The reactivation of water maser emission in the planetary nebula IRAS18061–2505 through a born-again episode

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ABSTRACT
Water maser emitting planetary nebulae (H2O-PNe) are believed to be among the youngest PNe. We present new optical narrow- and broad-band images, intermediate- and high-resolution long-slit spectra, and archival optical images of the H2O-PN IRAS18061–2505. It appears a pinched-waist bipolar PN consisting of knotty lobes with some point-symmetric regions, a bow-shock near the tip of each lobe, and a very compact inner nebula where five components are identified in the spectra by their kinematic and emission properties. The water masers most probably reside in an oxygen-rich ring tracing the equatorial region of the bipolar lobes. These two structures probably result from common envelope evolution plus several bipolar and non-bipolar collimated outflows that have distorted the lobes. The bow-shocks could be related to a previous phase to that of common envelope. The inner nebula may be attributed to a late or very late thermal pulse that occurred before ∼1951.6 when it was not detectable in the POSS I-Blue image. Chemical abundances and other properties favour a ∼3–4 M⊙ progenitor, although if the common envelope phase accelerated the evolution of the central star, masses < 1.5 M⊙ cannot be discarded. The age of the bipolar lobes is incompatible with the existence of water masers in IRAS18061–2505, which may have been lately reactivated through shocks in the oxygen-rich ring, that are generated by the thermal pulse, implying that this PN is not extremely young. We discuss H2O-PNe and possibly related objects in the light of our results for IRAS18061–2505.

Key words: planetary nebula: individual (IRAS18061–2505) – circumstellar matter – interstellar medium: jets and outflows

1 INTRODUCTION
The transformation of an asymptotic giant branch (AGB) star into a planetary nebula (PN) is one of the most astonishing processes in stellar evolution, through which most low- and intermediate-mass (M~0.8–8 M⊙) main-sequence (MS)
stars are believed to go through at the end of their lives. An outstanding characteristic of PNe are their enormous morphological variety (Schwarz, Corradi & Melnik 1992; Manchado et al. 1996; Parker et al. 2006; Sahai, Morris & Villar 2011). Different processes are suggested to explain their shapes, including anisotropic AGB envelopes, action of collimated outflows on the AGB envelope, and/or large-scale magnetic fields (e.g., Sahai & Trauger 1998; Balick & Frank 2002; Sabin 2015; Vlemmings 2019). In a broad context, it is now accepted that the formation of many PNe is ultimately related to the evolution of binary/multiple central stars (CS; De Marco 2009; Miszalski et al. 2009; Soker 2016; Jones & Bohlin 2017; and references therein). The large parameter space of CSs with stellar, substellar, or even planetary-mass companions provides a context in which the varied shapes of PNe maybe explained (De Marco & Soker 2011, and references therein; Soker 2016; Reichardt et al. 2019; Decin et al. 2020). To investigate the different situations and compare them with models, it is important to increase the number of well-studied PNe and find possible features that could be related to binary central star evolution.

Information about PNe formation can be obtained from the very earliest stages in this phase, in which we can study the properties of the shells before they may be modified by further evolutionary effects. Water maser emitting PNe (hereafter H$_2$O-PNe, Gómez et al. 2008) are believed to be among the youngest PNe. Water maser emission, typical of oxygen-rich AGB envelopes (e.g., Engels & Bunzel 2015), may survive $\approx$100 yr after strong AGB mass loss ceases (Lewis 1989; Gómez, Morán & Rodríguez 1990). Therefore, stars capable to reach the PN phase ($T_{\text{eff}} \approx 25000$ K) in $\lesssim 100$ yr from the end of AGB, are potential candidates to exhibit water masers in their very early PN phase, implying that H$_2$O-PNe should descend from intermediate-mass MS progenitors. Nevertheless, water masers in PNe may not necessarily be the remnants of the AGB ones but could be due to anisotropic ejections in the AGB to PN transition (e.g., Gómez et al. 2015b).

Five bona-fide H$_2$O-PNe have been confirmed so far, using interferometric water maser observations: IRAS 19255+2123 (K 3-35, Miranda et al. 2001a), IRAS 17347–3139 (de Gregorio-Monsalvo et al. 2004), IRAS 18061–2505 (Gómez et al. 2008), IRAS 16333–4807 (Uscanga et al. 2014), and IRAS 15103–5754 (Gómez et al. 2015a). Is another candidate, IRAS 17393–2727 (Gómez et al. 2015b), toward which water maser emission was detected with a single-dish telescope, but no interferometric confirmation is yet available. H$_2$O-PNe are revealing important aspects of PN formation. Interaction between jets and the AGB envelope may excite water masers in young PNe, as suggested by Miranda et al. (2001a) to explain the water masers at the tips of the processing jets in K 3-35 (see also Miranda et al. 2007; Tafoya et al. 2011; Blanco et al. 2014). Magnetic fields have been detected in some H$_2$O-PNe via OH maser polarisation (Miranda et al. 2001a; Gómez et al. 2009, 2016; Qiao et al. 2016; Hou & Gao 2020). Moreover, the only PN with non-thermal (probably synchrotron) radio continuum emission identified so far is IRAS 15013–5754, an extremely young, rapidly evolving H$_2$O-PN with high-velocity water masers arising in a magnetised jet (Suárez et al. 2015; Gómez et al. 2015a).

This paper is devoted to IRAS 18061–2505 (MaC 1-10, PN G005.9–02.6; hereafter IRAS18061). The object was discovered by MacConnell (1978) in H$_\alpha$ objective-prism plates (taken sometime between 1967 and 1974) and reported as a possible PN. Suárez et al. (2006) confirmed the PN nature of IRAS18061 from a spectrum in the range $\sim$3600–10000 Å obtained in 1994.2. Water maser emission towards IRAS18061 was first detected by Suárez, Gómez & Morata (2007) with single-dish observations. Gómez et al. (2008) used the Very Large Array (VLA) and confirmed the association between the radio continuum and water maser emission from the object.

The H$_\alpha$ image of IRAS18061 presented by Suárez et al. (2006) shows a bipolar nebula of $\sim$40 arcsec in size with two lobes oriented at PA $\sim$60$^\circ$, emanating from a bright compact (stellar-like) object that is detected at optical, near-, mid-, far-infrared, and radio continuum wavelengths (Gómez et al. 2008; Zhang, Hsia & Kwok 2012) and may be better referred to as the core of IRAS18061; the bipolar lobes have been detected so far at optical wavelengths only. The CS is hosted in the core, its spectrum presents broad carbon emission lines, and has been classified as [WC8] by Görny & Siódmiak (2003). Görny et al. (2004, 2009) reported peculiar chemical abundances in the nebula. As usually found in PNe with late [WC]-type central stars, IRAS18061 presents dual chemistry (Perea-Calderón et al. 2009; Guzmán-Ramírez et al. 2011).

IRAS18061 is a peculiar case among H$_2$O-PNe. It is the only one completely visible at optical wavelengths, including the CS, while the others are more extincted. It is also the only H$_2$O-PN without OH maser emission (Gómez et al. 2008), which is present in the rest (Zijlstra et al. 1989; Sevenster et al. 1997; Miranda et al. 2001a; de Gregorio-Monsalvo et al. 2004; Uscanga et al. 2012; Gómez et al. 2015a,b; Quiro et al. 2016). The angular size of the nebula ($\sim$40 arcsec) is very large when compared with that of $\sim$2–8 arcsec observed in the other H$_2$O-PNe. Apart from the presence of water masers and these peculiarities, that make IRAS18061 an interesting PN, many properties of the object remain largely unknown.

In this paper we present a study of IRAS18061 based on new narrow- and broad-band optical images, high- and intermediate-resolution long-slit spectra, and archival optical images. After analysing the properties of IRAS18061, we try to estimate the mass of its MS progenitor, describe the formation process of the nebula, and propose a new scenario to account for the presence of water masers in this PN. Finally, we discuss H$_2$O-PNe and possibly related objects in the light of the results obtained for IRAS18061 and evolutionary models for the AGB to PN transition.

2 OBSERVATIONS

2.1 Optical imaging

Narrow-band optical images of IRAS18061 were obtained on (1) 2000 June 12 with ALFOSC at the 2.5 m Nordic Optical Telescope (NOT) at El Roque de los Muchachos Observatory (La Palma, Spain); (2) 2010 July 30 with CAFOS at the 2.2 m telescope at Calar Alto Observatory (Almeria, Spain), and (3) 2013 August 7–9 with the 2.3 m Aristarchos Telescope at Helmos Observatory of the National Observatory of Athens (Greece). Broad-band images were obtained with CAFOS on 2017 June 28.

(1) The detector of ALFOSC was a Tektronik 1k×1k CCD
with a plate scale of 0.176 arcsec pixel$^{-1}$. Images were obtained through the H$\alpha$ ($\lambda_0 = 6563$ Å, FWHM = 9 Å), [N ii] ($\lambda_0 = 6584$ Å, FWHM = 15 Å), and [O ii] ($\lambda_0 = 6725$ Å, FWHM = 60 Å) 1ÅC filters, and through the [O iii] ($\lambda_0 = 5007$ Å, FWHM = 30 Å) NOT filter. Exposure time was 300 s in each filter. Seeing was $\sim 1.1$ arcsec.

(2) The detector of CAFOS was a SiTe 2k×2k CCD with a plate scale of 0.53 arcsec pixel$^{-1}$. Images were obtained through H$\alpha$ ($\lambda_0 = 6567$ Å, FWHM = 17 Å), [N ii] ($\lambda_0 = 6588$ Å, FWHM = 17 Å), and [O iii] ($\lambda_0 = 5011$ Å, FWHM = 30 Å) filters. Exposure time was 1800 s in each filter. Seeing was $\sim 1.4$ arcsec. The broad-band images were obtained in the Johnson B, V, R, and I filters with an exposure time of 900 s in each filter, poor seeing conditions ($\sim 3.5$ arcsec) and non-photometric night.

(3) At the Aristarchos telescope, the detector was an E2V 1k×1k CCD with a plate scale of 0.28 arcsec pixel$^{-1}$. Images were obtained through H$\alpha$ ($\lambda_0 = 6567$ Å, FWHM = 15 Å), [N ii] ($\lambda_0 = 6588$ Å, FWHM = 17 Å), and [O iii] ($\lambda_0 = 5011$ Å, FWHM = 30 Å) filters. Exposure time was 1800 s in each filter. Seeing was $\sim 1.5$ arcsec.

The images were cosmic rays cleaned, bias subtracted, and flat fielded using standard procedures in the MIDAS package.

