H₂ emission in the low-ionization structures of the Planetary Nebulae NGC 7009 and NGC 6543

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ABSTRACT

Despite the many studies in the last decades, the low-ionization structures (LISs) of planetary nebulae (PNe) still hold several mysteries. Recent imaging surveys have demonstrated that LISs are composed of molecular gas. Here, we report H₂ emission in the LISs of NGC 7009 and NGC 6543 by means of very deep narrow-band H₂ images taken with NIRI@Gemini. The surface brightness of the H₂ 1-0 S(1) line is estimated to be (0.46–2.9)×10⁻⁴ erg s⁻¹ cm⁻² sr⁻¹ in NGC 7009 and (0.29–0.48)×10⁻⁴ erg s⁻¹ cm⁻² sr⁻¹ in NGC 6543, with signal-to-noise ratios of 10-42 and 3-4, respectively. These findings provide further confirmation of hidden H₂ gas in LISs. The emission is discussed in terms of the recent proposed diagnostic diagram \( R(\text{H}_2) = \text{H}_2\ 1-0\ S(1)/\text{H}_2\ 2-1\ S(1) \) versus \( R(\text{Br}_γ) = \text{H}_2\ 1-0\ S(1)/\text{Br}_γ \), which was suggested to trace the mechanism responsible for the H₂ excitation. Comparing our observations to shock and ultraviolet (UV) molecular excitation models, as well as a number of observations compiled from the literature showed that we cannot conclude for either UV or shocks as the mechanism behind the molecular emission.

Key words: ISM: molecules; (ISM:) photodissociation region (PDR); planetary nebulae: individual: NGC 7009, NGC 6543; Infrared: general

1 INTRODUCTION

Thirty two years have passed since the report of the ‘low-ionization inclusions’ in planetary nebulae (PNe) by Balick (1987). After that pioneering work, several studies have been carried out, using high-quality imagery and spectroscopy, with the aim to unveil the true nature of these microstructures, explore the physical properties that make them differ from the surrounding nebular medium, in terms of the emission line fluxes, and give insights into their formation mechanism (e.g. Balick et al. 1993, 1994, 1998; Hajian et al. 1997).

Since then, several PNe have been found to host these microstructures (e.g. Corradi et al. 1996) and different labels have been given based on their properties: fast low-ionization emission regions (FLIERs, Balick et al. 1993), slow moving low ionization emitting regions (SLOWERs, Perinotto 2000) or bipolar, rotating, episodic jets (BRETs, Lopez et al. 1993, 1995). We will hereafter refer to all of them as low-ionization structures or LISs (see Gonçalves et al. 2001).

Gonçalves et al. (2001) reviewed the kinematic and morphological characteristics of LISs and discussed possible links with various formation models. The authors came to the conclusion that there is no direct connection between LISs and the morphology of PNe, since they appear in all types (round, elliptical, bipolar, or point-symmetric). Various formation models of knots and/or jets are able to explain some of their observable characteristics but not all of them. So far, there is not a general model that can provide an adequate explanation for all the microstructures.

Shock interactions have been proposed as a possible mechanism to explain the enhancement in low-ionization lines like [O I], [N I], [S I], [O II], and [N II] (e.g. Hartigan et al. 1994; Dopita 1997). Running a series of numerical simulations for a high-density knot moving outwards in a less dense medium, Raga et al. (2008) demonstrated that the spectral characteristics of shock-excited or photoionized regions can both be reproduced by changing the local photoionization rate. Low photoionization rate models gener-
ate spectroscopic characteristics similar to shock-excited regions. A crucial parameter to distinguish the mechanisms is the distance between the LISs and the source of ionizing photons, which determines the photoionization rate at the position of the structures (Aleman et al. 2011; Akras & Gonzáles 2016).

Based on Raga’s simulations and spectroscopic data from a sample of PNe with LISs, Gonzáles et al. (2009) argued that the spectra of high-velocity knots can be explained by shocks. A few years later, Akras, Gonzáles and Ramos-Larios (2015) showed that the enhancement of low-ionization lines in knots relative to the surrounding medium is the result of a combination of the ultraviolet (UV) radiation from the central star and shock interactions. However, it is not easy to distinguish the contribution from each mechanism. On the other hand, there are studies which attribute the enhancement of low-ionization lines in some LISs only to the UV stellar radiation of the central star (e.g. Hajian et al. 1997; Gonzáles 2004; Ali & Dopita 2017). Despite all this effort so far, LISs are still poorly understood.

