

# X-ray Studies of Planetary Nebulae

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**Abstract.** X-ray emission from planetary nebulae (PNe) provides unique insight on the formation and evolution of PNe. Past observations and the ongoing *Chandra* Planetary Nebulae Survey (ChanPlaNS) provide a consensus on the two types of X-ray emission detected from PNe: extended and compact point-like sources. Extended X-ray emission arises from a shocked “hot bubble” plasma that resides within the nebular shell. Cooler than expected hot bubble plasma temperatures spurred a number of potential solutions with one emerging as the likely dominate process. The origin of X-ray emission from compact sources at the location of the central star is less clear. These sources might arise from one or combinations of the following processes: self-shocking stellar winds, spun-up binary companions, and/or accretion, perhaps from mass transfer, PN fallback, or debris disks. In the discovery phase, X-ray studies of PNe have mainly focused on the origin of the various emission processes. New directions incorporate multi-wavelength observations to study the influence of X-ray emission on the rest of the electromagnetic spectrum.

**Keywords.** planetary nebulae: general, binaries: close, X-rays: general

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## 1. Introduction

The modern era of X-ray studies of Planetary Nebulae (PNe) began with the launches of the NASA-led *Chandra* X-ray Observatory and the ESA-led X-ray Multiple Mirror Newton Observatory (XMM). Both satellites launched in 1999 and continue observing today. These observatories are equipped with imaging spectrometers that provide spatial and spectral (energy) information for each detected X-ray photon. The information-rich X-ray data are essential for distinguishing between point-like and extended sources of X-ray emission; the former typically associated with central stars and/or their companions and the latter typically associated with hot bubble emission. The modest energy resolution of X-ray spectra are used to estimate the characteristics like plasma temperatures, densities, and fluxes of X-ray emission. As the impact of X-ray studies of PNe continue to build, this review presents the current state of these studies and the emerging directions for future research.

## 2. Insights from X-ray Emission from Planetary Nebulae

*Big Trouble in Hot Bubbles:* One of the first modern X-ray observations of a PNe was by *Chandra* of the young PN BD+30°3639 (Kastner *et al.* 2000). This observation used the high-spatial resolution ( $\sim 0.3''$ ) of *Chandra* to provide the first unambiguous detection of extended “hot bubble” emission. In the interacting stellar wind theory of PN formation, as the fast stellar wind collides with the slower AGB wind, AGB material is swept up to form the nebula while a reverse shock travels back towards the central star creating a post-shock region within the nebula. The post-shock region should be filled with hot ( $10^7$  K), low-density ( $n_e < 1 \text{ cm}^{-3}$ ) plasma, the so-called “hot bubble”. The spatial extent of the

X-ray emission detected from the early *Chandra* observation of BD+30°3639 fits within the nebula (as imaged in H $\alpha$  by HST), suggesting the nebula is filled with the X-ray emitting plasma. But the energy spectrum of the X-ray photons suggests that the hot bubble is only  $\sim 3 \times 10^6$  K.

Lower than expected hot bubble temperatures, first observed in BD+30°3639, emerge as a trend in all subsequent observations of hot bubbles (Chu *et al.* 2001, Guerrero, Gruendl, & Chu 2002, Montez *et al.* 2005, Ruiz *et al.* 2013), including those from the *Chandra* Planetary Nebulae Survey (ChaPlaNS; Kastner *et al.* 2012, Freeman *et al.* 2014). Several solutions have been proposed to resolve the hot bubble temperature discrepancy:

- *Early-phase stellar winds* during the formation of the nebula are expected to have lower velocities than present-day winds. Soker & Kastner (2003) study the formation of hot bubbles and argue that the lower wind speeds dictate the hot bubble temperatures not the present-day winds.

