Proof of shock-excited $H_2$ in low-ionization structure of PNe

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Abstract. We report the detection of near-IR $H_2$ line emission from the low-ionization structures (LISs) in planetary nebulae. The deepest, high-angular resolution $H_2$ 1-0 S(1) at 2.122 $\mu$m, and $H_2$ 2-1 S(1) at 2.248 $\mu$m images of K 4-47 and NGC 7662, obtained using NIRI@Gemini-North, are presented here. K 4-47 reveals a remarkable high-collimated bipolar structure, with the $H_2$ emission emanating from the walls of the outflows and a pair of knots at the tips of these outflows. The $H_2$ 1-0 S(1)/2-1 S(1) line ratio is $\sim$7-8 which indicates shock interaction due to both the lateral expansion of the gas and the high-velocity knots. The strongest line, $H_2$ v=1-0 S(1), is also detected in several LISs located at the periphery of the outer shell of the elliptical PN NGC 7662, whereas only four knots are detected in the $H_2$ v=2-1 S(1) line. These knots have $H_2$ v=1-0 S(1)/v=2-1 S(1) values between 3 and 5. These data confirm the presence of molecular gas in both highly (K 4-47) and slowly moving LISs (NGC 7662). The $H_2$ emission in K 4-47 is powered by shocks, whereas in NGC 7662 is due to photo-ionization by the central star. Moreover, a likely correlation is found between the $H_2$ v=1-0 S(1)/$H_2$ v=2-1 S(1) and $[N\text{ II}]/H\alpha$ line ratios.

1. Introduction
Optical imaging surveys of planetary nebulae (PNe) have revealed that a fraction of PNe possess, besides the large scale structure such as rims, shells, haloes, some small-scale structures (e.g. [1], [2], [3]). These structures are prominent in the low-ionization emission lines such as $[N\text{ II}], [S\text{ II}]$ and $[O\text{ I}]$ (hereafter LISs). They exhibit a variety of morphologies like knots, jets, and filaments, ([3]), whereas they cover a wide range of expansion velocities from 30 km s$^{-1}$ up to 350 km s$^{-1}$. Akras & Gonçalves ([4]), studying a sample of Galactic PNe with LISs, demonstrate that the excitation mechanism of these structures is a combination of UV-photons and shocks. The contribution of each mechanism depends on parameters like the distance of LISs to the central star, the stellar parameters ($T_{\text{eff}}, L_\odot$) and LIS’s expansion velocity.

The physical properties like $T_e$, $N_e$ and chemical abundances of LISs have been studied by different groups (e.g. [4], [5], [6]), and some of the most important conclusions are: i) there is no difference in $T_e$ between the LISs and the nebular components, ii) LISs have systematically lower $N_e$ compared to the surrounding medium (e.g.[4], [5]) and iii) there is no difference in chemical abundances that could provide an explanation for the enhancement of the low-ionization emission lines.
The formations models of LISs predict that they are denser structures than the surrounding ionized medium. This result is found to be inconsistent with the observations. A possible explanation for this discrepancy may be that the formation models refer to the total density of gas (dust, atomic and molecular) and not only to the \( N_e \). Gonçalves et al. ([6]) have proposed that LISs may also be made of molecular gas. \( \text{H}_2 \) emission has previously been detected from the cometary knots in the Helix PN ([7], [8]) and knots/filaments in NGC 2346 ([9]).

Generally, \( \text{H}_2 \) emission has been detected in several PNe (e.g. [10]). A comparison of \( \text{H}_2 \) and optical line (e.g. [\( \text{N} \ II \)] and [\( \text{O} \ I \)]) images has revealed similar morphologies, suggesting that both emissions emanate from the same regions. A recent theoretical work by Aleman & Gruenwald ([11]) has shown that the peak intensities of the optical low-ionization and \( \text{H}_2 \) lines occur in a narrow transition zone between the ionized and neutral (photo-dissociation) regions. Moreover, an empirical relation between the fluxes of the [\( \text{O} \ I \)] \( \lambda 6300 \) and \( \text{H}_2 \ v=1-0 \ S(1) \) lines for Galactic PNe was reported by Reay et al. ([12]). Hence, the detection of strong low-ionization lines in LISs may also suggest the presence of \( \text{H}_2 \) gas.

2. Observations

The deepest, high-angular resolution \( \text{H}_2 \ v=1-0 \ S(1) \) at 2.122 \( \mu \)m and \( \text{H}_2 \ v=2-1 \ S(1) \) at 2.242 \( \mu \)m images were obtained for K 4-47 and NGC 7662 using the NIRI instrument on the Gemini-North 8 m telescope on Mauna Kea in Hawaii. For these observations, the f/6 configuration (pixel scale=0.117 arcsec and field of view of 120 arcsec) were used. The exposure times were estimated using the empirical relation from Reay et al. ([12]). The final continuum-subtracted images are presented in Figures 1 and 2.

![Figure 1. Line images of the bipolar planetary nebula K 4-47.](image)

(a) Continuum subtracted \( \text{H}_2 \ v=1-0 \ S(1) \), (b) \( \text{H}_2 \ v=2-1 \ S(1) \) emission lines.

3. Discussion

3.1. The highly collimated bipolar nebula K 4-47

The narrow-band near-IR \( \text{H}_2 \) images of K 4-47 (Fig. 1) reveal a remarkable high-collimated bipolar structure with the emission arising from the walls of the bipolar outflows. At the tips of these outflows lies a pair of highly moving, low-ionization knots (100 km s\(^{-1}\); [13]).

