Wolf-Rayet Stars
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Planetary nebulae and Their Central Stars in X-rays

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Two types of X-ray sources are mostly found in planetary nebulae (PNe): point sources at their central stars and diffuse emission inside hot bubbles. Here we describe these two types of sources based on the most recent observations obtained in the framework of the *Chandra* Planetary Nebula Survey, ChanPlaNS, an X-ray survey targeting a volume-limited sample of PNe. Diffuse X-ray emission is found preferentially in young PNe with sharp, closed inner shells. Point sources of X-ray emission at the central stars reveal magnetically active binary companions and shock-in stellar winds.

1 High-Energy Processes in PNe

Planetary nebulae (PNe) are the result of the evolution of low- and intermediate-mass stars, i.e., those with initial masses in the range $1-8\,M_{\odot}$. These stars evolve through the asymptotic giant branch (AGB) phase losing mass through a slow (10–30 km s^{-1}) and dense wind that clears the interstellar medium. Once the star evolves off towards the post-AGB phase, it develops a fast wind ($v_{\infty} \simeq 500$–4000 km s^{-1}; e.g., Guerrero & De Marco 2013) that interacts with the previously ejected AGB material. This wind-wind interaction results in a double-shock pattern: a forward shock sweeps up the AGB material, producing a sharp shell, whereas a backward shock thermalizes and heats the fast wind, creating an adiabatically shocked "hot bubble" with temperatures 10^7–10^8 K. At the same time, the newly exposed stellar core (CSPNe) begins to ionize the swept-up AGB material, creating a PN (Kwok et al. 1978; Balick 1987).

The physical processes that lower the temperature of the gas within the hot bubble take place at its outer interface with the cold (10^4 K) nebular shell. Instabilities formed in the wind-wind interaction zone break up the swept-up shell into dense clumps and filaments that locally absorb heat inside the outer edge of the hot bubble and inject cold material into it (Stute & Sahai 2006; Toalá & Arthur 2014). Thermal conduction can boost these effects, additionally reducing the temperature of the shocked stellar wind and favoring the evaporation of cold nebular material into the hot bubble (e.g., Soker 1994; Steffen et al. 2008; Toalá & Arthur 2014,2015).

The central stars of PNe (CSPNe) are also expected to be sources of X-ray emission. Hot CSPNe with effective temperature in excess of 100,000 K exhibit photospheric emission in the soft X-ray domain (e.g., NGC 6853, Hoare et al. 1995). Otherwise, the coronal emission from an unresolved late-type companion star can produce (harder) X-ray emission (e.g., the G5 III companion of the CSPN of LoTr 5, Montez et al. 2010). Finally, the variability in the stellar wind of the CSPNe can also produce shocks, resulting in shock-in winds as is the case of massive OB and Wolf-Rayet stars (Lucy & White 1980; Gayley & Owocki 1995).

Fig. 1: *Chandra* X-ray (blue) and *HST* optical Hα (red) and [N II] (green) composite-color picture of NGC 6543. This PN shows diffuse X-ray emission inside the innermost nebular shell and a point-source of X-ray emission at its CSPN (Chu et al. 2001; Guerrero et al. 2001).

2 X-ray Observations of PNe

Early *Einstein*, *EXOSAT*, and *ROSAT* observations of PNe resulted in many cases in misidentifications of the emitting source and ambiguous interpretation of the emission mechanism. These problems were emphasized in 2001 by a comprehensive analysis of the entire *ROSAT* archive of pointed observations of over 60 PNe (Guerrero et al. 2000). The few detections of diffuse X-ray emission indicated that this emission is not universal among PNe or that their X-ray luminosities had to be much lower than predicted.

Far better more sensitive, *Chandra* and *XMM-Newton* observations have revealed the presence of diffuse X-ray emission within PNe (Figure 1), lending strong support to the interacting stellar winds model of PN formation (e.g., Kastner et al. 2000; Guerrero et al. 2002). *Chandra* has been particularly successful in the detection of point-sources at CSPNe (Guerrero et al. 2001; Ruiz et al. 2013).

