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X-ray Emission from Planetary Nebulae and their Central Stars: a Status Report

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Summary. In the era of *Chandra* and *XMM-Newton*, the detection (or nondetection) of diffuse and/or point-like X-ray sources within planetary nebulae (PNe) yields important, unique insight into PN shaping processes. Diffuse X-ray sources, whether due to "hot bubbles" or to collimated outflows or jets, allow us to probe the energetic shocks within PN wind interaction regions. Meanwhile, X-ray point sources provide potential diagnostics of magnetic fields, accretion disks, and/or binary companions at PN cores. Here, I highlight recent X-ray observational results and trends that have the potential to shed new light on the origin and evolution of the structure of PNe.

Key words: keyword list

1 Introduction

Over the past decade, X-ray imaging by the *Chandra* and *XMM-Newton* X-ray Observatories has provided fresh, compelling observational evidence for hot bubbles, highly energetic jets, and/or "active" central sources within planetary nebulae (PNe). So far, nine of ~ 25 PNe targeted by these two contemporary X-ray observatories[3] have been detected as diffuse X-ray sources (Kastner et al. 2000, 2001, 2003; Chu et al. 2001; Guerrero et al. 2002, 2005; Sahai et al. 2003; Montez et al. 2005; Gruendl et al. 2006), while an additional handful have been revealed to harbor X-ray point sources at their cores (e.g., Guerrero et al. 2001; Kastner et al. 2003). Both "flavors" of X-ray source — diffuse and point-like — can be used to probe PN shaping processes and to constrain models of PN structural evolution.

[3] Martin Guerrero maintains a list of PNe observed by *Chandra* or *XMM* at http://www.iaa.es/xpn/.

2 Diffuse X-ray Sources

2.1 X-rays from PN "hot bubbles"

Models of PN shaping have long predicted the formation of X-ray-emitting "hot bubbles." A hot bubble may be produced within a PN as the central star makes the transition from post-asymptotic giant branch (post-AGB) star to white dwarf, following an evolutionary track of increasing $T_\star$ at constant $L_\star$, followed by decreasing $L_\star$ and $T_\star$. In this phase the star produces very fast and energetic winds (with speeds $\sim$ 1000 km s^{-1} and mass loss rates $\gtrsim 10^{-7}$ $M_\odot$ yr^{-1}). When such a fast wind collides with ambient (previously ejected AGB) gas, it is shocked and superheated (e.g., Zhekov & Perinotto 1996). The shocked fast wind forms an overpressured bubble that accelerates outwards and displaces the ambient (visible, nebular) gas as it grows (Kwok, Purton, & Fitzgerald 1978). The supersonic growth of the bubble plows the displaced older material into a rim of dense gas which, when projected on the sky, is seen as a thin molecular, dust, and/or ionized structure that traces the bubble's perimeter.

In the majority of detections of diffuse X-ray emission from PNe, the X-ray-emitting region is fully contained within bright optical rims or bubbles (Fig. 1), as predicted by the preceding "hot bubble" scenario. Furthermore, many of the detected objects harbor central stars that are of Wolf-Rayet (WR) type (i.e., "[WC]" or "[WO]" stars) and/or display optical spectroscopic evidence for large mass-loss rates and wind velocities. These trends were already reasonably well established (Montez et al. 2005; Gruendl et al. 2006) when we stumbled upon yet another example of an X-ray-emitting "hot bubble" within a [WC] PN: NGC 5315.