2.2 High-resolution long-slit spectroscopy

High-resolution, long-slit spectra were obtained with the Manchester Echelle Spectrometer (MES, Meaburn et al. 2003) at the 2.12 m telescope at the San Pedro Mártir Observatory (OAN-SPM, Baja California, México) on 2008 June 4–6, 2015 May 16, and 2017 August 7. In 2008 the detector was a SiTe 1k×1k CCD (in 1×1 binning), providing wavelength and angular scales of 0.05 Å pixel$^{-1}$ and 0.33 arcsec pixel$^{-1}$, respectively. In 2015 and 2017 the detector was an E2V 2k×2k CCD (in 2×2 binning), providing wavelength and angular scales of 0.057 Å pixel$^{-1}$ and 0.351 arcsec pixel$^{-1}$, respectively. MES has no cross-dispersion, hence, a $\Delta \lambda = 90$ Å band-width filter was used to isolate the 87$^{th}$ order covering the H$\alpha$ and [N ii]6583 emission lines in the 2008 spectra and also including the [N ii]6548 emission line in the 2015 and 2017 spectra. The slit, with a length of 6.5 arcmin and a width of 1(2) arcsec in the 2008 (2015, 2017) observations, was centred on the core of IRAS18061 and oriented at position angles (PAs) $+55^{\circ}$, $+26^{\circ}$, $-35^{\circ}$, and $-81^{\circ}$ in 2008, PA $+55^{\circ}$ in 2015 (hereafter PA $+55^{\circ}$/2015), and PAs $+33^{\circ}$ and $+60^{\circ}$ in 2017. We note that the 2008 spectra have a lower signal-to-noise ratio than that obtained in 2015 and 2017. Exposure time was 1800 s for each spectrum. Seeing was $\sim 2$ arcsec in the three epochs.

The spectra were reduced using standard procedures for long-slit spectroscopy in the IRAF$^1$ package. Wavelength calibration was carried out using a Th-Ar lamp and the spectra were calibrated to an accuracy of $\pm 1$ km s$^{-1}$. The spectral resolution is $\sim 12$ km s$^{-1}$, as indicated by the FWHM of the Th-Ar lamp emission lines.

2.3 Intermediate-resolution long-slit spectroscopy

Intermediate-resolution, long slit-spectra were obtained on 2011 July 7 with the Boller & Chivens spectrograph mounted at the 2.12 m telescope at the OAN-SPM, using as detector a Marconi 2k×2k CCD. We employed a 400 lines mm$^{-1}$ dispersion grating along with a 2.5 arcsec slit width, giving a spectral resolution (FWHM) of $\sim 8.5$ Å and covering the 4200–7600 Å spectral range. The slit was centred on the core of IRAS18061 and oriented at PA $+55^{\circ}$. Two 1800 s exposures were obtained, reduced independently, and added to get a final spectrum with a total exposure time of 3600 s. Spectrophotometric standard stars were observed in the same night as the object for flux calibration. Seeing was $\sim 2$ arcsec during the observations. Spectra reduction was carried out following standard procedures in XVISTA$^2$.

3 RESULTS

3.1 Morphology

The H$\alpha$, [N ii], [O iii], and [S ii] NOT images of IRAS18061 are shown in Figure 1 in a linear flux scale. Figure 2 presents the [N ii] NOT image in a logarithmic flux scale to better show the faint nebular regions. Figure 3 presents a colour composite image obtained by combining the H$\alpha$, [N ii], and [O iii] images shown in Figure 1. To construct the colour image, we have carried out an approximate flux calibration of the individual ones using the observed fluxes of the three emission lines in the intermediate-resolution long-slit spectrum (Section 3.3).

IRAS18061 appears as a pinched-waist, knotty bipolar PN with some point-symmetrical regions and polar low-ionization features. The images allow us to identify three basic nebular structures (Figure 1): (1) the bright core at the centre of the object; (2) the bipolar lobes; and (3) two bow-shock-like structures at the tips of the lobes. The long-exposure Aristarchos and CAHA images do not show additional structures when compared with the short-exposure NOT images. In the following we will discuss the three components separately.

3.1.1 The core

The core is bright in H$\alpha$, [N ii], and [O iii], and noticeably weaker in [S ii] (Figure 1). Although it appears “stellar-like”, we noticed that its FWHM is larger than that of the field stars in each image, indicating that it is partially resolved. We have obtained the PSF of each image from several field stars of similar brightness to that of the core, which was used to derive the deconvolved size (FWHM) of the core in each image. Averaging the results in each filter, the deconvolved (FWHM) size of the core is $0.34 \pm 0.14$ arcsec in H$\alpha$, $0.45 \pm 0.10$ arcsec in [N ii], $0.70 \pm 0.15$ arcsec in [O iii], and $0.28 \pm 0.14$ arcsec in [S ii]. Moreover, from the radio continuum data presented by Gómez et al. (2008) and assuming that the emission at 1.665 GHz, detected only from the core, is optically thick, a

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

$^2$ XVISTA was originally developed as Lick Observatory Vista. It is currently maintained by Jon Holtzman at New Mexico State University and is available at http://ganymede.nmsu.edu/holts/xvista.
Figure 1. Grey-scale reproductions of the Hα, [N\textsc{ii}], [O\textsc{iii}], and [S\textsc{ii}] NOT images of IRAS18061. The grey levels are linear. The origin (0,0) is located at the position of the maximum intensity of the core at α(2016.0) = 18\textdegree 09\textquoteleft 12\textquoteleft .411, δ(2016.0) = −25\textdegree 04\textquoteleft 34\textquoteright .56 from the Gaia Early Data Release 3. The basic nebular structures discussed in the paper are marked in the [N\textsc{ii}] panel. Red crosses in the [S\textsc{ii}] image mark field stars on or close the nebula, as deduced from the PanSTARRs r and z images (see Appendix A). Seeing is ∼1.1 arcsec.

(FWHM) size of ∼0.41 arcsec is obtained. These results reveal the existence of a very (angularly) small ionised nebula in the core, that will be referred hereafter to as the inner nebula. Its deconvolved size is maximum in [O\textsc{iii}], minimum in [S\textsc{ii}], and presents intermediate values in [N\textsc{ii}] and Hα. This is not expected in a simple photoionised nebula, where high excitation should be observed closer to the central star than low excitation, suggesting the existence of several regions in the inner nebula with different excitation, physical conditions, and/or geometry.

Figure 4 shows images of IRAS18061 in different filters and from different epochs: the Palomar Observatory Sky Survey POSS I-Blue and -Red images taken in 1951.6, the POSS II-Red image taken in 1996.7, and our CAHA images in the Johnson B, V, and R filters obtained in 2017.5. The I image is not shown here because it is similar to the rest of the CAHA broad-band images, and the POSS II-Blue image from 1996.7 is not available for this region. The core/inner nebula can be identified in all the images, except in the POSSI-Blue one, while it is faint but clearly present in our B image. This difference cannot be attributed to sensitivity: the POSSI-Blue image has a somewhat better seeing and is deeper than our B image (see Figure 4). Most probably the internal extinction towards the core was higher in 1951.6 than in later epochs, hiding the inner nebula at blue wavelengths. We tried to measure the change of the $R - B$ colour between 1951.6 and 2017.5 but the poor spatial resolution of the images and the quality of the R image in the POSSI did not allow us to obtain a reliable result. Acker et al. (1991) reported faint Hβ and [O\textsc{iii}] emission lines in a spectrum obtained in 1989.4.

Figure 2. Grey-scale reproduction of the [N\textsc{ii}] NOT image of IRAS18061. The grey levels are logarithmic. The red lines trace the faint emission from the bipolar lobes. Otherwise as in Figure 1.
We have inspected this spectrum in the HASH PN database\(^3\) (Parker, Bojičić & Frew 2016) but these lines cannot be identified. Nevertheless, the exposure time of 600 s for this spectrum is too short for the brightness of IRAS18061. The first unambiguous reported detection of the inner nebula at blue wavelengths seems to date back to the spectrum obtained in 1994.2 by Suárez et al. (2006), that clearly shows the H\(\alpha\) and [O\(\text{iii}\)]\(\lambda\)4959,5007 emission lines, among others.

With narrow-band images obtained in three epochs, an investigation of nebular proper motions and variability would seem appropriate. However, the different characteristics of the filters used in each epoch (Section 2.1) preclude a proper analysis. We only mention that large flux variability in the nebula is not recognisable among the three epochs.

3.1.2 The bipolar lobes

The bipolar lobes are observed in the H\(\alpha\), [N\(\text{ii}\)], and [S\(\text{ii}\)] images, but are extremely faint in the [O\(\text{iii}\)] one (Figure 1). They extend \(\sim24\) arcsec and their main axis is oriented at PA \(\sim+60^\circ\pm1^\circ\). Although the lobes seem to be very narrow in Figure 1, their true extent can be recognised at low intensity levels, as shown in Figure 2. At PA \(\sim+35^\circ/215^\circ\) the lobes are disrupted and knots and filaments are observed up to \(\sim12–15\) arcsec from the centre. Point-symmetry is observed in H\(\alpha\) and [N\(\text{ii}\)] at PA \(\sim81^\circ\) and in some bright knots oriented at PA about \(+60^\circ\). However, bright knots and regions can also be recognized in one lobe, that have no counterpart in the opposite one. In [S\(\text{ii}\)], point-symmetry is difficult to recognized and seems to be restricted to bright knots oriented around PA at \(\sim60^\circ\) and, perhaps, to PA \(\sim–81^\circ\), and we note that some knots are field stars that are marked in Figure 1. In general, [N\(\text{ii}\)] dominates over H\(\alpha\) emission in the lobes, although variations of their relative intensity are recognisable (Figure 3).

![Figure 3. Colour composite image of IRAS18061 obtained by combining the H\(\alpha\) (green), [N\(\text{ii}\)] (red), and [O\(\text{iii}\)] (blue) images in Fig. 1 (see the text for details). The flux is represented in a linear scale. The size of the field shown is 53\(\times\)37 arcsec\(^2\). Seeing is \(\sim1.1\) arcsec. North is up, east to the left.](http://202.189.117.101:8999/gpne/)

3.1.3 The bow-shock-like structures

The bow-shock-like structures are clearly seen in the H\(\alpha\), [N\(\text{ii}\)], and [S\(\text{ii}\)] images while only faint emission from the NE bow-shock can be recognised in the [O\(\text{iii}\)] one (Figure 1). They present noticeable morphological differences from each other. The NE bow-shock-like structure shows a limb-brightened, bow-shaped morphology extending \(\sim10\) arcsec, that appears displaced towards the north with respect to the main bipolar axis. Its tip (hereafter referred to as the NE-BS) is located at \(\sim20\) arcsec from the centre and oriented at PA \(\sim+53.2^\circ\pm0.5^\circ\), slightly but clearly different from the main bipolar axis. The SW bow-shock-like structure (hereafter SW-BS) is more compact, located at \(\sim17\) arcsec from the centre, although faint emission can be seen up to \(\sim20\) arcsec (Figure 2), and oriented at PA\(\sim+240^\circ\pm1^\circ\), coincident with the main bipolar axis. The relative intensity of the [N\(\text{ii}\)] emission in the nebula reaches its maximum in the NE- and SW-BS (red colour in Figure 3).

3.2 Internal kinematics

Figure 5 (left) shows the six long-slits used for the MES spectra, superimposed on the Aristarchos [N\(\text{ii}\)] image. Figures 6 and 7 show position-velocity (PV) maps of the [N\(\text{ii}\)]\(\lambda\)6583 emission line at the PAs observed in 2008 and 2017, respectively, and Figure 8 presents the H\(\alpha\) and [N\(\text{ii}\)]\(\lambda\)6583 emission lines as observed in the PA \(+55^\circ/2015\) spectrum. The three basic nebular structures identified in the images have their correspondence in the PV maps, namely, (1) a bright and very broad emission feature at the position of the inner nebula; (2) extended, knotty emission associated to the bipolar lobes, and (3) emission from the bow-shocks-like structures in the PV maps at PA \(+55^\circ\) and \(+60^\circ\). In the following, we will describe the spatiokinematical properties of the three structures separately.

