On the Asymmetries and Temperatures of Extended X-ray Emission from Planetary Nebulae

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ABSTRACT

Chandra X-ray Observatory images have revealed that the X-ray emitting regions of the young planetary nebulae BD +30°3639 and NGC 7027 are much more asymmetric than their optical nebulosities. Furthermore, the spectra of extended X-ray emission from these and other planetaries are surprisingly soft. To evaluate the potential origins of X-ray asymmetries, we compare in detail the X-ray morphologies of BD +30°3639 and NGC 7027 with their optical and IR morphologies and their distributions of visual extinction, as determined from high-resolution, space- and ground-based imaging. The comparison suggests that the observed asymmetries can be explained in large part as due to the effects of intranebular extinction. We consider several processes potentially responsible for the rather low X-ray emission temperatures ($T_x \sim 1 - 3 \times 10^6$ K) characterizing extended X-ray emission from planetary nebulae. The most promising mechanism to simultaneously explain the observed X-ray emission morphologies and temperatures seems to be collimated winds with velocities of $\sim 300 - 500$ km s$^{-1}$. Such winds can be generated by the central star during the post-AGB phase, or by a main sequence companion during the AGB phase of the primary.

Subject headings: stars: mass loss — stars: winds, outflows — planetary nebulae: individual (BD +30°3639, NGC 7027) — X-rays: ISM

1. Introduction

The Chandra X-ray Observatory (CXO) and XMM-Newton have ushered in a new era in the study of X-ray emission from planetary nebulae (PNs). Models of the formation of PNs have long predicted that these objects, representing very late stages in the deaths of
intermediate-mass (1-8 \( M_\odot \)) stars, should emit X-rays. Such emission should arise in shocks at the interface between an active wind from the PN core (or its companion) and material ejected when the progenitor was on the asymptotic giant branch (AGB). Thus, extended X-ray emission, if present, likely traces the very processes responsible for sculpting PNs (for recent discussions of PN shaping mechanisms see, e.g., Frank 1999; Gardiner & Frank 2001; Kastner, Soker, & Rappaport 2000a; and Soker & Rappaport 2000).

The CXO, with its unprecedented spatial resolution, has now provided the first conclusive evidence of such extended X-ray emission from nebular gas, in the form of striking X-ray imagery of the young PNs BD +30\(^\circ\)3639 (Kastner et al. 2000b, hereafter KSVD), NGC 7027 (Kastner, Vrtilek, & Soker 2001a, hereafter KVS), and NGC 6543 (Chu et al. 2001). Observations of the PN NGC 7009 by XMM-Newton, which combines high sensitivity with good spatial and spectral resolution, also reveal marginally extended X-ray emitting gas (Guerrero, Chu, & Gruendl 2002). The PN NGC 7293 (the Helix), known to exhibit relatively hard X-ray emission, does not display evidence for extended emission in CXO imaging (Guerrero et al. 2001); instead, this PN and NGC 6543 contain point-like X-ray sources with temperatures of a few times 10\(^6\) K, possible due to magnetic activity on companions to their central stars (Gruendl et al. 2001; Soker & Kastner 2002).

While revealing the extended nature of the X-ray emission from these objects, these first CXO and XMM-Newton observations of PNs are notable and surprising in several respects. Of particular interest are the results that (1) the X-ray morphologies of the young PNs BD +30\(^\circ\)3639 and NGC 7027 are decisely asymmetric, much moreso than their optical nebulosities, and (2) the characteristic X-ray emission temperatures of these PNs and of NGC 6543 are much lower than expected for shocked fast (\( \geq 700 \text{ km s}^{-1} \)) winds from the central stars.

