Pushing the limits: detecting H$_2$ emission from faint bipolar planetary nebulae in the IPHAS sample

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ABSTRACT

We have obtained deep narrowband images in the near-IR H$_2$ λ2.122 µm emission line for a sample of 15 faint IPHAS bipolar planetary nebulae (PNe) to search for molecular material. H$_2$ emission is found in most of them (14 out of 15), mostly associated with rings at their equatorial regions and with their bipolar lobes. These detections add to the high occurrence of H$_2$ emission among bipolar PNe reported in previous works, resulting from the large reservoir of molecular material in these sources and the suitable excitation conditions for H$_2$ emission. The correlation between detailed bipolar morphology and H$_2$ luminosity is also confirmed: bipolar PNe with broad equatorial rings (R-BPNe) have almost no continuum at their equatorial regions and with their bipolar lobes. These detections add to the high occurrence of H$_2$ emission among bipolar PNe reported in previous works, resulting from the large reservoir of molecular material in these sources and the suitable excitation conditions for H$_2$ emission. The correlation between detailed bipolar morphology and H$_2$ luminosity is also confirmed: bipolar PNe with broad equatorial rings (R-BPNe) have almost no continuum at their equatorial regions and with their bipolar lobes. These detections add to the high occurrence of H$_2$ emission among bipolar PNe reported in previous works, resulting from the large reservoir of molecular material in these sources and the suitable excitation conditions for H$_2$ emission. The correlation between detailed bipolar morphology and H$_2$ luminosity is also confirmed: bipolar PNe with broad equatorial rings (R-BPNe) have almost no continuum at their equatorial regions and with their bipolar lobes.

Key words: infrared: ISM – ISM: lines and bands – ISM: molecules – planetary nebulae: general

1 INTRODUCTION

Planetary nebulae (PNe) are the descendants of low- and intermediate-mass stars (≈ 0.8-8 M$_\odot$) caught in the short transition between the asymptotic giant branch (AGB) and white dwarf (WD) phases. PNe are routinely observed in optical emission lines that reveal the distribution and physical properties of ionized material, but these observations are insensitive to the dusty and molecular material remnant from the AGB phase. Infrared (IR) and radio observations can be used to detect this component in order to determine the full extent and outer geometry of PNe, to constrain the physical conditions in the regions dominated by dust and molecules (e.g., clumps and photo-dissociation regions, PDR), and ultimately to investigate the final episodes of mass-loss during the late AGB phase (see for example the works by Huggins et al. 1996; Young et al. 1999; Matsuura et al. 2005; Peretto et al. 2007; Phillips & Marquez-Lugo 2011).

Among the molecular tracers, the $\nu = 1\rightarrow 0$ S(1) 2.122 µm molecular hydrogen (H$_2$) emission line (hereafter we will refer to this line as H$_2$ unless otherwise stated) is one of the most common in PNe alongside carbon monoxide (CO) emission. Since the early IR observations of PNe, it has been noted that the H$_2$ emission has a higher occurrence rate among bipolar PNe (see, e.g., Zuckerman & Gatley 1988). Bipolar PNe have been suggested to descend from the most massive low- and intermediate-mass stars (Peimbert & Torres-Peimbert 1983; Corradi & Schwarz 1995).

Although there is a clear association of bipolar PN, type I PN and PN with a lower scale height, all pointing to a higher mass progenitor for bipolar PNe, it is not clear why the incidence of bipo-
lar PN, ~20% (Parker et al. 2006), is larger than the fraction of stars that can produce a type I PN (≈3.5 \( M_\odot \) main sequence stars, Karakas et al. 2009).

As such, they exhibit larger and thicker envelopes, with dense equatorial regions and compact clumps or knots that act as a shield against the UV radiation from their central stars (CSPNe), preventing the molecules’ dissociation. The association between \( \text{H}_2 \) emission and the bipolar morphological class has been thoroughly discussed by Kastner et al. (1996, 1994) who defined the so-called “Gatley’s rule”, automatically assimilating the presence of the \( \text{H}_2 \) 2.122 \( \mu \)m emission line to a bipolar morphology. Although this is generally the case (Guerrero et al. 2000), sensitive observations reveal \( \text{H}_2 \) emission in PNe of morphological types other than bipolar (Marquez-Lugo et al. 2013; Akras, Gonçalves, & Ramos-Larios 2017).

It was also soon realized that the brightest \( \text{H}_2 \) emission was found at the equatorial regions of bipolar PNe with broad equatorial rings and a butterfly shape (Webster et al. 1988). These regions can be resolved into individual knots and dense clumps that are embedded within ionized material (Cox et al. 1998; Speck et al. 2002; Matsura et al. 2009; Manchado et al. 2015; Marquez-Lugo et al. 2015). On the other hand, PNe with a pinched-waist and a bow-tie shape have less prevalent \( \text{H}_2 \) emission which is furthermore associated to a PDR at their bipolar lobes (e.g., HB 12, Dinerstein et al. 1988; Hora & Latter 1996). Following Marquez-Lugo et al. (2015), we will refer to the group of broad-ring bipolar PNe (i.e., “butterflies”) as R-BPNe, and to the group of pinched-waist bipolar PNe (i.e., bow-ties or hour-glasses) as W-BPNe.

Guerrero et al. (2000) investigated the \( \text{H}_2 \) over \( \text{Br}\gamma \) line ratio in these two morphological sub-classes and concluded that R-BPNe have higher \( \text{H}_2 \) to \( \text{Br}\gamma \) line ratios than W-BPNe. This is consistent with the \( \text{H}_2 \)-dominated and H i-dominated PNe described by Hora, Latter, & Deutsch (1999). The origin of this branching among bipolar PNe is unclear, but it may be related to the dominant excitation mechanism of the \( \text{H}_2 \) molecules in PNe. The \( \text{H}_2 \) emission line spectrum can be excited (i) by fluorescence or radiative pumping through the absorption of the UV radiation from the CSPN in a PDR (Black & van Dishoeck 1987; Dinerstein et al. 1988; Sternberg & Dalgarno 1989), or (ii) by shocked gas (Burton et al. 1992).