3.2.1 The inner nebula

The emission feature due to the inner nebula is not spatially resolved in our spectra, in agreement with its very small deconvolved angular size (Section 3.1.1). Figure 9 shows its [N\(\text{ii}\)] and H\(\alpha\) emission line profiles from the PA \(+55^\circ/2015\) spectrum. Similar profiles are seen in the 2008 and 2017 spectra. The profiles exhibit asymmetries that suggest the presence of several blended kinematical components, particularly in the [N\(\text{ii}\)] emission lines. Satisfactory fits (but see also below) have been obtained by using a three-component Gaussian line fit with blue, central, and red main components. The results of the fit are shown in Figure 9 and Table 1 lists the values of the (LSR) radial velocity, the velocity width (FWHM), and the relative flux of the three main components, as averaged from all the H\(\alpha\) and [N\(\text{ii}\)] emission lines in our spectra. In Figure 8 we mark the radial velocity of these components on the H\(\alpha\) emission line. The central component presents the same (LSR) radial velocity in [N\(\text{ii}\)] and H\(\alpha\) \((\sim78\text{ km s}^{-1})\), Table 1), while the blue and red components are located symmetrically, at \(\sim\pm41\) in H\(\alpha\) and \(\sim\pm27\text{ km s}^{-1}\) in [N\(\text{ii}\)], with respect to the central one, being the velocity separation larger in H\(\alpha\) than in [N\(\text{ii}\)]. The FWHM of the central component is smaller than those of the blue and red ones, but larger in H\(\alpha\) than in [N\(\text{ii}\)]. The blue component is stronger than the

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\(^3\) http://202.189.117.101:8999/gpne/
Figure 4. Grey-scale images of IRAS18061 (linear flux scale) in different filters and epochs as labelled in the bottom left corner of each panel. The origin (0,0) is at the position of the core that is arrowed, except in the POSS I B panel where it is not detected. Seeing is \( \sim 3.5 \) arcsec in the 2017 and \( \sim 3 \) arcsec in the POSS images.

Table 1. Properties of the three main kinematical components identified in the inner nebula of IRAS18061−2505.

| Component | H\(\alpha\) \(V(\text{LSR})\) (km s\(^{-1}\)) | [N\(\text{ii}\)] \(V(\text{LSR})\) (km s\(^{-1}\)) | \(\Delta V\) (FWHM) (km s\(^{-1}\)) | \(\Delta V\) (FWHM) (km s\(^{-1}\)) | H\(\alpha\) Relative Flux\(^{(a)}\) | [N\(\text{ii}\)] Relative Flux\(^{(a)}\) | \(I([\text{N\(\text{ii}\)}])/I(H\(\alpha\))\) |
|-----------|----------------------|----------------------|----------------------|----------------------|-----------------|-----------------|----------------------|
| Blue      | +35±2                | +48±3                | 59±3                 | 96±4                 | 0.29±0.02       | 1.8±0.3         | 1.6±0.3             |
| Central   | +77±1                | +79±1                | 40±2                 | 30±3                 | 1.0             | 1.0             | 0.4±0.1             |
| Red       | +117±2               | +102±5               | 59±7                 | 79±8                 | 0.17±0.03       | 0.8±0.2         | 2.2±0.5             |

\(^{(a)}\) Flux(central component)=1.0

Inspecting Figure 9 reveals that the wings of the emission lines are very extended with a full width at zero intensity (FWZI) \( \sim 400 \) km s\(^{-1}\) that is not accounted for with the three main components, suggesting the presence of additional very faint high-velocity components (hereafter HV-components). The extended wings are detected in both [N\(\text{ii}\)] emission lines in the 2015 and 2017 spectra but not clearly in the 2008 ones, probably due to their lower S/N ratio (Section 2.2). In H\(\alpha\), the extended wings are identified in the three set of spectra, probably because the H\(\alpha\) emission line from the inner nebula is stronger than the [N\(\text{ii}\)] one (see Section 3.3.1). We have analysed the residuals of the subtraction between the observed and fitted profiles but the faintness of the HV-components allowed us to obtain only estimates for some parameters. In particular, the HV-components seem to be symmetrically located with respect to the central component, with their intensity peaks at \( \sim \pm 105 \) and \( \sim \pm 135 \) km s\(^{-1}\) in H\(\alpha\) and [N\(\text{ii}\)], respectively, and their flux amounts \( \sim 2\%-4\% \) that of the central component. The radial velocity of the HV-components is also marked in Figure 9 and we emphasize the need of much deeper spectra for a proper analysis.

To complete our analysis of the emission line profiles, we used the intermediate-resolution spectrum of the inner nebula (Section 3.3) and the relative contribution to the total flux of the three main components in each emission line (Table 1) to
obtain the [N\textsc{ii}]/H\textalpha\ line intensity ratio in each component. The results are included in Table 1. The ratio is much higher in the blue and red components than in central one, suggesting high excitation in the central component. Nevertheless, a high electron density region exists in the inner nebula (see Section 3.3.1), in which the [N\textsc{ii}]λ6548,6583 emissions from the central component may be collisionally de-excited.

Finally, very faint C\textsc{ii}λ6578 emission line can be identified in the long-slit spectrum at PA +55°/2015 (Figure 6). A single-component Gaussian line fit to this line gives an (LSR) radial velocity of 80±3 km s\(^{-1}\) and a FWHM of 65±10 km s\(^{-1}\). The radial velocity is similar to that of the central component in [N\textsc{ii}] and H\textalpha, but the FWHM is significantly larger (Table 1). Given the faintness of the C\textsc{ii} emission line, we cannot state whether its FWHM is due to the presence of blue and red components or to a stellar contribution.

The analysis of the emission line profiles has revealed structures in the inner nebula, that are distinguished by their kinematical and emission properties. Although our data do not provide information about the relative spatial positions of the kinematical components, their symmetry in radial velocity with respect to the central one strongly suggests spatial symmetry, too. The most simple explanation of the line profiles is that the central component is associated to an inner ring-like structure, the blue and red components trace inner bipolar lobes, and the HV-components represent a high-velocity bipolar outflow. This interpretation is favoured by the high excitation and/or high electron density in the central component (see above), the high [N\textsc{ii}]/H\textalpha intensity ratio in the blue and red ones, and the faintness of the HV-components. A sketch of the inner nebula is shown in Figure A1 where we also mark different regions that are discussed through this paper. With this geometry, the (LSR) systemic velocity of the inner nebula is \(V_{\text{sys}(\text{core})}=+78.1\pm1\) km s\(^{-1}\) that is marked on the [N\textsc{ii}] emission line of Figure 8, while (projected) expansion velocities of \(\sim20/41/103\) km s\(^{-1}\) in H\textalpha and \(\sim15/27/135\) km s\(^{-1}\) in [N\textsc{ii}] are indicated for the inner ring/inner bipolar lobes/high-velocity outflow. By combining the radial velocities of the inner ring and inner bipolar lobes, the corresponding de-convolved angular size (\(\sim0.34/04.45\) arcsec in H\textalpha/[N\textsc{ii}], Section 3.1.1), and a distance of 2 kpc (Appendix B), a kinematical age of \(\sim40–140\) yr is obtained for the inner nebula. The detection of the inner nebula in the POSS-II-Red plate from \(\sim1951.6\) (Figure 4) imposes a lower limit of \(\sim70\) yr for its age, while \(\sim140\) yr may be considered as an approximated upper limit. These numbers imply a very young structure and we emphasize that the very small angular size and the (projected) velocities in the inner nebula ensure that its age should accordingly be very small, irrespective of the precise geometry and projection effects, and for any reasonable distance.

### 3.2.2 The bipolar lobes

The long-slit at PA −35° only covers the inner nebula and does not provide information on the bipolar lobes. At the other PAs, the PV maps are compatible with an expanding bipolar shell such that the NE lobe points towards the observer and the SW lobe points away (Figures 6–8). However, there are large differences between the observed PV maps and those expected from a simple bipolar shell, and, in addition, the NE and SW lobes present kinematical properties very different from each other.

At PAs +55° and +60°, the NE lobe appears “closed” (in the PV maps) by several compact emission features (“knots”), while the expected redshifted emission from the SW lobe is very faint at PA +55° and seems to be absent (or extremely weak) at PA +60°. Two point-symmetric knots identified in the images can be recognized at these two PAs and are marked in Figure 6. The NE/SW “knot” is located at \(\sim+70/+58\) km s\(^{-1}\) (LSR) and \(\sim7.5/10\) arcsec from the cen-
If these two “knots” trace a bipolar outflow, its inclination with respect to the observer is contrary to that of the bipolar lobes. In addition, several “knots” are observed in the NE lobe, that do not have a counterpart in the SW one.

The PV map at PA $+26^\circ$ shows five “knots” in the NE lobe, including three “knots” at about the same spatial position but different radial velocity, which are incompatible with a simple bipolar shell; the SW lobe presents a more simple kinematics. At PA $+33^\circ$, the SW lobe appears closed whereas the NE lobe appears open in the PV map. These two PAs cover the distorted regions observed in the images at PAs between $\sim+25^\circ$ and $\sim+35^\circ$ and their kinematics is highly suggestive of a bipolar (collimated) outflow that impacted on and distorted the bipolar lobes.

The PV map at PA $-81^\circ$ shows point-symmetric features each consisting of two distinct velocity components with maximum radial velocity splitting close to the inner nebula, that merge at $\sim-7''$ from the centre; maximum velocity splitting close to the centre is not expected in a bipolar shell. Thus, the PV map suggests that a collimated outflow has distorted the the kinematics of the bipolar shell at PAs around $-81^\circ$.

The PV maps clearly show that the emission from the inner nebula, in particular, from its central component, is redshifted with respect to the apparent radial velocity centroid of the bipolar lobes, suggesting that $V_{\text{sys}}(\text{core})$ is not appropriate as systemic velocity for the bipolar lobes (Figures 6–8). We have extracted regions of the bipolar lobes close to the inner nebula from the spectra at PAs $+55^\circ$, $+60^\circ$, $+33^\circ$, and $-81^\circ$ and, from the measured radial velocities, obtained a centroid velocity of $+67\pm3 \, \text{km s}^{-1}$ (LSR), that will be considered as the systemic velocity of the bipolar lobes $V_{\text{sys}}(\text{lobes})$. The value is similar to $+63\pm4 \, \text{km s}^{-1}$ (LSR) obtained for IRAS18061 from several CO emission lines (Uscanga et al. 2021, in preparation). $V_{\text{sys}}(\text{lobes})$ differs by $\sim-11 \, \text{km s}^{-1}$ from $V_{\text{sys}}(\text{core})$ and is marked in Figure 9.

