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Pushing the Envelope: X-rays and PN Shaping

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X-ray observations of planetary nebulae (PNe) provide unique insights into the formation and evolution of PNe. We report on two successful pilot programs that explore the connections between PN X-rays and PN shaping. The first program exploits the ever-expanding *Chandra* and *XMM* data archives for serendipitously-observed PNe, and uses these unexpected results to examine the evolution of key physical properties (such as plasma X-ray luminosity, temperature, and density) in hot wind- or jet-blown PN bubbles. The second program investigates X-ray emission from binary central stars in PNe, to assess the potential to detect and characterize binary companions via X-ray observations. The summary of these pilot programs presented here is aimed at motivating future questions and directions.

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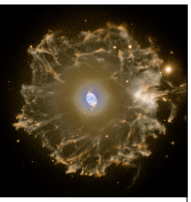

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ABSTRACT

X-ray observations of planetary nebulae (PNe) provide unique insights into the formation and evolution of PNe. We report on two successful pilot programs that explore the connections between PN X-rays and PN shaping. The first program exploits the ever-expanding Chandra (CXO) and XMM data archives for serendipitously observed PNe, and uses these unexpected results to examine the evolution of key physical properties (such as plasma X-ray luminosity, temperature, and density) in hot wind- or jet-blown PN bubbles. The second program investigates X-ray emission from binary central stars in PNe, to assess the potential to detect and characterize binary companions via X-ray observations. The summary of these pilot programs presented here is aimed at motivating future questions and directions.

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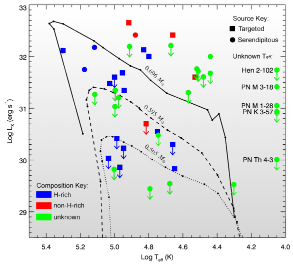

Fig 1: Preliminary sample of all PNe with diffuse X-ray emission or upper limits from the 3-sigma background count rates. The tracks show the evolution of L_X from a hot bubble with heat conduction (Steffen et al. 2008) that can accurately explain the observations.

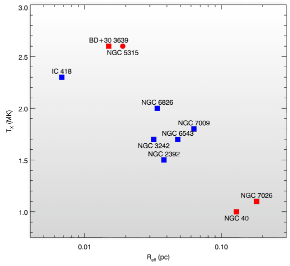

Fig 2: The plasma temperatures and radii of the hot bubble emission detected from PNe (excludes the hot collimated flows found in of NGC 7027 and Hb5). The perceived trend may only be due to the limited sample size.

OVERVIEW

Among the potential sources of X-ray emission from PNe are: hot central stars emitting into the EUV and soft X-ray range (100-400 kK), hot bubbles from the violent interaction of stellar winds (1-3 MK), shock-heated plasma of an active coronae around spun-up companions (5-20 MK), and hot accretion shocks and disks in accreting systems (10-100 MK). Some of the hottest central stars were detected by the ROSAT X-ray observatory and catalogued by Guerrero et al. 2000. Higher energy photons in the spectra of a few of these early discoveries suggested the presence of a hot bubble. However, it wasn't until the next generation of high resolution imaging spectrometers onboard the CXO and XMM X-ray observatories that this shock-heated plasma was securely detected and resolved within PNe.

DIFFUSE X-RAY PROPERTIES

Of the 18-20 PNe targeted by XMM and CXO, about 50% reveal diffuse X-ray emission indicative of a hot bubble. The diffuse X-ray sources (included in Figures 1 and 2) have lower plasma densities and temperatures than predicted by the theoretical treatment of interacting stellar winds. This spurred a number of groups to consider a range of solutions, i.e. slower antecedent winds, rapidly evolving winds (Akashi et al. 2007), collimated winds or jets (Akashi et al. 2008), and heat conduction (Steffen et al. 2008). Although many of these solutions can account for the X-ray properties, assumptions often compromise their credibility. The prevailing solution contends that heat conduction across the hot bubble-PN boundary produces changes in the plasma properties that explain the X-ray properties. However, the application of these heat conduction models are thus far limited to H-rich environments, where the physics of heat conduction and the evolution of the central star are reasonably well understood. Expanding heat conduction theory into H-deficient and chemically enriched environments provides yet another use of PNe as astrophysical laboratories.

SERENDIPITOUS SOURCES

Another limitation is the pitifully small data set available to test and constrain the potential solutions. To combat this limitation we have searched the ever-expanding CXO and XMM data archives for serendipitously observed PNe. In this initial search we found 26 additional PNe observed by CXO and XMM. We have found additional sources, e.g. shock-heated plasma in the multipolar PN NGC 5315 (Kastner et al. 2008) and the bipolar PN Hb5 (Montez et al. 2009), a surprising persistence of X-ray sources in symbiotic systems, and some useful upper limits from non-detections (Figure 1).

