The Secret X-ray Lives of Planetary Nebulae

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The generation of a planetary nebula (PN) has long been appreciated as one of the most photogenic steps in the late evolution of 1–8 $M_\odot$ stars — the last, lovely gasps of asymptotic giant branch (AGB) stars on their way to becoming white dwarfs. Planetary nebulae regularly serve as cover art for astronomy and astrophysics textbooks, and they make stunning subjects for *Hubble* Space Telescope imagery[1]. Beyond their aesthetic value, observations of PNe inform and test theories describing fundamental radiative processes, techniques to determine cosmic abundances, and models of stellar nucleosynthesis and the chemical enrichment of the universe.

Naively, one might assume that the X-ray regime would have little to offer to the PN enthusiasts among the astrophysics community – and vice versa. After all, in classical astrophysics textbooks, PNe are presented as near-ideal examples of $\sim 10^4$ K plasmas in uniform Strömgren spheres that are photoionized by central stars with effective temperatures of $\sim 10^5$ K. Surely, such objects shouldn't be luminous X-ray sources.

However, it had been recognized decades ago that the formation of planetary nebulae should result in strong, X-ray-emitting shocks generated during the abrupt transition from tenuous AGB star to high surface gravity white dwarf (e.g., Volk & Kwok 1985; Zhekov & Perinotto 1996). Furthermore, by the late 90's, the varied shapes and complex structures of PNe revealed by HST had made clear that many, or perhaps most, of the progenitors of PNe began their lives in binary systems (see review by Balick & Frank 2002). In these respects, PNe pose severe challenges to even the most sophisticated hydrodynamical simulations of stellar wind interactions, even as they offer tantalizing clues to the rapid, late binary star evolution processes that might result in X-ray binary systems and the occasional progenitor of a Type Ia supernova.

With its powerful combination of high spatial and spectral resolution, the *Chandra* X-ray Observatory is helping to unlock the potential of planetary nebulae in these astrophysically important areas. As we describe in the following, *Chandra* (and, to a lesser extent, *XMM-Newton*) has established that the majority of PNe do, in fact, harbor X-ray sources — yielding a trove of new insights in realms as diverse as heat conduction in astrophysical plasmas and the "spin-up" of binary companions to mass-losing evolved stars.

Diffuse X-ray Emission: Witnessing the Process of PN Shaping

According to the interacting stellar winds model describing the generation of a PN (Kwok et al. 1978), the nebular shell is formed by the interaction of a nascent fast wind from the stellar core (soon to be a white dwarf star) with an older and denser, slow, dusty AGB wind. This collision of winds should form a post-shock region that fills the nebular cavity with a super-heated, tenuous gas, or "hot bubble". Indications of the presence of such hot bubbles within PNe had already come from ROSAT and ASCA observations, which revealed that certain objects harbor relatively hard X-ray sources (e.g., Kreysing et al. 1992; Arnaud et al. 1996; Guerrero et al. 2000) — sources seemingly too hard to emanate from the photosphere of a recently unveiled