The analysis of the internal kinematics strengthens the idea that the bipolar lobes are strongly distorted. Their formation seems to involve several bipolar and non-bipolar collimated outflows at different directions, that impacted the bipolar shell, resulting in a very complex kinematics. The result of this interaction has been very different for each lobe. Under these circumstances, it is difficult to predict (or to impose
The NE- and SW-BS present a remarkable triangular shape in the PV maps with minimum velocity dispersion at their minimum distance to the centre and maximum velocity dispersion approximately at their maximum distance. Figure 10 shows their [Ni II] emission line profiles obtained from PAs +55°/2015 and +60°. The FWZI is ~160 km s⁻¹ in the SW-BS and ~190 km s⁻¹ in the NE-BS. Furthermore, as it can be immediately recognised in Figures 5, 6, and 9, both the NE- and SW-BS are blueshifted with respect to V_{sys}(lobes) and V_{sys}(core). The intensity peak of the NE-BS is at ~9 and +14 km s⁻¹ (LSR) in the spectra at PAs +55° and +60°, respectively. For the SW-BS, we obtain a +55 and +63 km s⁻¹ (LSR) in the spectra at PAs +55° and +60°, respectively. From the values at PAs +55° for the NE-BS and PA +60° for the SW-BS, that cover better each structure, the (LSR) centroid velocity of these structures is ~+27 km s⁻¹ that is also marked as V_{sys}(bow-shocks) in Figure 8 and differs by ~−40 and ~−51 km s⁻¹ from V_{sys}(lobes) and V_{sys}(core), respectively.

The properties of the NE- and SW-BS closely resemble those of bow-shocks associated to collimated jets or bullets in YSOs (e.g., Böhm & Solf 1985). Therefore, the same interpretation probably holds for the NE- and SW-BS. The FWZI of a bow-shock corresponds approximately to its expansion velocity (Hartigan, Raymond & Hartmann 1987), implying that the SW-BS moves at ~160 km s⁻¹ and the NE-BS at ~190 km s⁻¹. The shape of a bow-shock on a PV map and its emission line profile depend on the angle it moves with respect to the observer (Raga & Böhm 1986; Hartigan et al. 1987). A comparison of the observed profiles with these models shows that the SW-BS moves mainly perpendicular to the line of sight, and the NE-BS moves at ≥80° with respect to the observer. These results strengthen the existence of noticeable differences between the NE- and SW-BS, as already noticed in the images, and show that they are not aligned with each other and neither with the main axis defined by the bipolar lobes. In addition, the large difference between V_{sys}(bow-shocks) and V_{sys}(lobes) points out to particularities in the ejection of the NE- and SW-BS. The kinematical age for these structures is ~950–1000 yr.

3.3 Spectral analysis

Figure 5 (right) shows the long-slit used for the intermediate-resolution spectrum at PA +55° that has been used to carry out a spatially resolved analysis of the emission line intensities, physical conditions and chemical abundances in IRAS 18061. We have extracted five nebular regions from the long-slit spectrum, that are marked in Figure 5 right: (1) the inner nebula, corresponding to a region of 2.4 arcsec in size centred on the position of its intensity peak; (2) the NE lobe, between 7 and 12 arcsec from the centre; (3) the NE-BS, between 17 and 23 arcsec; (4) the SW lobe, between 5 and 10 arcsec; and (5) the SW-BS, between 12 and 18 arcsec. The spectrum of the NE-BS is heavily contaminated by the spectrum of a relatively bright field star (Figure 5) and only some emission lines could be measured. We note that some faint carbon emission lines due to the [WC8] CS (Górny & Siodmiak 2003) are identified in our spectrum of the inner nebula, but other lines are not detected. A much deeper spectrum is necessary to analyse the CS.

The spectra have been analysed with the nebular pack-
Table 2. Emission line intensities ($f$(H$\beta$) = 100.0) and derived physical parameters in IRAS 18061−2505.

| Emission line | $f_{\lambda}$ | Inner nebula | NE lobe | SW lobe | NE bow-shock | SW bow-shock |
|---------------|---------------|--------------|---------|---------|--------------|--------------|
| H$\gamma$ 4340 | 0.157         | 43.6±0.4     | 56.7±1.6 | 51.6±2.2 | ...          | 44.1±5.9     |
| [O ii] 3727   | 0.149         | 6.5±0.3      | ...      | ...      | ...          | ...          |
| He i 4471     | 0.115         | 6.1±0.2      | ...      | 3.9±2.0  | ...          | ...          |
| H$\beta$ 4861 | 0.000         | 100.0±0.4    | 100.0±1.2| 100.0±1.5| 100.0±7.7    | 100.0±4.1    |
| He i 4921     | −0.016        | 1.4±0.1      | ...      | ...      | ...          | ...          |
| [O iii] 4959  | −0.026        | 90.3±0.3     | 10.5±0.6 | 14.4±0.8 | ...          | 54.5±2.9     |
| [O iii] 5007  | −0.038        | 274.6±0.8    | 34.8±0.7 | 43.0±0.9 | 380.8±21.6   | 172.4±5.7    |
| [N ii] 5199   | −0.082        | 1.7±0.1      | 12.5±0.6 | 13.7±0.6 | ...          | ...          |
| [N ii] 5755   | −0.185        | 34.0±0.1     | 5.6±0.3  | 5.9±0.1  | 29.8±3.9     | 12.2±1.2     |
| He i 5873     | −0.203        | 17.7±0.1     | 13.9±0.4 | 14.0±0.4 | ...          | 14.40±1.2    |
| [O ii] 6300   | −0.263        | 10.7±0.1     | 12.1±0.5 | 19.0±0.6 | ...          | ...          |
| [Si ii] 6312  | −0.264        | 11.8±0.1     | ...      | 2.5±0.3  | ...          | ...          |
| [O ii] 6363   | −0.271        | 3.3±0.1      | 5.2±0.4  | 3.9±0.3  | ...          | 6.8±1.1      |
| [Si ii] 6716  | −0.318        | 4.4±0.1      | 4.7±0.3  | 3.8±0.2  | ...          | 4.7±0.8      |
| [Si ii] 6731  | −0.320        | 7.2±0.1      | 68.4±1.1 | 62.4±1.2 | 139.3±14.0   | 81.3±4.4     |
| He i 7065     | −0.364        | 7.0±0.1      | 2.1±0.2  | 2.6±0.2  | ...          | ...          |
| [Ar iii] 7136 | −0.374        | 25.4±0.1     | 4.6±0.2  | 5.6±0.2  | ...          | 12.9±1.0     |
| He i 7281     | −0.393        | 0.9±0.1      | ...      | ...      | ...          | ...          |
| [O ii] 7320   | −0.398        | 38.4±0.2     | 6.6±0.3  | 7.0±0.3  | ...          | 16.4±1.2     |
| [O ii] 7330   | −0.400        | 32.5±0.2     | 2.5±0.3  | 5.5±0.2  | ...          | 14.2±1.1     |

$c$(H$\beta$) = 2.54±0.01 1.42±0.02 1.94±0.02 1.43±0.11 1.80±0.06
$log F$(H$\beta$) = −13.68±0.01 −14.37±0.01 −14.51±0.01 −15.13±0.02 −15.00±0.01
$T_e$[N ii](K) = 8570±250 8970±300 14700±2700 10740±800
$T_e$[O ii](K) = 16600±380 ...
$N_e$[Si ii](cm$^{-3}$) = 4610±320 1410±180 1820±280 2490±1460 1350±580

Table 3. Ionic abundances in IRAS 18061−2505 relative to H$^+$.  

| Ion$^a$ | NE lobe | SW lobe | NE bow-shock | SW bow-shock |
|---------|---------|---------|--------------|--------------|
| He$^+$  | (10.3±0.3)$\times10^{-2}$ | (9.6±0.3)$\times10^{-2}$ | ... | (10.7±0.9)$\times10^{-2}$ |
| O$^0$   | (4.9±0.6)$\times10^{-5}$  | (5.2±0.7)$\times10^{-5}$  | ... | (3.2±0.2)$\times10^{-5}$  |
| O$^+$   | (3.0±0.7)$\times10^{-4}$  | (2.5±0.5)$\times10^{-4}$  | ... | (2.3±0.9)$\times10^{-4}$  |
| O$^{++}$ | (2.1±0.2)$\times10^{-5}$  | (2.2±0.3)$\times10^{-5}$  | (4.30±0.23)$\times10^{-5}$ | (4.7±0.9)$\times10^{-5}$ |
| N$^0$   | (2.0±0.3)$\times10^{-5}$  | (2.13±0.48)$\times10^{-5}$ | ... | ... |
| N$^+$   | (1.81±0.13)$\times10^{-4}$ | (1.44±0.12)$\times10^{-4}$ | (0.8±0.3)$\times10^{-4}$ | (1.2±0.2)$\times10^{-4}$ |
| S$^+$   | (5.3±0.4)$\times10^{-6}$  | (4.4±0.4)$\times10^{-6}$  | (3.5±0.2)$\times10^{-6}$ | (3.6±0.7)$\times10^{-6}$ |
| Ar$^{+++}$ | (6.3±0.8)$\times10^{-7}$ | (6.8±0.8)$\times10^{-7}$ | ... | (10.1±2.2)$\times10^{-7}$ |

$^a$ For ions with more than one transition, an intensity-weighted average has been used.

Table 4. Elemental abundances in IRAS 18061−2505 assuming photoionization.

| Element | NE lobe | SW lobe | SW bow-shock |
|---------|---------|---------|--------------|
| He/H    | 0.103±0.003 | 0.096±0.003 | 0.107±0.009 |
| O/H     | (3.7±0.7)$\times10^{-4}$ | (3.23±0.51)$\times10^{-4}$ | (3.1±0.9)$\times10^{-4}$ |
| N/H$^a$ | (2.4±0.7)$\times10^{-4}$ | (2.1±0.5)$\times10^{-4}$ | (1.62±0.83)$\times10^{-4}$ |
| N/H$^b$ | (2.7±0.8)$\times10^{-4}$ | (2.3±0.6)$\times10^{-4}$ | (2.1±1.1)$\times10^{-4}$ |
| Ar/H$^a$| (1.2±0.3)$\times10^{-6}$ | (1.3±0.3)$\times10^{-6}$ | (1.9±0.6)$\times10^{-6}$ |
| S/H$^a$ | (3.2±0.2)$\times10^{-5}$ | (1.4±0.1)$\times10^{-5}$ | (2.2±0.4)$\times10^{-5}$ |

$^a$ICFs from Kingsburgh & Barlow (1994)
$^b$ICFs from Delgado-Inglada et al. (2014)
age ANNeb that uses rAF 2.16, a description of which can be found in Olguín et al. (2011). Besides, we have checked the results from ANNeb with PyNeb (Luridiana, Morisset & Shaw 2015). Although there are some differences between the two packages (typically \( \sim 5\% - 15\% \) in the ionic abundances, see below), they do not change the conclusions of the paper. We used the extinction law \((f_\lambda)\) of Cardelli, Clayton & Mathis (1989) and note that other extinction laws do not produce significant changes in the results. For each of the five selected regions, Table 2 lists the emission line intensities; the logarithmic extinction coefficient \( c(H_\beta) \) obtained from the Balmer emission line ratios assuming recombination case B; the electron density \( N_e([S\text{II}]) \) derived from the \([S\text{II}])_{\lambda\lambda6716,6731}\) emission lines; and the electron temperature \( T_e([N\text{II}]) \) or \( T_e([O\text{III}]) \) derived from the auroral to nebular \([N\text{II}] \) or \([O\text{III}] \) emission line ratios \( R([N\text{II}]) = I(\lambda5755)/I(\lambda6548+\lambda6583) \) or \( R([O\text{III}]) = I(\lambda4363)/I(\lambda4959+\lambda5007) \), respectively.

