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# High-resolution X-ray Spectroscopy of BD +30°3639

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**Abstract.** We present preliminary results from the first X-ray gratings spectrometer observations of a planetary nebula (PN). We have used the Chandra X-ray Observatory Low Energy Transmission Gratings Spectrometer (LETGS) to observe the bright, diffuse X-ray source within the well-studied BD +30°3639. The LETGS spectrum of BD +30°3639 displays prominent and well-resolved emission lines of H-like C, O, and Ne and He-like O and Ne. Initial modeling indicates a plasma temperature $T_X \sim 2.5 \times 10^6$ K and abundance ratios of C/O $\sim$ 20, N/O $\lesssim$ 1, Ne/O $\sim$ 4, and Fe/O $\lesssim$ 0.1. These results suggest that the X-ray-emitting plasma is dominated by the shocked fast wind from the emerging PN core, where this wind gas likely originated from the intershell region of the progenitor asymptotic giant branch star.

**Keywords.** stars: mass loss, planetary nebulae: individual (BD +30°3639), X-rays: individual (BD +30°3639)

## 1. Introduction

The Chandra X-ray Observatory (CXO) and XMM-Newton X-ray Observatory have ushered in a new era in the study of X-ray emission from planetary nebulae (see review by Guerrero in these proceedings), providing new insight into wind-wind interactions in PNs. The CXO and XMM discoveries of diffuse X-ray emission within PNs such as BD +30°3639 (Kastner *et al.* 2000), NGC 6543 (Chu *et al.* 2001), NGC 7009 (Guerrero *et al.* 2002), and NGC 40 (Montez *et al.* 2005) are indicative of the interaction of a quasi-spherical fast wind from the newly unveiled central star with the former asymptotic giant branch (AGB) wind, whereas the X-ray morphologies of NGC 7027 (Kastner *et al.* 2001) and Menzel 3 (Kastner *et al.* 2003) are indicative of the presence and shaping action of collimated outflows.

The source of the X-ray emitting gas in PNs remains to be determined, however. It is thus intriguing that the X-ray data provide indications of significant abundance anomalies in the superheated plasma within PNs. In particular, greatly enhanced abundances of O and Ne and a large depletion of Fe (relative to solar) are suggested by CCD X-ray spectroscopy of BD +30°3639 (Arnaud *et al.* 1996; Kastner *et al.* 2000; Maness *et al.* 2003). These results stand in sharp contrast to observations at optical and infrared wavelengths, which show depleted Ne in the optically bright shell of this PN. Indications of abundance anomalies are also observed in NGC 6543 (Chu *et al.* 2001) and NGC 7027 (Maness *et al.* 2003). On the other hand, Georgiev *et al.* (2006) contend that the extant X-ray CCD spectra cannot provide useful constraints on the abundances of X-ray-emitting plasmas within PNs. Indeed, the various analyses cited above have arrived at very different results concerning plasma adundances within the hot bubble of BD

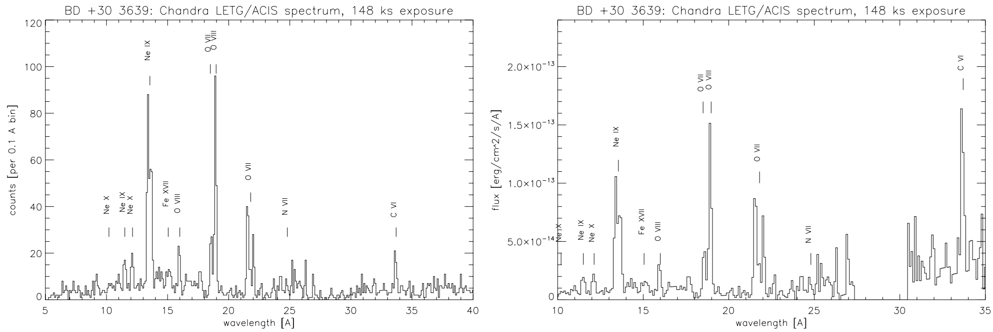


**Figure 1.** *a)* Combined positive and negative first-order LETG/ACIS-S counts spectrum of BD +30°3639. *b)* Flux-calibrated first-order LETG/ACIS-S spectrum, in energy units. The apparent rising "continuum" at $\lambda > 25$ Å is likely the result of low photon detection efficiency combined with incomplete background subtraction.