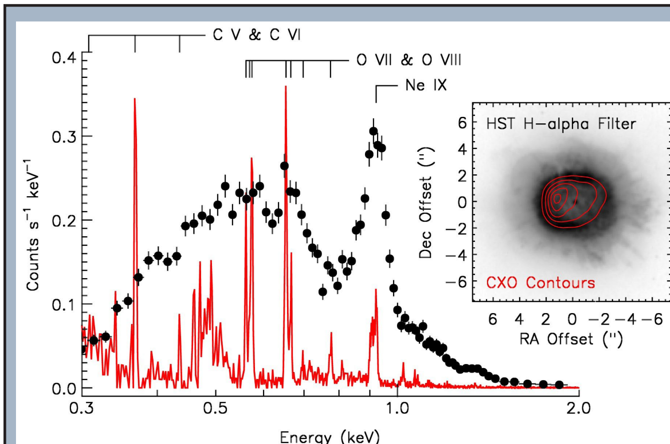

Fig. 1 - The first *Chandra* observations of a planetary nebula were of the compact PN BD +30°3639, and this object has also been the subject of the deepest *Chandra* observations of any PN (a total of ~400 ks in Cycles 1, 6, and 10). Both imaging and gratings (LETG) spectroscopy have been performed, with ACIS-S as the sensor (Kastner et al. 2000; Yu et al. 2009). Shown in the inset are contours of the X-ray-emitting "hot bubble," which fits snugly within the dense nebular rim as imaged by HST in Hα (greyscale). Strong Ne emission from the bubble was already apparent in the ACIS-S3 CCD spectrum (black circles). The LETGS data (red) further reveal that the low-energy end of the hot bubble spectrum is dominated by emission lines of C and O, and constrain its temperature to lie in the range 1.7–2.9 MK (Yu et al. 2009). The forest of lines near 0.5 keV is likely due to C^{6+} ions from the hot bubble penetrating exterior (cooler) nebular gas before recombining (Nordon et al. 2009).

1 See http://hubblesite.org/gallery/album/nebula/planetary/

white dwarf (however, see below!).

It took the unprecedented spatial resolution of *Chandra* to confirm these suspicions, in relatively dramatic fashion. Cycle 1 *Chandra* observations of the PN BD +30°3639 (Kastner et al. 2000; Fig. 1) and NGC 6543 (Chu et al. 2001) confirmed that their X-ray emitting regions were extended (as hinted at in ROSAT observations; Leahy et al. 2000, Guerrero et al. 2000). Moreover, in each case, the region of diffuse X-ray emission, as resolved by *Chandra*, fits neatly within the "cool" (~10^4 K), "classical," photoionized nebula as imaged by the *Hubble* Space Telescope (HST) — just as hot bubbles should. A deep X-ray gratings (*Chandra*/LETG/ACIS-S) observation of BD +30°3639 would later establish (Yu et al. 2009; Fig. 1) that its hot bubble plasma consists of almost pure fast stellar wind. This wind material is highly enriched in helium shell burning products, especially C, O, and Ne (Fig. 1).

However, as an assortment of additional detections of diffuse emission trickled in over subsequent *Chandra* cycles (e.g., Montez et al. 2005), and *XMM-Newton* joined in the hot bubble fun (Guerrero et al. 2002; Gruendl et al. 2006), it became clear that PN hot bubbles just aren't hot enough. That is, simple jump-condition calculations yield expected temperatures of T_X~10^7 K or more within the post-shock regions of the fast (~1000 km s^{-1}) winds of PNe — yet *Chandra* and *XMM-Newton* CCD spectra were consistently yielding T_X~10^6 K (Fig. 1). Explanations for this order-of-magnitude discrepancy (which our colleague Noam Soker has dubbed "the low temperature problem") became almost as numerous as PN hot bubble detections themselves: heat conduction from hot (X-ray) bubble to classical (optical) nebula (Steffen et al. 2008); mixing of nebular and hot bubble gas (Chu et al. 2001); the dominant footprint of an early, "slow" fast wind (Arnaud et al. 1996; Akashi et al. 2006); adiabatic expansion and cooling (Soker & Kastner 2003); and, most recently, the bubble's infiltration by an invading army of heat-sapping "pickup ions" (a model inspired by *in situ* Voyager measurements of the solar wind-ISM interface; Soker et al. 2010).

Moreover, by the end of *Chandra*'s first decade it was clear that not all PNe harbor diffuse X-ray-emitting regions and, furthermore, not all diffuse X-ray regions within PNe can be attributed to hot bubbles.

