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

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Summary. We present preliminary results from high resolution X-ray gratings spectrometer observations of the planetary nebula (PN) BD+30°3639. We observed this X-ray bright, young PN for 300 ks in 2006, using the Chandra X-ray Observatory's Low Energy Transmission Gratings in combination with its Advanced CCD Imaging Spectrometer (LETG/ACIS). The well-resolved emission lines in the dispersed spectrum and the spatial structure in the 0th order image provide constraints on the origin of the X-ray emitting plasma and the processes responsible for the structure of the nebula, respectively.

Key words: stars: mass loss, planetary nebulae: individual (BD+30°3639), X-rays: individual (BD+30°3639)

1 Introduction

The Chandra X-ray Observatory (CXO) and the XMM-Newton X-ray observatories have observed and detected many planetary nebulae (PNe) since their launches, providing new constraints on PN shaping mechanisms (see review by Kastner, these proceedings). To make further progress in our understanding of the physical processes governing the origin and shaping of PNe, sensitive X-ray observations at very high spatial and spectral resolution are essential.

BD+30°3639 is a well known, X-ray bright compact PN with a carbon-rich Wolf-Rayet ([WC]-type) central star. It is relatively nearby (distance 1.2 kpc; Li et al. 2002), and has a young dynamical age ($\sim$ 700 yr; Li et al. 2002). Kastner et al. (2000) reported well-resolved, extended X-ray emission in an image of BD+30°3639 obtained using Chandra's Advanced CCD Imaging Spectrometer (ACIS). These results serve as strong evidence of the existence of a hot bubble created via shocked wind interactions, although one cannot rule out other possibilities, such as the influence of a close companion (Bachiller et al. 2000; Soker & Kastner 2003). Furthermore, the source and precise (evidently non solar) abundances of the X-ray emitting gas in BD+30°3639 remain to be determined (Maness et al. 2003; Georgiev et al. 2006).

To adequately address the question of abundance anomalies in the X-ray-emitting plasma of BD+30°3639, and to understand the nature of this X-ray-emitting region, we need to exploit higher resolution X-ray spectroscopy and imaging.

2 Observation and data analysis

We obtained observations of BD+30°3639 totaling 300 ks exposure time with the Low Energy Transmission Gratings (LETG) and ACIS in 2006 February (85.4 ks), March (61.8 ks) and December (53.9 ks, 77.1 ks and 19.9 ks). In addition to the dispersed spectrum ($\sim$ 5800 counts), the 300 ks observation with LETG/ACIS produced a highly sensitive, undispersed 0th order image ($\sim$ 6000 counts). The data were subject to standard processing by Chandra X-ray Center pipeline software (CIAO, ver. 3.4). To optimize the spatial resolution of the 0th order image, we removed pixel randomization, and then applied subpixel event position corrections and maximum likelihood deconvolution (Li et al. 2003). We extracted the dispersed X-ray spectrum of BD+30°3639 as described in Kastner et al. (2006).

3 Results

3.1 LETG/ACIS 0th-order Image

In both the 2000 and 2006 Chandra/ACIS images, BD+30°3639 shows apparently compact and bright emission toward the east-northeast and weaker emission toward the southwest (Figure 1, top four panels). To determine whether the apparent variations between 2000 and 2006 observations (and between the two epochs of the 2006 observation) are real, we formed difference images and divided each by its respective root mean square error image (Fig. 1, bottom two panels). In contrast to the "salt and pepper" appearance of the 1st vs. 2nd epoch 2006 difference image, the 2006−2000 difference image exhibits a general trend wherein the nebula is brighter around the rim and fainter in the center. This trend is suggestive of an expansion signature, but even the largest measured changes are at somewhat less than the $\sim 3\sigma$ level. The other, more subtle variations in both difference images are only measured at the $< 2\sigma$ level, i.e., well within the range expected due to photon counting statistics.

3.2 LETG/ACIS Dispersed Spectrum

Figure 2a shows the merged, 300 ks exposure, 1st-order LETG/ACIS counts spectrum of BD+30°3639 overlaid with a model spectrum obtained from the Astrophysical Plasma Emission Database (APED; Smith et al. 2001; see below). The brightest lines in the spectrum are the resonance lines of H-like O VIII (λ 18.97) and C VI (λ 33.6) and the He-like triplet line complexes of Ne IX (λ 13.45, 13.55, 13.7) and O VII (λ 21.60, 21.80, 22.10). Other H-like resonance lines, such as N VII (λ 24.78), and

