The excitation mechanisms and evolutionary stages of UWISH2 planetary nebula candidates

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ABSTRACT
We present medium-resolution K-band long-slit spectroscopy of 29 true, likely, possible and candidate Galactic Plane planetary nebulae (PNe) from the UWISH2 survey - many of which have only been recently discovered. These objects are bright in molecular hydrogen (H2) emission, and many have bipolar morphologies. Through the detection of the Brγ emission line, which traces ionized hydrogen, we find that the majority of the candidate PNe are indeed likely to be PNe, while 2 of the targets are more likely young stellar objects (YSOs) or pre-planetary nebulae (pPNe). We detect Brγ in 13 objects which have no detection in IPHAS or SHS Hα surveys. This implies they are potential members of the little-known optically-obscured PN population, hidden from wide-field optical surveys. We use the spatial extent of the H2 1-0 S(1) and Brγ lines to estimate the evolutionary stage of our targets, and find that W-BPNe (bipolar PNe with pinched waist morphologies) are likely to be younger objects, while R-BPNe (bipolar PNe with large ring structures) are more evolved. We use line ratios to trace the excitation mechanism of the H2, and find the 1-0 S(1) / 2-1 S(1) and 1-0 S(1) / Brγ ratios are higher for R-BPNe, implying the H2 is thermally excited. However, in W-BPNe, these ratios are lower, and so UV-fluorescence may be contributing to the excitation of H2.

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

1 INTRODUCTION

A planetary nebula (PN, or PNe plural) is an expanding gaseous shell, formed from the material released during periods of heavy mass loss on the asymptotic giant branch (AGB) phase of stellar evolution (Paczyński 1970). It is the penultimate stage of evolution for a low to intermediate mass star (0.8 M⊙ to 8 M⊙). The star responsible for the formation of the PN (central star, or CSPN), will move to the left of the Hertzsprung-Russell diagram as its surface temperature increases, until eventually becoming a white dwarf. UV radiation from the CSPN excites and ionizes the gaseous material, creating strong emission lines in the optical and infrared.

There are currently over 3000 PNe known in the Milky Way (Parker et al. 2016). Many of these were discovered by Hα emission surveys, including the SuperCOSMOS Hα Survey (SHS; Parker et al. 2005) and INT Photometric Hα Survey of the Northern Galactic Plane (IPHAS; Drew et al. 2005). However it is likely that many PNe are yet to be discovered, obscured by dust in the Galactic Plane. It is therefore necessary to switch to infrared observations, which can penetrate the dust and reveal a variety of new objects. Studies such as those of Cohen et al. (2011) and Parker et al. (2012) have shown how certain infrared diagnostics can be used in order to successfully separate PNe from possible imposters.

The near-IR region is ideal for studying molecular hydrogen (H2) in PNe - something known to us since its first detection by Treffers et al. (1976). Many PNe contain large reservoirs of H2 in and outside the photodissociation region (PDR) (Tielens & Hollenbach 1993), and it has also been proposed that H2 emission can originate from the ionized region (Aleman & Gruenwald 2011). However, extended H2 emission can also be detected at large distances from the main nebula site, as shown recently by Fang et al. (2018). H2 is therefore an excellent tracer of the morphology of PNe, and many studies have been conducted to investigate relationships between morphology and H2 emission. For example, there is strong observational evidence that bipolar PNe (BPNe) have brighter H2 emission - known as Gatley’s Rule (Zuckerman & Gatley 1988; Kastner et al. 1994). How-
ever, H2 can also be detected in ellipsoidal or barrel-like PNe (Marquez-Lugo et al. 2013). Bipolar PNe can also be further divided into those showing broad, ring-like features (R-BPNe) and those with narrow waists or compact centres (W-BPNe) (Manchado et al. 1996). Bipolar PNe can be further divided into those showing broad, ring-like features (R-BPNe) and those with narrow waists or compact centres (W-BPNe) (Manchado et al. 1996). The nature of this divide is uncertain - they may form an evolutionary sequence, or originate from different progenitor populations (Guerrero et al. 2000).