One of the most intriguing characteristic of LISs is the electronic density (determined from the common diagnostic line ratios), which is systematically lower than or at most equal to the electronic density of the surrounding nebular gas (e.g. Balick et al. 1993; Hajian et al. 1997; Gonzáles et al. 2003, 2009; Monteiro et al. 2013; Akras & Gonzáles 2016; Ali & Dopita 2017). This finding contradicts the formation models of knots in which they are considered more dense than the surrounding nebular gas (e.g. Steffen et al. 2001; Raga et al. 2008). Gonzáles et al. (2009) proposed the scenario that LISs are also made of molecular gas and dust, similarly to the cometary knots of Helix (e.g. Huggins et al. 2002; Meixner et al. 2005; Matsuura et al. 2007, 2009).

Matsuura et al. (2007, 2008) shown that the intensities of the ro-vibrational H$_3$ lines from the cometary knots of Helix can be explained either by a low-velocity shock of 27 km s$^{-1}$ or a strong UV stellar radiation field. Interestingly, the latter requires a more luminous central star than the observations indicate i.e. higher local ionization parameter. More detailed simulations by Aleman et al. (2011) have, however, shown that shocks are not needed to explain the observed H$_3$ surface brightness.

Besides, the cometary of Helix, H$_2$ emission has also been detected in the cometary knots of the Ring nebula (Speck et al. 2003) and the Dumbbell nebula (Baldrudge 2017).

None the less, H$_2$ emission had not been detected in LISs despite various surveys (e.g. Latter et al. 1995; Kas-

| Filter | $\Delta \lambda$ (µm) | $\Delta \lambda$ (µm) | Timea (s) | Number of frames | Timea (s) | Number of frames |
|--------|-------------------|-------------------|-----------|----------------|-----------|----------------|
| K-cont-1 | 2.0975 | 0.0275 | 100 | 7 | 90 | 7 |
| H$_2$ 1-0 S(1) | 2.1239 | 0.0261 | 100 | 6 | 90 | 7 |
| Brackett y | 2.1686 | 0.0295 | 45 | 5 | 45 | 5 |
| H$_2$ 2-1 S(1) | 2.2465 | 0.0301 | 173 | 17 | 163 | 16 |
| K-cont-2 | 2.2718 | 0.0332 | 173 | 16 | 163 | 14 |

$^a$ Integration time of each individual frame.

The main reason for that was the limited spatial resolution and sensitivity of these observations. More sensitive and deeper observations over the last five years have already provided strong evidence as well as the first direct confirmations of H$_2$ emission associated with LISs in PNe. First, Fang et al. (2015) detected H$_2$ emission from the northwestern knot of Hu 1-2. Couple of years later, Akras, Gonzáles and Ramos-Larios (2017) succeed to detect the H$_2$ emission from the LISs in two PNe, K 4-47 and NGC 7662, using very deep narrow-band imagery from the 8 m Gemini North telescope. Fang et al. (2018) reported the detection of H$_2$ emission from two distant pairs of knots in Hb 12, from a number of randomly distributed knots in the haloes of NGC 6543 and NGC 7009 as well as from the pair of LISs in the ionized region of NGC 7009. Regarding Hb 12, it should be mentioned that despite the H$_2$ from its distant clumps, strong H$_2$ 1-0 S(1) emission has also been detected in the centre of the nebula (Dinerstein et al. 1988; Ramsay et al. 1993; Luhman & Rieke 1996), and its origin is pure UV-fluorescence. It should also be noted that H$_2$ emission detected in the equatorial regions of some bipolar PNe has been unveiled to be fragmented into clumps and filaments (Marquez-Lugo et al. 2013; Manchado et al. 2015).

In this paper, we present new deep H$_2$ narrow-band NIRI@Gemini images for two of the most well-studied PNe, NGC 7009 and NGC 6543. The paper is organized as follows: observations are described in Section 2. In Sections 3 and 4, we present the results of H$_2$ detection in NGC 7009 and NGC 6543. The mechanisms responsible for the excitation of molecular hydrogen in these structures is discussed in Section 5, and we finish with our conclusions in Section 6.

2 OBSERVATIONS

The observations of NGC 7009 and NGC 6543 were acquired in service mode on 2017 May 10 and June 24 (Program ID: GN-2017A-Q-58, PI: S. Akras) using the Near InfraRed Imager and Spectrometer on the Gemini-North Telescope at Mauna Kea in Hawaii.