Indeed, neither the asymmetric X-ray morphologies nor the relatively low X-ray
temperatures of the planetary nebulae detected thus far with CXO are predicted by standard interacting winds theory (for a recent review, see Frank 1999). Such theory predicts a collisionless, radiationless inner shock where stellar winds stop. Outside of this region should lie a large, hot ($\gtrsim 10^7$ K) bubble of very low emission measure. Although the extended emission detected in the CXO images of BD $+30^\circ$3639, NGC 7027, and NGC 6543 underscores the importance of strong shocks in shaping planetaries, the asymmetric structures observed by CXO cannot be easily explained in terms of “fossil” AGB envelopes acted on by isotropic white dwarf winds, even if the fossil envelopes themselves were axisymmetric, as described by Frank (1999). Furthermore, the temperatures of the regions of extended X-ray emission are a factor $3 - 10$ lower than predicted.

The new X-ray observations therefore appear to demand modifications to the standard interacting winds theory. Several such modifications have been proposed previously, most notably, (1) mixing of nebular and fast wind gas and (2) conduction fronts in the presence of magnetic fields. Substantial mixing of the shocked, fast white dwarf wind with nebular material would lower the temperature and increase the density of X-ray emitting material, as observed (Chu & Ho 1995; Arnaud, Borkowski, & Harrington 1996). This mechanism was invoked by Chu et al. (2001) as an explanation for both the low temperature and abundance anomalies apparent in the spectrum of extended X-ray emission from NGC 6543. Alternatively, heat conduction can result in gas temperatures much lower than that of the shocked fast wind and, given the presence of magnetic fields that limit the speed and direction of conduction fronts, can cause strong departures from spherical symmetry (Soker 1994).

In this paper, we further explore these and other potential mechanisms underlying the asymmetries and the relatively low temperatures of extended X-ray emission from PNs. In particular, we examine the role of intranebular extinction in determining the X-ray
morphologies of BD +30°3639 and NGC 7027, which are among the youngest, dustiest, and most molecule-rich of known PNs. We also consider whether collimated winds might generate the X-rays. In §2 we present reprocessed X-ray data and archival optical and near-infrared images that are useful in examining the relationship between X-ray surface brightness and intranebular extinction in BD +30°3639 and NGC 7027. We detail this relationship in §3. In §4, we consider the energetics of X-ray emission from PNs, and we elaborate on mechanisms that might explain the soft spectra of the X-ray emitting regions of BD +30°3639, NGC 7027, and other PNs. In §5, we present conclusions.

2. Data

2.1. Optical and Infrared Observations

2.1.1. BD +30°3639

Images of BD +30°3639 in the transitions of Hα (0.6563 µm) and Pα (1.87 µm) utilized in the present analysis (§3) were obtained with the *Hubble Space Telescope* using the WFPC2 and NICMOS cameras, respectively. These images appear in Fig. 1. The Hα and Pα images were first presented in Sahai & Trauger (1998) and Latter et al. (2000a), respectively; in addition, HST narrow-band images covering many diagnostic emission lines were presented in Arnaud et al. (1996) and Harrington et al. (1997). The reader is referred to these papers for details concerning the structure and physical conditions of BD +30°3639 as ascertained from HST imaging. As is readily apparent from Fig. 1, however, the inner nebula consists of a bright elliptical shell with major and minor axes of \( \sim 4'' \) and \( \sim 3'' \), respectively (this inner nebula is surrounded by a much larger, fainter halo; Sahai & Trauger 1998). There is a strong gradient in extinction across this region of the nebula, with many conspicuous knots and clumps of denser gas apparent in projection against the
bright elliptical shell (Harrington et al. 1997).

