((V_{LSR} \approx +51 \text{ km s}^{-1})\) is half way between that of the main nebula of Sab 19 \((V_{LSR} \approx +91 \text{ km s}^{-1})\) and that expected for the ISM \((-13 < V_{LSR} < -9 \text{ km s}^{-1})\). This seems to imply that the material in this external shell has experienced an interaction with the moving PN.

To investigate in more detail the possible interactions caused by the motion of Sab 19 through the ISM, the direction of its motion according to the Gaia proper motions of pmRA \(= 1.234 \pm 0.205\) mas yr\(^{-1}\) and pmDEC \(= 0.848 \pm 0.161\) mas yr\(^{-1}\) has been over-plotted in Figs 1, 2, and 6. The coincidence of the orientation of morphological asymmetries in the different shells of Sab 19 and the direction of its motion on the plane of the sky lends support to this interaction: the central star is offset towards the south-west of the main nebula, which shows a bow-shock-like brightness enhancement in the north-east direction (Fig. 1), the IR shell is compressed along this direction and shows a more diffuse and fainter emission along the opposite south-west trailing direction (Figs 2 and 6), and the radio emission shows a bow-shock-like morphology towards the north-east and a smooth decline in brightness towards the south-west along the trailing direction.

The interactions of the outer shells and haloes of PNe with the surrounding ISM have been largely reported and described (e.g. Tweedy & Kwitter 1996; Wareing, Zijlstra & O’Brien 2007). Indeed, the location of Sab 19 in the Perseus Arm and the large-scale IR emission around it indicates that the local ISM is relatively dense. The external shell of Sab 19 is not a halo, however, as most of (if not all) the material in this shell belongs to a Strømgren zone in the ISM, which is being ionized by the CSPN of Sab 19. Still, the H-shaped filaments in this external shell may arise as a result of Rayleigh–Taylor (RT) instabilities formed by the interaction of a fast-moving ionized shell with a cold, dense, perhaps magnetized ISM. The shape of the structures formed depends on many parameters, such as the intensity of the magnetic field and the pitch angle between the velocity of the PN and the local magnetic field. For a fast-moving PN, the shock formed between the PN and the local ISM is isothermal, and the ISM magnetic field can contribute to form RT instabilities just behind the shock wave (Soker & Dgani 1997). At any rate, RT structures normally do not penetrate the ionized main PN shell, but they are restricted to the external, fragmented external shell (Soker & Dgani 1997; Dgani & Soker 1998), as is the case of Sab 19.

It is interesting to note that the module of the velocity vector of Sab 19 on the plane of the sky, \(\approx 19 \text{ km s}^{-1}\), is about five times smaller than its radial component along the line of sight, \(\approx 91 \text{ km s}^{-1}\). We can thus expect that the external shell of Sab 19 would be much thicker along the line of sight than its projection on the plane of the sky. If we keep in mind that the velocity component of Mira on the plane of the sky is \(\approx 130 \text{ km s}^{-1}\), quite similar to the radial velocity of Sab 19, it could be envisaged the external shell of Sab 19 as the long tail left behind by Mira (Martin et al. 2007), but seen face-on. A similar structure on the plane of the sky might also be observed in the PN HFG1 (Boumis et al. 2009; Chiostellis et al. 2016).

### 4.4 The nature of Sab 19

The peculiar velocity of Sab 19 and the maximum height of its orbit over the Galactic plane can be used to further investigate its past evolution. It has been noted that the average peculiar velocity increases among the different Peimbert’s types of PNe (Peimbert 1978), increasing from 20 \(\pm 14\) km s\(^{-1}\) for the N- and He-rich Type I PNe descending from more massive progenitors up to 170 \(\pm 80\) km s\(^{-1}\) for Type IV PNe of the halo evolving from low-mass progenitors (Maciel & Dutra 1992). The maximum height over the Galactic plane of Sab 19 implies that it is not a halo Type IV PN, but rather it can be classified as a Type III PN. The peculiar velocities of Type III PNe are indeed typically high, \(\approx 60 \text{ km s}^{-1}\), with many of them showing higher peculiar velocities, such as Me 2-2 (\(-140 \text{ km s}^{-1}\), IC 5217 (87 km s\(^{-1}\)), or K 3-67 (\(-84 \text{ km s}^{-1}\)).