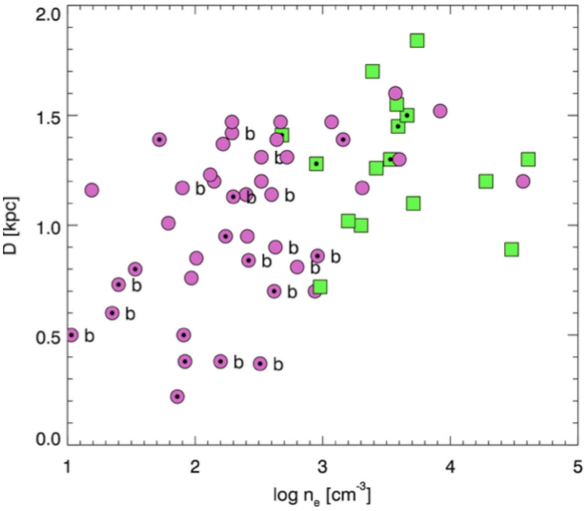

Fig. 2: Distribution with distance and density of the ChanPlaNS detections (green) and non-detections (purple) of diffuse X-ray emission among PNe. A point inside the symbol indicates that the CSPN also emits in X-rays. The "b" letter indicates the bipolar morphology of the PN. Adapted from Freeman et al. (2014).

Building over multiple programs for X-ray observation of individual sources, the PN community has joined efforts into the *Chandra* Planetary Nebulae Survey (ChanPlaNS) aiming at the X-ray study of a volume-limited sample of PNe within 1.5 kpc of the Sun. So far, ChanPlaNS has been awarded with a Cycle 12 Program and a Cycle 14 Large Project to observe 45 PNe with total observing times $\simeq$1 Msec. Including archival *Chandra* observations, the present sample of ChanPlaNS PNe amounts up to 60 sources. ChanPlaNS has provided important insight into the X-ray emission from PNe (Kastner et al. 2012; Freeman et al. 2014) and their CSPNe (Montez et al. 2015).

2.1 Hot Bubbles in PNe

Diffuse X-ray emission has now been detected in almost 20 PNe (Freeman et al. 2014). This emission is preferentially found in PNe with sharp, closed inner shells and is rarely associated with bipolar PNe (Gruendl et al. 2006). Diffuse X-rays are mostly associated with compact ($\lesssim$0.15 pc in radius) and high nebular electron densities ($\gtrsim$2500 cm^{-3}, see Figure 2). This suggests that the detection of diffuse X-ray emission is limited to relatively young ($\lesssim$5,000 yrs) PNe (Ruiz et al. 2013; Freeman et al. 2014). The X-ray-emitting gas has temperatures (1–3)$\times 10^6$ K (Ruiz et al. 2013, and references therein), well below the expectations from adiabatic shocks.

2.2 Point-Sources at CSPNe

ChanPlaNS has also detected point-sources at the CSPNe of $\sim$20 PNe (Montez et al. 2015). Some of these detections correspond to the soft photospheric emission from hot CSPNe, but in most cases they display relatively hard, $\gtrsim$0.5 keV X-ray emission. The plasma properties and energetic budget allow us to identify at least two different types of X-ray sources among CSPNe.

The X-ray luminosity of CSPNe (Figure 3) reveals a group of CSPNe that follows the typical X-ray to bolometric luminosity relationship of massive stars, $L_X/L_{bol} \simeq 10^{-7}$. The X-ray emission in massive stars is caused by shocks inside their unstable radiatively-driven stellar winds, the so-called shock-in winds. A similar physical scenario may cause the "hard" X-ray emission in CSPNe, as their stellar winds are also known to exhibit variability (Prinja et al. 2007; Guerrero & De Marco 2013).

The other group of CSPNe show X-ray luminosities above the $L_X/L_{bol} \simeq 10^{-7}$ relationship. In these cases, there is either evidence of binarity or the properties of the X-ray emission, indicating plasmas at higher temperatures, are similar to those from active companion stars (Montez et al. 2015). In those cases, the X-ray emission is enhanced up to the critical limit $L_X/L_{bol} \simeq 10^{-3}$, suggesting that during the binary evolution the CSPN transferred angular momentum to the companion to spin up its rotation rate and increase its coronal activity.

2.3 Other Sources of X-rays in PNe

Besides the diffuse X-ray emission from hot bubbles and point-source emission from CSPN, there are two other sources of X-ray emission in PNe. Born-again PNe, with their rejuvenated fast stellar winds blowing away highly processed material, have revealed to be sources of soft diffuse X-ray emission. Complex wind-interaction processes and even charge-exchange reactions can be responsible for this emission (Guerrero et al. 2012; Toalá et al. 2015).