2.1.2. NGC 7027

Images of NGC 7027 in the transitions of Br\(\gamma\) (2.16 \(\mu\)m) and Br\(\alpha\) (4.05 \(\mu\)m) utilized in the present analysis (§3) were obtained with the National Optical Astronomy Observatories 4 m telescope and Cryogenic Optical Bench (COB) at Kitt Peak National Observatory in 1995 September (for details concerning COB imaging on the 4 m, see Weintraub et al. 1996). These images appear in Fig. 2. Like BD +30\(^{\circ}\)3639, NGC 7027 displays a bright, elliptical shell, with a fainter surrounding halo; the major and minor axes of the shell are \(\sim 10''\) and \(\sim 7''\), respectively. While extensive near-infrared imagery of NGC 7027 has been obtained in the 2–3 \(\mu\)m wavelength range (e.g., Graham et al. 1993; Kastner et al. 1994, 1996; Latter et al. 2000b; Cox et al. 2002), the Br\(\alpha\) image presented here represents the longest wavelength image of the nebula presently available at \(\sim 1''\) resolution. As we demonstrate in §3, this image is valuable for examining, at high spatial resolution, highly obscured regions of the nebula.

2.2. X-ray Observations

BD +30\(^{\circ}\)3639 and NGC 7027 were observed by CXO in 2000 March and 2000 June, with net integration times of 18.8 ks and 18.2 ks, respectively. Both PNs were imaged with the central back-illuminated CCD on the Advanced CCD Imaging Spectrometer (ACIS-S3). These observations were first presented in KSVD and KVS. In this paper, we make use of broad-band (0.3 keV to 3.0 keV) images constructed from event data as reprocessed by the Chandra X-ray Center (CXC) in 2000 December for BD +30\(^{\circ}\)3639 and in 2001 January for NGC 7027 (Figs. 3 and 4, respectively). The absolute astrometry of the reprocessed data
is improved over that available to KSVD and KVS, due to refined aspect solutions. For BD +30°3639, the relative alignment of the Pα and reprocessed CXO images agrees to within $\sim 0.5''$, based on comparison of the outlying CXO image contours with the elliptical shell seen in Pα (Fig. 3, right). For NGC 7027, we have adjusted the position of the X-ray image by $\sim 1''$, to better align the positions of peak X-ray surface brightness with the bright elliptical shell in the Brα image (Fig. 4, right). The resulting overlays of reprocessed X-ray images on infrared images indicate: (a) the central stars of both PNs are confirmed to lie very near the center of their X-ray nebulosities; and (b) unlike both NGC 7293 and NGC 6543 (Guerrero et al. 2001), neither BD +30°3639 nor NGC 7027 clearly contains an X-ray-bright central star (a possibility left open for NGC 7027 by the preliminary analysis of KVS).

3. X-ray Surface Brightness vs. Optical/IR Extinction

Assuming Case B recombination, the hydrogen emission line ratios $I_{H\alpha}/I_{P\alpha}$ and $I_{Br\gamma}/I_{Br\alpha}$ are relatively insensitive to temperature in the regime of interest for planetary nebulae, $T \sim 10^4$ K (e.g., Osterbrock 1989, Table 4.2). Therefore, we can assume that deviations of the observed line ratios from their “canonical” Case B recombination values are due to extinction. Hence, assuming a standard interstellar dependence of extinction on wavelength (e.g., Osterbrock 1989, Table 7.2), we use the spatial distribution of the ratios $I_{H\alpha}/I_{P\alpha}$ and $I_{Br\gamma}/I_{Br\alpha}$, as derived from the ratios of images presented in §2.2, to infer visual extinction ($A_V$) as a function of position within BD +30°3639 (Fig. 5) and NGC 7027 (Fig. 6), respectively.

Harrington et al. (1997) and Robberto et al. (1993) employed techniques similar to the preceding, to infer the spatial distribution of $A_V$ for BD +30°3639 and NGC 7027. Their results are qualitatively similar to those derived here. The extinction across both
nebulae can be quite large, however, and use of near-infrared images provides a better “lever arm” for deducing $A_V$ in very highly obscured regions. For example, the Robberto et al. extinction map of NGC 7027, constructed from optical hydrogen recombination line imaging, is limited to regions with $A_V < 5$, whereas the $A_V$ map constructed from longer-wavelength hydrogen transitions available to COB (Fig. 6) remains sensitive to $A_V \sim 15$.