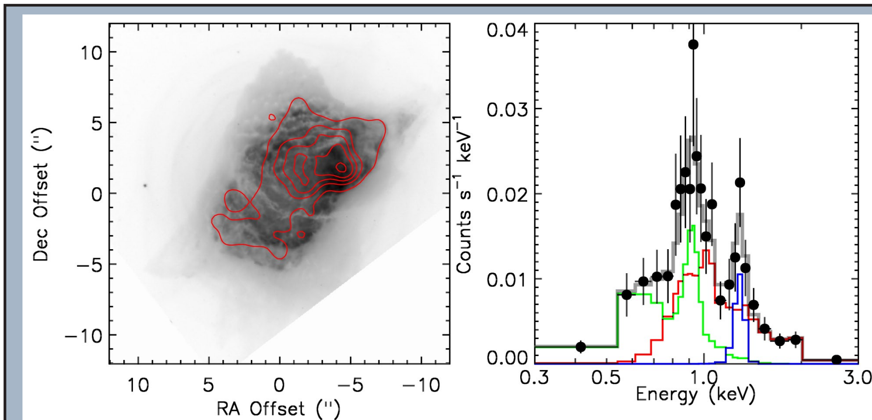

Fig. 2 - *Chandra* and HST observations of the compact PN NGC 7027. Contours of the X-ray emission detected from NGC 7027 (observed for 20 ks in Cycle 1; Kastner et al. 2001) trace the emerging complex structure revealed by the H-alpha HST image (greyscale). The X-ray emission morphology corresponds closely to high-velocity flows that are puncturing the inner shell of the nebula (Cox et al. 2002); the southeast-northwest asymmetry is due to differential absorption across the nebula (Kastner et al. 2001). On the right is the 0.3–3.0 keV spectral energy distribution as extracted from the ACIS-S3 data, indicating the presence of multiple emission features due to the strong shocks in the dense, chemically-enriched, circumstellar environment. In our new spectral analysis (overplotted model), we find a good fit to a two-component thermal plasma (T_X =1 and 8 MK, shown in green and red, respectively) with the addition of an emission line (blue) that is likely due to Mg.

Early *Chandra* observations of the famous yet enigmatic PN NGC 7027 had revealed a double-lobed morphology that added new complexity to its already puzzling structure (Kastner et al. 2001; Fig. 2). The diffuse X-ray emission within this PN appears to reveal the process of explosive shrapnel shredding a (more or less elliptical) central bubble. This object is one of only three diffuse X-ray PNe detected thus far that are seen to depart from a classical "hot bubble" morphology: the linear bubble structure that lends the Ant Nebula (Menzel 3) its name appears to be threaded from within by X-ray-emitting jets (Kastner et al. 2003), while a bullet shot out of the core of the S-shaped pre-PN Hen 3-1475 appears to have shocked downstream material to temperatures of a few ×10^6 K (Sahai et al. 2003). Together with the assorted detections and nondetections of hot bubble X-ray emission within PNe obtained by *Chandra* and *XMM-Newton* over their first years of operation (Kastner et al. 2008), these early X-ray detections of collimated flows offered tantalizing hints as to the potential power of X-ray imaging spectroscopy to reveal the shaping processes at work within PNe.

Point Sources at the Central Stars: Just What is Going on Way Down There?

It was recognized early in the *Chandra* mission that, even when imaged at subarcsecond spatial resolution, not all PNe X-ray sources were extended; some objects displayed unresolved sources at their central stars (Chu et al. 2001, Guerrero et al. 2001). While one might expect the Wien tails of the hot "proto white dwarfs" within PNe to produce some X-ray emission, none of the early *Chandra* central star detections were consistent with such an explanation. The central PN point sources were too hard.

The most puzzling example remains that of the Helix Nebula, whose ($\sim 10^7$ K) X-ray emission is far too energetic to originate from a blackbody-like white dwarf photosphere (see image and spectrum on back cover). For old white dwarfs in the field, such hard X-ray emission is typically attributed to coronal emission from a late-type, main-sequence companion (O'Dwyer et al. 2003) — and, in at least some cases, this appears to hold for PN central stars as well (see below). However, attempts to detect such a low-mass companion to the Helix central star have failed thus far, placing severe constraints on the putative companion mass.

Serendipitous *Chandra* and *XMM-Newton* observations of another old PN, LoTr 5, revealed an even hotter compact X-ray-emitting source (Montez et al. 2010). However, in this case, there is evidence that the central star has a giant companion that is rotating at near break-up speed (Strassmeier et al. 1997). Attributing the X-ray emission to this companion suggests it resembles members of the class of rapidly rotating giants exemplified by FK Comae, a star that is thought to have emerged from a coalescing binary after a common envelope phase (Jasniewicz et al. 1996). Unfortunately, since the orbit of the central binary within LoTr 5 likely lies nearly in the plane of the sky, we have only limited information concerning its binary system parameters.

Meanwhile, a few candidate post-common envelope (short-period) binaries (PCEBs) are known to reside within PNe (De Marco, Hillwig, & Smith 2008). These PCEBs likely avoided coalescence by unbinding and ejecting their common envelope. During the common envelope phase, an embedded late-type companion accretes angular momentum along with envelope material; such a star should spin up and become more magnetically active (Jefferies & Stevens 1996). Surviving PCEB companions therefore should resemble "born-again" (pre-main sequence) stars, with rejuvenated coronae and (hence) luminous X-ray emission (Soker & Kastner 2002).