These excitation mechanisms result in notably different intensities of the \( \text{H}_2 \) 1-0 S(1) line, being much brighter for shock-excited \( \text{H}_2 \). Thus, Marquez-Lugo et al. (2015) used the very different efficiency of these two excitation mechanisms to argue that large \( \text{H}_2 \) 1-0 S(1) to \( \text{Br}\gamma \) emission line ratios are indicative of shock excitation. They conclude that the \( \text{H}_2 \) brighter R-BPNe are preferentially excited by shocks, whereas the \( \text{H}_2 \) weaker W-BPNe are excited by UV fluorescence.

In this paper, we aim to extend the search for \( \text{H}_2 \) emission to PNe that are fainter than those included in previous works. If more evolved, these faint bipolar PNe can be used to investigate the evolution of the molecular content in bipolar PNe. The U/WISH2 survey has detected \( \text{H}_2 \) emission from a number of bipolar PNe candidates which seems to be highly obscured, as they are not detected in H\(\alpha\) (Froebrich et al. 2015; Gledhill et al. 2017). Similarly, the INT Photometric H\(\alpha\) Survey data (IPHAS\(^3\);Drew et al. 2005; González-Solares et al. 2008; Barentsen et al. 2014) has unveiled a number of new faint PNe (e.g., Viironen et al. 2009). In particular, the IPHAS catalogue of extended PNe (Sabin et al. 2014) has revealed a set of 159 new true and possible PNe located in the Galactic Plane in the latitude range \( b \approx [5^\circ] \) among which 45 has been described as bipolar. This sample can be used to investigate the occurrence of \( \text{H}_2 \) emission among faint bipolar PNe. This research has also benefited from a new work on the estimation of distances to PNe (Frew, Parker, & Bojić 2016). Otherwise, by selecting carefully sources whose nebular emission is not overimposed on crowded stellar fields, their \( \text{H}_2 \) fluxes can be measured accurately, contrary to nearby PNe with large angular sizes projecting onto multiple field stars.

The paper is organized as follows. Section 2 presents the sample and describes the selection criteria. The details of the new IR and archival optical observations that have been used in this work are given in section 3. The data reduction is also explained in this section. A discussion on the individual \( \text{H}_2 \) morphologies of each PNe and on their ionized and molecular distributions is presented in §4, as well as the different morphological groups which can be drawn from our sample. Finally a general discussion, including here the sample from Guerrero et al. (2000), and the conclusions are presented in §5 and §6, respectively.

### 2. Sample

We selected a set of fifteen PNe from the IPHAS sample of true and possible PNe (Sabin et al. 2014) mostly based on H\(\alpha\)+[N ii] morphologies indicative of the presence of bipolar lobes collimated by equatorial rings or waists. To maximize their detection, we chose PNe which were optically “bright” among IPHAS sources, implying H\(\alpha\) dereddened peak fluxes up to \( 10^{-14} \text{ erg cm}^{-2} \text{s}^{-1} \).

Furthermore, to assess the \( \text{H}_2 \) spatial distribution, we selected sources large enough to be resolved, but not too large so they can fit within the field of view (FoV) of the instrument used for these observations (see below). An additional selection criterion requires minimizing the number of field stars overimposed on the optical nebular emission. Thus our sample includes PNe with optical diameters (major axis) ranging from \( \sim 9'' \) to \( \sim 78'' \).

The IAU-PNG and IAU-IPHAS designations of the PNe in our sample (the latter includes their J2000 equatorial coordinates) are listed in columns 1 and 2 of Table 1. Detailed information of these sources can be found in the HASH database.

Table 1. Sample of IPHAS PNe observed with WHT LIRIS in the near-IR.

| PNG          | IPHASX J |
|--------------|----------|
| G035.4+03.4  | 184336.6+0346401 |
| G035.9−01.3  | 190718.1+04056   |
| G045.7+01.0  | 190930.7+1205452 |
| G045.7−03.8  | 192847.2+093436  |
| G054.2+03.4  | 194359.5+170900 |
| G057.9−00.7  | 194226.0+2154215 |
| G062.7+00.0  | 194940.9+261521  |
| G062.7−00.7  | 195248.8+255359  |
| G064.1−00.9  | 195657.6+265713  |
| G066.0+00.0  | 200224.3+304845  |
| G069.0−03.9  | 205527.2+305394  |
| G091.6−01.0  | 212335.3+484717  |
| G095.8+02.6  | 216208.3+542015  |
| G101.5−00.6  | 221180.0+552841  |
| G126.6+01.3  | 012507.9+635653  |

Other names: \(^{1}\) PM 1-253, \(^{2}\)Te 6, \(^{3}\)Kn 7, \(^{4}\)TEUTSCH PN J2055.4+3903.

\(^1\) http://www.iphas.org/
3 OBSERVATIONS

3.1 Near-IR imaging

Narrow-band $H_2$ 2.122 $\mu$m and $K_c$ continuum near-IR images were obtained with the Long-slit Intermediate Resolution Infrared Spectrograph (LIRIS: Manchado et al. 2003; Acosta Pulido et al. 2003) at the 4.2m William Herschel Telescope (WHT) on Roque de Los Muchachos Observatory (ORM: La Palma, Spain). The characteristics of the filters are shown in Table 2. The detector is a 1024 × 1024 HAWAII array with plate scale of 0′′.25 pixel$^{-1}$ and an FoV of 4′ × 4′.

Most observations were carried out on 2014 July 13. One object, IPHASX J194359.5+170900 (a.k.a., the Necklace nebula, Sabin 2008; Corradi et al. 2011; Miszalski et al. 2013) has been previously observed on the same telescope on 2007 September 19. We acquired 16 × 60s exposures in $H_2$ and 8 × 60s exposures in $K_c$ for each object during the most recent run, and 150 × 20s exposures during the 2007 run. The IR observing procedure which includes images jittering has been described in details by Ramos-Larios et al. (2012)\(^2\). The data reduction was performed using the package LIRISDR (LIRIS Data Reduction), which is an IRAF\(^3\)-based pipeline dedicated to the automatic reduction of near-IR data. The processing steps include bad pixel mapping, cross-talk correction, flat-fielding, sky subtraction, removal of reset anomaly effect, field distortion correction, and co-addition to form the final image. The procedure is repeated for each $H_2$ and $K_c$ data-sets separately. The latter, which corresponds to the continuum emission, is subsequently scaled and subtracted from its $H_2$ image counterpart. The near-IR images are presented in Figures 1, 2, 3 and 4 arranged by their Galactic longitude.