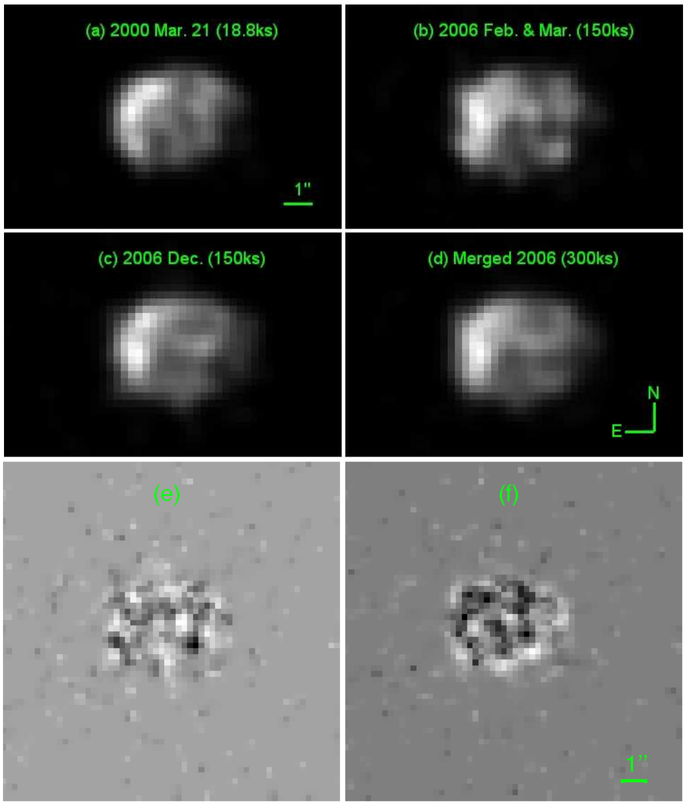

Fig. 1. X-ray images (0.3 - 3.0 keV) of BD+30°3639. Panels a-d show the 2000 and 2006 images on a linear grey scale, with the dates of data acquisition indicated. Error-normalized difference images are displayed in the bottom two panels (2nd minus 1st epoch 2006, panel e; 2006 minus 2000, panel f). The linear grey scale in these difference ranges from -3σ to $+3\sigma$.

lines of highly ionized Fe, are weak or absent. The flux-calibrated spectrum makes apparent the strength of C VI (λ 33.6) relative to the other strong lines (Ne IX, O VII and O VIII; Figure 2b).

To investigate plasma physical conditions, we used the Interactive Spectral Interpretation System (ISIS; Houck & Denicola 2000) to construct APED models with varying plasma elemental abundances and with O fixed at solar. With respect to solar abundances (Anders & Grevesse 1989), the preliminary model fitting indicates that C is very overabundant (C/O $\sim$ 50) and Ne is overabundant (Ne/O $\sim$ 4.5) but Fe and N are quite depleted (Fe/O and N/O $\sim$ 0.3). We note that the high N/O ratio inferred by Murashima et al. (2006) from Suzaku satellite X-ray CCD spectra might be caused by contamination from high order C VI lines clearly seen in the LETGS spectrum between 25 $\sim$ 26 Å (Figure 2). The plasma temperature obtained from the fitting, $\sim 2.3\times10^6$ K, is somewhat lower than the lower limit obtained from

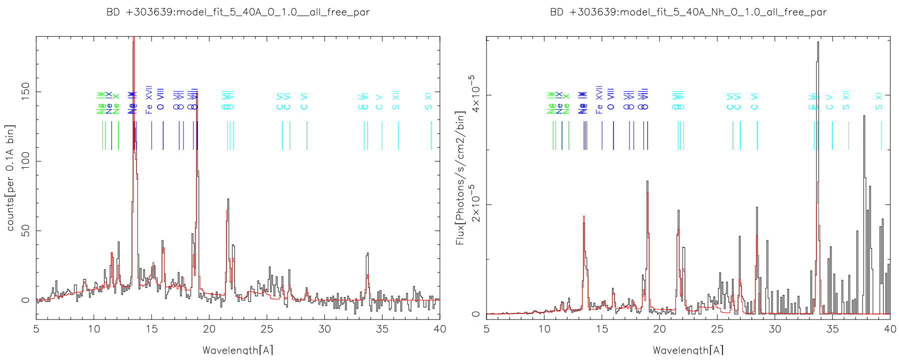

Fig. 2. (a) Combined positive and negative first-order LETG/ACIS-S counts spectrum of BD+30°3639 overlaid with a representative APED model. (b) Flux-calibrated first-order LETG/ACIS-S spectrum. In each panel, black shows the source spectrum and red indicates the model.

preliminary model fits to the first 150 ks LETG/ACIS exposure by Kastner et al. (2006). The derived intervening absorbing column is log $N_H \sim 21.4$ (cm^{-2}).

4 Discussion

Kastner et al. (2000) had previously demonstrated that the well resolved and extended region of X-ray emission from BD+30°3639 is fully contained within the interior of the photoionized bright rim seen in optical and IR images. Our new X-ray image (figure 1) shows a consistent result.

The comparison of the 2000 and the merged 2006 images in Figure 1 (panels a and d) suggests a change in the intensities and positions of the X-ray "hot spot" and other X-ray bright blobs inside the nebulae over the past 6 years. However, we find these changes are most likely due to photon counting statistics. The merged 2006 image appears slightly ($\sim 0.5''$) wider than the 2000 image, suggesting an expansion speed of ~ 200 km s^{-1} for the X-ray nebula. Such a large expansion velocity is not expected theoretically; the "hot bubble" formed by the interaction of fast (post-AGB) and slow (AGB) winds should expand at approximately the same speed as the bright rim of optical nebulosity (~ 50 km s^{-1}). Hence, we tentatively attribute the apparent expansion signature to the somewhat greater sensitivity (greater total counts) of the (300 ks, 0th-order) 2006 image relative to the 2000 image; further study is required.

The products of nucleosynthesis in the progenitor AGB star (see review in Herwig 2005) likely play an important role in the non solar composition of the shocked, X-ray emitting gas in BD+30°3639. Specifically, it seems likely that the large abundance of carbon we infer from the X-ray spectral modeling (C/O ~ 50; Sec. 3.2) originated within the intershell region (i.e., the region between the H-and He-burning shells) present during the AGB stage. Meanwhile, the observed enhanced Ne/O and low Fe/O and N/O abundance ratios can perhaps be explained as a natural consequence of the s-process within the "pulse driven convection zone" (Herwig 2005). The Ne may be predominantly ^{22}Ne, which can be readily generated (at the expense of ^{14}N) within the He burning shell. The ^{22}Ne can then serve as an iron-depleting neutron source during the s-process. In such a scenario, one expects Ne to be enhanced while iron (Fe) and Nitrogen (N) are depleted, as observed.

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