### 3.3.1 Description of the nebular spectra and physical conditions

Table 2 shows that relatively high-excitation emission lines (e.g., \([O\text{III}] \), \([Ar\text{III}] \)) are stronger in the inner nebula and bow-shocks than in the bipolar lobes. In particular, \( I([O\text{III}]) / I(H_\beta) \) is \( \sim 0.45-0.57 \) in the bipolar lobes, indeed a very small value. Low-excitation emission line ratios are weaker in the inner nebula than in bipolar lobes and bow-shocks, reaching in the two last structures relatively high values of \( I([N\text{II}]) / I(H_\alpha) \sim 2.5-4.5 \) and of \( I([S\text{II}]) / I(H_\alpha) \sim 0.4-0.8 \). \([He\text{II}] \) and \([Ar\text{IV}] \) emission lines are not detected in our spectra, and the \([O\text{III}] \) or \([N\text{II}] \) emission line ratios \( R([N\text{II}]) = I(\lambda5755)/I(\lambda6548+\lambda6583) \) or \( R([O\text{III}]) = I(\lambda4363)/I(\lambda4959+\lambda5007) \), respectively.

The extinction \((c(H_\beta))\), Table 2) is relatively high and reaches its maximum value in the inner nebula, most probably due to dust and neutral gas that are mainly concentrated in the core (e.g., Zhang et al. 2012). The extinction is higher in the SW lobe and SW-BS than in their NE counterparts, in consonance with the inclination of the main nebular axis.

Electron temperature cannot be obtained for the inner nebula from the \([N\text{II}] \) emission lines because \( R([N\text{II}]) \sim 0.15 \) is anomaly high (see also below), although in the bipolar lobes and bow-shocks \( T_e([N\text{II}]) \) can indeed be obtained and presents lower values in the lobes than in the bow-shocks. \( T_e([O\text{III}]) \) can only be obtained for the inner nebula and its value of \( \sim 16000 \text{K} \) is typical for PNe. This value differs from that of \( \sim 26000 \text{K} \) obtained by Górsny et al. (2004). These authors analysed a single spectrum that probably was a combination of inner nebula and bipolar lobes spectra. The very different spectra and reddening corrections in these two regions (Table 2) may have led to underestimate, from the combined spectrum, the intensity of the \([O\text{III}] \lambda5007 \) emission line, with respect to that of the \([O\text{III}] \lambda4363 \) one only detected in the inner nebula, resulting in a high \( T_e([O\text{III}]) \) and, in consequence, in the peculiar chemical abundances in IRAS18061 (see below).

The electron density \( N_e([S\text{II}]) \) presents moderate values although it is higher in the inner nebula. Remarkably, evidence for a high electron density region in the inner nebula is provided by the large value of \( R([N\text{II}]) \sim 0.15 \) that is much higher than those usually observed in PNe. Although at low electron densities \( R([N\text{II}]) \) mainly depends on \( T_e \), at higher electron densities than the critical one for the \( ^1D_2 \) level of \( N^+ \) \((N_e \sim 7 \times 10^4 \text{ cm}^{-3}) \), \( R([N\text{II}]) \) depends on \( N_e \) (e.g., Osterbrock 1974) because collisional de-excitation is more important for the nebular \([N\text{II}] \) lines than for the auroral \([N\text{II}] \) one \((N_e \sim 3.2 \times 10^5 \text{ cm}^{-3}) \). Assuming \( T_e([N\text{II}]) \) in the inner nebula in the range found in the other nebular regions \((\sim 9000-16000 \text{K}) \), we obtain \( N_e([N\text{II}]) \sim 5.3-2.0 \times 10^5 \text{ cm}^{-3} \), much higher than the value of \( N_e([S\text{II}]) \). This result is corroborated by the radio continuum data (Gómez et al. 2008). If the radio continuum emissions at 22 and at 1.665 GHz arise in the same region (size \( \sim 0.41 \) arcsec, Section 3.1.1), we obtain an electron density of \( \sim 2.1 \times 10^5 \text{ cm}^{-3} \), consistent with the value of \( N_e([N\text{II}]) \). \( R([O\text{III}]) \) is \( \sim 0.018 \), similar to the values observed in most PNe, and does not clearly suggest high electron density. This may be explained because \( N_e \) is \( \sim 7 \times 10^5 \text{ cm}^{-3} \) for the \( ^1D_2 \) level of \( O^+ \) and collisional de-excitation of the nebular \([O\text{III}] \) lines is not important at the derived \( N_e([N\text{II}]) \), although some collisional effects cannot be completely discarded. In any case, we will not use \( T_e([O\text{III}]) \) further.

The compact core/inner nebula of IRAS18061 resembles that of other pinched-waist PNe as, e.g., Hubble12 (Hyung & Aller 1996), He 2-25 and Th 2-B (Corradi 1995), and K 4-47 (Gonçalves et al. 2004), which also present low and high electron density regions. In all these PNe, the existing spectra do not spatially resolve the different density regions in the core. Therefore, the observed emission line fluxes are an unknown combination of fluxes generated in different density regions, with high electron density playing a crucial role in quenching some emission lines. In these conditions, abundance calculations will give unrealistic results, and we will not carry out such calculations for the inner nebula of IRAS18061.

The derived electron densities allow us to obtain a crude estimate for the ionised nebular mass. For the inner nebula, we assume a sphere of 0.7 arcsec in diameter (Section 3.1.1), and for electron densities of 4600 and 3.6 \( \times 10^5 \text{ cm}^{-3} \), we obtain an ionised mass between \( \sim 2 \times 10^{-5} \) and \( \sim 1.4 \times 10^{-3} \text{ M}_\odot \), where \( \epsilon \) is the filling factor. For each bipolar lobe and bow-shock, we consider a cylinder of 18.5 arcsec in length, circular (mean) cross section of 10 arcsec in size, and electron density of 1600 cm\(^{-3}\) to obtain an ionised mass for the pair of \( \sim 5.2 \times 10^{-2} \text{ M}_\odot \) that may be considered as an estimate for the total ionised nebular mass.

### 3.3.2 Chemical abundances

Ionic abundances were obtained for the bipolar lobes and bow-shocks, assuming their own values of \( N_e \) and \( T_e \) (Table 2) and are listed in Table 3. For oxygen, three ionisation states are observed and the lack of nebular \([Ar\text{IV}] \) (ionisation potential IP=40.7 eV) makes it highly improbable that \( O^{3+} \) (IP=54.93 eV) exists in the nebula. The abundance of \( N^0 \) in the main lobes is high, amounting to \( \sim 11\% -15\% \) of \( N^+ \). The few ionic abundances obtained in the NE-BS may be considered similar to those in the SW-BS, owing to the difficulties to measure the emission lines in the NE-BS that will not be considered in further calculations.

Elemental abundances are usually derived from the ionic ones by using ionisation correction factors (ICFs) that are calculated assuming photoionization. This procedure is not appropriate if shocks contribute to the nebular excitation
have been derived as follows. Because of the lack of nebular [ArI\textsc{v}] and He\textsc{ii} emission lines, helium and oxygen abundances have been obtained as \( \text{He}/H = \text{He}^+/H^- \) and \( O/H = O^+/H^+ + O^{2+}/H^+ \), respectively, and we note that no ICF is needed for oxygen. For nitrogen, we follow both Kingsburgh & Barlow (1994, hereafter KB94) and Delgado-Inglada, Morrisset & Stasińska (2014, hereafter D-I+14) to correct for \( N^{2+} \) that may exist in the nebula (\( IP = 29.6 \text{ eV} \)), and to the result we add the value of \( N^0/H^+ \). The nitrogen abundance obtained from D-I+14 is higher by a factor \( \sim 1.1 \) and \( \sim 1.3 \) in the bipolar lobes and SW-BS, respectively, than that obtained from KB94. For sulfur and argon we follow KB94 and note that their abundances should be considered with caution because they are based in a few emission lines/ionisation states only. In fact, the sulfur abundance in the NE lobe and SW-BS may be largely uncertain because the [S\textsc{iii}]\( \lambda 6312 \) emission line has not been detected in these two structures, which is only detected in the SW lobe.

The bipolar lobes and SW-BS present similar helium and oxygen abundances. The argon abundance does not present very discrepant values while the sulfur abundance in the SW lobe could be more reliable. Irrespective of the ICF, the nitrogen abundance is very similar in both lobes and lower in the SW-BS, although the value in the SW-BS has a larger error and the [N\textsc{i}]\( \lambda 5199 \) emission line has not been detected. Considering mean values in these structures, the oxygen abundance is subsolar by a factor \( \sim 0.7 \), and helium and nitrogen abundances are enhanced by a factor \( \sim 1.2 \) and \( \sim 3-4 \), respectively, with respect to solar values (Asplund et al. 2009). The mean nitrogen abundance in the bipolar lobes (\( 12+\log (N/H) \sim 8.4 \)) and the mean N/O abundance ratio (\( \sim 0.7 \)) suggest a type I classification for IRAS18061 (Peimbert 1990) and that hot bottom burning (HBB) has taken place in the AGB progenitor. The mean helium abundance is \( \sim 0.102, \) lower than but still within the range found in other type I PNe. A comparison with other PNe shows that IRAS18061 does not present peculiar abundances (KB94).

4 DISCUSSION

4.1 The progenitor star of \textit{IRAS 18061–2505}

As already mentioned, H\textsubscript{2}O-PNe have been associated to intermediate-mass MS progenitors. A lower limit of \( \sim 4M\odot \) is usually assigned to the initial mass, following the models by, e.g., Karakas & Lugaro (2016), and Marigo et al. (2017) that predict a lower limit of \( \sim 4M\odot \) for HBB. Nevertheless, models by, e.g., Miller Bertolami (2016) predict a lower limit of \( \sim 3M\odot \). Recent observations of the PN M31 B477-1 by Davis et al. (2019) provide evidence that HBB has occurred in the AGB phase of its \( \sim 3.4M\odot \) MS progenitor. Intermediate-mass MS progenitors are also suggested by the low Galactic latitudes (\( |b| \leq 2^\circ 6 \)) and high extinction at visible wavelengths of these objects, although the amount of extinction is quite different among H\textsubscript{2}O-PNe. For instance, IRAS18061 is completely visible (now, but not in \( \sim 1951.6, \) Figure 4), K3-35 is highly extincted towards its equatorial region but its bipolar lobes are clearly visible (e.g., Blanco et al. 2014), and \textit{IRAS 15103–5754} is not optically visible. A possible shortcoming for an intermediate-mass MS progenitor in IRAS18061 is the small ionised nebular mass. Near-, mid- and far-IR data, and the water masers suggest that noticeable amounts of dust and molecular gas should exist in the object, most probably in the core, although their masses have yet to be estimated (see below). The nitrogen abundance and N/O ratio in IRAS18061 are compatible with HBB, if shocks do not contribute to the nebular excitation.