The K-band (2 - 2.4 μm) is home to a wide range of ro-vibrational lines of H2, including the ν = 1-0 S(1) (2.1218 μm) and 2-1 S(1) (2.2477 μm) lines. Ratios of these lines can indicate the mechanisms responsible for the excitation of the H2 (Black & Dalgarno 1976). Also in this waveband lie recombination lines of hydrogen and helium. The detection of the Brγ recombination line at 2.1661 μm signifies that the CSPN has begun to photoionize its environment, however this line can also be produced in shocks. Imaging of this line is a powerful tool for studying the evolution of PNe, especially in the transition from proto-planetary nebulae (pPNe) to PNe (Gledhill & Forde 2015). The presence of these emission lines makes the K-band particularly advantageous to study both the molecular and ionized components of PNe.

In this work, we present K-band long-slit spectra of a sample of PNe and candidate PNe taken from the recent UWISH2 imaging survey (UKIRT Widefield Infrared Survey for H2) (Froebrich et al. 2011). We focus on the mechanisms governing the excitation of H2, and how these relate to the evolutionary stages and morphologies of the targets. Along with spectra, we make use of near-IR H2 and optical Hα imaging, and mid-IR colours where available. In Sect. 2, we describe the sample and the available data. Sect. 3 outlines our observations, and methods used to reduce the data. In Sect. 4 we describe the spectra and images of the objects, and discuss the links between morphology, line ratios and evolution in Sect. 5. Finally, we make our conclusions in Sect. 6.

### 2 SAMPLE

UWISH2 was an unbiased Galactic Plane survey, focussed on the H2 1-0 S(1) line at 2.1218 μm. A total of 284 candidate PNe were found to lie in its survey area, including those already known to us, and many new discoveries with no known optical counterparts (Froebrich et al. 2015). Gledhill et al. (2018), hereafter G18, have since updated this number to 291 candidates. Our sample for spectroscopic follow-up consisted of 29 targets, selected mainly due to their bright H2 fluxes. The objects lie at low Galactic latitudes (|b| < 1.5°) and have longitudes in the range (0° < l < 65°). Table 1 lists all the targets observed.

Four of our targets have a PN status of ‘true’, and have been confirmed as PNe through available multi-wavelength data. Two have the status ‘likely’, for objects that are likely to be PNe but do not have completely conclusive morphology/spectroscopy data. One is labelled ‘possible’, indicating a possible PN with currently insufficient data. The remaining 22 targets have the status ‘new candidate’ - these have been classified as candidate PNe by the UWISH2 survey on the basis of morphology and lack of association with known morphological features.
This section contains a detailed description of the observational setup and data reduction techniques used for the K-band spectroscopic study of PNe. The authors discuss the selection of targets, the methods for extracting spectra, and the analysis of emission lines. The data reduction techniques include flat-fielding, image alignment, and stacking, as well as the use of IRAF and Starlink packages. The authors also highlight the detection of He I and H α emission lines in their targets. The results are presented in the context of previous studies, and the implications of their findings are discussed.
The object has a very bright central region, which is likely a combination of H$_2$ and K-band continuum emission ($K_c$). We also find strong Br$\gamma$ emission here, which extends slightly into the lobes where there is a void of H$_2$; more noticeable in the northern lobe (Fig. 1c).

We overlay contours on Fig. 1a to highlight structure in the centre. We find the emission here is not uniform, but instead peaks at a point slightly to the southeast. This encouraged us to attempt narrow band Br$\gamma$ and $K_c$ imaging, to see if it would be possible to further resolve the central region, and to investigate the structure of the ionized and continuum emission both originate from the unresolved central region, and are being scattered by the same spatially extended dusty structure.

Higher vibrational level H$_2$ lines, and recombination lines of helium (including those of He$\,$I and He$\,$II) are seen in the spectra of PN G050.5+00.0 (Figures 1d and 1e). The Pfund series is also visible in the spectrum of the central region, from 2.3 $\mu$m onwards. In the two-dimensional spectrum of PN G050.5+00.0, we find the H$_2$ emission lines are slanted, indicating that the northern lobe is blueshifted, while the southern lobe is redshifted. We suggest two possible scenarios - either the object has curved outflows (where the northern lobe curves towards us, while the southern lobe curves away), or the outflows are accelerating. We show a region of the two-dimensional spectrum, centred on the 1-0 S(1) line, in Fig. 1c, which is essentially a position-velocity diagram. We measure the wavelength shift from the centre to the end of each lobe to be 7.2 $\pm$ 3.6 $\AA$, which gives a line-of-sight velocity of 100 $\pm$ 50 km s$^{-1}$, relative to the systemic velocity. This is a lower limit on the expansion velocity, as any inclination to the line-of-sight will act to raise this value. Mid-IR colours measured by G18 suggest that PN G050.5+00.0 is more likely to be a PN rather than a H$\,$II region.