To investigate this scenario, we performed a *Chandra* pilot study of two PCEB central stars, and found that both displayed X-ray emission consistent with highly magnetically active companions (Montez et al. 2010). Combined with the serendipitous detection of hard X-rays from the central star within LoTr 5, these results suggested that *Chandra* searches for relatively hard X-ray emission from PN central stars could effectively probe central star binarity. However, it would remain to rule out other potential explanations for relatively hard, point-like emission at PN cores — such as hot circumstellar plasma originating in wind shocks (analogous to those of main-sequence O stars; e.g., Herald & Bianchi 2011), fallback of PN material (perhaps from residual debris disks orbiting the central stars; Su et al. 2007, Bilikova et al. 2012), or sharp departures from local thermal equilibrium (LTE) in the central stars' atmospheres (e.g., Hoogerwerf et al. 2007).

Enter ChanPlaNS

In 2009, a cross-section of the community of PN astronomers gathered in Rochester, NY to develop a comprehensive theoretical and observational campaign aimed at understanding how PNe acquire their diverse array of shapes. Among the conclusions of the resulting "Rochester White Paper" (De Marco et al. 2011) was the need for a systematic *Chandra* survey of PNe — a survey that could yield insights into the X-ray characteristics of PNe far exceeding those already obtained from the small, scattershot sample of PNe assembled during the first decade of *Chandra* and *XMM-Newton*. The PN community rallied around a plan to obtain *Chandra*/ACIS-S3 imaging spectroscopy of a volume-limited sample of PNe — specifically, observations of all ~120 known PNe within ~1.5 kpc of Earth.

This survey (the *Chandra* Planetary Nebula Survey; ChanPlaNS) began in Cycle 12, with a Large Program consisting of observations of 21 (mostly high-excitation) PNe. The Cycle 12 ChanPlaNS data were combined with archival data for all (14) additional

PNe within ~1.5 kpc previously observed by *Chandra* to yield an initial sample of 35 objects, i.e., roughly a quarter of the known PNe within 1.5 kpc. Although data analysis for these 35 PNe is still in its initial stages, PN astronomers now finally have in hand a reasonably healthy sample of observations of representative PNe, and some statistical inferences can already be drawn (Kastner et al. 2012). Specifically, it appears ~70% of PNe harbor some form of X-ray source; ~50% of PNe display X-ray-luminous central stars, while ~30% display soft, diffuse X-ray emission that can be traced to shocks formed by energetic wind collisions. A handful of objects among the initial ChanPlaNS sample of 35 display both varieties of X-ray source (front cover).

Notably, all 10 or so objects among the initial ChanPlaNS sample that show diffuse X-ray emission within hot bubbles have inner shell dynamical ages $\lesssim$5000 yr. It seems, therefore, that the epoch of PN-shaping wind collisions only constitutes the first ~10% of a typical PN's lifetime. These results strongly support other lines of evidence indicating that the varied shapes of PNe are established in the earliest stages of their evolution, perhaps even before the progenitor AGB stars blow away their last, innermost, chemically rich layers of stellar envelope (e.g., Sahai & Trauger 1998).

The fact that so many of the surveyed PNe display relatively hard, point-like X-ray sources at their central stars (Fig. 3) came as a surprise to most of the ChanPlaNS team (with the possible exception of our colleagues You-Hua Chu and Martin Guerrero, who had already recognized the potential significance of such sources). Among the central star X-ray sources, only the core of the famous Dumbbell Nebula (M 27) behaves like the Wien tail of a hot blackbody. These results demonstrate that the (equally famous) Helix Nebula is not exceptional among PNe, in hosting a mysterious, compact source of relatively hard X-rays (see back cover).

A handful of the 21 Cycle 12 targets had been previously observed by *XMM-Newton*, and these objects illustrate how the superior spatial resolution of *Chandra* proves essential in distinguishing diffuse, softer (hot bubble) emission from point-like, harder emission originating with the central stars. The case of NGC 7009 is exemplary in this regard; ChanPlaNS observations of this object, like the earlier observations of the more famous NGC 6543, well illustrate the power of *Chandra* where understanding the origin of PN structure is concerned (Fig. 4).