It is worth emphasizing the high throughput and efficiency of the LIRIS instrument at the WHT in terms of detection of molecular hydrogen at low surface brightness levels. M 2-48 and NGC 6778 were reported as $H_2$-free by Kastner et al. (1996) and Webster et al. (1988), respectively, but recent WHT LIRIS observations actually detected $H_2$ emission (Marquez-Lugo et al. 2013). This is critical for this project, as we initially deal with even fainter optical PNe than M 2-48 and NGC 6778.

\(^2\) See also the WHT/LIRIS website at: http://www.ing.iac.es/Astronomy/instruments/liris/imaging.html

\(^3\) IRAF (Image Reduction and Analysis Facility) is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

3.2 Optical imaging

The optical images presented in this article were retrieved from the IPHAS images data bank\(^4\). These images were originally obtained with the Wide Field Camera (WFC) mounted on the 2.5m Isaac Newton Telescope (INT), also located at the ORM. The camera has a FoV of 34′ × 34′ arcmin\(^2\) and a plate scale of 0′′.33 pixel$^{-1}$. The properties of the $H_α$ filter used during the survey are given in Table 2. We note that the $H_α$ filter also contains the $[N II]$ $λ6583$ $\AA$ emission line (Drew et al. 2005). We will therefore refer to these as $H_α$/$[N II]$ images. Exposure times were always 120 s.

These images were combined with the near-IR images to create the colour-composite pictures presented in the right panels of Figures 1, 2, 3 and 4.

4 BASIC MORPHOLOGY IN THE NEAR-IR $H_2$ LINE

All the sources in our sample, but PN G045.7+01.4 (a.k.a. Te 6), are detected in $H_2$. Te 6 is a barrel-like PN with broad ansae which can be interpreted as bipolar lobes. The nebula has a diameter of 17′′.3 × 13′′.8 in the $H_α$ line (Fig. 1). The optical emission is mostly localized in a broad, diffuse equatorial region, whereas the polar protrusions (particularly the Southern one) are much fainter.

According to the morphology and intensity of the $H_2$ emission, the sources in our sample with detected $H_2$ emission can be organized into two different groups. PNe with equatorial pinched waist (i.e., W-BPNe) have typically faint $H_2$ emission (e.g., PN G035.4+03.4, Fig. 1), whereas those with a well developed equatorial ring (i.e., R-BPNe) tend to have bright $H_2$ emission (e.g., PN G126.6+01.3, Fig. 4). These two groups are described in more detail below.

4.1 W-BPNe: PNe with pinched equatorial waists

This group includes PN G035.4+03.4, G038.9−01.3 (Figure 1), and G062.7−00.7 (Figure 3). The optical morphology of these PNe is characterized by narrow waists in between a pair of bipolar lobes (PN G035.4+03.4), a highly collimated bipolar outflow (PN G038.9−01.3), and a pair of hourglass-shaped bipolar lobes (PN G062.7−00.7).

In the near-IR continuum $K_c$ filter, they show mostly compact, bright emission in the innermost regions, whereas the images in the $H_2$ filter show additional extended emission along the collimated structures. (Fig. 1, and 3 left and middle-left). The continuum subtracted images (Fig. 1, and 3 middle-right) reveal the lack of 2.122 $\mu$m $H_2$ emission in the innermost regions, being the molecular emission mostly restricted to the collimated structures. Otherwise, the details of the diffuse $H_2$ emission differs among these three sources.

- PN G035.4+03.4 (a.k.a. PM 1-253)
  The 2.122$\mu$m $H_2$ emission traces the onset of the bipolar ejections, much smaller in size than the ~9′′6 emission detected in the $H_α$/$[N II]$ IPHAS image (Fig. 1). The eastern side of the equatorial plane seems to present very faint $H_2$ emission, but we reckon it may be an artifact caused by a bright defective subtraction of the bright continuum emission. The distribution of the $H_2$ region is somehow similar to that described for M 2-9 (Phillips et al. 1985; Kastner et al. 1996), although the detailed morphology is not that...
close. The H$_2$ emission in M 2-9 follows the walls of the bipolar lobes in their full extent, what has been referred to as a ”thin H$_2$ skin“ (Hora & Latter 1994; Smith et al. 2005), whereas in the “IPHAS counterpart” PN G035.4+03.4 it is concentrated at the base of the lobes.

- PN G038.9$-$01.3

The molecular hydrogen emission is mostly detected along the collimated outflow, with the north-west component of the outflow being brighter than the south-east one (Fig. 1). The asymmetry of the H$_2$ emission could be interpreted as the result of asymmetric mass loss, but also produced by an orientation effect causing higher extinction to the south-east region. In this sense, the H$\alpha$+[N II] IPHAS image also reveals brighter emission of the north-west region. The nebular morphology of PN G038.9$-$01.3 is rather similar to that of M 1-91 (Guerrero et al. 2000). The latter has been classified as an SS (e.g. Schmeja & Kimeswenger 2001), whereas PN G038.9$-$01.3 is flagged as a likely PN in the HASH database (Parker, Bojičić, & Frew 2016).

- PN G062.7$-$00.7

The H$_2$ emission follows the ionized emission seen in the light of...
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4.2 R-BPNe: PNe with broad equatorial rings

This group includes the remaining PNe in our sample, namely PN G045.7−03.8, G045.7−03.8, G057.9−00.7, G062.7+00.0, G064.1−00.9, G068.0+00.0, G081.0−03.9, G091.6−01.0, G095.8+02.6, G101.5−00.6, and G126.6+01.3. These PNe are characterized by the presence of large equatorial rings or broad structures that are at the origin of bipolar lobes or other axisymmetrical structures such as ansae or protrusions.

