First proof of shock-excited $\mathrm{H}_2$ in low-ionization structure of PNe

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What do we know about the low-ionization structures?

I. They are bright in the \([\text{N II}], [\text{O II}], [\text{S II}], [\text{O I}]\) emission lines. Moreover, they are found in variety of morphological types: knots, jets, filaments, etc. either in pairs or isolated (e.g. Gonçalves et al. 2001)

II. \(T_e\) and chemical abundances are the same in the main nebular components (rims, shells, halos) and LISs (Balick et al. 1993, Gonçalves et al. 2003, 2009, Akras & Gonçalves 2016)

III. A large range of expansion velocities from a few tens of km/s up to a few hundreds of km/s → shock interaction has to been taken into account
   - FLIERs (Fast Low Ionization emission regions; Balick et al. 1993)
   - BRETS (Bipolar rotating episodic jets; Lopez et al. 1995)
   - SLOWERs (Slow moving Low Ionization Emitting Regions; Perinotto 2000)

IV. LISs are the result of photo-ionization and shock-excitation mechanisms depending on the stellar \(T_{\text{eff}}\) and \(L/\odot\) and LISs’ parameters \(V_{\text{exp}}, \text{Ne}, \text{distance to the CS}\) (Akras & Gonçalves 2016)

V. \(\text{Ne}\) is usually lower in the LISs compared to the main nebular components (Balick et al. 1993, Gonçalves et al. 2003, 2009, Akras & Gonçalves 2016)

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Molecular Hydrogen emission

I. Deep, high angular resolution $\text{H}_2$ images of K 4-47 and NGC 7662 were obtained with the 8-m Gemini-North telescope on September 6 and October 13, 2014

- $\text{H}_2 \nu=1-0 \ S(1)$ at 2.122 $\mu$m (90s x 9 frames / 115s x 9 frames)
- $\text{H}_2 \nu=2-1 \ S(1)$ at 2.248 $\mu$m (155s x 21 frames / 190s x 14 frames)

II. The $\text{H}_2 \nu=1-0/\nu=2-1$ ratio is an indicator of the excitation mechanism (Black & van Dishoeck 1987, Burton 1992)

- $\sim2 \rightarrow$ photo-ionized regions
- $\sim10 \rightarrow$ shocked-excited regions

III. $\text{H}_2$ emission was recently detected in cometary knots and clumps at the equatorial region of the bipolar PN NGC 2346 (Manchado et al. 2015)
K 4-47

(Corradi et al. 2000)
- H$_2$ emission shows a bipolar structure that is not seen in the optical emission lines → is K 4-47 a very young PN?
- First detection of H$_2$ emission from high velocity LISs ($V_{\text{knots}}$~100-300 km/s, Corradi et al. 2000; Goncalves et al. 2004)
- The H$_2$ v=1-0/ v=2-1 ratio is around 7-8 → shock excitation mechanism
Several small scale LISs are identified in H$_2$ v=1-0 S(1) line (2.12 μm).

The H$_2$ v=1-0/v=2-1 ratio is between 3 and 5 → photo-ionized & shock excited regions.

F$_{H2}$ (v=1-0): $1-4.8\times10^{-16}$ erg/cm$^2$/s/arc$^2$, F$_{H2}$ (v=2-1):$0.6-1\times10^{-16}$ erg/cm$^2$/s/arc$^2$

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(Gonçalves et al. 2004 & K4-47, LISs)

NGC 7662, LISs

NGC 7662, shells, rims

H2 v=1-0/v=2-1~7

NE SLOWER

~4

~5

S FLIER b

~3

~3

(Akras & Gonçalves 2016)
Conclusion

- The new Log($f_{\text{shock}}/f_{\text{star}}$) vs I(N[II], [O I], etc) diagnostic diagrams provide a useful tool to disentangle the photo-ionized and shock-excited regions.
- The excitation mechanisms in LISs is a combination of shock and UV excitation mechanisms.
- H$_2$ emission is detected for the first time in LISs of two Galactic PNe (K4-47 and NGC 7662).
- LISs are also made of H$_2$ gas.
- The H$_2$ v=1-0/v=2-1 ratio increases with the intensity of low-ionization lines.
- The H$_2$ v=1-0/v=2-1 ratio in K 4-47 indicates shock excitation.
- The H$_2$ v=1-0/v=2-1 ratio in NGC 7662 indicates shock and UV excitation.

Thank you
NGC 6572

(Miranda et al. 1999)

(Akras & Gonçalves 2016)
Electron temperature

(Gonçalves et al. 2009)
Chemical abundances

(Akras & Gonçalves 2016)
Shock-excited vs. photo-ionized regions

Raga et al. (2008)

- $a \rightarrow b \rightarrow c$, the distance from the central source decreases from $3 \rightarrow 1 \rightarrow 0.3 \ (10^{18} \text{ cm})$
- $a \rightarrow A$, the $T_{\text{eff}}$ increases ($50000 \text{K} \rightarrow 70000 \text{K}$); Raga et al. (2008)
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(Akras & Gonçalves 2016)
Log\((f_{\text{shock}}/f_{\text{star}})\) vs \(I(\lambda)\)

\(\Rightarrow f_{\text{star}}\)
- \(T_{\text{eff}}\) and \(L_{\odot}\)
- Distance of the PN
- Knot's distance from the central star

\(\Rightarrow f_{\text{shock}}\)
- Expansion velocity
- Density

\(f_{\text{shock}} = 2.28 \times 10^{-3} (V_{s}/100 \text{ km s}^{-1})^3 \times (n/cm^{-3})\)

(Dopita & Sutherland 1996)
Formation mechanisms

- GISW model with an equatorial enhancement (e.g. torus/disk)
  → a close binary system in a common-envelope phase (Soker & Livio 1994)
  → magnetic fields (Garcia-Segura et al. 1999, Blackman et al. 2000)
- Interaction with the ISM (Soker & Zucker 1997, Cliff et al. 1995)
- Dynamical and radiation instabilities during the evolution of PNe (Garcia-Segura et al. 1999)
- Stagnation models (Steffen & Lopez 2000)
- Fossil AGB condensations
Excitation mechanisms?

I. Absorptions of UV photons emitted from the central star (photo-ionized or fluorescence regions)

II. Shock interactions

III. A combination of both
Low-ionization lines and $\text{H}_2$ emission

- $\text{H}_2$ molecule coexists with $\text{N}^+$, $\text{S}^+$ and $\text{O}^0$

- $\text{H}_2$ flux increases with $T_{\text{eff}}$

- A linear relation between the $\text{H}_2$ and $[\text{O I}]$ fluxes in PNe has been reported (Reay et al. 1988)

(Aleman et al. 2011)