Alternatively, oxygen-rich AGB stars may have low-mass MS progenitors (\( M \lesssim 1.25M\odot \)), a possibility that would be favoured for IRAS18061 by its small ionised mass. However, current evolutionary models (but see below) are not compatible with a low-mass MS progenitor. A \( \lesssim 1.25M\odot \) MS progenitor needs \( >7000 \text{ yr} \) (choosing the fastest evolution, Miller Bertolami 2016, hereafter MB16; see also Vassiliadis & Wood 1994; Blöcker 1995) to evolve from the AGB to the PN phase, and the resulting PN could be expected to present characteristics of an evolved PN. The electron densities in IRAS18061 are not typical of evolved PNe (Miranda et al. 2017 and references therein), and its small kinematical age (\( \sim 1100 \text{ yr} \)) is not very suggestive of an evolved PN. Moreover, if H\textsubscript{2}O-PNe were related to low-mass MS progenitors, one could expect to detect more H\textsubscript{2}O-PNe than the very small number of identified objects. Finally, if shocks do not contribute to the nebular excitation, the chemical abundances are incompatible with a low-mass MS progenitor.

An estimate for the MS progenitor mass of a CS may be obtained by comparing the nebular abundances with models for stellar yields. However, this comparison requires that photoionization dominates the nebular excitation and, hence, that the use of ICFs is appropriated to obtain the elemental abundances. The strong low-excitation emission lines observed in some PNe (e.g., Gonçalves et al. 2009), including IRAS18061, have been explained by shocks in a highly ionised medium (Dopita 1997). Nevertheless, photoionization models are also able to reproduce the observed strong low-excitation emission lines, as recently shown by Akras et al. (2020). We have compared several line intensity ratios in the bipolar lobes of IRAS18061 with the diagnostic diagrams by Akras et al. (2020), their Figures 5 to 7 and they are well reproduced with their photoionization models, while the line intensity ratios in the SW-BS seem to be more compatible with shock-excitation. These authors assume a CS with \( T_{\text{eff}} = 1 - 2 \times 10^5 \text{ K} \) to compute their models. The \( T_{\text{eff}} \) of the CS of IRAS18061 is unknown but most probably \( <6 \times 10^4 \text{ K} \) that would be more favourable to produce strong low-excitation emission lines than models with higher \( T_{\text{eff}} \).

To check further the possible contribution of shocks in IRAS18061, we will follow the prescription by Akras & Gonçalves (2016) who use the photon flux relation (or the ratio of fluxes, Lago et al. 2019) due to shocks (\( f_{\text{shock}} \)) and central star (\( f_{\text{star}} \)) to distinguish the excitation mechanisms. These authors found that for values of $\log(f_{\text{shock}}/f_{\text{star}}) > -1$ the nebular excitation is dominated by shocks, for values $\sim -2$ photoionization dominates, whereas for intermediate values both shocks and photoionization contribute to the excitation. For IRAS18061 we will obtain $\log(f_{\text{shock}}/f_{\text{star}})$ as a function of the stellar luminosity for the bipolar lobes and SW-BS (Lago et al. 2019, their equation 3), considering luminosities...
and use different hypothesis and treatments, the comparison suggests MS progenitor masses between ~3 and ~4.2 M⊙, excludes masses ≥ 4.5 M⊙, and points to a subsolar initial metallicity ~0.008-0.01. The mass range is approximately bracketed by the lower limits for HBB in the different models and is compatible with the luminosities required for photoionization (Figure 10). It is worth noting that most models predict a drop in the helium abundance around 3–4 M⊙, compatible with the apparent low helium abundance in IRAS18061. We also note that the minimum MS progenitor mass required for photoionization derived from Figure 10 and that obtained from the chemical abundances are based in two methods that are independent from each other.

The diagram in Figure 10 has been obtained assuming a distance of 2 kpc for IRAS18061 but it is interesting to discuss the results for other distances. For values <2 kpc, the lines in Figure 10 shift downwards and the minimum mass required for photoionization decreases. However, masses between ~1.25 and ~3 M⊙ are incompatible with an oxygen-rich PN, as it is indicated by the water masers in IRAS18061. For values >2 kpc, the lines in Figure 10 shift upwards and the minimum mass increases. These masses lead to higher He and N abundances, and N/O ratio than the values obtained in IRAS18061 (e.g., Karakas & Lugaro 2016), resulting incompatible with the abundances in IRAS18061.

The results discussed above show that a ~3–4 M⊙ MS progenitor is able to account for the chemical abundances in IRAS18061, which is in agreement with the expectation of intermediate-mass MS stars as progenitors for H2O-PNe (but see below). If so, as already mentioned, large amounts of dust and neutral material should exist in IRAS18061. In this respect, it is worth noting “water fountains” (WFs), post-AGB stars with high velocity water masers tracing very young jets (e.g., Imai 2007), that have been suggested to be the immediate precursors of H2O-PNe, which is strongly supported by IRAS 15013—5754 that presents both WF and PN characteristics (Suárez et al. 2015; Gómez et al. 2015a, 2018b). Alike H2O-PNe, WFs have also been associated with ~4–8 M⊙ progenitors (e.g., Suárez et al. 2008; Young et al. 2011; Imai et al. 2012; Rizzo et al. 2013). Models for the spectral energy distribution of WFs seem to require the existence of massive dusty toroids/rings (~0.5–2.5 M⊙) in these objects (Durán-Rojas et al. 2014). An analysis of the SED of IRAS18061 would allow us to estimate the dust and gas mass. However, making a realistic SED model for IRAS18061 is far from simple. The stellar spectrum, T eff, and the precise density distribution in the inner nebula are unknown; amorphous carbon, graphite, and silicates with different compositions and grain sizes should be included and tested in the model. In consequence, a dedicated study should be carried out to obtain reliable values for the dust and gas masses, which is beyond the scope of this paper.

Finally, the results from Figure 10 impose some constraints to the distance of the object, that should be around 2 kpc to make compatible the observed chemical abundances, the MS progenitor mass, and the oxygen-rich nature of the object.

Even though the results obtained above are consistent with a ~3–4 M⊙ MS progenitor, it should be emphasized that the role of shocks in the nebular excitation of PNe is a very complex problem that is not solved yet. Therefore, a low-mass MS progenitor for IRAS18061 cannot be conclusively ruled

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**Figure 10**. Diagram of the ratio of flux due to shocks (f_{shocks}) to flux due to the central star (f_{star}) as a function of the stellar luminosity for the NE and SW lobes, and SW-BS. The dashed horizontal lines mark the shock-excited and photoionised regimes that are separated by a region where both shocks and photoionization contributed to the emission (see text for details).

**Figure 11.** Diagram of the ratio of flux due to shocks (f_{shocks}) to flux due to the central star (f_{star}) as a function of the stellar luminosity for the NE and SW lobes, and SW-BS. The dashed horizontal lines mark the shock-excited and photoionised regimes that are separated by a region where both shocks and photoionization contributed to the emission (see text for details).
out, and we will consider this possibility at some points of the discussion below.

4.2 An oxygen-rich neutral ring in the core of IRAS18061

Water maser emission is always observed towards the central regions of H$_2$O-PNe, although in K–3-35 and IRAS15103–5754 it has also been detected associated to jets (Miranda et al. 2001a; Suárez et al. 2015; Gómez et al. 2015a, 2018a). Moreover, water masers in H$_2$O-PNe tend to be distributed mainly perpendicular to the main nebular axis, suggesting that they are associated to equatorial rings, as in K–3-35 (Us-canga et al. 2008), IRAS17347–3139 (Tafoya et al. 2009), and IRAS15103–5754 (Gómez et al. 2018a), and was also proposed for IRAS18061 (Gómez et al. 2012). The water masers in IRAS18061 are observed at ~0.02–0.05 arcsec towards the southwest from the CS, oriented approximately at PA~160°, and with (LSR) radial velocities between ~+57 and ~+64 km s$^{-1}$ (Gómez et al. 2008). These properties, when combined with the morphokinematic ones of the bipolar lobes, provide solid arguments for the existence of a neutral ring in the core of IRAS18061 traced by the water masers. The water masers are blueshifted with respect to $V_{\text{sys}}$ (lobes) and $V_{\text{sys}}$ (core), distributed approximately perpendicular to the major nebular axis, and projected onto the (redshifted) SW lobe, as expected if they arise in the front part of a ring that is tilted in the same sense as the main bipolar axis. Furthermore, a ring-like structure and not a spherical distribution of neutral material in the core, is required to detect the CS (Górrn & Siodmiak 2003). The oxygen-rich ring is drawn in Figure A1 and we note that it would be compatible with the red component of the inner nebula being fainter than the blue one. From the positions of the water masers in Gómez et al. (2008, 2012), a crude estimate of the ring radius is ~0.1 arcsec, corresponding to ~200 AU, similar to the radius of water maser rings in other H$_2$O-PNe. Water maser emission requires high temperatures of ~100–400 K and high particle densities of ~10$^{6}$–9 cm$^{-3}$ (Hollenbach, Elitzur & McKee 2013). Therefore, the derived radius probably corresponds to the innermost hottest and densest region of the neutral ring (Figure A1), although the ring may be larger.

The water masers undoubtedly indicate that the neutral ring is oxygen-rich. This agrees with the scenario proposed by Cohen et al. (1999) that oxygen-rich material in PNe with late-type [WC] central stars resides in a ring which could also be the place where the crystalline silicate emission from IRAS18061 arises (Perea-Calderón et al. 2009). This ring should have been formed during the oxygen-rich phase of the AGB progenitor of IRAS18061, before the transition to a carbon-rich chemistry. According to Cohen et al. (1999), carbon-rich material should be interior to the oxygen-rich ring and the inner nebula may be expected to be carbon-rich.

4.3 The formation of IRAS 18061–2505

Binary/multiple central stars provide a scenario in which many properties of PNe may be accounted for, at least qualitatively (see, Boffin & Jones 2019 for a recent review). Particularly relevant is the case of binary CSs that evolved in a common envelope (CE). At least ~20% of PNe may be the ejected CE (Miszalski et al. 2009) and bipolarity has been suggested as a possible signature of common envelope evolution (CEE, Reichardt et al. 2019). Numerical simulations of CEE are able to reproduce bipolar PNe (e.g., García-Segura, Ricker & Taam 2018; Reichardt et al. 2019 and references therein). The bipolar lobes and water maser ring in IRAS18061 are compatible with the characteristics expected from CEE. The high particle density in the oxygen-rich ring, as compared with the low density in the bipolar lobes, strongly suggests a very high density contrast in the AGB envelope, with most material concentrated at the equatorial/orbital plane, and very low density regions above and below that plane. When the fast wind from the CS interacts with such a highly anisotropic density distribution, it will be strongly decelerated in the equatorial plane while it will encounter less resistance along the polar regions, resulting in a pinched-waist PN, in agreement with the morphology of IRAS18061. A very high density contrast suggests a relatively low mass ratio between CS and companion (e.g., Zou et al. 2020) and that the presumable companion is not a very low-mass star. Moreover, bipolar and asymmetric jets from the secondary may also be ejected during CEE at different directions, shaping the CE (Soker 2019; Frank et al. 2018; Shiber et al. 2019) and contributing to the large differences between the two bipolar lobes and their strongly disrupted morphology. Nevertheless, collimated outflows could be ejected after CEE, contributing to further disruption of the bipolar lobes.