X-RAYS FROM BINARY CSPNE

Bond & Livio (1990) argue that PN with dense equatorial waists, often called butterfly PNe, form from a common envelope (CE) ejection immediately following the primary's early AGB phase, while elliptical PNe form from a CE ejection following a later AGB phase. While in the CE, a main sequence companion may accrete angular momentum and mass leading to a spun up envelope that gives rise to coronal emission (Jeffries & Stevens 1996; Soker & Kastner 2002). Coronal X-ray luminosity is strongly correlated with rotation for late-type main sequence stars (Gudel & Naze 2009) and is believed to arise, as in our sun, from dynamo-generated magnetic fields in the star's convective zone. There is a linear increase in the X-ray luminosity with increasing the rotation until saturation is reached at the activity ratio log $L_X/L_{bol} \sim -3$. Higher energy photons are indicative of such activity. The CXO and XMM observatories expand detector sensitivity to these higher energies, opening a new range of tests of the *Binary Hypothesis* on the origin of PNe (De Marco 2009).

CLOSE BINARY NUCLEI OF HFG1 & DS1

The close binary nuclei of HFG 1 (P_{orb}=0.58 days) and DS 1 (P_{orb}=0.35 days) harbor evolved sdO primaries with late-type main sequence companions. We obtained CXO imaging spectroscopy of these two PNe and detected their central stars. The resulting X-ray spectra (Figure 3) are best modeled with two plasma components at different temperatures. Often, two temperature fits are indicative of a range of temperatures present in a source. In particular, the temperatures we find in this binary systems coincide with peaks found in the continuous emission measure distributions (EMD) of nearby active binary systems (Sanz-Forcada et al. 2003). The EMD is perhaps best explained as a number of unresolved, stable, coronal loops, varying from solar-like loops with modest temperatures (~ 2 MK) and densities (~ 10^9 cm^{-3}) to hotter loops (> 8 MK) with higher densities (> 10^9 cm^{-3}) (Cargill & Klimchuk 2006). Hence, the spun-up companions are the most likely sources of the observed X-rays.

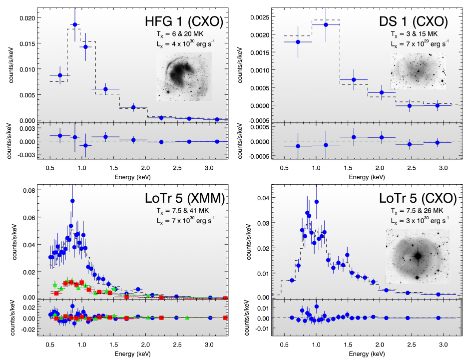

Fig 3: X-ray spectra of binary CSPNe from CXO and XMM. HFG 1 and DS 1 harbor close binary systems and the emission is consistent with similar active binary systems with bright coronal emission. The period of the giant companion in LoTr 5 is unknown, but its rapid rotation is well studied and shows remarkable resemblance to the rapid rotating, active coronae found in other G- and K-giants and RS CVn systems.

GIANT COMPANION IN LOTR 5

The central system in the bipolar PN LoTr 5 is comprised of an evolved sdO primary and a G-type giant. The orbital period of this binary is unknown but the giant is rapidly rotating, with a period of 5.9 days (Strassmeier et al. 1997). X-ray emission has been detected from the CSPN of LoTr 5 via serendipitous CXO and XMM observations. There is compelling and corroborating evidence that the X-ray emission is due to coronal activity of the giant companion. The strongest indicator of such activity is the Ca II H & K emission lines, which are due to chromospheric activity rather than disk-related activity (Jasniewicz et al. 1996). These emission lines are also consistent with the projected rotational velocity of the giant companion, $v \sin i = 67$ km s^{-1} (Strassmeier et al. 1997). The activity ratio, log $L_X/L_{bol} \sim -5$, and projected rotational velocity, $v \sin i \sim 67$ km s^{-1}, are similar to that of other rapidly rotating, intermediate mass, G- and K-type giants with active coronae, both in single systems (Gondoin 2005) and binary systems (Gondoin 2007). According to Gondoin (2007), these giants do not follow the empirical activity-rotation relation for main sequence late-type stars (Pallavicini et al. 1981) and do not appear to reach a saturation level. These results are also similar to those by found by Dempsey et al. (1993a,b) from the rapidly rotating companions in RS CVn systems, where tidal interactions help maintain the rapid rotation beyond that in single stars of a similar age.

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