Ortiz & Maciel (1994) observed that AGB stars can also be classified into types similar to the Peimbert scheme according to their kinematics. The theoretical models of Vassiliadis & Wood (1994) and Miller-Bertolami (2016) can be used to estimate the mass of the precursor zero-age main sequence (ZAMS) stars for a set of metallicities. The mass of 0.546–0.565 M\(_\odot\) of the CSPN of Sab 19 is consistent with the final mass of 0.528–0.652 M\(_\odot\) of a solar-metallicity \((Z = 0.02)\) ZAMS star with an initial mass in the range of 1.00–1.25 M\(_\odot\). Adopting a lower metallicity of \(Z = 0.001\), the final mass of 0.534–0.552 M\(_\odot\) implies initial masses of ZAMS stars in the range of 0.90–1.00 M\(_\odot\). Therefore, according to these theoretical models and the mass of the CSPN determined in Section 3.5, Sab 19 descends from a nearly-solar-mass main-sequence star. Its maximum rotational velocity of 250 km s\(^{-1}\) makes it very likely a member of the thin disc population.

### 5 SUMMARY AND CONCLUSION

We have presented new and archival multiwavelength images and new intermediate- and high-dispersion spectroscopic observations of Sab 19, aka IPHASX J055242.8+262116. These observations reveal that Sab 19 consists of two morphological components, a double-shell main nebula and an external shell dominated by a prominent set of H-shaped filaments. At a distance of 2.6 kpc, as derived from Gaia, the size of these shells is 0.10 and 2.8 pc, respectively. The origin of these two components is different.

The double-shell main nebula is a Type III PN descending from a low-mass \((0.90–1.25 \text{ M}_\odot)\) progenitor star, according to the small nebular ionized mass, the 0.56–0.76 M\(_\odot\) low-mass CSPN, the peculiar velocity of the nebula, its small expansion velocity, and the nebular sub-solar N/O ratio. On the other hand, the higher N/O ratio, large ionized mass, and radial velocity shift with the main nebula of the external shell suggested by the present data make it very likely to be a Strømgren zone in the ISM ionized by the CSPN of Sab 19. A complete spatio-kinematic study and investigation of the physical conditions in the external shell will certainly help to confirm it.

Sab 19 is located in the Perseus Arm, but its peculiar radial velocity implies that it is not associated with it, but it is actually crossing it as it moves towards the apogee of its galactic orbit at about 15 kpc from the Galactic Centre. Apparently, the progenitor of Sab 19 is a low-mass star of the thin disc on a very eccentric orbit that happened to become a double-shell PN as it was crossing the Perseus Arm. The interactions of the PN and its associated Strømgren zone with the local ISM are quite notorious.

### ACKNOWLEDGEMENTS

We acknowledge support of the publication fee by the CSIC Open Access Publication Support Initiative through its Unit of Information Resources for Research (URICI). MAG acknowledges support from the Spanish Government Ministerio de Ciencia, Innovación y Universidades (MCIU) through grant PGC2018-102184-B-I00. LS acknowledges support from DGAPA, UNAM PAPIIT project IN101819. GR-L acknowledges support from Consejo Nacional de Ciencia y Tecnología (CONACyT) grant 263373 and Programa para el Desarrollo Profesional (PRODEP) Mexico, and EJA acknowledges...
support from MCIU grant PGC2018-095049-B-C21. MAG and EJA are supported by the State Agency for Research of the Spanish MCIU through the “Center of Excellence Severo Ochoa” award for the Instituto de Astrofísica de Andalucía (SEV-2017-0709).

We appreciate Dr V. M. A. Gómez-González for helpful discussion on the nature and properties of the central star of Sab 19.

This research has made use of the SIMBAD database operated at CDS (Strasbourg, France), the NASA/IPAC Infrared Science Archive, which is funded by the National Aeronautics and Space Administration and operated by the California Institute of Technology, the NASA’s Astrophysics Data System, and NRAO VLA Sky Survey. It has also made use of data obtained as part of the INT Photometric H r Survey (IPHAS) of the Northern Galactic Plane carried out at the Isaac Newton Telescope (INT), which is operated on the island of La Palma by the Isaac Newton Group in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias, in the island of La Palma. NOT is owned by the Spanish Government. It was partly based on data obtained with the instruments ALFOSC, NOTSA, and OSIRIS, built by a Consortium led by the Instituto de Astrofísica de Andalucía (IAA) and operated jointly by Aarhus University, the University of Turku and Stockholm University. This work is partly based on data obtained with the instruments ALFOSC, which is provided by the Instituto de Astrofísica de Andalucía (IAA) under a joint agreement with the University of Copenhagen and NOTSA, and OSIRIS, built by a Consortium led by the Instituto de Astrofísica de Canarias in collaboration with the Instituto de Astronomía of the Universidad Autónoma de México. OSIRIS was funded by GRANTECAN and the National Plan of Astronomy and Astrophysics of the Spanish Government.

DATA AVAILABILITY
All data used in this manuscript are available through public archives, but the NOT narrow-band images can be obtained from the authors after a justified requirement.

REFERENCES
Martin D. C. et al., 2007, Nature, 448, 780
Wright E. L. et al., 2010, AJ, 140, 1868

This paper has been typeset from a \TeX/\LaTeX file prepared by the author.