The narrow-band filters G0216, G0218 and G0220 were used to isolate the H$_2$ 1-0 S(1), H$_2$ 2-1 S(1) and Bry lines centred at 2.1239, 2.2465 and 2.1686 µm, respectively, as well as the filters G0217 and G0219 centred at 2.0975 and 2.2718 µm to obtain the continuum emission. Due to the targets’ sizes, the f/6 configuration was adopted providing a field of view of 120 arcsec$^2$ and pixel size of 0.117 arcsec.
Several individual frames, with different exposure times per filter, were obtained in order to increase the signal-to-noise (S/N) ratio. The observing log is summarized in Table 1. Darks and GCAL flat frames were also obtained for flux calibration of the data.

All first frames from each sequence were removed from the reduction/analysis as recommended by Gemini. Before start the reduction process, the PYTHON routines CLEARIR.py and NIRLIN.py\(^1\) were applied to all the frames for the correction of the vertical stricking and the non-linearity of the detector. The reduction of the data was then performed with the GEMINI IRAF\(^2\) package for NIRI. The routines Nprepare, Nisky, Niflat, Nirreduce and finally Imcoadd were used for each imaging set accordingly.

The estimated surface brightness sensitivity of the H\(_2\) 1-0 S(1), H\(_2\) 2-1 S(1) and Bry images are 2.8\(\times\)10\(^{-16}\), 1.3\(\times\)10\(^{-16}\), and 1.9\(\times\)10\(^{-15}\) erg s\(^{-1}\) cm\(^{-2}\) sr\(^{-1}\) respectively for NGC 7009. For NGC 6543, the corresponding sensitivities are 3.1\(\times\)10\(^{-16}\), 2.4\(\times\)10\(^{-16}\) and 2.3\(\times\)10\(^{-15}\) erg s\(^{-1}\) cm\(^{-2}\) sr\(^{-1}\), respectively.

\(^{1}\)CLEARIR.py and NIRLIN.py PYTHON routines were developed and are distributed by Gemini for a preparatory reduction of the data obtained with NIRI and GNIRS, https://www.gemini.edu/sciops/instruments/niri/

\(^{2}\) IRAF 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 H\(_2\) IN NGC 7009

In spite of NGC 7009 being one of the most well-studied PN, only a year ago H\(_2\) emission was reported at the tips of the two jet or jet-like LISs in the ionized region of this nebula (Fang et al. 2018). However, these detections were not supported by a continuum-subtracted image or any H\(_2\) 1-0 S(1) flux measurement, but only by the spatial offset between the H\(_2\) and Bry emission-lines. Therefore, more observations were needed to confirm the results.

Before the undoubted detection of H\(_2\) gas in the LISs of NGC 7009, Phillips et al. (2010) had carried out a detailed analysis of this PN using Infrared Array Camera (IRAC) images (i.e. [3.6], [4.5], [5.8] and [8] \(\mu\)m) and the available spectra in the ISO and Spitzer archives. From the three-colours RGB IRAC image of NGC 7009 (see fig. 1 in Phillips et al. 2010), both LISs (outflow+knots) are displayed with green emission was reported at the tips of the two jet or jet-like LISs in the ionized region of this nebula. However, these detections were not supported by a continuum-subtracted image or any H\(_2\) 1-0 S(1) flux measurement, but only by the spatial offset between the H\(_2\) and Bry emission-lines. Therefore, more observations were needed to confirm the results.

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Table 2. Emission-line fluxes for NGC 7009 and NGC 6543, in units of 10\(^{-15}\) erg s\(^{-1}\) cm\(^{-2}\). R(H\(_2\)) = H\(_2\) 1-0 S(1)/1-2 S(1) and R(Bry) = H\(_2\) 1-0 S(1)/Bry. Numbers in parenthesis correspond to the S/Ns. Lower rows give the surface brightness in units of 10\(^{-4}\) erg s\(^{-1}\) cm\(^{-2}\) sr\(^{-1}\).

