Abstract. Planetary nebulae (PNe) are an exciting addition to the zoo of X-ray sources. Recent Chandra and XMM-Newton observations have detected diffuse X-ray emission from shocked fast winds in PN interiors as well as bow-shocks of fast collimated outflows impinging on the nebular envelope. Point X-ray sources associated with PN central stars are also detected, with the soft X-ray ($<0.5$ keV) emission originating from the photospheres of stars hotter than $\sim 100,000$ K, and the hard X-ray ($>0.5$ keV) emission from instability shocks in the fast stellar wind itself or from a low-mass companion’s coronal activity. X-ray observations of PNe offer a unique opportunity to directly examine the dynamic effects of fast stellar winds and collimated outflows, and help us understand the formation and evolution of PNe.

1. Introduction

Planetary nebulae (PNe) can host different sources of X-ray emission:
1. Photospheric emission from hot, 100,000–200,000 K, central stars. Such emission is expected at photon energies $\ll 0.5$ keV.
2. Emission from shock-heated gas in PN interiors generated in the interaction of the current fast stellar wind (1,000–4,000 km s$^{-1}$) with the previous slow AGB wind. The shocked fast wind, at temperatures of $10^7$–$10^8$ K, is too tenuous to produce appreciable X-ray emission. The mixing of nebular shell material into the hot PN interior raises the density to produce detectable X-ray emission with a limb-brightened morphology.
3. Emission from shock-heated gas in bow-shocks formed by collimated outflows or jets impinging on the AGB wind at velocities $\geq 300$ km s$^{-1}$. The prolonged action of collimated outflows may bore through the AGB wind and form extended cavities, which can be filled by hot shocked gas and emit X-rays, too.
4. Coronal emission from an unseen and unresolved late-type dwarf companion. In this case, the PN central star is not responsible for the X-ray emission. As stellar coronae have temperatures of a few $\times 10^6$ K, their X-ray emission peaks above 0.5 keV, in sharp contrast to the photospheric emission from a hot PN central star.

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X-ray observations of hot, shocked-heated gas in PNe allow us to examine how fast stellar winds and collimated outflows interact with the AGB wind and transfer energy and momentum to the PN envelope. X-ray observations may also reveal unseen faint binary companions through their coronal emission, and allow us to assess the importance of binary shaping of PNe. Exciting new views of PNe can be obtained through the X-ray window. In recent years, the Chandra and XMM-Newton X-ray Observatories have made major strides in detecting and resolving the X-ray emission from PNe. In this paper we review the X-ray observations of PNe made by these great X-ray observatories.

2. X-Ray Observations of PNe

X-ray emission from PNe was detected in the mid-1980s by Einstein and EXOSAT, but all these detections can be interpreted as soft X-ray emission from their hot central stars (see Guerrero, Chu, & Gruendl 2000 for a complete review). In the 1990s, ROSAT made useful observations of more than 60 PNe; only three PNe (A30, BD+30°3639, and NGC 6543) show marginally extended X-ray emission, while two other PNe (NGC 7009 and NGC 7293) show a hard, >0.5 keV, X-ray component not expected from the stellar photosphere (Guerrero et al. 2000). These ROSAT observations showed for the first time hints of emission from the hot gas in PN interiors, but the evidence was not very convincing because of the limited angular resolution and low S/N ratios.

| PN           | Observatory | Hard X-ray Emission          | Reference |
|--------------|-------------|------------------------------|-----------|
| BD+30°3639   | Chandra     | Diffuse                      | 1         |
| Hen 3-1475   | Chandra     | Diffuse                      | 2, 3      |
| Mz 3         | Chandra     | Diffuse and Central Star     | 4         |
| NGC 6543     | Chandra     | Diffuse and Central Star     | 5, 6      |
| NGC 7009     | XMM-Newton  | Diffuse                      | 7         |
| NGC 7027     | Chandra     | Diffuse                      | 8         |
| NGC 7293     | Chandra     | Central Star                 | 6         |

References. — (1) Kastner et al. 2000; (2) this paper; (3) Sahai 2004; (4) Kastner et al. 2003; (5) Chu et al. 2001; (6) Guerrero et al. 2001; (7) Guerrero et al. 2002; (8) Kastner et al. 2001.