The distributions of $A_V$ are similar for the two nebulae, in that the largest values of extinction lie near the nebular perimeters, and extinction “holes” are observed toward the nebular interiors. Generally, however, we find $A_V$ within NGC 7027 (for which $A_V$ lies largely between the range $1.5 \lesssim A_V \lesssim 15$) to be a factor 3-4 larger than $A_V$ within BD $+30^\circ 3639$ (for which $0.5 \lesssim A_V \lesssim 5$). Also, the dark lane apparent in high-resolution optical images of NGC 7027 (e.g. KVS, their Fig. 1) appears as an enhancement of $A_V$ in Fig. 6. This is consistent with the hypothesis (KVS) that BD $+30^\circ 3639$ and NGC 7027 share a common structure — bipolar, with a dense equatorial region — but that NGC 7027 is viewed at intermediate inclination angle whereas BD $+30^\circ 3639$ is viewed nearly pole-on.

Notably, the X-ray surface brightnesses of both nebulae are strongly anticorrelated with the local value of $A_V$. In each case, the peak of X-ray emission lies very near the minimum in $A_V$, and little or no X-ray emission is observed toward regions of highest $A_V$. There is a gradient of $A_V$ in interior regions of BD $+30^\circ 3639$ (i.e., regions of the nebula interior to the bright shell seen in H recombination lines), such that there is greater extinction toward the southwestern side of the central star (a result independently obtained by Harrington et al. 1997), and there is an extinction “hole” 1-2″ to the eastern side of the central star. The X-ray emission, correspondingly, is much brighter to the east than to the west of the star (Fig. 5). In NGC 7027, the relationship between $A_V$ and X-ray surface brightness is perhaps even more striking, with the lowest contours of X-ray emission very closely tracing
the regions of large $A_V$ (Fig. 6). In particular, the “pinched waist” apparent in the X-ray emission morphology lies at the position of the enhancement of $A_V$ that appears to define the equatorial plane of the nebula. Also, the strongest X-ray emission from NGC 7027 lies very near — though slightly farther from the central star than — the extinction “hole” apparent to the northwest of the star.

4. Discussion

In this section, we consider the energetics of shocked winds from PNs in the light of the available X-ray results, and we examine the mechanisms that might explain X-ray asymmetries and unexpectedly low X-ray emitting region temperatures. Before doing so, we briefly re-examine the distances to and properties of the central stars of BD $+30^\circ 3639$ and NGC 7027.

4.1. Nebular Distances and Central Star Properties

Assuming a distance of $d = 2.68$ kpc to BD $+30^\circ 3639$, Leuenhagen, Hamann, & Jeffery (1996) find the central star luminosity and radius to be $5 \times 10^4 L_\odot$ and $3.3 R_\odot$, respectively, and the fast wind mass loss rate to be $\dot{M}_f = 1.3 \times 10^{-5} M_\odot$ yr$^{-1}$. The fast wind velocity is $v_f = 700$ km s$^{-1}$. Given such a high luminosity, the central star most likely would be the descendant of a massive main sequence star, and the object’s status as a PN would be in doubt. However, for a distance of 2.68 kpc, BD $+30^\circ 3639$ would also be 230 pc from the galactic plane, quite high for a massive progenitor. In addition, the escape velocity from a star with a mass of $1 M_\odot$ and a radius of $3.3 R_\odot$ is 340 km s$^{-1}$, or only about half the observed wind speed. For a wind speed of 700 km s$^{-1}$, it seems that a more compact object is required (e.g., Marten & Schönberner 1991). We conclude that BD $+30^\circ 3639$ is likely
much closer to Earth than 2.68 kpc.