The properties of the NE-, SW-BS do not suggest that they have played a role in the formation of the bipolar lobes. The NE- and SW-BS are the oldest component identified in IRAS18061 and their formation may have preceded that of the bipolar lobes and, therefore, occurred before CEE. Although several scenarios are possible (Blackman & Lucchini 2014), an interesting possibility for IRAS18061 is that the NE- and SW-BS may be related to Roche-lobe overflow or grazing envelope evolution that may result in the formation of an accretion disk around the companion, from which collimated outflows are ejected (Soker 2015; Shiber, Kashi & Soker 2017; Shiber et al. 2019). Precession/wobbling and/or non strictly simultaneous ejection from each side of the accretion disk (Velázquez et al. 2014), and/or contribution of the orbital velocity to the velocity of the collimated ejecta (Miranda et al. 2001b,c) could account for the morphological differences between the NE- and SW-BS, their non-relationship to the axis of the bipolar lobes, and the difference between $V_{\text{sys}}$ (bow-shocks) and $V_{\text{sys}}$ (lobes).

The formation of the inner nebula may be understood in the context of the [WC] nature of the CS, which strongly suggests a thermal pulse (e.g., Blöcker 2001). The large amounts of material ejected in a thermal pulse form a new PN or shell which, in IRAS18061, can be identified with its inner nebula. The youth of IRAS18061 makes it attractive the idea of a final thermal pulse at the very end of the AGB. However, the IRAS fluxes of IRAS18061 are incompatible with those of IR-[WC] stars that are expected to result from a final thermal pulse (Zijlstra 2001). In particular, the flux in the IRAS bands of IRAS18061 is ~0.36×10$^{-11}$ W m$^{-2}$ (Iyengar 1987), lower than 0.8×10$^{-11}$ W m$^{-2}$ required for IR-[WC] stars, and its position in the logF(60)/F(25) vs. log(F(25)/F(12)) and logF(60)/F(12) vs. [WC] subclass diagrams does not coincide with that of IR-[WC] stars, as defined by Zijlstra (2001). A late thermal pulse (LTP) on the post-AGB horizontal track or a very late thermal pulse (VLTP) on the cooling track are
then the options, in both cases suggesting a born-again scenario (e.g., Blöcker 2001; Herwig 2001; Miller Bertolami et al. 2006; see also below).

A born-again scenario is favoured by several results. After an LTP/VLTP, the CS returns to the AGB in a few hundreds to a few years (e.g., Blöcker 1995; Hajduk et al. 2005; Miller Bertolami et al. 2006), and large amounts of dust are formed, hiding the CS at optical wavelengths until reheating of the central star and/or shocks destroy the dust and the CS is seen again (Seitter 1987; Kerber et al. 2002; Hajduk et al. 2005; Hinkle et al. 2008; Rechy-García et al. 2020). The non-detection of the inner nebula in ~1951.6 (Figure 4) suggests large amounts of dust in the core and that the CS revisited the AGB, placing the occurrence of the thermal pulse sometime before ~1951.6. The decrease of the extinction from ~1951.6 to ~1994.2 indicates that dust has been destroyed during those years and that the CS is reheating. The high velocity material ejected in a thermal pulse causes shocks that propagate in the surrounding material (Guererro et al. 2018). Evidence for these shocks is provided by the expansion velocities in the inner nebula that are higher in He than in [N ii], while the opposite is expected in a photoionised nebula. Shocks may also cause an inverted ionisation structure (Guererro et al. 2018) that is partially recognised in the inner nebula, where the [O iii] emission shows a larger (deconvolved) size than the [S ii] emission. The Ho and [N ii] emissions do not follow this behaviour, although the ring and bipolar lobes of the inner nebula contribute very differently to the Ho and [N ii] emission lines, and their (deconvolved) size could be dominated by different structures. Finally, shocks (and photoionisation) may contribute to the ionization of the innermost layer of the oxygen-rich ring, resulting in a high electron density region which may be associated with the inner ring/central component (see Figure A1).

A possibility to distinguish between LTP and VLTP in IRAS18061 is comparing the evolutionary time scales of its CS and the age of its bipolar lobes. However, if CEE has occurred in IRAS18061 as proposed above, evolutionary models constructed for single CSs cannot be applied to its CS (Miller Bertolami 2019). In particular, a CE may be ejected in a several years or a few decades (Chamandy et al. 2020), drastically reducing the transition times\(^4\) that single star models predict to be ~1400–930 yr for a 3–4 M\(_\odot\) MS progenitor (MB16). If we assume that, after (or a short time after) the ejection of the CE, the CS evolves approximately as predicted by single star models, the crossing times\(^5\) for a 3–4 M\(_\odot\) MS progenitor are ~340–70 yr (MB16), much smaller than the age of the bipolar lobes, placing the CS on the cooling track at the instant of the thermal pulse, and favouring a VLTP. For a low-mass MS progenitor of <1.5 M\(_\odot\), the crossing time is >3000 yr, larger than the age of the bipolar lobes, favouring an LTP. In any case, a definitive distinction between LTP and VLTP in IRAS18061 requires obtaining the chemical abundances in the CS, that are determined by the instant when the thermal pulse occurs (Herwig 2001).

High velocity outflows and rings are systematically ob-

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\(^4\) the duration of the early AGB phase, from the end of AGB to \(T_{\text{eff}}\sim10000\text{ K}\) (MB16).

\(^5\) the duration of the late AGB phase, from \(T_{\text{eff}}\sim10000\text{ K}\) to the maximum \(T_{\text{eff}}\) attainable on the horizontal track (MB16).
emission, the resulting H$_2$O-PN will not be at the very moment of its first entrance in the PN phase and IRAS18061 cannot be considered as a very young PN, although its inner nebula indeed is extremely young. In consequence, the presence of water maser emission may not necessarily indicate always an extremely young PN.

4.4 Implications for the formation and evolution of H$_2$O-PNe and related objects

IRAS18061 gathers many characteristics that pertain to a variety of phenomena and structures observed in PNe, including narrow waist bipolar lobes, collimated outflows, multiple ejections, rings, and could be a key object to understand the formation of complex PNe. In what follows, we will concentrate on the possible implications of our results to understand other H$_2$O-PNe and possibly related objects.

As already mentioned, jet-envelope interaction may excite water masers in very young PNe. On the other hand, it has been suggested that water masers in PNe are the remnants of the AGB ones. According to single star evolutionary models (B95; MB16), MS progenitors with $\gtrsim 6$ M$_\odot$ should be required, that would already be on the cooling track, owning their extremely fast evolution. However, the properties of H$_2$O-PNe strongly suggest that they host binary/multiple CSs. If the formation of H$_2$O-PNe is associated with CEE, as suggested by IRAS18061 (see also Gómez et al. 2018b), that the CS evolution is accelerated, low-mass MS progenitors may also explain water masers in young PNe as the remnants of the AGB ones, with the only requirement that they are oxygen-rich in the AGB phase. Moreover, as already mentioned, WFs have also been associated with 4–8 M$_\odot$ MS progenitors (Section 4.1). The highest mass range ($\sim 6$–$8$ M$_\odot$) may probably be discarded because the extremely fast CS evolution would result in photoionization of envelope in a few or several decades, in consequence, in free-free radio continuum emission that is not observed in WFs, except in IRAS15013–5754. On the other hand, the lack of free-free emission in WFs suggests a relatively stable phase to maintain a (small) population of WFs (see Gómez et al. 2017). In any case, alike H$_2$O-PNe, the observations strongly support that WFs host binary/multiple CSs (Imai 2007; Yung et al. 2011; Gómez et al. 2015a, 2018b; Orosz et al. 2019) and they could represent a phase in the evolution of binary/multiple CSs, that is previous to that of H$_2$O-PNe.

IRAS18061 suggests a new, additional scenario in which water maser emission is reactivated during the post-AGB evolution through an LTP/VLTP. Noteworthy, the H$_2$O-PN IRAS17347–3139 also presents dual chemistry (Jiménez-Esteban et al. 2006; Hsia et al. 2016) and Jiménez-Esteban et al. already proposed the possibility of a thermal pulse to explain it. If this was the case, a final thermal pulse might probably be discarded because the IRAS fluxes of IRAS17347–3139 are incompatible with those of IR-[WC] stars (Section 4.3); an LTP or VLTP would be more appropriate. Furthermore, although H$_2$O-PNe share several common characteristics (Miranda et al. 2010; Gómez et al. 2018a), the similarities between IRAS18061 and IRAS17347–3139 are extraordinary and many properties of IRAS18061 are replicated in IRAS17347–3139 that shows narrow-waist bipolar lobes ending in bow-shock-like structures at different distance from the centre; some point-symmetric structures; a compact ionised ring with a high electron density ($1$–$3\times10^6$ cm$^{-3}$); and water masers distributed along the ionised torus, that most probably trace an oxygen-rich neutral ring surrounding the ionised one (de Gregorio-Monsalvo et al. 2004; Sahai et al. 2007; Tafoya et al. 2009; Lagadec et al. 2011). These remarkable similarities strongly suggest very similar formation processes in both PNe. Identifying the spectral type of the central star of IRAS17347–3139 is crucial to establish whether this PN is related to a born-again episode. In addition, a born-again scenario should be investigated for other H$_2$O-PNe.

5 CONCLUSIONS

We have analysed new optical narrow- and broad-band images, intermediate- and high-resolution long-slit spectra of the H$_2$O-PN IRAS18061–2505. We have also included in our analysis archival POSS images obtained in $\sim$1951.6 and $\sim$1996.7.

The images show a pinched-waist bipolar PN (size $\sim$40 arcsec) consisting of narrow-waist bipolar lobes with some point-symmetric structures, a bow-shock-like structure at the end of each lobe, and a compact (size $\lesssim 0.7$ arcsec) inner nebula at the centre of the object that is recognisable in all images, except in the POSS I-Blue one from $\sim$1951.6.

The nebular kinematics shows that the bipolar lobes are strongly disrupted and present very different properties from each other. The bow-shock-like structures exhibit the characteristics of highly collimated outflows/bullets, their properties differ from each other, and are not aligned with the axis of the bipolar lobes. In the inner nebula, we identify five (spatially unresolved) components in the spectra by their kinematic and emission properties, which are compatible with a structure consisting in an inner ring, inner bipolar lobes and high velocity outflows. In addition, the morphokinematic properties of the bipolar lobes and the water masers provide compelling arguments to conclude that the water masers and, probably, the silicate emission from IRAS18061, arise from a neutral oxygen-rich ring that traces the dense equatorial region of the bipolar lobes. The bow-shocks are the oldest structure identified in IRAS18061 ($\sim$950–1000 yr), followed by the bipolar lobes ($\sim$760 yr), while the inner nebula is extremely young ($\sim$70–140 yr). Each of these components presents its own centroid/systemic (LSR) radial velocity, which may be explained if the CS is a binary/multiple system.