4.2 PN G059.7-00.8

PN G059.7-00.8 is a ‘possible’ PN, with an optical spectrum and imaging available$^5$. The object has a steady rising continuum in the optical (4000 to 8000 $\AA$), with strong emission lines of [O$\,$III], [N$\,$II] and H$\alpha$. It has an elliptical morphology in H$\alpha$ emission, however its H$_2$ structure is spider-like, with stronger shells of emission to the northeast and southwest (Fig. 2a). In the centre of PN G059.7-00.8, we find a very

$^5$ These can be found on the HASH PN database.
Figure 2. K-band image and spectra for PN G059.7-00.8. a) H$_2$ - K image from UWISH2, showing position and width of slit, and extraction sections. Contours are located at 50 and 150 counts. b) K-band spectrum of central region, with CO bandheads labelled. c) K-band spectrum of the sum of the lobes.

bright source, and investigate to see if it is related to the object. The spectrum of this source, with a bright continuum, is shown in Fig. 2b. The continuum falls at longer wavelengths, and we find multiple CO bandheads in absorption, including the v = 2-0 (2.2935 μm), 3-1 (2.3227 μm), 4-2 (2.3535 μm) and 5-3 (2.3829 μm). These are characteristics common among YSOs (Casali & Eiroa 1996; Reipurth & Aspin 1997) but are also present in main sequence dwarf stars of spectral type K and later. The nebula spectrum at optical wavelengths shows emission lines typical of a PN, plus G18 measure mid-IR colours consistent with a PN. We suspect, therefore, that the bright central source is an unrelated field star projected onto the PN.

4.3 Candidate PNe

22 targets in our sample are candidate PNe selected by the UWISH2 survey, with the remaining 7 targets either true, likely or possible PNe. 7 of the candidates have Hα emission in either IPHAS or SHS images (see Table 1). 13 candidate PNe have the Bry line, but show no signs of Hα emission in optical surveys. These are likely to be members of the optically-obscured PN population. Two of the candidates, PN G004.7-00.8 and PN G020.8+00.4, show no signs of Bry or Hα emission - a lack of H$^+$ suggests these may not be PNe. Both objects have bipolar morphologies, however the former has multiple extended structures, including a large sweeping tail of H$_2$ extending eastward before turning south, while the latter consists of two small blobs of H$_2$ emission. G18 find mid-IR colours which place PN G004.7-00.8 in the YSO region, while the mid-IR colours of PN G020.8+00.4 are not consistent with PNe, YSOs or H$^+$ regions; instead it seems more likely to be a proto-planetary nebula (pPN).

We classified 4 of the candidates as W-BPNe, including PN G009.7-00.9, G024.8+00.4, G036.4+00.1 and G040.4+01.1. These objects have either a compact core or a narrow, pinched waist in H$_2$ emission. All of these have strong Bry and He$^+_1$ (2.0587 μm) lines in their central regions, while the first two have v = 3-2 H$_2$ lines and additional helium lines (He$^+_1$ at 2.1127 μm and He$^+_1$ at 2.1891 μm) in their spectra. None show evidence of Hα emission, implying strong line-of-sight extinction. The cores of PN G009.7-00.9 and G036.4+00.1 can be resolved into two knots of H$_2$, which could be signs of molecular tori being viewed side-on (Kerber & Claeskens 1997). PN G024.8+00.4 has well-separated H$_2$ lobes, with a smaller knot of emission just south of the centre. Its spectrum has a continuum gradually rising with wavelength, which is often a sign of dust. PN G040.4+01.1 also has two separated lobes, with two smaller knots to the northwest and southeast of the centre, which again could be due to a molecular torus.