| Name     | R.A.    | Dec.     | H\(_2\) 1-0 S(1) | H\(_2\) 2-1 S(1) | Bry     | R(H\(_2\)) | R(Bry) | Box (arcsec\(^2\)) |
|----------|---------|----------|-----------------|-----------------|---------|------------|--------|-------------------|
| NGC 7009: |         |          |                 |                 |         |            |        |                   |
| LIS-E1   | 21:04:12.486 | -11:21:41.903 | 3.71 (42)       | 0.38 (19)       | 2.61 (17) | 9.76       | 1.42   | 5.083 \(\times\) 9.931 |
| LIS-E2   | 21:04:12.743 | -11:21:36.836 | 1.06 (10)       | 0.13 (5)        | 2.05 (9)  | 8.15       | 0.52   | 0.932 \(\times\) 1.049 |
| LIS-W1   | 21:04:09.029 | -11:21:52.942 | 11.4 (14)       | 3.26 (8)        | 28.2 (11) | 3.50       | 0.40   | 3.965 \(\times\) 2.564 |
| LIS-W1   | 21:04:09.029 | -11:21:53.175 | 8.13 (15)       | 2.39 (10)       | 16.7 (12) | 3.40       | 0.49   | 2.682 \(\times\) 2.214 |
| LIS-W1   | 21:04:09.009 | -11:21:52.933 | 7.36 (15)       | 1.98 (7)        | 13.6 (11) | 3.72       | 0.54   | 3.382 \(\times\) 1.515 |
| NGC 6543: |         |          |                 |                 |         |            |        |                   |
| LIS-SW   | 17:58:32.103 | +66:37:47.725 | 2.99 (3)        | <0.9\(^a\)       | 44.8 (7)  | >3.32\(^b\) | 0.07   | 2.020 \(\times\) 1.858 |
| LIS-SE   | 17:58:32.053 | +66:37:47.404 | 6.03 (3)        | <2.08\(^a\)      | 86.3 (7)  | >2.89\(^b\) | 0.07   | 3.150 \(\times\) 2.760 |
| LIS-SW   | 17:58:32.155 | +66:37:46.968 | 1.26 (3)        | <0.44\(^a\)      | 8.56 (6)  | >2.86\(^b\) | 0.15   | 0.747 \(\times\) 2.468 |
| LIS-NE   | 17:58:33.800 | +66:38:11.717 | 1.97 (4)        | <0.42\(^a\)      | 35.1 (7)  | >4.69\(^b\) | 0.06   | 1.725 \(\times\) 1.002 |

\(^{a}\)These numbers correspond to the 3\(\sigma\) upper limits. \(^{b}\)These numbers correspond to the 3\(\sigma\) lower limits.
Our more sensitive and high spatial resolution narrowband images of NGC 7009 have detected the ro-vibrational H$_2$ 1-0 S(1) and 2-1 S(1) emission-lines from three substructures, confirming the results from Fang et al. (2018). They are designated E1, E2, and W1 in Figures 1–3. The main body of NGC 7009 is characterized by an ellipsoidal nebula, known as Saturn nebula, with a pair of highly collimated outflows and knots. Both knots are bright in low-ionization lines such as [N\textsc{ii}], [O\textsc{ii}], [S\textsc{ii}], and [O\textsc{i}] (Gonçalves et al. 2003, 2006; Walsh et al. 2018). The E1 and W1 LISs correspond to the K1 and K4 knots in Gonçalves et al. (2003, 2006). There is also a marginal detection of H$_2$ emission from the main nebula but only spectroscopic follow-up observations can confirm whether it is real or remnant from the continuum subtraction process. It is interesting, though, that this emission follows the morphology of the outer edge of the ellipsoidal nebula.

The emission line fluxes of the three LISs are listed in Table 2. The H$_2$ 1-0 S(1) line flux varies from 1.06 to 11.4×10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2} with an S/N higher than 10, while the H$_2$ 2-1 S(1) line flux varies between 0.129 and 3.26×10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2} with an S/N higher than 5. The R(H$_2$) = H$_2$ 1-0 S(1)/H$_2$ 2-1 S(1) line ratio is found to be significantly different between the eastern and western LISs. In particular, the E1 and E2 LISs have R(H$_2$) equal to 9.81 and 8.22, respectively, which are approximately three times higher than the value of W1 LIS. Because of the irregular morphology of W1 LIS, we present three estimates of the fluxes obtained from different aperture sizes, and all of them result in very similar R(H$_2$) ratio, from 3.40 to 3.72.

The R(H$_2$) ratio does not show significant differences among the LISs (see Table 1), and it is comparable with the values derived for the LISs in NGC 7662 (Akras et al. 2017).