In the following, we instead adopt a conservative estimate of 1.0 kpc to BD +30°3639. This assumed distance is similar to the estimate of 1.5 kpc adopted by Arnaud et al. (1996), but is more consistent with estimates summarized in the Strasbourg-ESO PN Catalogue (Acker et al. 1992). A distance of 1 kpc rather than 2.68 kpc to BD +30°3639 suggests a much smaller mass loss rate, more compatible with the star’s post-AGB, young PN status. Here, we adopt $\dot{M}_f = 10^{-7} M_\odot \text{ yr}^{-1}$, similar to typical values that are found from IUE observations of central stars of PNs (e.g., Patriarchi & Perinotto 1991; Modigliani, Patriarchi & Perinotto 1993). The central star luminosity would be $\sim 7000 L_\odot$ at a distance of 1.0 kpc.

The distance to NGC 7027 is somewhat less controversial. The widely accepted value is $880 \pm 150$ pc, based on a proper motion study of its expanding shell at radio wavelengths (Masson 1989). Given this distance, and the (very high) temperature inferred for the central star ($T_* \approx 2 \times 10^5$ K), near-infrared HST imaging suggests a central star luminosity of $\sim 8000 L_\odot$ and radius $0.07 R_\odot$ (Latter et al. 2000b). The very similar luminosities of NGC 7027 and BD +30°3639, assuming a distance of 1.0 kpc for the latter, serve as strong evidence that these objects had progenitors of similar initial mass (3–4 $M_\odot$; Blöcker 1995). This would help explain their many observational resemblances. The important differences between the two nebulae — in, e.g., average line-of-sight visual extinction and central star temperature — therefore may be due almost entirely to different viewing angles and a few hundred years of evolution (with NGC 7027 being the “older” PN, according to theoretical evolutionary tracks in Blöcker 1995).
4.2. Theoretical Considerations

4.2.1. Energetics

The total (unabsorbed) X-ray luminosities of both BD +30°3639 and NGC 7027 are $L_x \simeq 10^{32}$ erg s$^{-1}$ (0.3-3.0 keV; KSVD, KVS). The kinetic energy of the fast wind is $\dot{E}_f = \frac{1}{2} \dot{M} v_f^2$, so that for BD +30°3639 we find, given our scaling of parameters,

$$\frac{L_x}{\dot{E}_f} \simeq 3 \times 10^{-3} \left( \frac{\dot{M}}{10^{-7} M_\odot \text{yr}^{-1}} \right)^{-1} \left( \frac{v_f}{1000 \text{ km s}^{-1}} \right)^{-2}$$

Hence, the fast wind from the central star of BD +30°3639 carries much more kinetic energy than that radiated in X-rays. This implies that nebular gas heated by the shocked fast wind does not have time to cool significantly, consistent with the formation of a hot bubble inside the dense shell of BD +30°3639. Similar arguments should apply to NGC 7027, although we caution that no fast wind has been detected for the central star of this PN.

4.2.2. Temperature

As noted in §1, the temperature of extended, X-ray emitting gas in all PNs detected thus far by CXO or XMM-Newton is more than a factor of 3 lower than the expected post-shock temperature, given the speeds of fast winds from hot, compact PN central stars. We now consider six processes that might produce (relatively) low temperature X-ray-emitting gas. The first four involve mechanisms that moderate the temperature of shocked gas produced by interactions between the central star’s isotropic, fast wind and previously ejected, slow-moving nebular gas. The last two invoke a more moderate-speed, collimated wind driven either by the central star or a companion.

(1) **Cold electrons.** In a collisionless shock the ions are much hotter than the electrons. Coulomb equilibration and plasma instabilities will then heat up the electrons.
For conditions appropriate to young PNs, Coulomb equilibration by itself will heat electrons in a relatively short time. Taking a mass loss rate of $10^{-7} \, M_\odot \, yr^{-1}$, a preshock velocity of 1000 km s$^{-1}$, and a shock position of $2 \times 10^{16}$ cm from the central star, we find from equation (3) of Laming (2001) that the electrons will be heated up to $\sim 10^7$ K in $\sim 100$ yr. Plasma instabilities will make the equilibration time much shorter. Therefore, departure from thermal equilibrium is unlikely as a general explanation for the (relatively) cool X-ray-emitting plasma observed in PNs.