Most of the remaining candidates we consider to be R-BPNe, which are bipolars with equatorial ring structures, with the exception of PN G025.9-00.5, G037.4-00.1 and G047.5-00.34, whose H$_2$ morphologies are more elliptical. The R-BPNe in our sample have fairly similar spectra which lack the v = 3-2 H$_2$ lines. The He$^+_1$ (2.0587 μm) line is observed in 3 of these objects, and one of the elliptical PNe (PN G037.4-00.1). The most impressive of the R-BPNe is PN G035.7-00.8, which has the largest angular size of the sample. The object has arcs of H$_2$, which are likely to be cavity walls.

PN G047.1+00.4 also has an interesting morphology, which is point-symmetric resembling an eye rotated by 90°. It has a ring of H$_2$ emission, and two curved arms extending in the north and south directions. Spectra and Hα images reveal

6 It is sometimes difficult to see a clear ring feature, however we label any bipolar objects as R-BPNe if their morphology is obviously not of the W-BPN or elliptical type.
an ionized region localised to the centre, where we also observe the HeII (2.1891 μm) line - this is the only R-BPNe in our sample which shows this feature. However, this could be an orientation effect, where we are looking down the major axis of the object, and from another viewing angle, the object could look more like a W-BPNe.

5 DISCUSSION

A simple means of determining the evolutionary stage of a PN is to observe the spatial extent of ionized material, traced by Brγ emission, in relation to the extent of H2 emission. It follows that in pPNe, Brγ emission should be absent, as their central stars are not yet hot enough to ionize the surrounding envelope. When the temperature reaches ≈ 25000 K, ionization produces Brγ emission localised to the central region. As the PN evolves, the ionization front moves outwards, gradually replacing the molecular material. This process can be clearly seen in young PNe (Gledhill & Forde 2015). As not all of our targets are visible at Hα, we can use the two-dimensional spectra to measure the radius of the ionized region along the slit using the Brγ emission, which can then be compared to the radius of H2 1-0 S(1) emission. In Fig. 3, we demonstrate how the ionized and molecular radii are estimated using this technique for two objects, PN G024.8+00.4 (left) and PN G032.6-01.2 (right). The position along the slit is given on the x-axis, and the flux (summed over the slit width) is on the y-axis. The flux of the molecular and ionized hydrogen emission lines along the slit are given by the black and red lines respectively. The point at which the flux reaches the noise level is the maximum extent of the emission line, and therefore the radius, where the shaded areas show the regions where the radii are estimated to lie. For the two objects in Fig. 3, we estimate the ratio of the diameters (or equivalently the radii) of the Brγ and 1-0 S(1) lines to 0.2 ± 0.07 and 0.75 ± 0.18 for PN G024.8+00.4 and PN G032.6-01.2 respectively. We plot the ratio of the ionized to molecular radius on the x-axis of Fig. 4a for the bipolar objects in our sample. Error bars on these values reflect the regions in which the radii are estimated to lie, as the exact point at which the emission reaches the background level when using plots such as Fig. 3 is not always clear. This is certainly the case when the signal to noise ratio is low, or when nearby stars contaminate the two-dimensional spectra. In cases where it was deemed too difficult to estimate a radius using this technique alone, H2 and Hα imaging were also inspected when available.

We separate the objects in Fig. 4a according to their bipolar type, with W-BPNe (compact core or narrow waist) in red and the R-BPNe (broad ring structures) in blue. We classify five of our targets as W-BPNe, including PN G009.7-00.9, G024.8+00.4, G036.4+00.1, G040.4+01.1 and G050.5+00.0. Most of the remaining sample we classify as R-BPNe. Three of the W-BPNe have ionized regions localised to their centres, so they are positioned to the very left of the figure. These values are upper limits, indicated by hollow arrows, as their Brγ extents match the average seeing of the observations, given by the width of stellar continua in the same field of view. Fig. 3a, for PN G024.8+00.4, clearly shows the small angular extent of the Brγ emission when compared to the much more extended 1-0 S(1) emission. PN G050.5+00.0 lies to the right of this group, however we showed in Sec 4.1 that this object’s Brγ emission is likely to be generated in an unresolved central region, and therefore scattered, possibly by a dusty torus, which increases its apparent Brγ extent. If this scattering process were not occurring, PN G050.5+00.0 would move to the left, which we indicate by a solid arrow in Fig. 4a. PN G036.4+00.1 lies to the right of PN G050.5+00.0, however we note the slit was not positioned along the major axis of the nebula, which we believe to run northeast to southwest. Therefore, there were no information as to what extent the ionization front has travelled into the lobes. We believe if the slit were positioned along the major axis, the Brγ to H2 radius would decrease, and so we mark this object with a solid arrow to show it could also move to the left.