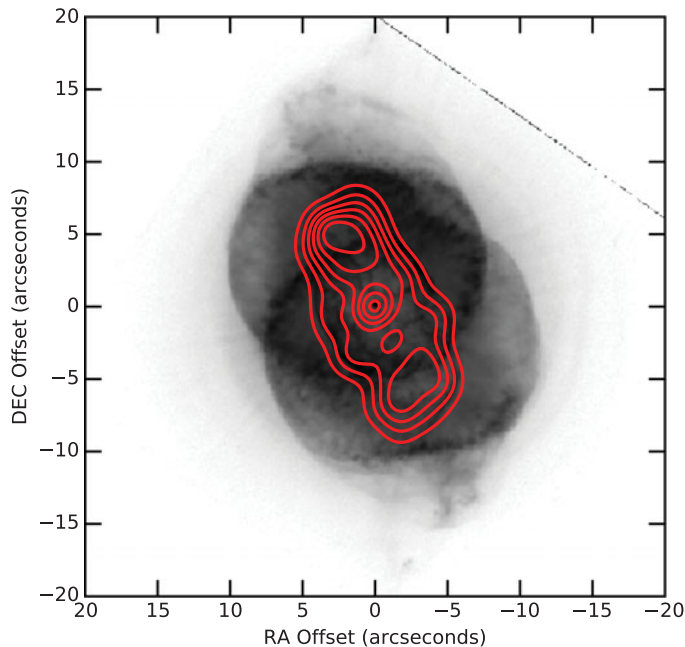
- *Collimated winds or outflows* driven by companions and studied with hydrodynamic simulations (Akashi, Meiron, & Soker 2008) are found to produce plasmas with characteristics (temperature and spatial distribution) consistent with some sources of extended X-ray emission.

- *Heat conduction* across the nebula-hot bubble interface are considered in Steffen, Schönberner, & Warmuth (2008) and the process is shown to efficiently regulate the hot bubble temperature from  $10^7$  K to the observed range of  $1 - 3 \times 10^6$  K. Heat conduction acts by “evaporating” nebular material into the hot bubble, which has the effect of increasing the hot bubble density and lowering its temperature.

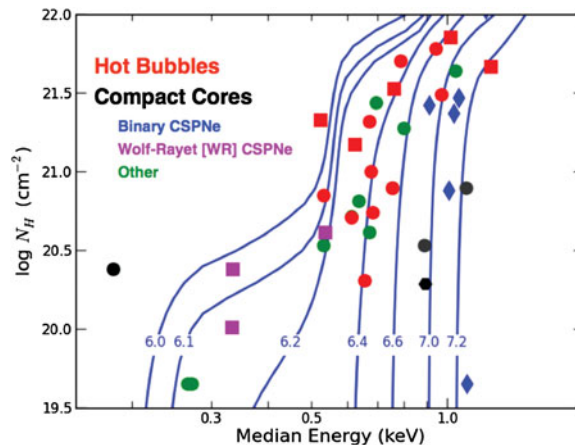
Heat conduction appears to be the dominate process that explains the lower than expected hot bubble temperatures. Supporting evidence for heat conduction has been found from multi-wavelength studies of the  $10^5$  K transition region (see Ruiz *et al.* 2013 and the contribution by Guerrero in this volume). Studies of heat conduction in nebula with distinct chemical compositions are ongoing (see Sandin *et al.* 2016 and the contribution by Schoenberner in this volume). Other predictions of heat conduction models, such as the radial distribution of hot bubble emission (Freeman & Kastner 2016) and mixing of nebular and fast wind elemental abundances (Maness & Vrtilik 2003) are limited by the capabilities of the two modern X-ray observatories.

*Colliding Winds, Hidden Companions:* The perplexing characteristics of point-like X-ray emission from central stars of PNe (CSPNe) began with early *Chandra* observations of the Cat’s Eye and Helix Nebulae (Guerrero *et al.* 2001). The spatial resolution of *Chandra* allows us to pin-point the location of the point-like sources to the central stars. Spectral characteristics of the X-ray emission indicate higher temperatures ( $> 10^6$  K) than expected from the CSPNe. Such X-ray emission could arise from wind shocks, accretion, or binary companions. Montez *et al.* (2010) argue that short-period ( $< 1$  day) post-common envelope binary companions are spun-up during the common envelope phase resulting in rejuvenated coronal activity. It is the companions and not the CSPNe that are the source of hard, point-like X-ray emission from a sample of short-period ( $< 1$  day) post-common envelope binary CSPNe.