(2) Adiabatic expansion. In 3 of 4 PNs for which extended X-ray emission has been detected, this process seems to be ruled out both theoretically and observationally. Theoretically, in order to lower the temperature by a factor of $\sim 3$, the shocked gas should expand such that its density drops by a factor of $\sim 5$. However, if the fast wind in a PN is still active, the ram pressure of the fast wind from inside the nebula, combined with the continued supply of shocked fast wind gas, will prevent adiabatic expansion by such a large factor. Only in older PNs, for which the fast wind has ceased, should this mechanism become significant. The X-ray emission from PN NGC 7009 (Guerrero et al. 2002) may be an example of such adiabatic cooling of X-ray-emitting gas, although we favor heat conduction as a mechanism to explain its relatively low X-ray temperature (see below). Observationally, the X-ray surface brightness of NGC 6543 shows that most of the emission comes from a region close to the dense shell (rim), with little emission from the inner region (Chu et al. 2001). Similarly, there are hints of limb-brightening and/or clumping of X-ray emission toward the rims of BD +30°3639 and NGC 7027. A hot bubble that is cooling adiabatically is expected to fill most of the inner region, and to be more or less homogeneous, in contradiction to the available X-ray imaging.

(3) Mixing of hot and nebular gas. This process, which was discussed by Chu & Ho (1995) for A30 and Arnaud et al. (1996) for BD +30°3639, is likely to take place
when there are many small clumps of optically bright gas in the nebular interior. Gas from these clumps, at $\sim 10^4$ K, is mixed with the fast wind, thereby lowering its temperature. Arnaud et al. (1996) argue that the mixing ratio required to form the cooler X-ray emitting gas should result in elevated oxygen abundances. In contrast, analyses of X-ray spectra of BD +30°3639 (Arnaud et al.; KSVD) and NGC 6543 (Chu et al. 2001) suggest that the X-ray-emitting gas is, if anything, somewhat depleted in oxygen. Thus, while mixing may occur to some extent in certain nebulae, it is unlikely to explain in general the relatively low X-ray emission temperatures of PNs.

(4) Heat conduction. It has been noticed previously that heat conduction can form PN X-ray emission regions having temperatures much lower than that of the shocked fast wind (Soker 1994; Zhekov & Perinotto 1996) and can cause departures from spherical symmetry (Soker 1994; Zhekov & Myasnikov 2000). The heat-conduction front goes through three stages: evaporative, quasi-static, and condensation. During the first two stages, the intermediate temperature region is inside the initially cold gas, while in the third phase it is in the initially hot gas (Borkowski, Balbus, & Fristro 1990). This may explain certain aspects of the observations that are not easily explained by, e.g., mixing of nebular and fast wind material. For example, in the frame of the heat conduction front model, the observed depleted abundance of oxygen in BD +30°3639 suggests that the conduction front in this PN is in one of the first two phases; i.e., it is located in the initially cold (nebular) gas. The interface during the early stages (the evaporation and quasi-static stages) is at a temperature of $T_I \gtrsim 0.4 T_h$, where $T_h$ is the temperature of the hot gas (Borkowski et al. 1990). Therefore, in the heat conduction model, the emitting gas at $T_x \sim 3 \times 10^6$ K is the gas ejected during the AGB phase, consistent with the result that its oxygen abundance is much lower than the present abundance of the central Wolf-Rayet star. In NGC 6543, on the other hand, the abundances are those of the central fast wind (Chu et al. 2001), despite the very low temperature of the X-ray emitting gas (Chu et al.) and the very high
speed of the wind (1750 km s\(^{-1}\); Perinotto, Cerruti-Sola, & Lamers 1989). In the present context, this is explained as a heat conduction front in the condensation phase; that is, the intermediate temperature region lies within the initially hot (fast wind) gas. A similar situation appears to characterize NGC 7009 (Guerrero et al. 2002). Hence, invoking the heat conduction model, we would conclude that the heat conduction fronts in NGC 6543 and NGC 7009 are more evolved than those in BD +30°3639. However, we caution that heat conduction alone cannot easily explain the X-ray emission morphologies of NGC 6543, NGC 7027, or BD +30°3639.