Once these considerations are taken into account, Fig. 4a shows a clear divide between the two morphological types, where the W-BPNe have a smaller ratio of Brγ to H2 radius, and so are less evolved, while the R-BPNe have larger Brγ to H2 radii and are therefore more evolved. Fig. 3b compares the extents of the ionized and molecular emission for an R-BPN (PN G032.6-01.2), and it can be seen these are comparable. This idea makes sense, considering that many pPNe, in the stage of evolution immediately before the PN phase, have morphologies closely resembling those of W-BPNe. It is also known that strong emission lines of HeI (2.0587 μm) and Brγ are seen in young PNe (Gledhill & Forde 2015), which is what we observe. On the other hand, the fact that the ionization front in the R-BPNe has moved further from the central region approaching the outer bound of the H2 radius, means that R-BPNe have had more time to form broad, ring-like structures. Ramos-Larios et al. (2017) measure physical sizes, kinematic ages and luminosities of a sample of bipolar PNe, and also find that R-BPNe are more evolved than W-BPNe.

Information about how the H2 is being excited can be found by comparing the fluxes of emission lines. These line ratios have the advantage that the effect of differential extinction on their values is relatively small, due to small wavelength separations between lines. H2 can be excited thermally (e.g. in shocks) or non-thermally (e.g. UV-fluorescence). In the thermal process, H2 molecules are collisionally heated to a few thousand degrees, and radiate near-IR photons as they cool (Burton 1987). In the non-thermal process, a H2 molecule is excited when it absorbs a UV photon, and quickly decays to to a vibrationally-excited level of the electronic ground state. Further decays result in the emission of infrared photons (Black & Dalgarno 1976). A mixture of these processes contribute to the emission lines we observe in our spectra. However, thermal processes populate the H2 levels from the lowest (v = 0) to the highest (v ≥ 2) states, whereas non-thermal processes populate from the top (v ≥ 3) down. Therefore, ratios such as the 1-0 S(1) / 2-1 S(1) and 1-0 S(1) / 3-2 S(3) will have typical values depending on the excitation environment. A purely UV pumped spectrum will have a 1-0 S(1) / 2-1 S(1) ratio equal to 1.8 (Black & Dalgarno 1976, Black & van Dishoeck 1987), while in the thermal case, indicative of shocks, this ratio will be at least 10 (Hollenbach & Shull 1977, Burton et al. 1992). We present key line ratios in Table 2.

On the y-axis of Fig. 4a we plot the 1-0 S(1) / 2-1 S(1) ratio, summed over the object, and again there is good evi-
Figure 3. Slices showing the variation of the flux along the slit for PN G024.8+00.4 (a) and PN G032.6-01.2 (b), where the black and red lines are for the 1-0 S(1) and Brγ hydrogen emission lines respectively. The shaded regions represent the regions where the radii are estimated to lie. The green dotted line represents zero flux.

Figure 4. a) Ionized to molecular radius ratio versus 1-0 S(1) / 2-1 S(1) ratio for bipolar PNe. Error bars for radii are estimated from two-dimensional spectra. We mark solid arrows (not to scale) on two objects as we believe these should move to the left of the diagram, and hollow arrows on objects thought to represent upper limits (see text for details) b) Line ratio plot with data from this work overlaid onto previous results. This includes the individual ratios extracted at different positions along the slit.