A comparison between the H$_2$ 1-0 S(1) and H$_2$ 2-1 S(1) lines with the [N\textsc{ii}] Hubble Space Telescope (HST) image at 6584 Å shows a very good match (Figures 1 and 3), with the former being engulfed by the [N\textsc{ii}] emission. Figure 2 displays the distribution of the Bry line and its comparison...
with the bright $H_2$ 1-0 S(1) line. The spatial displacement between the $Br_\gamma$ and $H_2$ emissions reported by Fang et al. (2018) is also observed in our data.

Gonçalves et al. (2003, 2006) identified two more LISs, labelled K2 and K3, which lie closer to the central star, but no $H_2$ emission is detected in these two LISs. The detection of $H_2$ emission in four more knots distributed in the halo of NGC 7009, at distances higher than 1 arcmin from the central star, has also been reported (Fang et al. 2018).

4 $H_2$ IN NGC 6543

NGC 6543, the second PN observed with NIRI at the Gemini-North (Program ID:GN-2017A-Q-58), is characterized by a bipolar structure with a pair of condensations and jets bright in low ionization lines (Balick et al. 1994; Balick 2004; Balick & Hajian 2004).

Similar to NGC 7009, halo features in NGC 6543 also appear with green colour in the three-colours RGB IRAC images (fig. 1 and 9 in Hora et al. 2004; Fang et al. 2018). As we have already pointed out, the strong emission from the [4.5] band is attributed to molecular lines that fall within this band (Hora et al. 1999; De Buizer & Vacca 2010). Only last year, Fang and coworkers reported the detection of $H_2$ emission from the knotty and filamentary halo that surrounds NGC 6543 (Fang et al. 2018).

In contrast to Fang et al.’s (2018) work, the focus of this work is on the bright ionized bipolar nebula of NGC 6543, also known as the Cat’s Eye Nebula, and not on its recombination halo. The narrow-band $H_2$ 1-0 S(1) NIRI image of NGC 6543 is presented in Figure 4. The image is smoothed using a Gaussian function with a radius of 2 $\sigma$ so as we can better illustrate the detection of the emission in the SW and NE LISs. These LISs correspond to the F-F’ condensations between the caps and the jets in Miranda & Solf (1992). The $H_2$ 1-0 S(1) line fluxes are estimated between 1.26 and 2.99x10^{-15} erg s^{-1} cm^{-2} with S/N ratio of 3-4 (see also Table 2). Three flux measurements derived from different aperture sizes are given for the SW LIS. The detection of $H_2$ emission from both LISs of NGC 6543 is reported for the first time. A marginal detection of $H_2$ emission at the edges of the bipolar lobes, labelled as “caps” in Balick et al. (1994) and D-D’ in Miranda & Solf (1992) can also be seen in Figure 4, but deep follow-up spectroscopic observations are necessary to confirm this emission. The $H_2$ 2-1 S(1) line at 2.24 $\mu$m is not detected in NGC 6543, but we obtained upper limits for its emission, which yields lower limits for the $R(H_2)$ ratio between 2.9 and 4.7 (Table 2).

Both LISs in NGC 6543 are detected in the $Br_\gamma$ line (Figure 5) with fluxes between 8.56 and 86.3x10^{-15} erg s^{-1} cm^{-2} and S/N ratio of 6-7 (see Table 2). Their $R(Bry)$ ratios have been estimated between 0.06 and 0.15, close to the values calculated for some LISs in NGC 7662 (Akras et al. 2017). From Figure 5, it can also be seen that a diffuse
emission from the nebula itself surrounds the LISs and it may contribute to the Br\textsuperscript{\textgamma} fluxes. This additional emission may be responsible for the very low $R(\text{Br}\gamma)$ ratios found in the LISs.

A comparison of our H\textsubscript{2} 1-0 S(1) image with the HST [N\textsc{ii}] $\lambda$6584 image show a strong correlation (Figure 4). Similarly to NGC 7009, H\textsubscript{2} emission is engulfed by the more extended [N\textsc{ii}] emission. Comparison of the spatial distribution in H\textsubscript{2} and Br\textsuperscript{\textgamma} emission-lines illustrates an offset between the two emissions as in NGC 7009.

5 MOLECULAR HYDROGEN EXCITATION

The mechanisms to populate the H\textsubscript{2} (v,J) = (1,3) and (2,3) rovibrational levels, whose decay yield the emission in the 1-0 S(1) and 2-1 S(1) line, respectively, may be dominated by UV pumping or collisions with gas particles, depending on the local physical conditions (see Aleman & Gruenwald 2011, and references therein). For these levels, direct radiative excitation and de-excitation are forbidden via dipole transitions, but allowed by electric quadrupole. The latter has low probability of occurrence, but is the decay mechanism that produces the lines we observe. Formation pumping is also possible, but it is not an important mechanism for those levels in PNe conditions.