(5) Post-AGB wind. To produce shocks with characteristic temperatures \(T_x \approx 2 - 3 \times 10^6\) K, the wind speed should be only a few hundred km s\(^{-1}\). Such a “moderate speed” wind likely arises in the central star’s late post-AGB phase, as the star traverses the H-R diagram (e.g., Kastner et al. 2001b). Arnaud et al. (1996) have proposed that a moderate-speed wind, generated at the post-AGB phase, is the source of the X-ray emitting gas in BD +30°3639. Whereas the shocked moderate-speed gas cools very quickly, the high speed gas cools slowly and emits at a low rate per unit volume. Therefore, even if a fast wind is present, the dominant X-ray emission would still come from gas originating in a moderate-speed, post-AGB wind driven at \(\sim 300 - 500\) km s\(^{-1}\). This mechanism, if responsible for the X-ray emitting gas, predicts that most, if not all, PNs will display extended, low-\(T_x\) X-ray emission during early phases of their evolution (i.e., during protoplanetary and very young planetary nebula phases).

(6) Collimated wind from a companion. A main sequence companion outside the progenitor AGB star may accrete from the AGB wind, forming an accretion disk and driving jets or a collimated wind at speeds of \(\sim 200 - 600\) km s\(^{-1}\) — sufficient to explain both the temperature and morphology of the extended X-ray emission from, e.g., NGC 7027. Such a mechanism, described in detail by Soker & Rapaport (2000), would be similar
to that thought responsible for X-ray emission apparently associated with protostellar outflows (e.g., Pravdo et al. 2001; Favata et al. 2002) and for the collimated X-ray-emitting jets in the symbiotic binary system R Aqr (Kellogg, Pedelty & Lyon 2001). Interestingly, the temperatures of the X-ray-emitting plasms in these systems are similar to those in X-ray-emitting young PNs, i.e., $\sim 10^6$ K. The observations of R Aqr are perhaps most relevant, as symbiotic binaries are frequently associated with PNs displaying pronounced bipolar structure. If such a companion-driven, collimated wind is responsible for the X-ray emission in young PNs, then the X-ray emission should be confined to the polar regions, as is indeed observed in NGC 7027, NGC 6543, and, possibly, BD $+30^\circ 3639$. In this scenario, furthermore, the X-ray emission properties of most elliptical PNs, which have no collimated winds, should be very different from those of bipolar PNs (although some elliptical PNs may have been shaped by main sequence companions which generated a collimated wind; Soker 2001).

In the case of NGC 7027, it seems unlikely that a moderate-speed ($\sim 400$ km s$^{-1}$), collimated wind could be driven by the present central star, as such a wind speed is much smaller than the escape velocity from a star of mass of $0.7 M_\odot$ and radius $0.07 R_\odot$ (Latter et al. 2000b). Intriguingly, a collimated outflow with a morphology very similar to that of the X-ray emission is evident in velocity-resolved near-infrared (Br$\gamma$) imaging of NGC 7027 (Cox et al. 2002). As noted by Cox et al., if this outflow is in fact the same wind that is responsible for generating the X-ray-emitting gas in NGC 7027, then the observed outflow velocity ($\sim 55$ km s$^{-1}$) suggests the moderate speed wind is nearly perpendicular to our line of sight.
5. Conclusions