In the near-IR, these sources show basically no emission in the $K_c$ continuum images. The diffuse H$_2$ emission is spatially coincident with the optically brighter equatorial structure and, in a few cases, with the fainter bipolar components. The intensity of the H$_2$ emission echoes that seen in the H$\alpha$+[N II] IPHAS images, with brighter emission in the equatorial regions. We describe briefly the H$_2$ morphology of some individual sources.

- PN 045.7−03.8
  The optical images show two interleaved circular rings \~58$^{\prime}$1×68$^{\prime}$2 in size with brighter emission in the central regions where they overlap. Weak H$_2$ emission is detected in the...
central regions, spatially coincident with the brightest patches in the Hα+[N II] IPHAS image (Fig. 1).

• PN G054.2−03.4 (a.k.a. the Necklace Nebula)
The optical images of the Necklace Nebula show a knotty ring and a pair of high velocity collimated outflow/jets. These have been presumably launched from an accretion disk before the common envelope phase of the close binary system formed by its central star and a carbon dwarf companion (Corradi et al. 2011; Miszalski et al. 2013). The 2.122 µm H$_2$ emission arises exactly at the location of the ionized knots, but also at the polar caps (Figure 2). The H$_2$ surface brightness in this PN is extremely low and its detection required an integration time about three times longer than that for the other objects in our sample.

The detailed image of the Northwest quadrant of the equatorial ring of the Necklace Nebula shown in Figure 5 is revealing. The H$_2$ emission comes from a discrete distribution of compact knots and filaments associated with the [N II] knots and their tails, rather than from a classical PDR. This is very similar to the distribution of the H$_2$-emitting knots embedded in the equatorial regions of NGC 650-51 (Marquez-Lugo et al. 2015) and NGC 2346 (Manchado et al. 2015), but also in the low-ionization features (FLIERs) of NGC 7662 (Akras, Gonçalves, & Ramos-Larios 2017). It is worth emphasizing the varying spatial distribution of the molecular and...
low-ionization material in these knots; sometimes the H$_2$ emission in the knot faces the central star and the [N II] emission lies beyond (for instance, the central knot in Fig. 5), but in some other cases the H$_2$ emission seems to peak further away from the central star than the [N II] emission (as in the two other knots in Fig. 5). This may reveal projection effects, suggesting that the H$_2$ and [N II] emissions are not coplanar. Certainly, an H$_2$ image of spatial resolution similar to that of the HST WFC [N II] image is required to investigate the details of the varying spatial distribution of molecular and low-ionisation material in this nebula.

- PN G057.9−00.7 (a.k.a. Kn 7)
  The optical images reveal a bipolar PN showing a bright central ring partially filled with ionized material and faint bipolar lobes. The H$_2$ emission follows the spatial location of the H$\alpha$+[N II] emission, being particularly bright in the ring and relatively fainter in its interior (Figure 2). The bipolar lobes are also detected in the H$_2$ image.

- PN G062.7+00.0
  The optical image shows a butterfly nebula with size $\sim$18.5′×11.0′ and a bright wide waist. The H$_2$ emission largely covers the whole ionized region, with stronger emission in the waist (Fig. 2).

- PN G064.1−00.9 and PN G068.0+00.0
  Bipolar PNe with an equatorial ring and two diffuse bipolar outflows. There is an excellent spatial match between the H$_2$ and op-
tical Hα+[N II] morphologies, with the equatorial ring being the brightest structure (Fig.3).
- PN G081.0–03.9 Bipolar PN with an open barrel-like structure from whose tips protrude fainter bipolar extensions. The H2 emission is rather diffuse and located at the barrel-like feature, i.e., the brightest region of the optical Hα+[N II] emission (Fig.3).
- PN G091.6–01.0 and PN G126.6+01.3 (a.k.a. “Príncipe de Asturias” Nebula)
- Bipolar PNe with a classical butterfly morphology viewed side-on (Figs. 4). The central rings are thus seen mostly as bars or very elongated ellipses. Both nebulae exhibit stars located very close to the centre of the nebular equatorial regions. Molecular hydrogen is detected along the central bars, enveloping the tips of the equatorial rings, as well as at the outer walls of the bipolar lobes.
- PN G095.8+02.6 Bipolar PN with a remarkable point-symmetric morphology. The spatial distribution of the molecular hydrogen confirms this point-symmetric morphology (Fig.4). Molecular emission is detected in the main nebular shell, and faintly at the ansae.
- PN 101.5–00.6 The optical image displays an equatorial structure and two fainter bipolar lobes. The emission in the Hα+[N II] IPHAS image is suggestive of a broad equatorial belt seen from the side, so that the bipolar lobes lie on the plane of the sky. The H2 emission is extremely poor and only a patchy feature is seen towards the brighter north-western edge of the optical emission (Fig.4).

5 DISCUSSION

5.1 General properties of the H2 emission in the IPHAS sample of PNe

This study confirms the prevalence of H2 emission among bipolar PNe; only one source (PN G045.7+01.4) out of 15 bipolar PNe in this sample shows no trace of H2 emission in its continuum-subtracted H2 image (Fig. 1).

Narrow-band near-IR imaging of a combined sample of 141 PNe (Kastner et al. 1996; Guerrero et al. 2000; Marquez-Lugo et al. 2015; Akras, Gonçalves, & Ramos-Larios 2017, this work) support this prevalence: ~75% (66 out of 89) of bipolar PNe are detected in H2, whereas only ~25% (13 out of 52) of non-bipolar PNe are detected in H2.

The H2 emission originates from the equatorial regions and bipolar lobes of the PNe in the IPHAS sample. Whenever there is a broad ring-like structure (i.e., in the 11 R-BPNe with H2 emission), the H2 emission is brighter in these regions than in the bipolar lobes. This is the case even for the faint source PN G101.5–00.6 whose bipolar lobes are most likely missing detection. In the remaining three sources that show a pinched-waist (the W-BPNe sources PN G035.4+03.4, G038.9–01.3, and G062.7–00.7), the H2 emission is brighter in the bipolar lobes, whereas the central regions are dominated by continuum emission. Continuum emission in R-BPNe is basically negligible, pointing to the absence of dust thermal emission.