With the *Chandra* Planetary Nebulae Survey (ChanPlaNS), it becomes clear that X-ray emission of these known binary systems have distinct spectral characteristics than some of the other detected point-like sources (Montez *et al.* 2015). Specifically, known close binary CSPNe tend to harbor hard X-ray emitting sources with  $T_X \geq 10^7$  K, while other CSPNe with X-ray emission and no known close companions tend to harbor softer X-ray sources with  $T_X \sim 10^6$  K. These softer CSPNe tend to be high-luminosity sources driving fast stellar winds, suggesting that their X-ray emission might be analogous to the self-shocking winds observed from O-stars. Such a hypothesis is supported by the



**Figure 1.** Cat's Eye Nebula showing the two types of X-ray emission detected from PNe: extended and point-like emission. Contours of the smoothed X-ray emission from *Chandra* are overlaid upon an  $H\alpha$  image acquired by HST.



**Figure 2.** Median energy of detected X-ray photons from PNe in ChanPlaNS and column densities,  $N_H$ , derived from nebular observations of the Balmer decrement. Red symbols indicate hot bubbles, other colors indicate point sources. PNe with Wolf-Rayet central stars, H-rich central stars, or close binary companions are represented by square, circles, and diamonds, respectively. The Helix central star is represented by the octagon shape. The blue lines indicate the loci for plasma models with labels in  $\log T_X$ .

fact that  $L_X/L_{\text{bol}}$  ratios of CSPNe ( $10^{-7}$ ) are similar to ratios of O-stars (Montez *et al.* 2015).

A few point-like sources without known companions feature the hard X-ray emission associated with close binary systems. This includes the Cat's Eye and Eskimo Nebulae.

If the hard X-ray emission is indicative of spun-up companions, the X-ray emission might betray the hidden binary companions.

### 3. Future of X-ray Astronomy

The studies made possible with modern X-ray observations of PNe have provided insight into nebular formation, wind shocks, and binary interactions. These observations maximize the capabilities of the present observatories. Future X-ray missions, such as eRosita (2017), Athena+ (2028), and Lynx/X-ray Surveyor (beyond 2030), will offer improved sensitivities and capabilities to address the open questions regarding the origin of X-ray emission from PNe. The all-sky imaging spectroscopy survey offered by eRosita has the potential to expand the number X-ray detections of PNe and improve signal to noise for presently known sources with modest spatial resolution. Presently, only BD+30°3639 has been a suitable target for high-resolution spectroscopic X-ray observations Yu *et al.* (2009) but the high-throughput, high-resolution spectroscopy offered by Athena+ will allow for comprehensive survey of PNe X-ray emitting plasma, including elemental abundances that may provide evidence for the mixing of nebular and fast wind material.

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### Discussion

MUTHUMARIAPPAN: How do the hot bubble in [WR]PNe differ with normal PNe: Are they hotter and possess He, C abundances of their H-poor central star photosphere?

BARLOW: To explain the excess X-ray emission from the Helix Nebular central star, are you predicting that it is a binary?

MONTEZ: Yes, I think the X-ray emission is consistent with all the close binary X-ray characteristics so it suggests there is a companion.

GUZMAN-RAMIREZ: For the point source X-ray emission, how does the binary produce the hard X-ray emission? And do you need a binary to produce this?

MONTEZ: For late type spun up companions, the idea is that the convection and differential rotation is enhanced leading to increased magnetic activity and so flares and coronal emission in X-rays. A binary companion can do this but a CSPN cannot because they are convective.

MENDEZ: When you say “binary” do you mean specifically a close binary, with  $P < 1$  day?

MONTEZ: Yes for a spun-up companion. But late type dwarfs can remain active formost of their lives so you could get away with a wide binary in that case but we should have found a companion to the Helix central star.