However, the X-ray emission from even nearby PNe can be extraordinarily faint by, say, supernova remnant standards, and analysis of PN X-ray sources sometimes requires less orthodox strategies. For example, to determine the physical mechanism responsible for the X-ray emission, we consider source photon energy distributions (a method also applied by Getman et al. [2010] to the hundreds of faint sources detected in the *Chandra* Orion Ultradeep Program). Based on this analysis we find that, with the lone exception of the Dumbbell (M 27), the median energies of the compact sources of X-ray emission among the ChanPlaNS sample are incompatible with simple blackbody emission from hot central star photospheres (Fig. 5). Instead, such emission evidently originates, at least in

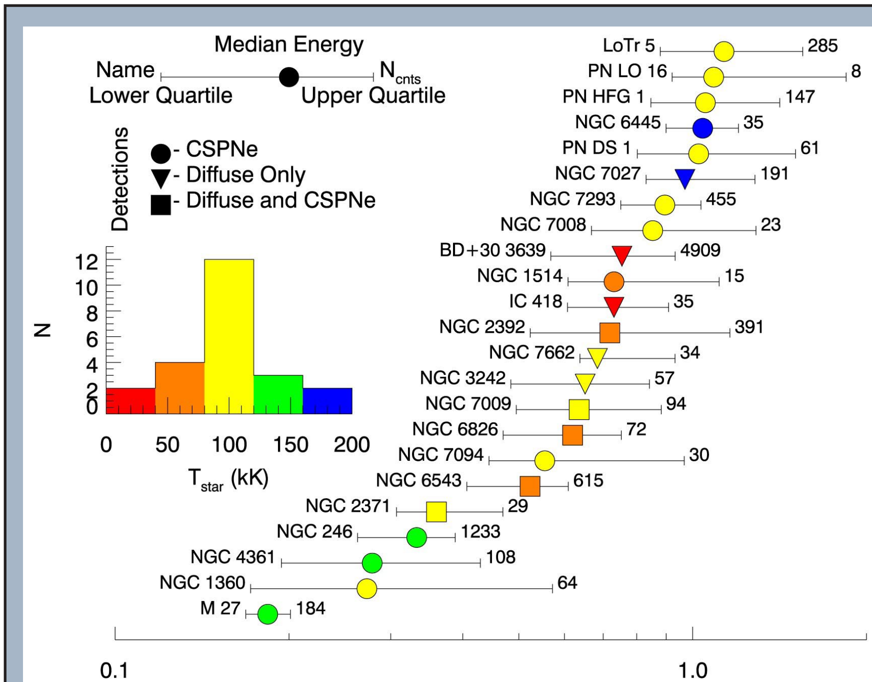

Fig. 3 - Photon energy statistics (net source counts; median energy; first and third quartile energies) for planetary nebula X-ray sources, ordered from lowest to highest median energy (bottom to top). Symbols indicate the nature of each X-ray source (point-like at central star, diffuse, or both central star and diffuse) and are color-coded according to the effective temperature of the central star T_{star} (see inset histogram, which also displays the distribution of T_{eff} for PN central stars detected as X-ray sources). (Figure from Kastner et al. 2012.)