When the spatial distributions of the emission from molecular and ionized material can be compared, it can be seen that the innermost regions close to the central star are dominated by ionized material. Molecular material, as traced by the H2 emission, is confined to the outer edges of the ionized regions (Beckwith, Gatley, & Persson 1978).

The preferential detection of H2 emission associated with the equatorial regions of bipolar PNe and its distribution at the outer edges of these confirm that equatorial density enhancements provide ideal conditions to shelter the H2 molecule from UV radiation and avoid its dissociation. However, the detailed comparison between the molecular H2 and low-ionization [N II] emissions for the North-west quadrant of the equatorial ring of the Necklace Nebula (Fig. 5) suggests that the H2 emission arises from knots and filaments which are spatially coincident with the [N II] knots. When deep H2 and optical observations of the highest spatial resolution are obtained, they unveil that the molecular material in the equatorial regions of bipolar PNe is embedded within ionized gas (e.g., Manchado et al. 2015).

5.2 Prevalence of H2 or H I emission

The prevalence of the emission from the H2 1-0 S(1) line over Brγ is commonly used to classify sources into molecular- or ionized-dominated (e.g., Hora, Latter, & Deutsch 1999). This classification is useful to investigate the evolutionary stage of the nebula (e.g., Alemán & Gruenwald 2011; Likkel et al. 2006) or possible different evolutionary paths (Guerrero et al. 2000).

As noted in Section §1, this same ratio has been associated with different bipolar morphologies: R-BPNe show brighter H2 than Brγ, whereas W-BPNe have brighter Brγ than H2 (Guerrero et al. 2000; Marquez-Lugo et al. 2015).

In this context, it is worthwhile to investigate the relative intensity of the H2 1-0 S(1) and Brγ emission lines in the IPHAS sample and compare them to those presented by Guerrero et al. (2000).
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There is also a notable correlation between the near-IR H$_2$/Br$^+$ and optical [N II]/H$\alpha$ line ratios (Figure 6-right); sources with larger H$_2$/Br$^+$ line ratios tend to show also larger [N II]/H$\alpha$ line ratios. Furthermore, R-BPNe do not only have the largest H$_2$/Br$^+$ ratios, but they also show the largest [N II]/H$\alpha$ line ratios. Most R-BPNe have H$_2$/Br$^+$ line ratios $\geq 10$, thus implying shock excitation (Marquez-Lugo et al. 2015). Similarly, the low H$_2$/Br$^+$ line ratio of most W-BPNe implies UV excitation.

5.3 The H$_2$ Luminosity Distribution and Physical Properties of BPNe

The H$\alpha$ intrinsic flux of each source has been combined with its size according to the prescriptions of Frew, Parker, & Bojičić (2016) to derive its distance. The distribution of the sources in the Galaxy is shown in Figure 7. Whereas the sources sampled by Guerrero et al. (2000) are generally closer than 5 kpc (4.2±1.2 kpc in average), the IPHAS sources are mostly distributed above 5 kpc from the Sun (8.4±3.8 kpc in average), with some of them as far as 15 kpc. This results confirms that the IPHAS sample of bipolar PNe presented in this work probes sources at further distances in the Galaxy. Meanwhile, the faintest H$\alpha$ bipolar PNe sampled by UWISH2 (Froebrich et al. 2015) correspond to very extincted sources or even to sources that have not been ionized yet (Gledhill et al. 2017).

The distance is then used to derive the luminosity in the H$_2$ and Br$^+$ emission lines of these BPNe, as well as their Galactic height and linear size. The comparison between the H$_2$ and Br$^+$ luminosities (Figure 8-left) confirms that both samples of bipolar PNe are rather similar, with the IPHAS sample being generally only a bit fainter than the bipolar PNe sampled by Guerrero et al. (2000). The low H$\alpha$ surface brightness of the bipolar PNe in the IPHAS sample does not imply these are more evolved sources, but rather more distant and extinguished.

W-BPNe have typically larger Br$^+$ luminosities than R-BPNe, whereas the opposite is true for H$_2$. There are two outstandingly faint H$_2$ R-BPNe in this plot, namely the Necklace Nebula and PN G101.5−00.6. The former has been claimed to be a post-AGB/post-PNe ejecta nebula (Misalski et al. 2013).

As for the correlation between PN size and H$_2$ luminosity (Figure 8-right), W-BPNe (0.28±0.10 pc) are notably smaller than R-BPNe (0.56±0.29 pc). The latter show a notable flat distribution of H$_2$ luminosity with size, i.e., the nebular size does not affect the H$_2$ luminosity. If nebular size can be correlated with nebular age (assuming similar expansion velocities), then the above result implies that there is very little evolution of the total H$_2$ luminosity with age and expansion for R-BPNe. As H$_2$ emission is still detectable (and bright) in very extended and presumably old PNe, it indicates that molecular hydrogen is likely to survive during a significant fraction of the life of an R-BPNe, only declining in the final stages of their nebular evolution.

The “longevity” of the H$_2$ emission in R-BPNe is most likely linked with the true nature of molecular material in evolved bipolar PNe. The H$_2$ emission does not come from a global PDR, but from a number of compact knots distributed into equatorial regions pervaded by ionized material. Molecular material survives in these knots and the H$_2$ molecule is mostly excited by shocks. This is in agreement with the high-resolution images of the molecular material in NGC 2346 (Manchado et al. 2015). Similar structures are identified in the classical butterfly PN NGC 650-51, where the diffuse H$_2$ emission is mostly tracing a ring which is composed of a set of knots and filamentary structures (Marquez-Lugo et al. 2015).

The H$_2$ 1-0 S(1) fluxes of the PNe in our sample can be derived from the WHT LIRIS images. First, we have used an aperture encompassing the whole nebular extent of each PN to derive the total count rate. This has been also estimated for a number of stars in the field of view using IRAF DIGIPHOT routines. The count rates from these stars are then compared to their 2MASS $K_s$ magnitudes to derive a photometric zero point magnitude. Then, taken into account the filter transmission curve to derive the filter equivalent width (EW), the count rates of the nebular emission in the H$_2$ 1-0 S(1) line have been converted into observed fluxes. For bright sources, the flux uncertainty is dominated by the Poisson statistics and it may range from 5% to 20%. For faint and extended sources, the flux uncertainty can amount up to 50%.