Evidence for a dichotomy between the two bipolar types. Using Fig. 4a, the mean 1-0 S(1) / 2-1 S(1) ratios for the W-BPNe and R-BPNe are 7.3 ± 1.0 and 12.6 ± 1.1 respectively. This leads us to believe that on average, thermal excitation is the main mechanism exciting H$_2$ in R-BPNe, while the lower ratios of W-BPNe, and the fact that we only observe ν = 3-2 H$_2$ transitions in these objects, could mean that UV-fluorescence plays a more important role in their excitation. While a mean 1-0 S(1) / 2-1 S(1) ratio of 7.3 is higher than the theoretical value for a purely UV pumped spectrum, a fluoresced dense gas (n ≥ 10$^5$ cm$^{-3}$) subjected to intense UV radiation will have an increased 1-0 S(1) / 2-1 S(1) ratio due to collisional heating (Sternberg & Dalgarno 1989, Hollenbach & Natta 1995). Further observational evidence is provided by Marquez-Lugo et al. (2015), who find UV excitation is likely occurring in the cores of W-BPNe, while R-BPNe are dominated by shock excitation. If R-BPNe are more evolved than W-BPNe, then it follows that UV-fluorescence is a process associated with younger objects, while thermal excitation prevails as the PN evolves; a trend found observationally by Davis et al. (2003). This broadly agrees with the theoretical work of Natta & Hollenbach (1998), however once high resolution integral field spectroscopy is obtained, it is evident that line ratios, and therefore excitation mechanisms, can vary across the surface of young PNe, and highlights the importance of the dependence of line ratios on density (Gledhill & Forde 2015). This is to be explored further in subsequent modelling papers.
Table 2. Key line flux ratios and errors, uncorrected for extinction. The regions of the objects these fluxes have been extracted from are shown in Appendix A1.

| ID       | Region       | 1-0 S(1) / 2-1 S(1) | 1-0 S(1) / 3-2 S(3) | 1-0 S(1) / Brγ | He2 (2.0587 µm) / Brγ |
|----------|--------------|---------------------|---------------------|----------------|----------------------|
| 004.7-00.8 | Centre       | 12 ± 2              | —                   | —              | —                    |
| 009.7-00.9 | Centre       | 7.3 ± 0.6           | 54 ± 19             | 2.4 ± 0.1      | 0.58 ± 0.04          |
|           | Lobes        | 7.2 ± 0.7           | 25 ± 7              | —              | —                    |
| 020.7-00.1 | Centre       | —                   | —                   | 6.4 ± 1.5      | —                    |
|           | Lobes        | 12 ± 2              | —                   | 19 ± 6         | —                    |
| 020.8+00.4 | Centre       | 7.1 ± 1.3           | —                   | —              | —                    |
|           | Lobes        | 6.3 ± 1.0           | —                   | —              | —                    |
| 024.8+00.4 | Centre       | 5.7 ± 2.0           | —                   | 0.50 ± 0.07    | 0.67 ± 0.03          |
|           | Lobes        | 8.6 ± 1.0           | 43 ± 9              | —              | —                    |
| 025.9-00.5 | North lobe   | —                   | —                   | 11 ± 4         | —                    |
| 032.6-01.2 | Centre       | 12 ± 2              | —                   | 2.9 ± 0.2      | 0.50 ± 0.05          |
|           | Lobes        | 14 ± 2              | —                   | 7.5 ± 0.8      | —                    |
| 034.8+01.3 | Centre       | —                   | —                   | 3.4 ± 0.4      | 0.25 ± 0.08          |
|           | Lobes        | 11 ± 2              | —                   | 11 ± 1         | 0.48 ± 0.14          |
| 035.7-01.2 | Centre       | —                   | —                   | 6.4 ± 1.3      | —                    |
|           | Lobes        | 12 ± 2              | —                   | 9.1 ± 1.1      | —                    |
| 036.4+00.1 | Centre       | 7.0 ± 1.5           | —                   | 1.6 ± 0.1      | 0.34 ± 0.06          |
|           | South lobe   | 8.4 ± 1.7           | —                   | 2.2 ± 0.2      | 0.31 ± 0.04          |
| 037.4-00.1 | Centre       | 6.3 ± 1.7           | —                   | 0.44 ± 0.07    | 0.28 ± 0.07          |
|           | Lobes        | 9.3 ± 1.7           | —                   | 3.7 ± 0.4      | 0.28 ± 0.0          |
| 040.4+01.1 | Centre       | 7.4 ± 2.5           | —                   | 1.4 ± 0.1      | 0.50 ± 0.10          |
|           | Lobes        | 7.8 ± 0.7           | —                   | —              | —                    |
| 040.5-00.7 | All          | —                   | —                   | 9.8 ± 3.7      | —                    |
| 042.1+00.4 | All          | —                   | —                   | 12 ± 2         | —                    |
| 047.1+00.4 | Centre       | —                   | —                   | 0.59 ± 0.03    | 0.46 ± 0.06          |
|           | Lobes        | —                   | —                   | 9.2 ± 2.6      | —                    |
| 047.5-00.3 | All          | —                   | —                   | 5.5 ± 0.7      | —                    |
| 048.2-00.4 | All          | —                   | —                   | 12 ± 3         | —                    |
| 050.0-00.7 | Centre       | —                   | —                   | 6.0 ± 1.5      | —                    |
|           | Lobes        | —                   | —                   | —              | —                    |
| 050.5+00.0 | Centre       | 4.5 ± 0.4           | —                   | 0.05 ± 0.01    | 0.49 ± 0.01          |
|           | Lobes        | 5.8 ± 0.4           | 16 ± 3              | 2.0 ± 0.1      | 0.43 ± 0.04          |
| 057.9-00.7 | Centre       | 14 ± 4              | —                   | 6.4 ± 0.7      | —                    |
|           | Lobes        | 13 ± 1              | —                   | 2.3 ± 7        | —                    |
| 058.1-00.8 | Centre       | —                   | —                   | 7.9 ± 3.2      | —                    |
|           | Lobes        | 14 ± 4              | —                   | 10 ± 3         | —                    |
| 059.7-00.8 | Lobes        | 13 ± 2              | —                   | 8.5 ± 1.0      | —                    |
| 060.5-00.3 | Centre       | 12 ± 2              | —                   | 4.6 ± 0.3      | —                    |
|           | Lobes        | 14 ± 5              | —                   | 12 ± 3         | —                    |
| 061.8+00.8 | Centre       | —                   | —                   | 7.0 ± 1.2      | —                    |
|           | Lobes        | 13 ± 2              | —                   | 11 ± 3         | —                    |
| 062.1+00.1 | North lobe   | —                   | —                   | —              | —                    |
| 062.2+01.1 | Centre       | —                   | —                   | —              | —                    |
|           | Lobes        | —                   | —                   | —              | —                    |
| 062.7+00.0 | Centre       | 12 ± 3              | —                   | 2.7 ± 0.3      | —                    |
|           | North lobe   | —                   | —                   | 6.3 ± 1.0      | —                    |
| 064.1+00.7 | Centre       | 9.3 ± 1.8           | —                   | 9.1 ± 1.6      | —                    |
|           | Lobes        | 13.3 ± 3.7          | —                   | 20 ± 5         | —                    |
| 064.9+00.7 | Lobes        | —                   | —                   | —              | —                    |