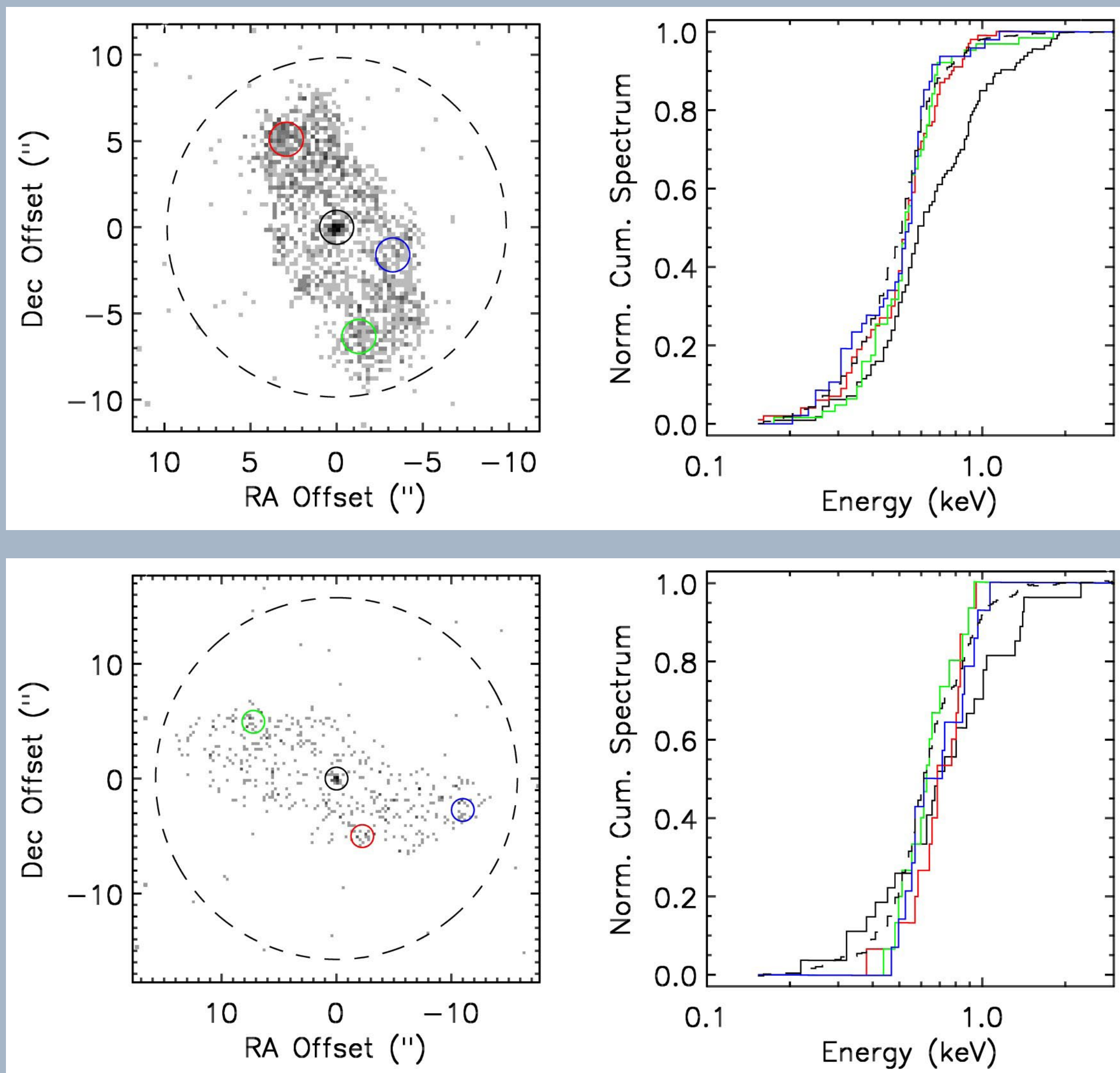

Fig. 4 - Spatial/spectral analysis of *Chandra*/ACIS-S3 imaging spectroscopy of NGC 6543 and 7009 (two of the four nebulae featured on the cover image). The left panels display images of the X-rays detected by *Chandra*, which cleanly distinguishes between diffuse, hot bubble emission and the compact sources at the central stars. In the right panels, we plot the normalized cumulative spectral energy distributions (SEDs) of photons extracted from the regions shown in the left panels; the cumulative SEDs are color-coded (and linestyle-coded) according to their respective spatial extraction regions. These cumulative distributions allow for easy comparison, highlighting differences in X-ray SEDs that are likely due to temperature and/or chemical differences between the diffuse and point-like components. Note, in particular, that (in both cases) the central point source is clearly harder than the hot bubble emission: compare the large-radius extraction region (dashed black), which is dominated by the soft, diffuse emission (note the similarity to the "pure" diffuse emission SEDs shown in red, green, and blue), with the small-radius extraction region centered on the central point source (solid black), which includes relatively little contamination from the diffuse emission.

part, from optically-thin thermal plasma emission in the immediate circumstellar environment, although non-LTE atmospheric models for hot PN central stars also predict a significant soft X-ray contribution in certain cases (see below).