Similarly, the IPHAS images can be used to determine the Br$^+$ fluxes of these sources. The images are used to obtain the count rates in the INT H$\alpha$+[N II] filter. Optical spectroscopic observations obtained for these sources in the IPHAS framework (Sabín et al. 2014) are used in conjunction with the filter transmission curve to assess and subtract the contribution of the [N II] $\lambda\lambda$6548,6584 lines to the emission detected in the IPHAS H$\alpha$+[N II] image. The net H$\alpha$ count rate is then converted into observed flux$^5$ using the zero point magnitude $z_p$ provided by Barentsen et al. (2014). This flux is corrected from extinction using the $H_B$ logarithmic extinction coefficient, $c(H_B)$. This is derived from the observed H$\alpha$ to $H_B$ flux ratio measured in the IPHAS optical spectra compared to the theoretical ratio expected for Case A at 10,000 K (Osterbrock & Ferland 2006). For those sources with no available optical spectra covering the H$\alpha$ and H$\beta$ emission lines (namely, PN G035.4+03.4, G045.7−03.8, G054.2−03.4, G062.7+00.0, and G062.7−00.7), $c(H_B)$ was computed from their H I column density provided by Dickey & Lockman (1990) and Kalberla et al. (2005) assuming the gas-to-dust ratio from Bohlin, Savage, & Drake (1978). The intrinsic Br$^+$ flux is then derived using the theoretical Br$^+$ to H$\alpha$ flux ratio of 0.00990 which can be derived using Osterbrock & Ferland (2006) theoretical line ratios for case A at 10,000 K. To allow a fair comparison between the H$_2$ 1-0 S(1) and Br$^+$ fluxes, the flux from the former line is also dereddened using the measured ($c(H_B)$).

The intrinsic H$_2$ and Br$^+$ fluxes and the [N II] $\lambda\lambda$6584 to H$\alpha$ and H$_2$ to Br$^+$ ratios are collected in Table 3. The detailed bipolar morphological sub-types (R-BPNe and W-BPNe) are also included in this Table. For completeness, the sample of bipolar PNe in Guerrero et al. (2000) has been added to this table. The H$_2$ flux of NGC 6881 listed by Guerrero et al. (2000) is considered to be a lower limit in view of the deeper H$_2$ images presented by Ramos-Larios, Guerrero, & Miranda (2008).

The trends are shown in Figures 6, 7, and 8. The new IPHAS PNe extend towards regions of lower H$_2$ and Br$^+$ fluxes (Figure 6-left). In agreement with previous results, R-BPNe have generally larger H$_2$ than Br$^+$ fluxes, whereas W-BPNe are typically fainter in H$_2$ than in Br$^+$. All R-BPNe are detected in H$_2$ with the only exception of Hen 2-428 and PN G045.7+01.4. Most R-BPNe have H$_2$/Br$^+$ ratios above unity, with the exceptions of PC 20, M 1-59, the Necklace Nebula, and PN G101.5−00.6. Most W-BPNe have H$_2$/Br$^+$ ratios below unity, with the only exceptions of NGC 6881 and PN G062.7−00.7. These exceptions are labeled in Figure 6-left.

$^5$ No spectrum in the spectral range covering the H$\alpha$ and [N II] emission lines is available for PN G035.4+03.4. The H$\alpha$ flux for this nebula has not been corrected from the [N II] contribution, and thus it provides an upper limit of its true H$\alpha$ flux.
Table 3. H$_2$ fluxes for the IPHAS and Guerrero+2000 samples