+30°3639, indicative of the large uncertainties inherent in spectral modeling that relies on relatively low resolution X-ray CCD spectra.

To make progress on these and other problems that have surfaced as a consequence of the recent X-ray detections of PNs by CXO and XMM, we require observations combining high spatial and spectral resolution, so as to infer gas temperature and composition as a function of position within the X-ray emitting plasma. Just prior to this conference, we obtained such an observation of the well-studied BD +30°3639 – the brightest diffuse X-ray source among PNs – using Chandra's Low Energy Transmission Grating Apectrometer in combination with its Advanced CCD Imaging Spectrometer (LETG/ACIS-S). Here, we report on preliminary results obtained from this, the first X-ray grating spectrometer observation of a planetary nebula.

## 2. Observations and Results

We obtained the first of two 150 ks LETG/ACIS-S observations† of BD +30°3639 in 2006 February (86 ks) and March (61 ks). We used standard Chandra X-ray Center spectral calibration and analysis tools‡ to update calibrations and to extract and merge the first-order LETG spectra. Defaults were used for all spectral extraction parameters (e.g., cross-dispersion region width and first-order event pulse height ranges) except for the spectral bins, which were rebinned to 0.126 Å. Corresponding LETG/ACIS-S spectral sensitivity and spectral resolution calibration files were constructed in parallel with the spectral extraction.

Fig. 1a shows the resulting, first-order LETG/ACIS-S counts spectrum of BD +30°3639. The brightest lines in the spectrum, in terms of total counts, are the resonance line of O VIII ($\lambda$ 18.97), the He-like triplet line complex of Ne IX ($\lambda\lambda$ 13.45, 13.55, 13.7), and the He-like triplet of O VII ($\lambda\lambda$ 21.60, 21.80, 22.10). The resonance line of C VI ($\lambda$ 33.6) is also detected, as are various other, weaker lines of H-like and He-like O and Ne. Lines of H-like N (e.g., the resonance line at $\lambda$ 24.78) and highly ionized Fe are notably weak or absent. The flux-calibrated spectrum, obtained as the efficiency-weighted average of the positive and negative first-order spectra after correction for their respective efficiencies, is displayed in Fig. 1b. The strength of C VI relative to the strongest lines of Ne IX, O VII, and O VIII is apparent in this flux-calibrated spectrum.

† The second 150 ks observation is presently scheduled for 2007 January.
‡ http://cxc.harvard.edu/ciao/

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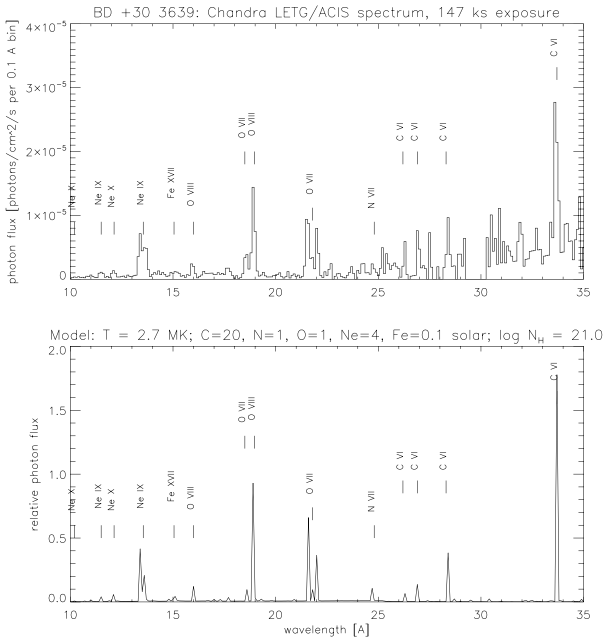


**Figure 2.** Observed LETG/ACIS-S spectrum of BD +30°3639 in photon flux units *(top panel)* and ISIS model *(bottom panel)*.