Early works on H\textsubscript{2} excitation in PNe (e.g. Beckwith et al. 1980) suggested the $R(\text{H}_2)$ ratio as a diagnostic for the molecular excitation mechanism. $R(\text{H}_2)$~2 would indicate that H\textsubscript{2} is excited by UV radiation, while $R(\text{H}_2)$>4 would point out to H\textsubscript{2} gas excited by collisions with gas particles in shock regions. This inference was based on the sets of models available for UV excitation (e.g. Black & Dalgarno 1976; Black 1978; Shull 1978), and for shocks (Kwan et al. 1977; Shull & Hollenbach 1978). Sternberg & Dalgarno (1989) showed, however, that the real picture was not that simple. In certain conditions, such as high-density gas irradiated by UV, collisional excitation can dominate the level excitation and give $R(\text{H}_2)$ ratios that resemble those of a thermalized shock-heated gas.

Marquez-Lugo et al. (2015) proposed as diagnostic for UV- and shock-excited H\textsubscript{2} gas in PNe a plot between the $R(\text{H}_2)$ and $R(\text{Br}\gamma)$ line ratios. Yet, these two line ratios are not enough to argue for the excitation mechanism of molecular hydrogen. For a better diagnostic analysis, it is necessary to study the H\textsubscript{2} level population of more levels, having in mind that all the mechanisms may compete in importance and that the dominant mechanism may vary for different levels and in different physical conditions (Aleman & Gruenwald 2011). Excitation diagrams are helpful tools to determine the excitation mechanism of H\textsubscript{2} (e.g., Hora et al. 1999; Lumsden et al. 2001). However, for narrow-band imaging studies like ours, it is not feasible to measure several lines and construct such diagrams. As we can derive the $R(\text{H}_2)$ and $R(\text{Br}\gamma)$ ratios from our observations, we construct
the diagnostic diagram as suggested by Marquez-Lugo et al. (2015) to make a preliminary assessment of which excitation mechanism dominates the H\(_2\) level population in LISs. Follow-up spectroscopy studies will be necessary in order to construct more conclusive diagnostic diagrams.

Our \(R(\text{H}_2)\) vs. \(R(\text{Br}\gamma)\) diagnostic diagram is shown in Figure 6. In the top panel, we show pre-PNe (orange circles), PNe (blue circles), and candidates PNe (gray circles) gathered from the literature (Geballe et al. 1991; Aspin et al. 1993; Vicini et al. 1999; Hora et al. 1999; Lumsden et al. 2001; García-Hernández et al. 2002; Davis et al. 2003; Kelly & Hrivnak 2005; Likkel et al. 2006; Ramos-Larios et al. 2008; Gledhill & Forde 2015; Marquez-Lugo et al. 2015; Jones et al. 2018). Model predictions of the \(R(\text{H}_2)\) ratio obtained from UV irradiated cloud models (photodissociation regions; Sternberg & Dalgarno 1989; Burton et al. 1990) and shock models (Smith 1995; Novikov & Smith 2018) are indicated as red and green vertical stripes, respectively.

From a quick observation of the diagnostic diagram, it can be seen that there is a trend between \(R(\text{H}_2)\) and \(R(\text{Br}\gamma)\) line ratios, both increasing from the lower right to the upper left corner. This behaviour was attributed to the transition from UV-dominated regions (left-hand side) to shock-dominated regions (right-hand side) (Marquez-Lugo et al. 2015). But, according to the shocks and UV-irradiated cloud models, both mechanisms can provide a reasonable explanation for the observable range of \(R(\text{H}_2)\) values (~2-45).

Note that all but three pre-PNe exhibit \(R(\text{Br}\gamma)>1\), while PNe cover the whole range of \(R(\text{Br}\gamma)\) line ratio from 0.01 up to 100. On the other hand, both PN and pre-PNe shows the same range of \(R(\text{H}_2)\) from ~2 up to ~20 (Figure 6). The high \(R(\text{H}_2)\) found in pre-PNe (or some PNe) indicates that the emission is thermalized, while for those with low \(R(\text{H}_2)\) the H\(_2\) emission is non-thermal. These findings are consistent with the conclusions of Davis et al. (2003) that shocks may play an important role in the molecular gas excitation of pre-PNe and PNe (see also Akras et al. 2017; Akras & Gonçalves 2016). However, it is not possible to trace and disentangle the contribution of each excitation mechanism (UV fluorescence or shocks), with this diagnostic diagram.