Chandra's serendipitous detection of NGC 5315

In a Cycle 5 *Chandra* study, we observed two [WC] PNs, NGC 40 and Hen 2-99; we detected the former, but failed to detect the latter (Montez et al. 2005). In March 2007, while searching the Chandra archives for targeted observations of PNs in support of a *Chandra* observing proposal, Rudy Montez discovered — to our great surprise and amusement — that a *second* [WC] PN, NGC 5315, was present at the edge of the field of our 29 ks *Chandra* Advanced CCD Imaging Spectrometer (ACIS) observation targeting Hen 2-99. Rudy's examination of the Chandra/ACIS image revealed an X-ray source at the position of NGC 5315, $\sim 12.5'$ off-axis. This serendipitous *Chandra* detection of X-rays from NGC 5315 is all the more remarkable when one considers that there are only $\sim$ 50 known [WC] PNe in the sky (Gorny & Stasinska 1995; Tylenda 1996). Of course, it could also be said that this author pointed one of NASA's Great Observatories at the wrong object! Indeed, due to the relatively poor *Chandra*/ACIS-S image quality at the far off-axis position of NGC 5315, it is not possible to ascertain from the ACIS image alone whether

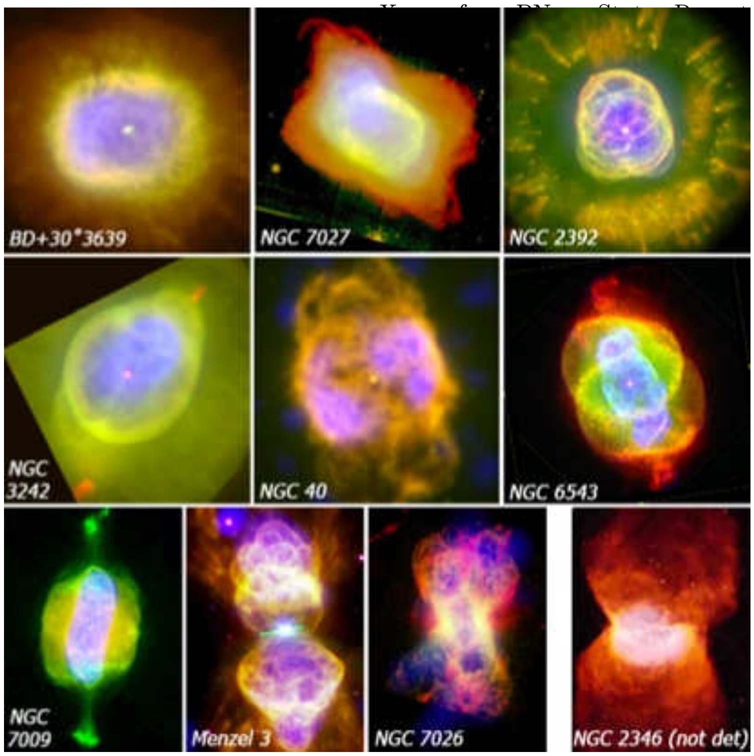

Fig. 1. Images of all of the PNe for which extended X-ray emission (shown in blue) has been detected (as of this writing) by *Chandra* (BD +30°3639, Mz 3, NGC 6543, 7027, 40) or *XMM-Newton* (NGC 2392, 3242, 7009, 7026) — and one XMM nondetection (NGC 2346, with open bipolar lobes) — arranged according to optical morphology. (Image montage courtesy Bruce Balick and Martin Guerrero.)

the X-rays trace a hot bubble within this PN, emanate from the PN nucleus, or are emitted by both the nebula and its central star(s).

Fortunately, the background-subtracted spectrum (Fig. 2), the luminosity, and the temporal behavior of the X-ray source associated with NGC 5315 appear quite definitive regarding the origin of the X-rays. The spectrum shows strong Ne IX line emission as well as a blend of O VII and O VIII lines, with no evidence of Fe L-shell lines. Spectral modeling indicates that the emission arises in a $\sim 2.5 \times 10^6$ K thermal plasma with enhanced Ne and depleted Fe. These results, and the inferred intrinsic source luminosity of $L_X \sim 2 \times 10^{32}$ erg s^{-1}, are very similar to those obtained for the best-characterized diffuse X-ray PN, BD +30°3639 (Kastner et al. 2000, 2006a). Meanwhile, the Chandra/ACIS light curve shows no evidence for variability, and the absorption-corrected X-ray luminosity of NGC 5315 is at least an order of magnitude larger than that of any unresolved PN core region detected thus far (Guerrero et al. 2001; Kastner et al. 2003), further supporting the interpretation that