Theoretical ratios for the resonance lines of H-like to He-like species of O and Ne obtained from the Astrophysical Plasma Emission Database (APED¶; Smith *et al.* 2001) as well as the "G ratio" calculated from the triplet complex of He-like O VII (Smith *et al.*) indicate a plasma temperature in the relatively narrow range $T_x = (2.4 - 2.8) \times 10^6$ K. In light of these results for $T_x$, we used the Interactive Spectral Interpretation System (ISIS‖) to construct a series of APED models of varying plasma elemental abundances with $T_x$ fixed at $2.7 \times 10^6$ K and the intervening absorbing column fixed at $\log N_H(\mathrm{cm}^{-2}) = 21.0$ (the latter constraint is based on results from ACIS-S X-ray CCD spectroscopy, and is consistent with measurements of visible-wavelength extinction; Arnaud *et al.* 1996, Kastner *et al.* 2000). With $T_x$ and $N_H$ so constrained, we find good agreement between data and model for abundance ratios (relative to solar) of C/O = 20, Ne/O = 4, N/O = 1, and Fe/O = 0.1 (Fig. 2). The last two abundance ratios should be interpreted as upper limits, as the N and Fe lines are not well detected. Although these results (and, in particular, the inferred C/O ratio) are somewhat dependent on the assumed value of $N_H$, we estimate a relatively firm upper limit of C/O $\sim 40$, corresponding to $\log N_H(\mathrm{cm}^{-2}) = 21.4$ (the largest value of $N_H$ obtained from X-ray CCD spectroscopy of BD +30°3639; Maness *et al.* 2003). We also cannot yet rule out the presence of a lower-$T_x$ component in the plasma, in which case the C/O abundance ratio would still be enhanced but is very unlikely to be $> 20$ with respect to solar.

## 3. Discussion

The sharply non-solar composition of the shocked, X-ray-emitting plasma in BD +30° 3639 strongly suggests this gas originated in an AGB star "intershell" region (Herwig

¶ http://cxc.harvard.edu/atomdb/
‖ http://space.mit.edu/CXC/ISIS/

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2005 and references therein). Specifically, the measured C overabundance corresponds to a C/O number ratio of $\sim 10$ (as compared with C/O $\sim 1.6$ in the nebular gas; Pwa *et al.* 1986). This C/O number ratio is consistent with the predictions of models that describe He shell burning and subsequent dredge-up into the layer between the He- and H-burning shells of the former AGB star. In addition, the combination of strong Fe depletion and Ne enhancement can be readily explained as due to the $s$ process within the "pulse-driven convection zone" (PDCZ) associated with the He-burning shell within the former AGB star. Formation of excess Ne would occur due to alpha capture on $^{14}$N and then $^{18}$O. The resulting $^{22}$Ne then serves as a neutron source for the $s$ process within the PDCZ, thereby depleting Fe.

The temperature of shocked gas probed by lines of H- and He-like O and Ne is $T_x \sim 2.5 \times 10^6$, confirming an earlier estimate of $T_x$ we obtained by modeling the lower-resolution X-ray CCD spectrum of BD +30°3639 (Kastner *et al.* 2000). This plasma temperature is lower than expected from a simple adiabatic shock model, given the present central star wind speed of $v_f \sim 700$ km s$^{-1}$. Among the numerous potential explanations for this discrepancy (see Soker & Kastner 2003 and references therein), mixing of nebular gas with the shocked fast wind appears to be ruled out as a plasma "coolant", given the highly non-nebular abundance signatures apparent in the LETG/ACIS-S spectrum. On the other hand, these observations cannot rule out heat conduction as a mechanism for moderating $T_x$; further numerical calculations like those conducted by Schoenberner *et al.* (these proceedings) should examine this mechanism, in light of our results. It also remains possible that the shocked wind presently seen radiating in X-rays was ejected at an earlier epoch, when the fast wind velocity was lower ($v_f \sim 450$ km s$^{-1}$); such an explanation, initially proposed by Arnaud *et al.* (1996), has recently been elaborated on by Soker & Kastner (2003) and Akashi *et al.* (2006).

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