Future Prospects

The initial ChanPlaNS results for diffuse and point-like X-ray sources within PNe are pointing out potential new directions in PN research — directions that should be further clarified once results are in for the next batch of (24) ChanPlaNS targets, to be observed during Cycle 14 (Fig. 6). In the case of X-rays from PN central stars, the preliminary ChanPlaNS results — including the fact that ~70% of the sample PNe that are known to harbor binary central stars also display compact, central X-ray sources — point to binary companions as the likely culprits in many if not most cases. Such an origin would lend support to the working hypothesis that most of the known PNe result from binary interactions (De Marco 2009). On the other hand, ROSAT established that most O stars exhibit X-rays, with the emission arising in self-shocking winds. Perhaps ChanPlaNS is establishing that some PN central stars exhibit the very same phenomenon. Indeed, most of the hard X-ray emitting central stars reside on the horizontal part of their H-R diagram evolution, where the wind power, $\dot{M}v^2$, steadily increases until the "turnaround" towards the white dwarf cooling track (Fig. 6). The ChanPlaNS non-detections then tend to increase beyond this turnaround, where the wind power becomes negligible. Detection statistics for Cycle 14 targets in this region of the H-R diagram, combined with further ground-based optical and HST UV spectroscopic investigations of their central stars, should further establish the contribution (or lack thereof) of winds to the central star X-ray budget.

The search for a potential explanation for the relatively hard emission from PN central stars extends beyond ChanPlaNS, in the form of new analyses of X-rays from the central star within K 1–16 and Abell 30 (both of which are just a bit too distant to be included in the ChanPlaNS sample). In our analysis of K 1–16, we invoke non-LTE models of the proto-white dwarf atmosphere, combined with some hot, C-rich circumstellar plasma, to explain the hard X-ray "tail" of the central star (Montez & Kastner 2013, ApJ, in press); in the case of Abell 30, Guerrero et al. (2012) suggest charge exchange or a compact, recently formed hot bubble as potential explanations for its (similar) X-ray spectral energy distribution (SED). The X-ray SEDs of the central stars within these two PNe bear strong similarities to those of a handful of ChanPlaNS sample objects (NGC 246, 1360, and 4361), suggesting promising new directions for X-ray spectral modeling of these and future ChanPlaNS detections of central stars.

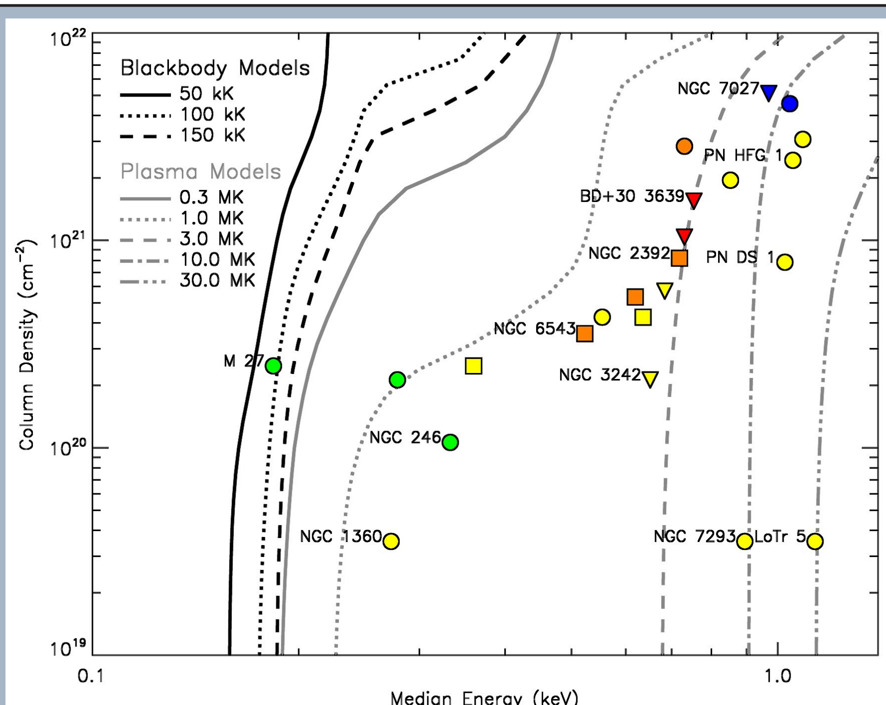

Fig. 5 - Plot of estimated intervening absorbing column density N_H vs. median source photon energy for ChanPlaNS sample PNe detected as either diffuse or point-like X-ray sources (with symbols as in Fig. 3). The N_H estimates are obtained from measurements of the Balmer decrement (Frew 2008). We used a grid of spectral models (absorbed blackbody or absorbed thermal plasma) convolved with the *Chandra*-ACIS-S response to determine model median energies. Clearly, only the central star of the Dumbbell (M 27) can be modeled in terms of simple blackbody emission at temperatures expected of PN central stars; the rest of the central star X-ray sources appear to be affected (in some cases, dominated) by hotter, thermal plasma emission.