| Common name   | PN G   | Radius (pc) | d$^a$ (kpc) | F(Br$\gamma$) ($\times 10^{15}$ erg cm$^{-2}$ s$^{-1}$) | F(H$_2$) ($\times 10^{15}$ erg cm$^{-2}$ s$^{-1}$) | H$_2$/Br$\gamma$ | [N II]/H$\alpha$ | BPN type | $z$ (pc) | L(Br$\gamma$) ($\times 10^{30}$ erg s$^{-1}$) | L(H$_2$) ($\times 10^{30}$ erg s$^{-1}$) |
|---------------|--------|-------------|-------------|-------------------------------------------------|-----------------------------------------------|-----------------|----------------|-----------|---------|--------------------------------|----------------------------------|
| PM 1-253      | G035.4+03.4 | 0.29 | 6.9 | <88 | 12.3 | >0.14 | W | 407.32 | 499.57 | 70.06 |
| ...           | G038.9+01.3 | 0.35 | 17.1 | 10.4 | 3.7 | 0.35 | 0.74 | W | 387.61 | 366.60 | 130.50 |
| Te 6          | G045.7+01.4 | 0.26 | 3.4 | 420 | <6.1 | <0.015 | 0.24 | R | 83.39 | 590.82 | 8.58 |
| ...           | G045.7+03.8 | 1.82 | 6.4 | 5.1 | 43.2 | 8.5 | 4.35 | R | 426.54 | 25.26 | 215.85 |
| Necklace      | G054.2+03.4 | 0.72 | 6.9 | 20 | 1.9 | 0.093 | 0.47 | R | 409.57 | 113.46 | 10.67 |
| Kn 7          | G057.9+00.7 | 0.53 | 6.8 | 34 | 730 | 21.9 | 1.69 | R | 82.94 | 186.46 | 408.80 |
| ...           | G062.7+00.0 | 0.28 | 6.1 | 120 | 260 | 2.2 | 1.96 | R | 6.42 | 539.58 | 1172.70 |
| ...           | G062.7+00.7 | 0.45 | 6.9 | 42 | 185 | 4.4 | 2.73 | W | 84.57 | 245.34 | 1071.03 |
| ...           | G064.1+00.9 | 1.04 | 9.8 | 5.4 | 120 | 22.6 | 4.92 | R | 154.03 | 62.59 | 1419.02 |
| ...           | G068+00.0   | 1.88 | 15.3 | 0.8 | 200 | 239.1 | 5.41 | R | 9.89 | 23.84 | 5704.47 |
| ...           | G081.0−03.9 | 0.84 | 8.6 | 10 | 190 | 19.3 | 1.30 | R | 581.67 | 88.32 | 1701.08 |
| ...           | G091.6−01.0 | 0.74 | 11.8 | 6.6 | 230 | 34.0 | 0.96 | R | 205.12 | 110.26 | 3758.30 |
| ...           | G095.8+02.6 | 0.44 | 9.8 | 22 | 230 | 10.1 | 1.05 | R | 444.29 | 259.48 | 2634.17 |
| ...           | G101.5−00.9 | 0.83 | 5.3 | 23 | 1.8 | 0.065 | 0.47 | R | 54.98 | 74.89 | 4.91 |
| ...           | G126.6+01.3 | 0.43 | 5.1 | 82 | 500 | 6.1 | 2.45 | R | 115.37 | 255.43 | 1556.61 |
| M 1-57        | G022.1−02.4 | 0.20 | 4.0 | 510 | 210 | 0.41 | 1.25 | W | 165.33 | 950.56 | 395.28 |
| M 1-59        | G023.9−02.3 | 0.16 | 2.9 | 1350 | 610 | 0.45 | 0.80 | R | 115.98 | 1361.64 | 615.26 |
| M 2-46        | G024.8−02.7 | 0.24 | 4.2 | 330 | 110 | 0.33 | 1.00 | W | 196.58 | 687.67 | 231.33 |
| PC 20         | G031.7+01.7 | 0.14 | 3.8 | 900 | 530 | 0.58 | 0.80 | R | 113.21 | 1582.68 | 932.02 |
| M 4-14        | G043.0−03.0 | 0.45 | 4.6 | 96 | 1920 | 20.0 | 1.77 | R | 242.89 | 249.97 | 4994.10 |
| Hen 2-428     | G049.4+02.4 | 0.38 | 2.6 | 370 | <3.6 | <0.010 | 0.47 | R | 110.38 | 312.99 | 3.05 |
| K 3-34        | G059.0+04.6 | 1.22 | 6.9 | 8.5 | 470 | 55.2 | 1.88 | R | 549.84 | 48.31 | 2667.92 |
| M 1-91        | G061.3+03.6 | 0.28 | 4.5 | 210 | 120 | 0.57 | 0.24 | R | 285.19 | 523.17 | 298.96 |
| M 1-75        | G068+00.0   | 0.39 | 2.6 | 380 | 3890 | 10.3 | 2.86 | R | 1.86 | 304.23 | 3139.09 |
| K 3-58        | G069.6−03.9 | 0.46 | 6.7 | 45 | 270 | 50.9 | 1.03 | R | 453.59 | 239.55 | 1219.2 |
| NGC 6881      | G074.5+02.1 | 0.17 | 3.3 | 880 | >1250 | >1.4 | 0.61 | W | 122.24 | 1188.06 | 1679.95 |
| M 4-17        | G079.6+05.8 | 0.66 | 4.1 | 64 | 3240 | 50.6 | 0.65 | R | 415.75 | 130.81 | 6622.27 |
| K 4-55        | G084.2+01.1 | 0.65 | 4.5 | 54 | 2450 | 45.1 | 7.13 | R | 86.54 | 133.01 | 6012.67 |
| M 2-52        | G103.7+00.4 | 0.38 | 3.6 | 200 | 1980 | 9.7 | 1.79 | R | 25.06 | 317.51 | 3081.68 |
| Bv 5-1        | G119.3+00.3 | 0.46 | 4.6 | 92 | 1970 | 21.3 | 3.40 | R | 24.19 | 237.91 | 5077.89 |

$^a$ All distances computed according to Frew, Parker, & Bojić (2016)

Figure 6. Comparison of the H$_2$ and Br$\gamma$ unabsorbed fluxes (left) and the H$_2$/Br$\gamma$ vs. [N II]/H$\alpha$ line ratios (right) of the IPHAS PNe in this work and Guerrero et al. (2000)'s sample. Different symbols are used for the different data samples and morphologies as described in the left panel. Singular objects are labeled.
Figure 7. Distribution of the PNe in our sample in the Galaxy. The PNe have been located on an artistic view of the Milky Way (Image credit: NASA/JPL-Caltech/R. Hurt SSC/Caltech).

Figure 8. Comparison of the H$_2$ and Br$\gamma$ intrinsic luminosities (left) and distribution of nebular sizes with H$_2$ luminosities (right). Different symbols are used for the different data samples and morphologies as described in the left panel of Figure 6. Singular objects are labeled.

5.4 Bipolar PNe: two of a kind?

The results reported here confirm the dichotomy between bipolar PNe with broad rings and those with pinched waists first reported by Webster et al. (1988). Guerrero et al. (2000) questioned the origin of these two different branches of bipolar PNe, but it could not conclude whether W-BPNe and R-BPNe are different in nature or are the same kind of sources, but found at different evolutionary stages.

The larger physical size of R-BPNe with respect to W-BPNe (Fig. 8-right) can be interpreted as evidence of the later evolutionary stage of R-BPNe with respect to W-BPNe.

To further confirm this observational fact, we have examined the PNe in the sample listed by Frew, Parker, & Bojić (2016) and selected those with W-BPN and R-BPN morphologies. Their sizes
have been derived using the angular sizes listed in this same reference and compared in Figure 9-bottom. This plot, based on a larger data sample, indeed confirms that R-BPNe are larger than W-BPNe.

There is limited information on the kinematics of the PNe in Table 3. Kinematic studies are only available for two W-BPNe (M2-46 and NGC 6881, Manchado, Stanghellini, & Guerrero 1996; Guerrero & Manchado 1998), but for nine R-BPNe (Hen 2-428, K 3-58, K 4-55, M 1-59, M 1-75, M 2-52, M 4-14, Necklace, and Príncipe de Asturias, Weinberger 1989; Guerrero, Manchado, & Serra-Ricart 1996; Peña & Medina 2002; Mampaso et al. 2006; Dobrinčić et al. 2008; Santander-García et al. 2010; Corradi et al. 2011). Using the new distances listed in Table 3, the innermost lobes of W-BPNe have kinematic ages between 1300 yrs (NGC 6881) and 6300 yrs (M 2-46), whereas for R-BPNe these range from 2100 yrs (Príncipe de Asturias) to 13800 yrs (K 4-55), with a mean kinematic age of 8000 yrs. These figures also suggest that R-BPNe are older than W-BPNe.