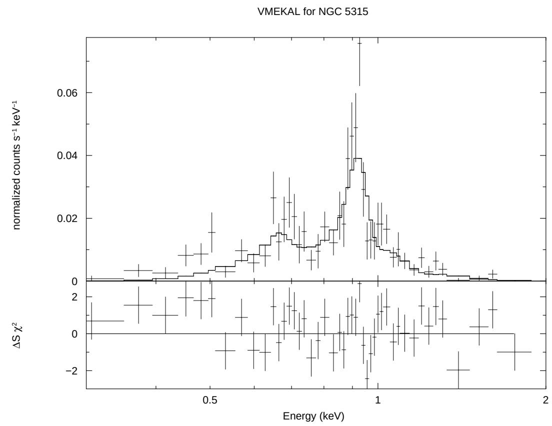

Fig. 2. Chandra/ACIS spectrum of the X-ray source associated with NGC 5315 (crosses), with best-fit absorbed thermal plasma (VMEKAL) model spectrum overlaid. The fit residuals are indicated in the lower panel. (From Kastner et al. 2007.)

the X-rays arise from an extended region within NGC 5315. These results, described in detail in Kastner et al. (2007), establish NGC 5315 as one of the most luminous "hot bubble" PN X-ray sources yet detected.

2.2 NGC 5315 and other hot bubbles: the picture thus far

The detection of the [WC] PN NGC 5315 by *Chandra* underscores two significant trends that have emerged from the X-ray observations of PNe obtained thus far by *Chandra* and *XMM* (Kastner et al. 2007):

1. Objects with WR-type (i.e., [WC], [WO], or WR(H)) central stars — which display characteristically large wind velocities (v_w) and mass-loss rates ($\dot{M}$) — account for a disportionately large fraction of PNe that are established sources of luminous, diffuse X-ray emission. Specifically, five of the seven known "hot bubble" PN X-ray sources are associated with WR-type PNe.
2. In all cases in which diffuse X-ray emission is detected, the optical/IR structures that enclose the regions of diffuse X-rays are clearly defined, and these structures generally display thin, bright, uninterrupted edges (or "rims") surrounding a cavity of lower surface brightness that is coincident with the extended X-ray emission (see also Gruendl et al. 2006).

These results indicate that the combination of (1) large wind kinetic energies ($L_w \gtrsim 10^{33}$ erg s^{-1}) and (2) a "closed containment vessel" is necessary to yield PN hot bubbles with plasma densities sufficient to produce detectable soft (0.3-2.0 keV) X-ray luminosities $L_X \gtrsim 10^{31}$ erg s^{-1}.

Fig. 3 displays scatter diagrams for various PN and central star parameters measured for the X-ray-detected objects. The top panels demonstrate that