There are also indications that the 1-0 S(1) / Bry ratio is linked with the evolutionary stage, for example Guerrero et al. (2000) find this ratio is low for young PNe, while more evolved objects have larger ratios. This is supported by G18, who find that for a small sample of 23 PNe covering a range in physical radii of 0.03 to 0.6 pc, the average H$_2$ surface brightness is approximately independent of size, and therefore age. Combining this with the fact that the average H$_2$ and therefore Bry, surface brightness decreases with size (Frew et al. 2016), it follows that the average H$_2$ 1-0 S(1) / Bry surface brightness ratio increases with size and age. The trend between the 1-0 S(1) / Bry and 1-0 S(1) / 2-1 S(1) ratios has been investigated in Marquez-Lugo et al. (2015). We have taken fig. 7 from this work, included our data, and reproduced the graph here as Fig. 4b. Additional data comes from Hora et al. (1999), Lumsden et al. (2001), Garcia-Hernández et al. (2002), Davis et al. (2003), Likkel et al. (2006) and Marquez-Lugo et al. (2015). This plot shows a loose positive correlation between the 1-0 S(1) / 2-1 S(1) and 1-0 S(1) / Bry ratios, and our data is no exception to this trend. Again, we separate our targets into W-BPNe and R-BPNe, and there is a clear separation between the two bipolar types, where W-BPNe have lower 1-0 S(1) / Bry ratios than the R-BPNe (mean values of 1.5±0.8 and 10.6±6.0).
have been used to constrain the mechanisms dominating the excitation of H$_2$. Most of our targets that we believe to be PNe are either R-BPNe (large ring structures) or W-BPNe (pinched waist), while the remaining 3 are considered to be elliptical. In agreement with previous studies, we find the former are predominantly thermally excited, while in the latter, UV fluorescence may have more influence. The link between line ratios and the spatial extent of ionized emission could mean that W-BPNe are younger objects, while the R-BPNe are more evolved, and an evolutionary scheme in which one class evolves into the other is worth further investigation. While long-slit spectroscopy is a useful tool for measuring line ratios with the advantage of spatial information in one dimension, more detailed spatial information can be achieved using integral field spectroscopy (IFS). This would allow excitation mechanisms to be inferred over the entire target, while comparing to the two-dimensional structure of the ionized region.