Two more sets of models, one for PNe (Aleman & Gruenwald 2011) and one for the Helix nebula cometary knots (Aleman et al. 2011) are also presented. Both sets correspond to self-consistent photoionization plus photodissociation region models, with the former corresponding to uniform density PNe, while the latter models were specifically developed to simulate one cometary knot (dense clump) subject to different conditions inside the Helix nebula. It is worth mentioning that for the three cometary knot models with \(R(\text{Br}\gamma)>2\), the distance from the central source varies and the model with the largest distance predicts highest ra-
Figure 5. The same as Figure 4. Brγ line image (panel a), H2 1-0 S(1) continuum-subtracted image smoothed using a Gaussian function with a radius of 2σ (panel b), and H2 1-0 S(1) continuum-subtracted images of SW and NE LISs overlaid by Brγ emission contours (panels c and d).

The importance of the distance between the dense knot and the central ionization source becomes clear from these models, as discussed in Aleman & Gruenwald (2011), Akras & Gonçalves (2016) and Akras et al. (2017).

The R(H2) and R(Bry) ratios of the LISs in NGC 7009 and NGC 6543 obtained in this work as well as those from NGC 7662 and K 4-47 published in Akras et al. (2017) are shown in the bottom panel of Figure 6. A few other measurements obtained for PNe knots are also added in the plot. Studies of the H2 emission from the PN Hb 12 (green diamonds; Dinerstein et al. 1988, Ramsay et al. 1993, Luhman & Rieke 1996) are also included in order to show the R(H2) and R(Bry) ratios for a molecular gas excited by UV stellar radiation. The R(H2) ratio of the K1 cometary knot in Helix determined by Matsuura et al. (2007) is indicated with a cyan diamond. Bry emission is not detected in this knot and a lower limit is provided for the R(Bry), assuming an upper limit intensity that of the marginally detected H2 2-1 S(2) line at 2.154 μm (see Table 2 in Matsuura et al. 2007). The H2 excitation diagram of the K1 Helix’s knot indicate a thermal origin for its H2 emission and the dominant mechanism for the excitation of molecular hydrogen is UV-fluorescence pumping, rather than shocks (O’Dell et al. 2000; Matsuura et al. 2007; Aleman et al. 2011; Andriantsaralaza et al. 2020). We also included measurements made for a diffuse region and a knot in Dumbbell by Baldridge (2017). The comparable rotational and vibrational excitation temperatures inferred from a few lines indicates a thermal origin for the H2 emission in Dumbbell nebula.

For NGC 7009, the R(H2) ratios of LISs are determined ~3.5 for the western LIS and around 9 for the eastern LISs. This difference in the R(H2) ratio between the western and eastern LISs is attributed to the potential variation in the incident radiation field at their positions and/or in their column densities (Sternberg & Dalgarno 1989; Burton et al. 1990; Aleman et al. 2011).

The high R(H2) ratios of the eastern LISs (between 8 and 10) indicate a thermal origin and the excitation mechanism can be either shock collisions or thermalized UV-pumping in a warm and high density (>10⁵ cm⁻³) H2 gas (e.g. Sternberg & Dalgarno 1989; Burton et al. 1990). As discussed above, for such values, it is not possible to disentangle the two mechanisms only from the R(H2) ratio. The values of R(H2) for the eastern LISs are comparable with those measured for two cometary knots in Helix and Dumbbell, and those in K 4-47 (Figure 6). In K 4-47, its H2 emission is attributed to a thermalized shock-heated gas because of the high expansion velocities of the LISs (>100 km s⁻¹; Corradi et al. 2000) and high R(H2) ratio (Akras et al. 2017). Although, thermal emission from pumped-H₂ molecules in warm and dense gas cannot be rule out. The western LIS exhibits R(H₂)~3, which is indicative of UV radiation deter-
mining the H$_2$ level population. This ratio is comparable to the values found for Hb 12.

A further comparison between the observed H$_2$ 1-0 S(1) and 2-1 S(1) emission-lines intensities and the theoretical predictions from photodissociation region (PDR) models (see Table 5 in Burton et al. 1990) shows a very good agreement for high-density models. Models with densities of $10^5$ and $10^6$ cm$^{-3}$ provide surface brightness close to our observed values for the W1 and E1 LISs, respectively. The gas density difference indicates that the collisional deexcitation of pumped-H$_2$ is more efficient in E1 than in W1, resulting...
in more populated lower vibrational states and thus higher $R(H_2)$ ratio.