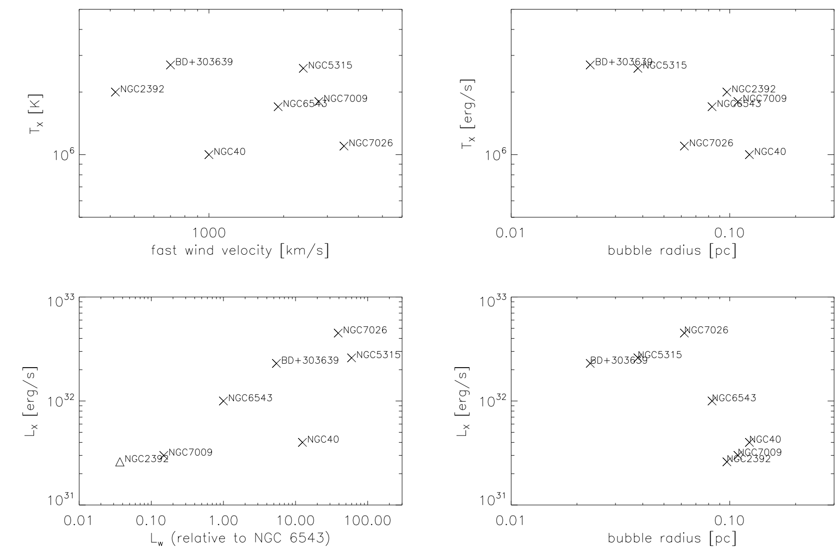

Fig. 3. Results obtained thus far for PNe detected as "hot bubble" X-ray sources by Chandra and XMM-Newton. Upper left: PN plasma temperature (T_X) vs. central star fast wind velocity. Upper right: T_X vs. PN optical bubble radius. Lower left: PN X-ray luminosity (L_X) vs. wind luminosity of the PN central star (L_w) relative to L_w of the central star of NGC 6543 (L_w for NGC 2392 [triangle] is an upper limit). Lower right: L_X vs. PN optical bubble radius. (From Kastner et al. 2007.)

the characteristic temperature of the X-ray-emitting plasma is far lower than expected, based on simple shock models, in almost all PNs in which diffuse X-ray emission has been detected thus far. Indeed, there is only one "hot bubble" PN, NGC 2392, for which the predicted temperature of the shocked wind gas is consistent with T_X; for all other such objects, the predicted post-shock temperatures are larger than observed by factors ranging from ~ 2 (BD $+30°3639$) to ~ 200 (NGC 7026). It also appears that T_X is uncorrelated with present-day central star wind velocity, but is weakly anticorrelated with PN bubble radius (Fig. 3, upper panels), suggesting that PN age is more important than present-day wind kinetic energy in determining the temperature of the X-ray-emitting plasma within hot bubbles.

The bottom panels of Fig. 3 indicate that X-ray luminosity is correlated with present-day central star wind luminosity $L_w = \frac{1}{2}\dot{M}v_w^2$, and is perhaps anticorrelated with bubble radius. The shallow slope of the L_X vs. L_w correlation — wherein 4 orders of magnitude in L_w results in only a factor ~ 20 range in L_X — may suggest either that the conversion of wind kinetic energy to plasma radiation becomes more efficient as the central star wind declines in strength, or that the luminosities (and, perhaps, temperatures) of the hot bubbles within these PNe are established during early phases of the post-AGB evolution of central stars with rapidly evolving winds (Akashi et al. 2007; see also Schönberner et al. 2006).

2.3 X-rays from collimated outflows and jets

A review of X-rays from collimated outflows and jets in PNe was presented by Martin Guerrero at APN IV (these proceedings). Here, I merely point out that detections of X-ray emission from the energetic shocks that are expected to result from the interaction of PN collimated outflows, jets, and/or bullets with slower-moving (AGB) material remain few and far between; only 2 or 3 such detections have been made to date (Hen 3-1475, Sahai et al. 2003; Mz 3, Kastner et al. 2003; and, perhaps, NGC 7027, Kastner et al. 2001). The dearth of X-ray detections of PN jets and jet-like structures is not particularly surprising, in light of the similarly small X-ray detection rate of highly collimated outflows from young stellar objects (e.g., Grosso et al. 2006 and references therein).

Nevertheless, some trends may be emerging. In particular, it seems that the characteristic temperatures of X-ray sources associated with PNe jets ($\sim$ 3–6 MK) are systematically higher than those of "hot bubble" PNe. Also, as would be expected, all three "X-ray jet" PNe show evidence for dusty, molecule-rich (H_2-emitting) central tori that are potential collimating agents for the outflows that produce the X-ray-emitting shocks, whereas only one "hot bubble" PN X-ray source (BD+30°3639) was detected in the H_2 survey of Kastner et al. (1996).