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Figure A1. $\text{H}_2$ - K images taken from the UWISH2 survey, for targets PN G004.7-00.8 to G047.5-00.3, in order of increasing Galactic longitude. We overlay the LIRIS slit size and position, and the sections used for extraction - these are denoted ‘C’ for the centre, ‘L’ for a lobe and ‘A’ for all the target. The horizontal bar in the bottom left corner is a scale bar representing 5 arcsec. In all figures, north is up, east is left.
Figure A1. (cont.) H$_2$ - K images for PN G048.2-00.4 to G064.9+00.7, excluding PN G050.5+00.0 and G059.7-00.8.
Figure B1. K-band spectra for targets PN G004.7-00.8 to G032.6-01.2, in order of increasing Galactic longitude. This includes spectra extracted from different regions of the same target, which are given in the title. We label any emission lines present.
Figure B1. (cont.) Spectra for PN G034.8+01.3 to G042.1+00.4.
Figure B1. (cont.) Spectra for PN G047.1+00.4 to G060.5-00.3, excluding PN G050.5+00.0 and G059.7-00.8.
Figure B1. (cont.) Spectra for PN G061.8+00.8 to G064.9+00.7.
| ID          | Region       | He   | 3-2(S3) | 4-3(S0) | 5-4(S1) | 6-5(S2) | 7-6(S3) |
|------------|--------------|------|---------|---------|---------|---------|---------|
| 000-7-00-9 | Centre       | 8.9  | 1.1     | 0.8     | 0.5     | 0.4     | 0.3     |
| 000-7-00-9 | Lobes        | 7.8  | 1.1     | 0.8     | 0.5     | 0.4     | 0.3     |
| 023-7-00-1 | Centre       | 8.9  | 1.1     | 0.8     | 0.5     | 0.4     | 0.3     |
| 023-7-00-1 | Lobes        | 7.8  | 1.1     | 0.8     | 0.5     | 0.4     | 0.3     |
| 029-8+00-4 | Centre       | 8.9  | 1.1     | 0.8     | 0.5     | 0.4     | 0.3     |
| 029-8+00-4 | Lobes        | 7.8  | 1.1     | 0.8     | 0.5     | 0.4     | 0.3     |
| 033-9+00-5 | Centre       | 8.9  | 1.1     | 0.8     | 0.5     | 0.4     | 0.3     |
| 033-9+00-5 | Lobes        | 7.8  | 1.1     | 0.8     | 0.5     | 0.4     | 0.3     |
| 039-0+01-3 | Centre       | 8.9  | 1.1     | 0.8     | 0.5     | 0.4     | 0.3     |
| 039-0+01-3 | Lobes        | 7.8  | 1.1     | 0.8     | 0.5     | 0.4     | 0.3     |
| 039-0+01-3 | Centre       | 8.9  | 1.1     | 0.8     | 0.5     | 0.4     | 0.3     |
| 039-0+01-3 | Lobes        | 7.8  | 1.1     | 0.8     | 0.5     | 0.4     | 0.3     |
| 039-0+01-3 | Centre       | 8.9  | 1.1     | 0.8     | 0.5     | 0.4     | 0.3     |
| 039-0+01-3 | Lobes        | 7.8  | 1.1     | 0.8     | 0.5     | 0.4     | 0.3     |
| 039-0+01-3 | Centre       | 8.9  | 1.1     | 0.8     | 0.5     | 0.4     | 0.3     |
| 039-0+01-3 | Lobes        | 7.8  | 1.1     | 0.8     | 0.5     | 0.4     | 0.3     |
| 039-0+01-3 | Centre       | 8.9  | 1.1     | 0.8     | 0.5     | 0.4     | 0.3     |

**Note:** These values are not corrected for extinction.

**Table C1:** Continuum-subtracted line fluxes and errors (×10⁻³ W m⁻²) for K-band emission lines. Best wavelengths of the emission lines are given in µm.
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