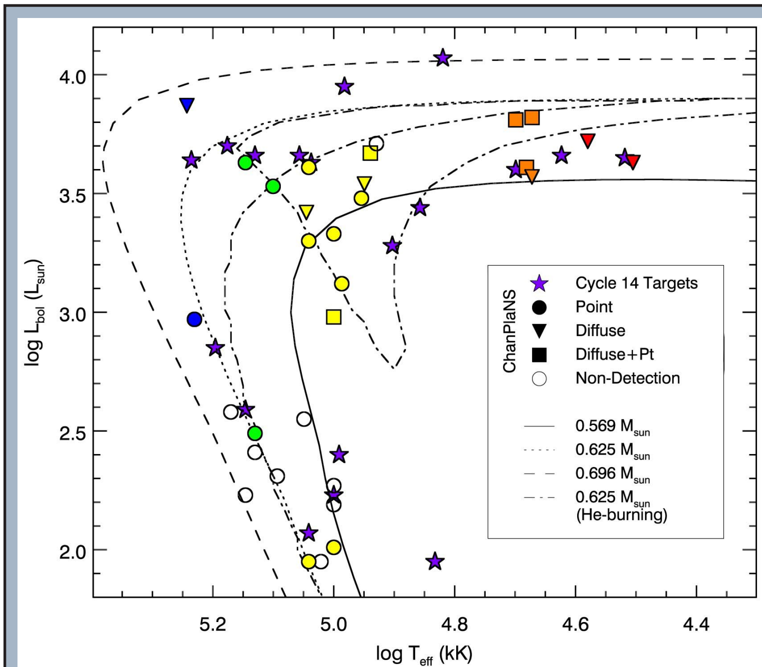

Fig. 6 - HR diagram for central stars of Cycle 12 and archival target PNe, illustrating initial ChanPlaNS results (colored symbols as in Fig. 3 for X-ray detections; nondetections are shown as open circles). The positions of forthcoming (Cycle 14) ChanPlaNS targets are also indicated (as purple stars).

Naturally, it would be beneficial to obtain additional X-ray gratings spectra of additional PN hot bubbles and central stars; BD +30°3639 remains the only PN for which such a gratings study has been published thus far. The Helix and NGC 246 central star X-ray sources are crying out for similar attention. However, most PN X-ray sources are far too faint for gratings observations; even inferences drawn from analysis of the CCD (ACIS) spectra of these objects are likely to be tentative. Still, the growing PN sample size provided by ChanPlaNS affords the opportunity to study an entire class of PNe via, for example, analysis of the composite X-ray spectrum of a set of hot bubbles or central star point sources. In the case of hot bubbles, such investigations should help establish the presence of abundance anomalies of the sort apparent in the gratings spectrum of BD +30°3639 (Yu et al. 2009), thereby shedding light on the as-yet unsolved "low temperature hot bubble" problem. Meanwhile, for central stars, we might be able to tease out differences between abundance patterns and characteristic emission region temperatures for various object classes, thereby distinguishing between the alternative models proposed to explain their hard X-ray "tails."

We hope to obtain *Chandra*/ACIS-S3 observations of the remaining ~60 PNe within ~1.5 kpc in Cycles 15–17, thereby completing a major piece of the multiwavelength observational assault on PNe envisioned in the "Rochester White Paper." Other pieces include (or will include) a parallel *Herschel* Space Telescope Large Program focusing on about a dozen objects selected from among the ChanPlaNS sample PNe ("HerPlaNS"; Ueta et al. 2012), HST Cosmic Origins Spectrograph UV observations of PN central stars, and comprehensive ground-based spectroscopic surveys in the optical & radio, with the Galex and Wide-field Infrared Explorer (WISE) all-sky surveys (as well as the *Spitzer* Space Telescope archive; e.g., Bilikova et al. 2012) filling in the picture in the UV and IR, respectively. Hence, astronomers should expect many new, important insights into stellar wind collisions and stellar (binary) evolution from studies of planetary nebulae during *Chandra*'s second decade.

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