These knots exhibit very strong [\( \text{N} \ II \)] \( \lambda 5200 \) and [\( \text{O} \ I \)] \( \lambda 6300 \) emission lines that usually are attributed to high-velocity shocks. Gonçalves et al. ([14]), running a number of shock models, came to the conclusion that the expansion velocity of these knots must be up to 250–300 km s\(^{-1}\). Despite their very high velocities, their \( \text{H}_2 \ v=1-0 \ S(1)/\text{H}_2 \ v=2-1 \ S(1) \) line ratio is found to be 7.3, lower than the typical value of 10 for shock-excited regions ([15]).

Regarding the bipolar outflows, a comparison between our near-IR and optical images from [13] illustrates that the ionized gas (optical emission) is concentrated in a inner highly collimated structure, surrounded by the \( \text{H}_2 \) outflows. This structure of K 4-47 completely resembles that of the M 2-9 and CRL 618 PNe indicating a possible connection among these objects. The large
\( \text{H}_2 \) \( v=1-0 \) S(1)/\( \text{H}_2 \) \( v=2-1 \) S(1) line ratio, estimated in the bipolar shell, was quite unexpected. Although, the recent hydrodynamic models by Balick B. and collaborators ([16]) can adequately explain our findings. The \( \text{H}_2 \) emission from the bipolar outflows can be explained as the result of the interactions between a jet or bullet with the AGB material. As the jet/bullet moves through the AGB material forms an conical structure that expands laterally outward with a velocity that increases with the distance from the central star. At the same time, the jet/bullet continues moving outwards, with a velocity proportional to the distance from the central star, dissociating the AGB \( \text{H}_2 \) gas, which then is ionized by UV-photons (optical images). The surface brightnesses in the \( \text{H}_2 \) \( v=1-0 \) S(1) and \( \text{H}_2 \) \( v=2-1 \) S(1) emission lines are found to range from 0.2 to 1\( \times \)10\(^{-15} \) erg cm\(^{-1} \) s\(^{-1} \) arc\(^{-2} \) and from 0.2 to 1 \( \times \)10\(^{-16} \) erg cm\(^{-1} \) s\(^{-1} \) arc\(^{-2} \), respectively.

**Figure 2.** Continuum subtracted \( \text{H}_2 \) \( v=1-0 \) S(1) line image of the elliptical planetary nebula NGC 7662. The arrows indicate the four LISs in which the \( \text{H}_2 \) \( v=2-1 \) S(1) emission is detected.

### 3.2. The elliptical nebula NGC 7662

NGC 7662 is an elliptical PN that posses almost two dozens of LISs (knots and a jet-like structure) embedded in the outer shell with expansion velocities that vary from 30 to 70 km s\(^{-1} \) (see [17]). All these structures are easily discerned in the [N ii] line image ([18]), whereas spectroscopic data have revealed that they also exhibit a strong [O i] \( \lambda \)6300 line ([17],[6]). Despite that the former line is a strong indicator of shock interactions, most of the LISs have low velocities except from the southern jet-like feature. (see [17]).

Here, we present the deepest near-IR images of this nebula. The \( \text{H}_2 \) \( v=1-0 \) S(1) emission line is detected in almost all optically identified LISs (Fig. 2, right panel.), whereas only four LISs are found to have \( \text{H}_2 \) \( v=2-1 \) S(1) emission. The former line is found to range from 1 to 4.8 \( \times \)10\(^{-16} \) erg cm\(^{-1} \) s\(^{-1} \) arc\(^{-2} \), whereas the latter from 0.6 to 1 \( \times \)10\(^{-16} \) erg cm\(^{-1} \) s\(^{-1} \) arc\(^{-2} \). No \( \text{H}_2 \) emission is found associated with the nebular shells. This confirmed that LISs are molecular condensations embedded in a high excitation nebula. The value of \( \text{H}_2 \) \( v=1-0 \) S(1)/\( \text{H}_2 \) \( v=2-1 \) S(1) line ratio is found to range between 3 and 5. These values implies that the LISs in this nebula are predominantly photo-ionized. Nevertheless, shocks cannot be discarded.

### 4. Conclusion

New, deep, high-angular resolution near-IR \( \text{H}_2 \) images confirmed the presence of molecular gas in highly (K 4-47) and slowly moving LISs (NGC 7662). \( \text{H}_2 \) emission was also detected at the dense walls of the bipolar outflows of K 4-47 which implies a lateral expansion in agreement with the predictions from hydrodynamic models. Important morphological similarities among K 4-47, M 2-9 and CRL 618 have been found.
In the NGC 7662 nebula, H$_2$ emission was detected in several LISs while it is totally absent in the nebular shells. Using the new diagnostic diagram from Akras & Gonçalves ([4]), and the spectroscopic data of the six LISs with measured H$_2$ v=1-0 S(1)/H$_2$ v=2-1 S(1) line ratio, we found that the near-IR line ratio increases with the [N II]/H$\alpha$ optical line ratio (Fig. 3). This result may reflect a similar origin for the near-IR and optical line ratios. In conclusion, the H$_2$ emission in K 4-47 is powered by shocks, whereas in NGC 7662 is due to photo-ionization by the central star with a possible contribution of shocks.

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