Recall that long-slit low-resolution spectroscopy of NGC 7009 has shown that E1 and W1 LISs are also characterized by significantly different optical line ratios (Gonçalves et al. 2003, 2006). Based on 3D photoionization modelling, Gonçalves et al. (2006) demonstrated that two models with different optical depths between the LISs and the central star (or in other words altering the intensity of the ionizing field of the central star at the distance of each LIS) are needed in order to reproduce their emission line fluxes. There is no clear reason why the optical depth or the photoionization rate between the eastern and western LISs should be different, given that both are located at approximately the same projected distance from the central star. Hence, the density of the gas in the LISs is more likely responsible for the divergences found in the line ratios.

For the pair of LISs (NE and SW) in NGC 6543, we determine $R(Bry)$ and lower limits for $R(H_2)$. With the current data available, we cannot trace the excitation mechanism of the molecular gas in NGC 6543’s LISs and spectroscopic follow-up observations are needed. UV-fluorescence emission (Black & van Dishoeck 1987; Sternberg & Dalgarno 1989; Burton et al. 1990) as well as thermal $H_2$ emission from shock-heated gas (Hollenbach & McKee 1989; Burton et al. 1992; Smith 1995; Novikov & Smith 2018) can explain the values obtained for the LISs in this nebula (Figure 6).

Besides the detection of $H_2$ emission in the LISs of NGC 6543, Fang et al. (2018) also reported the detection of $H_2$ emission from several clumpy structures in the halo of the PN. Because of the strong optical [S$\text{ii}$] and [N$\text{ii}$] emission-lines detected in these structures, it was claimed that $H_2$ gas was shock-excited. However, strong [S$\text{ii}$] and [N$\text{ii}$] lines are not necessarily indicative of a shock-heated gas in PNe Akras et al. (2020).

6 CONCLUSIONS

We presented new very deep narrow-band $H_2$ 1-0 S(1) and $H_2$ 2-1 S(1) images of NGC 7009, and $H_2$ 1-0 S(1) image of NGC 6543. $H_2$ emission was detected from the low-ionization structures in both PNe. The surface brightness of the $H_2$ 1-0 line was estimated between 0.46 and $2.9 \times 10^{-4}$ erg s$^{-1}$ cm$^{-2}$ sr$^{-1}$ for the LISs in NGC 7009 and between 0.29 and $0.48 \times 10^{-4}$ erg s$^{-1}$ cm$^{-2}$ sr$^{-1}$ for the LISs in NGC 6543, with S/N ratios between 10 and 42, and between 3 and 4, respectively. This findings increased the number of LISs with $H_2$ from four to six, further supporting the scenario that LISs are dense microstructures embedded in PNe, partially consisting of molecular gas.

Scrutinizing the $R(H_2)$ and $R(Bry)$ diagnostic diagram, we concluded that the positive trend does not indicate a smooth transition from UV-fluorescence-dominated regions to shock-dominated regions. Based on the theoretical predictions from shock and UV-irradiated cloud models, both mechanisms are able to produce either low or high ratios. Therefore, both mechanisms are important in PNe and they contribute to the molecular hydrogen excitation. However, it is not feasible to trace the mechanism from this diagnostic diagram.

Regarding the NGC 7009, the high $R(H_2)$ ratios ($\sim 8$-10) derived from the eastern LISs were attributed either to a warm and dense gas with thermally populated states or to a thermalized shock-heated gas, whilst the low $R(H_2)$ and $R(Bry)$ line ratios determined for the western LIS imply a non-thermal UV-fluorescence $H_2$ emission from a low-density gas.

On the other hand, the no detection of $H_2$ 2-1 emission from the LISs of NGC 6543 and the lower limit values obtained for $R(H_2)$ ratio did not allow us to trace the origin of its emission. Radiative UV-fluorescence emission is more likely responsible for the excitation of $H_2$ gas, but shocks cannot be ruled out.

Overall, these new detections further confirmed the presence of molecular gas in high density, LISs in PNe. Although, a systematic $H_2$ imaging and spectroscopic survey of PNe with LISs is required in order to understand how the molecular hydrogen was formed or how it survived from the intense UV radiation and what is its dominant excitation mechanism.

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