In this paper, we have investigated mechanisms that might explain the recent discoveries of asymmetric, low-temperature X-ray emission from young planetary nebulae. We used high-resolution, space- and ground-based imaging to compare the X-ray and optical/IR extinction morphologies of the PNs BD +30°3639 and NGC 7027. We find a striking correspondence between the spatial distribution of $A_V$ and the X-ray surface brightnesses of these nebulae. From these results we conclude that — whatever the mechanism responsible for their low X-ray emission temperatures — intranebular extinction plays a very important role in determining the X-ray emission morphologies of young, dusty PNs. The close correspondence of regions of low extinction and bright X-ray emission in both nebulae suggests that some extended X-ray emission may remain undetected, making it difficult to draw conclusions as to the intrinsic shape (e.g., axisymmetric vs. elliptically symmetric) of the emitting regions.

We reviewed six mechanisms that might explain the low temperatures of extended X-ray emission from all PNs detected thus far by CXO and XMM-Newton. We rule out departure from energy equipartition between electrons and ions, as well as adiabatic cooling. Mixing between the shocked hot gas and the cold nebular gas might occur, but does not seem to be capable of explaining low-temperature X-ray emission in all cases. Heat conduction also has the potential to explain some (though probably not all) of the X-ray emission at lower temperatures, as well as some variations in the abundances of the X-ray emitting gas, as heat conduction fronts move from the nebular gas to an interior “hot bubble.”

The most promising mechanisms to explain the low temperatures of X-ray emitting gas involve collimated winds (or jets) driven at velocities of $\sim 400 \text{ km s}^{-1}$. We considered two possible sources for such winds: the central star, during its late post-AGB phase, or a
collimated wind from a companion. At present, it is not possible to distinguish between these alternatives; it may be that different collimated, moderate-speed wind mechanisms operate in different PNs.

Under either of the “collimated wind” scenarios, it seems likely that the X-ray emission from a young planetary traces an important epoch in the transition from spherical to non-spherical mass loss. That is, it is possible that, in the X-ray images of BD +30°3639 and NGC 7027, we are witnessing the disruption of the spherically and elliptically symmetric structures seen in optical and infrared emission line images of these nebulae. High-resolution X-ray imaging of other, similar objects should help clarify if such a process is widespread among young PNs. Sensitive X-ray observations of a much larger sample of PNs — including spherical, or almost spherical, nebulae, for which no collimated central star winds are expected — would establish the importance of such winds in generating extended X-ray emission from PNs in general.

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Fig. 1.— *Hubble Space Telescope* Hα 0.6563 μm (left) and Pa 1.87 μm (right) images of BD +30°3639 obtained with WFPC2 and NICMOS, respectively.
Fig. 2.— Brγ 2.16 µm (left) and Brα 4.05 µm (right) images of NGC 7027, obtained with the Cryogenic Optical Bench on the Kitt Peak 4 m telescope.
Fig. 3.— Left: CXO X-ray image of BD +30°3639. Right: Contours of X-ray surface brightness overlaid on the P\(\alpha\) image of Fig. 1. Contour levels are at 5, 15, 40, 80, 120, 160, and 200 counts pix\(^{-1}\). In this Figure and in Fig. 4, the CXO image has been convolved with a Gaussian function with width approximating that of the instrumental point spread function.
Fig. 4.— Left: CXO X-ray image of NGC 7027. Right: Contours of X-ray surface brightness overlaid on the Br$\alpha$ image of Fig. 2. Contour levels are at 2, 4, 6, and 10 counts pix$^{-1}$. In each panel, offset (0,0) corresponds to the position of the central star to $\sim 0.2''$ (as determined from comparison of the Br$\alpha$ image with HST near-infrared imagery; Latter et al. 2000).
Fig. 5.— Overlay of CXO X-ray image (contours) on extinction map of BD +30°3639 (color).
Fig. 6.— Overlay of CXO X-ray image (contours) on extinction map of NGC 7027 (color).