The larger H$_2$ luminosity and H$_2$/Br$\gamma$ ratio of R-BPNe with respect to W-BPNe can also be interpreted into an evolutionary scheme. The dominant H$_2$ excitation mechanism in young PNe is UV fluorescence, because the density is not too high to collisionally de-excite the H$_2$ molecules as in proto PNe (PPNe), but the nebular size is not too large to dilute the UV radiation field (Natta & Hollenbach 1998). Later on, as the PN keeps growing and the stellar luminosity declines, the local intensity of the UV radiation field is too low to produce significant UV excitation, whereas thermal emission from shock-excited hot H$_2$ molecules prevails (Natta & Hollenbach 1998). The collisional excitation in the ionized regions of PNe with high CSPN temperatures (Aleman & Gruenwald 2011) can certainly enhance this excitation among evolved PNe. These trends are observationally confirmed in samples of PNe at different evolutionary stages (Davis et al. 2003).

Can W-BPNe evolve into R-BPNe? Balick (1987) presented an evolutionary scheme for PNe, defining “early”, “middle”, and “late” PNe according to the relative distance of the bright inner rim to the central star. In this scheme, late bipolar PNe develop large bipolar lobes and achieve large aspect ratios. The average aspect ratios of R-BPNe (0.70±0.18) and W-BPNe (0.60±0.27) are, however, very similar. Actually, detailed hydrodynamic simulations of bipolar PNe do not support this interpretation of the evolution of bipolar PNe, as they achieve a shape early in their evolution that keeps growing with time (Icke, Balick, & Frank 1992) which is determined by the azimuthal density enhancement of the AGB wind (Frank et al. 1993). In this paradigm, W-BPNe do not evolve into R-BPNe, although it has been recognised that hydrodynamic models have great difficulties to reproduce the most axisymmetric bipolar PNe (Balick 2000). Other shaping agents (for instance, fast-moving knots and collimated outflows Sahai & Trauger 1998; Dennis et al. 2008) have been proposed to be responsible of these extreme morphologies, but the time-evolution of the detailed morphology predicted in these scenarios has not been sufficiently explored.

Alternatively, W-BPNe and R-BPNe can evolve from different progenitor populations. This can be investigated by looking at the Galactic height distributions of R-BPNe and W-BPNe shown in Figure 9-top. R-BPNe and W-BPNe are mostly concentrated towards the Galactic Plane, with mean Galactic heights of 290±310 pc and 300±270 pc, respectively. As first described by Corradi & Schwarz (1995) and later on by Kastner et al. (1996), bipolar H$_2$-emitting PNe are concentrated towards the Galactic Plane. Although the Galactic height distribution of W-BPNe have a secondary peak at ~700 pc, both samples have statistically consistent Galactic height distribution, indicating that they can be drawn from the same population of progenitor stars.

Even if W-BPNe and R-BPNe descend from the same progenitor population (relatively massive low- and intermediate-mass stars), they may have different progenitors. Sahai et al. (1991) proposed a two-fold formation mechanism for bipolar PNe, arguing that equatorial tori results from ‘born again’ disks formed through the destruction of planetary systems at the end of the AGB evolutionary phase.

The original amounts of dust in these sources can be very high, resulting in higher rates of H$_2$ formation, although R-BPNe show a conspicuous absence of dust thermal emission.

Finally, it must be noted that a number of sources in our sample with low H$_2$/Br$\gamma$ ratio, namely PN G035.4+0.3, PN G038.901.3, PN G054.203.4, Hen 2-428, and M 1-91, have questionable PN nature. In this sense, it must be noted that the morphology of W-BPNe is strikingly similar to that of sources classified as SS, such as M 2-9 (Schruba & Kimeswenger 2001; Rodríguez, Corradi, & Mampaso 2001; Smith & Gehrz 2005; Clyne et al. 2015; Parker, Bojičić, & Frew 2016), and that the scale height distribution of SS is similar to that of bipolar PNe (Boiarchuk 1975; Belczyński et al. 2002; PN G035.4+0.3 and M 1-91 have been classified as SS, whereas the PN nature of PN G038.901.3 has been questioned (Parker, Bojičić, & Frew 2016). Otherwise, the central star of Hen 2-428 has been claimed to harbor a short-period double-degenerate core with combined mass above the Chandrasekhar limit (Santander-García et al. 2015), whereas PN G054.203.4 (the Necklace Nebula) is suspected to have gone through a common envelope phase (Misalski et al. 2013).
6 CONCLUSION

We have obtained deep near-IR observations of a sample of faint bipolar PNe selected from the IPHAS sample to search for H$_2$ emission. Molecular H$_2$ emission is found in most of them, mostly associated with the brightest nebular regions in equatorial rings, but also in bipolar lobes. The present work also strengthens the dichotomy between H$_2$-bright R-BPNe and H$_2$-weak W-BPNe. A sample from the literature has been assembled to further investigate these two sub-classes of bipolar PNe. The excitation of W-BPNe is most likely caused by UV pumping, whereas R-BPNe are mostly excited by shocks. W-BPNe also show continuum emission at their central regions, but this is absent in R-BPNe. W-BPNe are not only intrinsically fainter in H$_2$ than R-BPNe, but they are also smaller and have lower kinematic ages. This suggests that W-BPNe are younger than R-BPNe, but it does not necessarily implies that W-BPNe evolve into R-BPNe. On the other hand, it seems they proceed from the same population of progenitor stars. The nature of many of those H$_2$-weak bipolar PNe has been disputed, with a notable contamination of SS and post-common envelope binary systems.

The H$_2$ emission from bipolar PNe with broad equatorial rings is not associated with a classical PDR, but it rather comes from a discrete distribution of compact knots and filaments. The H$_2$ emission from these features is long-living, as the H$_2$ molecules in them survive long in the nebular evolution. As a result, their H$_2$ luminosity does not vary with the nebular expansion, i.e., with the nebular age.

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