3 Point-like X-ray Sources within PNe

We have been revisiting all *Chandra* observations targeting PNe, so as to place constraints on the X-ray luminosities of PNe central star systems (Kastner & Montez, in prep.). The superior ($\sim$ 0.5") spatial resolution of *Chandra* (compared with *XMM-Newton's* $\sim$ 5" resolution) is required to distinguish such point-like X-ray emission from diffuse emission originating with the surrounding nebula. To ascertain the *Chandra* point-source X-ray luminosities or luminosity upper limits, we determine the ACIS count rate within an aperture of radius $\sim$ 2.5" placed at the nominal position of the PN central star (this radius accounts for typical *Chandra* pointing errors of $\lesssim$ 1"). We then compare this ACIS count rate with that obtained for a suitably chosen background region (typically, an annulus surrounding the source region).

3.1 "Classical" PNe

Applying this technique to *Chandra* observations of PNe whose central stars are not symbiotic in nature (see below), we confirm the detection of X-ray point sources within four nebulae (NGC 246, NGC 4361, NGC 6543, and NGC 7293; see Guerrero et al. 2001 and `http://www.iaa.es/xpn/`) and obtain X-ray flux upper limits for 10 other nebulae (including three sources of diffuse X-ray emission, i.e., NGC 40, BD+30, and NGC 7027). We hence obtain a preliminary (and potentially highly biased) point-source detection rate of $\sim 30\%$ within "classical" PNe at typical sensitivities of 10^{29-30} erg s^{-1}.

For purposes of understanding the potential implications of these preliminary results for models of magnetic and/or accretion activity associated wth PN cores, it may be helpful (though potentially misleading!) to compare PN core X-ray emission levels with those of solar- and subsolar-mass, pre-main sequence (T Tauri) stars. Evidently the hard (∼2–8 keV) X-ray emission from such stars is usually coronal in origin (e.g., Preibisch et al. 2005), although for some fraction of T Tauri stars the hard X-rays — as well as some or all of the softer (∼0.3–1.0 keV) emission — likely arise as a consequence of magnetically-governed accretion activity (e.g., Kastner et al. 2006b; Telleschi et al. 2007). Comparing our *Chandra* results for the X-ray luminosities and luminosity upper limits of point-like PNe X-ray sources with the L_X distributions of a nearly complete sample of pre-main sequence stars in Orion (Feigelson et al. 2005), one might speculate that the nondetected PN cores, as a group, are less magnetically active than $\sim 0.5\ M_\odot$ T Tauri stars; while the magnetic activity levels of the four relatively X-ray-luminous PN cores (for which $L_X \sim 10^{30-31}$ erg s^{-1}) are comparable to 1–3 $M_\odot$ T Tauri stars (ignoring for the moment the likelihood that the X-ray-luminous cores harbor close binary stars; §3.2).

3.2 Symbiotic Mira systems

In stark contrast to "classical" PNe, it seems that X-ray-luminous point sources are a common (perhaps ubiquitous) feature of symbiotic Mira systems: all but one of the six such systems observed thus far by Chandra — R Aqr, CH Cyg, Mz 3, Hen 2-104, and Mira itself — display X-ray sources at the positions of their central stars. The only symbiotic Mira nebula in which no central X-ray point source is detected, OH 231.8+4.2, possesses a very highly obscured central region (i.e., a dusty torus). The luminosities of the symbiotic Mira X-ray point sources range over ~ 4 orders of magnitude (from $\sim 10^{28}$ to $\sim 10^{32}$ erg s^{-1}); this emission is typically harder than that of diffuse (shock-induced) PN X-ray emission (e.g., Kastner et al. 2003) and may be highly variable.

By analogy with low-mass X-ray binaries, the presence of X-ray point sources within symbiotic Miras is likely indicative of binary mass transfer processes. Hence, further observations and analyses of these X-ray sources should provide unique diagnostics of accretion of AGB wind material by white dwarf (or, in some cases, main sequence) secondaries. More generally, studies of compact X-ray sources within symbiotic Miras should provide insight into the disks, jets, and disk-jet interactions that are the likely consequence of central binary systems within PNe (see also Montez & Kastner, these proceedings).

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