The launch of modern X-ray observatories, Chandra and XMM-Newton, has made it possible to observe PNe with unprecedented sensitivity and angular resolution. To date, Chandra and XMM-Newton have observed 14 PNe. Diffuse X-ray emission is unambiguously resolved in 6 PNe and hard X-ray point sources coincident with the central stars are found in 3 PNe. These detections and their references are listed in Table 1. The diffuse X-ray sources and hard X-ray point sources are discussed separately in the next two subsections.
Figure 1.  *HST* WFPC2 Hα images of four PNe with diffuse X-ray emission. The overlaying contours are extracted from X-ray images in the 0.3-1.0 keV band. The X-ray observations of BD+30°3639, Hen 3-1475, and NGC 6543 were obtained with *Chandra* ACIS-S, while NGC 7009 was observed with *XMM-Newton* EPIC pn.

2.1. Diffuse X-ray Emission from PNe

The distribution of diffuse X-ray emission relative to the nebular shell is illustrated for four PNe in Figure 1, where X-ray contours are overplotted on Hα images. With the exception of Hen 3-1475, the diffuse X-ray emission from each PN is confined within the innermost nebular shell, consistent with the expectation for shocked fast wind in an interacting-stellar-winds model. In NGC 6543 and Mz 3, the most well-resolved PNe, a limb-brightened X-ray morphology can be seen (Chu et al. 2001; Kastner et al. 2003).

As for Hen 3-1475, the X-ray emission is located at the tip of a bow-shock structure where an abrupt change in velocity of the fast collimated outflow emanating from its core has been identified (Riera 2004). The X-ray emission in Hen 3-1475 is, thus, associated with its collimated outflows, as observed in Herbig-Haro objects (e.g., Pravdo et al. 2001). X-ray-emitting gas shock-heated...
Figure 2. *Chandra* ACIS-S spectra of BD+30°3639, Hen 3-1475, and NGC 6543, and *XMM-Newton* spectrum of NGC 7009. The histogram overlaid on each spectrum corresponds to the best-fit model. The temperature of this best-fit model is shown in each panel.

by collimated outflows has also been suggest to exist in Mz 3 (Kastner et al. 2003).

As most of the X-ray emission from PNe is detected at <1 keV (see below), this emission is easily absorbed by intervening material, including the nebular shell and the circumstellar material. The importance of internal absorption has been demonstrated by the anti-correlation between the X-ray surface brightness and nebular extinction. Because of the differential absorption across PNe, the X-ray morphology of a PN may not be representative of the spatial distribution of the hot gas (Kastner et al. 2002).

The X-ray spectra of four PNe with diffuse X-ray emission are presented in Figure 2. Their X-ray emission is soft, peaking at energies <1.0 keV. The spectral shape is dominated by emission lines of N vii, O iii, and Ne ix indicative of thin-plasma emission. Spectral fits using a thin-plasma emission model give plasma temperatures of 1–3×10^6 K and suggest chemical enrichment of nitrogen and neon. In Hen 3-1475, the X-ray spectrum implies a hot gas temperature corresponds to a shock velocity of ~400 km s⁻¹.

The X-ray luminosities of PNe derived from these spectral fits range from 3×10^{31} ergs s⁻¹ to 1×10^{33} ergs s⁻¹. The younger PN (BD+30°3639, Mz 3, and
NGC 7027) have systematically higher X-ray luminosities and temperatures than the more evolved PNe (NGC 6543 and NGC 7009).

*Chandra* observations of another four PNe have resulted in non-detections of diffuse X-ray emission. In these cases, the PNe either have collimated outflows at only modest velocities (Hen 2-90 and M1-16), or are evolved nebulae with no measurable fast winds from the central stars (NGC 246 and NGC 7293). The symbiotic star with a bipolar nebula Hen 2-104 was also not detected by *Chandra* observations.