We carried out a spatially resolved analysis of the emission lines, physical conditions and chemical abundances in IRAS18061. The nebula presents a very low-excitation, electron temperatures of $\sim$8500–17000 K, and moderate electron densities of $\sim$1400–4600 cm$^{-3}$, although we identify a high electron density region ($\sim$2–5$\times10^5$ cm$^{-3}$) in the inner nebula. [N ii] and [S ii] emission lines are relatively strong, suggesting a shock-excitation mechanism. However, comparison with recent photoionization models and methods to discriminate between photoionised and shocks in PNe suggest that the spectra from the bipolar lobes may be explained with photoionization alone if the mass of the MS progenitor star of IRAS18061 is $\gtrsim 3$M$_\odot$. A comparison of the chemical abundances in the bipolar lobes with models for stellar yields suggests a mass of $\sim$3–4M$_\odot$ for the MS progenitor, in agreement with the expectations that H$_2$O-PNe evolve from intermediate-mass MS
progenitors. Nevertheless, the role of shocks in the nebular excitation of PNe is a very complex, still unsolved problem and the possibility of a low-mass MS progenitor cannot be definitively ruled out.

The properties of the bipolar lobes and oxygen-rich ring are consistent with those expected from CEE, if several bipolar and non-bipolar collimated outflows at different directions have been ejected during or after CEE, that have strongly distorted the bipolar lobes. The pinched-waist morphology indicates a very high density contrast in the CE, suggesting a relatively low mass ratio between central star and the presumable companion. The bipolar outflows associated to the bow-shocks could be associated with the formation of an accretion disk around a companion through Roche-lobe overflow or grazing envelope evolution before the CEE.

The inner nebula may be attributed to an LTP or VLTP. Taken into account the age of the bipolar lobes and that CEE may drastically reduced the duration of the early AGB phase, a VLTP scenario would be favoured if the progenitor mass is $\sim 3-4 M_\odot$, whereas an LTP would be favoured for progenitor masses $\lesssim 1.5 M_\odot$. The non-detection of the inner nebula in the POSSI-Blue image from $\sim 1951.6$ indicates that the thermal pulse occurred sometime before that date, while its detection in a spectrum from 1992.4 suggests that the CS is reheating. Shock excitation exists in the inner nebula, as revealed by the larger expansion velocities in H$\alpha$ than in [N$\text{II}$], and by its inverted ionisation structure, being the size in [O$\text{III}$] larger than in [S$\text{II}$].

Bipolar lobes, ring, and collimated outflows are identified in both the main and inner shell of IRAS18061, in all these cases suggesting a binary/multiple CS scenario. CEE is a plausible possibility to explain the formation of the main shell (bipolar lobes and oxygen-rich ring). We speculate that the formation of the inner shell could be related to a second CE phase that occurred when the CS expanded in its return to the AGB after the thermal pulse, and engulfed the presumable close companion resulting from the first CEE phase.

The survival time of water masers after the AGB and the age of the bipolar lobes are incompatible with the presence of water maser emission in IRAS18061. We propose that the water maser emission in IRAS18061 has been lately reactivated in the post-AGB phase, through shocks propagating in the pre-existing oxygen-rich ring, that are generated by the thermal pulse. This implies that the CSs of IRAS18061 is not at the very moment of its first entrance in the PN phase, in consequence, IRAS18061 cannot be considered as an extremely young PN. The distinction between LTP and VLTP could strongly depend on the MS progenitor mass-

We discussed $\text{H}_2\text{O}$-PNe and WFs in the light of the results obtained for IRAS18061. Although other mechanisms (e.g., jets, outflow-envelope interaction) may excite water masers in the very early PN phase, if CEE is usually involved in the formation of $\text{H}_2\text{O}$-PNe, accelerating the CS evolution, progenitor masses of $\sim 3-4$ as well as $\lesssim 1.5 M_\odot$ may explain water masers in PNe as the remnants of the AGB ones. The properties of WFs strongly support the idea that they are also associated with binary/multiple CSs and could represent an evolutionary stage that is previous to that of $\text{H}_2\text{O}$-PNe.

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DATA AVAILABILITY

The CAHA, VLA, and POSS data used in this paper can be accessed through the corresponding archives: http://caha.sdc.cab.inta-csic.es/calto/, https://science.nrao.edu/observing/data-archive, https://archive.stsci.edu/dss/, respectively. The rest of the data may be obtained upon justified request to the first author.

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APPENDIX A: ADDITIONAL FIGURE: THE INNERMOST REGIONS OF \textit{IRAS 18061–2505}

APPENDIX B: THE DISTANCE OF \textit{IRAS 18061–2505}

\textit{IRAS 18061} has been considered as a bulge PN due to its Galactic coordinates ($l = 5\degree 9747$, $b = -2\degree 6125$). However, most probably this is not the case because, as noticed by Górný et al. (2009), the spectral type of the central star is most probably this is not the case because, as noticed by Ā. Source ID GEDR3 provides: refers to the field star arrowed in Figure A1, for which images show that this is not the case and that the parallax cause no (bright) star is observed within a radius 1.414 arcsec from the position of the core of IRAS18061. Be-±parallax from GEDR3 of 0.5534 K 3-35 (see Tafoya et al. 2011). We have used the \textit{Gaia} \textit{Early Data Release 3} (GEDR3; Gaia Collaboration, A.G.A. Brown et al. 2020) to search for a possible parallax of IRAS18061, and downloaded the images of the Pan-STARRS1 survey around the object in the z, g, and r filters (Chambers et al. 2016; Flewelling et al. 2016). Figure A1 shows the field around IRAS18061 as it appears in Aladin-Lite, superimposed with the sources identified in GEDR3. The core of IRAS18061 is clearly identified and GEDR3 provides the following information for it:

\begin{verbatim}
Source ID = 4065774303370565376
α(2016.0) = 18\degree 09\arcmin 12\arcsec 411
δ(2016.0) = −25\degree 04′ 34′ 56
G magnitude = 16.966175 ± 0.0013412 mag
Parallax = −0.5450 ± 0.4355 mas
\end{verbatim}

The negative Parallax for the core of IRAS18061 is most probably due to its nebulous nature and, in consequence, the difficulty of measuring its photocenter.

Distance estimates to IRAS18061 using statistical methods are 1.3 kpc (Preite-Martínez 1988), 2.8 kpc (Tajitsu & Tamura 1998), and 6.62 kpc (Vickers et al. 2015). The third distance may be ruled out because it has been obtained assuming that IRAS18061 is a bulge PN and, in fact, places the object in the bulge (see above). In this paper, we will adopt a distance for IRAS18061 of 2 kpc, as the mean value of 1.3 and 2.8 kpc. A more precise value for the distance may be obtained from measurements of the parallax of its water masers using VLBI techniques, as in the case of the H2O-PN K 3-35 (see Tafoya et al. 2011).

We note that a search of IRAS18061 in Vizier provides a parallax from GEDR3 of 0.5534±0.1214 mas for an object at 1.414 arcsec from the position of the core of IRAS18061. Because no (bright) star is observed within a radius <1.5 arcsec from the core, it is tantalizing to associate that parallax to the core. However, a detailed inspection of the data and images show that this is not the case and that the parallax refers to the field star arrowed in Figure A1, for which GEDR3 provides:

\begin{verbatim}
Source ID = 4065774307705264384
α(2015.5) = 18\degree 09′ 12′′ 966
δ(2015.5) = −25′ 04′ 34′ 03
G magnitude = 17.904875 ± 0.003966 mag
Parallax = 0.5534±0.1214 mas
\end{verbatim}

This discrepancy may be due to errors in the coordinates of IRAS18061 in SIMBAD (see Figure A1, green square) or con-

APPENDIX C: SHAPE RECONSTRUCTION OF THE BIPOLAR LOBES OF \textit{IRAS 18061–2505}

We have used the tool \textit{shape} (Stephen et al. 2011) to reconstruct the morphokinematic structure of IRAS18061, based on the images and high-resolution long-slit spectra. We have concentrated on the extended emission from the bipolar lobes as observed in the [N\textsc{ii}] image and in the PV maps at PAs +33\degree, +55\degree, and +60\degree. The spectrum at PA −81\degree will not be considered because the kinematics at this PA is not typical of a bipolar shell but of the action of a collimated outflow on the shell (Section 3.2.2). The multiple knots observed in the PV maps will not be considered because no constrains can be imposed on the parameters of “isolated” knots (see Section 3.2.2). We have followed the standard process to reconstruct a bipolar nebula, starting with a spherical structure that is then deformed by the modifiers \textit{Squeeze} and \textit{Bump}, in a self-consistent way, so that image and PV maps must be simultaneously reproduced.

The reconstructed image and PV maps are shown in Figure C1 (cyan) superimposed on the observed data. The basic structure of the bipolar lobes is well reproduced, although some details are not well addressed. For instance, some faint features at PA +55\degree and +60\degree, that appear separated from the shell, and, particularly, features observed at PA +33\degree, that deviated from the general tendency. These differences may be attributed to peculiar local motions that are caused by jet–shell interaction.

The best fit model was obtained iteratively and corresponds to a distorted bipolar shell with main bipolar axis at PA=+63\degree (very similar to that deduced from the images), inclination angle respect to the plane of the sky $i=15\degree$, and a homologous velocity law $V[\text{km s}^{-1}]=12[r[\text{arcsec}]]$. The polar radius and expansion velocity are 13 arcsec and 163 km s$^{-1}$, respectively, implying a kinematical age of ~760 yr with an estimated error of ±60 km s$^{-1}$. Nevertheless, expansion velocities of 190–200 km s$^{-1}$ are required along PA +33\degree, which are consistent with acceleration of these regions by the impact of collimated bipolar outflow on the shell.

This paper has been typeset from a \textit{T\!E\!X/\textsc{H}\!E\!X} file prepared by the author.
Figure A1. Sketch of the innermost regions of IRAS18061. The structures are not to scale. The inclination of the inner shell accounts for the redshifted component being fainter than the blueshifted one (Sections 3.2.1 and 4.2). The different structures and regions are labelled, and information about chemistry, particle density ($n$), and electron density ($N_e$) is provided for some of them. The inner shell is probably carbon-rich, as expected from an LTP/VLTP.

Figure B1. Colour composite image of the field around IRAS18061 obtained by combining the images in the z (red) and g (blue) filters from the PanSTARRS archive. The core of IRAS18061 and the field star discussed in the text are arrowed, the empty blue squares mark the sources identified in GEDR3, and the filled green square marks the position of IRAS18061 from SIMBAD. North is up, east to the left, and the angular scale is indicated.
Figure C1. Shape reconstruction of the bipolar lobes of IRAS18061. The reconstructed image and PV maps are shown in cyan, superimposed on the data. The slit positions of the PV maps are schematically drawn on the image for reference (see Figure 5 for more details).