X-ray emission can be caused by strong shocks associated to fast collimated outflows, as those seen, e.g., in IC 4634 (Guerrero et al. 2008). So far, however, only the fast, 1000 km s^{-1} collimated outflow of Hen 3-1475 has been detected by its X-ray emission (Sahai et al. 2003).

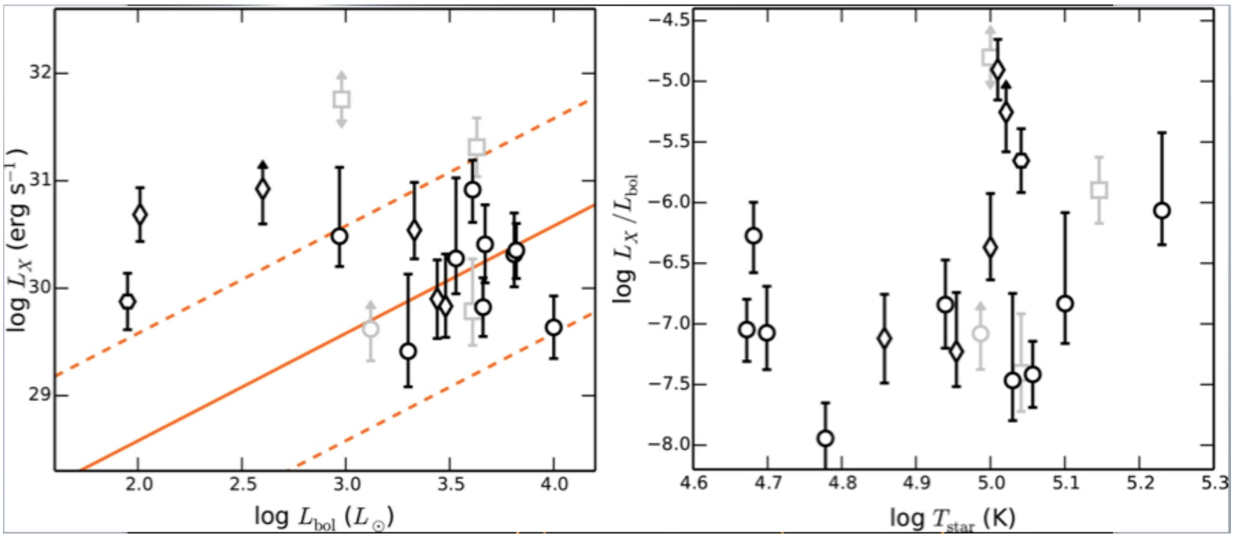

Fig. 3: X-ray luminosity of the CSPNe in the ChanPlaNS sample plotted with respect to the star bolometric luminosity (left) and effective temperature (right).

3 Future X-ray Observations of PNe

Most of our knowledge about the hot gas content of PNe comes from low-dispersion CCD spectroscopy. To date, high-dispersion X-ray spectroscopy has only been obtained for two PNe, BD+30°3639 (Yu et al. 2009) and NGC 6543 (Guerrero et al. 2015). These observations provide invaluable information. The high-dispersion *Chandra* LETG observation of BD+30°3639 shows bright H-like resonance lines of O VIII and C VI and He-like triplets of Ne IX and O VII, but weak/absent lines of N VII. This indicates that the chemical abundances of the hot gas are similar to those of the [WC] central star, i.e. mixing is not operating. In the future, *Athena* XIFU will allow routinely high-dispersion X-ray spectroscopic observations of a large number of PNe to test the efficiency of heat conduction and mixing inside the hot bubbles of PNe.

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Kenji Hamaguchi: Do you see any correlation of the temperature of the diffuse plasma with stellar wind velocity?

Martín Guerrero: Not really. The plasma temperature tends quickly to an asymptotic value at 1-2×10^6 K. The reason is that the bubble grows and the stellar wind mechanical luminosity diminishes, even though its terminal velocity increases.

Vikram Dwarkadas: Have you seen any correlation between X-ray emission and binarity, or morphological features that suggest binarity (as in Brent's talk)? Have you looked for this in your sample?

Martín Guerrero: The sample of binary CSPNe is very recent, so there is very little overlap with the ChanPlaNS sample. Binary CSPNe evolve so that they produce broken nebular shells which cannot contain the hot gas inside.

Gloria Koenigsberger: Is NGC 6543 a binary?

Martín Guerrero: The precessing-like jet features point to a binary star, but so far there is no direct evidence. B. Miszalski confirms this point from this RV studies. These can be difficulted by wind variability.