### 2.2. Hard X-ray Emission from PN Central Stars

The unprecedented *Chandra* resolution has made possible the detection of hard X-ray point sources at the central stars of Mz3, NGC 6543, NGC 7293, and possibly Hen 3-1475 (Guerrero et al. 2001; Kastner et al. 2003; this paper). Figure 3 shows the X-ray spectra of the central stars of NGC 6543 and NGC 7293. These spectra suggest thin plasma emission at temperatures up to a few $\times 10^6$ K and with X-ray luminosities $\sim 10^{29}$ ergs s$^{-1}$.

The origin of these point sources is uncertain. For the central star of NGC 7293 (the Helix Nebula), its temporal variability in X-rays and in the H$\alpha$ line suggests the presence of an unseen dMe companion with an active corona (Gruendl et al. 2001; Guerrero et al. 2001). In other cases (e.g., NGC 6543), especially ones with moderate to strong stellar winds, the instability shocks in the fast stellar wind itself may be responsible for the hard X-ray emission.

### 3. Summary and Future Work

*Chandra* and *XMM-Newton* observations of PNe have detected diffuse X-ray emission from hot gas in PN interiors and in bow-shocks of fast ($\geq 500$ km s$^{-1}$) collimated outflows, as well as unresolved point sources at the central stars.
These results have provided a wealth of information on the distribution and physical conditions of hot gas in PNe, and allow us to investigate the physical structure of PNe as a whole and how collimated outflows transfer energy to the nebular envelope.

The emerging picture revealed by these X-ray observations is that young PNe with a sharp shell morphology contain significant amounts of hot gas in their interiors. This hot gas is over-pressurized and drives the nebular expansion. The duration for the presence of hot gas is short, as only the youngest PNe have detectable diffuse X-ray emission. It is possible that excessive mixing of nebular material lowered the hot gas temperatures to below $1 \times 10^6$ K, where the cooling function peaks and a runaway cooling ensues.

*Chandra* and *XMM-Newton* have the ideal resolution and sensitivity to observe PNe. As the amounts of hot gas in PN interiors or bow-shocks of collimated outflows are usually small, PNe are faint X-ray sources. One must be careful in selecting PN targets for X-ray observations. Factors that should be taken into consideration include: fast stellar wind strength, speed of collimated outflows, foreground absorption, nebular shell morphology, etc. As presented by Chu et al. (2004), the O vi $\lambda\lambda 1032,1037$ lines provide a promising diagnostic for the existence of $10^6$ K hot gas for PNe with central stars cooler than 125,000 K. While we need to actively request new *Chandra* and *XMM-Newton* observations of PNe, the targets must be carefully selected with the above considerations to maximize the likelihood of detection. Only positive detections can be analyzed and advance our understanding of physical structures of PNe.

**References**

Chu, Y.-H., Gruendl, R. A., & Guerrero, M. A. 2004, in this volume
Chu, Y.-H., Guerrero, M. A., Gruendl, R. A., Williams, R. M., & Kaler, J. B. 2001, ApJ, 553, L69
Gruendl, R. A., Chu, Y.-H., O’Dwyer, I., & Guerrero, M. A. 2001, AJ, 122, 308
Guerrero, M. A., Chu, Y.-H., & Gruendl, R. A. 2000, ApJS, 129, 295
Guerrero, M. A., Chu, Y.-H., & Gruendl, R. A. 2002, A&A, 387, L1
Guerrero, M. A., Chu, Y.-H., Gruendl, R. A., Williams, R. M., & Kaler, J. B. 2001, ApJ, 553, L55
Kastner, J. H., Balick, B., Blackman, E. G., et al. 2003, ApJ, 591, L37
Kastner, J. H., Li, J., Vrtilek, S. D., et al. 2002, ApJ, 581, 1225
Kastner, J. H., Soker, N., Vrtilek, S. D., & Dgani, R. 2000, ApJ, 545, L57
Kastner, J. H., Vrtilek, S. D., & Soker, N. 2001, ApJ, 550, L189
Pravdo, S. H., Feigelson, E. D., Garmire, G., et al. 2001, Nature, 413, 708
Riera, A. 2004, in this volume
Sahai, R. 2004, in this volume