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Low charge states of Si and S in Cygnus X-1

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Abstract

Strong, relatively short, absorption dips have been observed in the x-ray light curves measured from the high mass x-ray binary system Cygnus X-1. With increasing strength of the dips, which are believed to be caused by 'clumps' of cold material present in the stellar wind of Cyg X-1's companion star, K-shell absorption lines in L-shell ions of Si and S develop. To determine the bulk motion of the clumps via the Doppler shifts of these lines with high accuracy, we measured their reference energies using the Lawrence Livermore National Laboratory electron beam ion trap EBIT-I and EBIT Calorimeter Spectrometer. Our findings—shifts consistent with zero velocity of the absorber throughout all ionization states at orbital phase zero—provide evidence for an onion-like ion structure of the clumps.

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(Some figures may appear in color only in the online journal)

1. Introduction

The Cygnus X-1 system is probably the best studied black hole high mass x-ray binary. Its O9.7 type supergiant companion star HDE 226868 fills 97% of its Roche lobe (Herrero *et al* 1995), causing its strong stellar wind to be highly focused toward the black hole (Friend and Castor 1982). This focused wind is photoionized by the X-radiation emitted during the accretion process, creating a complex wind structure within the binary system. Resulting 'clumps' of denser material crossing our line of sight toward Cyg X-1 can give rise to severe absorption dips in the observed lightcurves (figure 1). It is possible to study these different parts of the stellar wind separately by applying cuts to these lightcurves according to the flux in different energy bands and extracting separate spectra for different dipping stages (Hanke *et al* 2009). While the unabsorbed non-dip spectra, which correspond to the highly photoionized wind, are dominated by absorption lines of the Rydberg series of highly charged, i.e. H- and He-like, ions (Hanke *et al* 2009, Miškovičová *et al* 2012), in the case of silicon and, with lower signal to noise, sulfur those lines grow significantly weaker with increasing dipping strength. Instead, 1s–2p transitions of low charge states (Li- through N-like) of the same elements appear, indicating a shift of the charge balance of the observed spectra toward low ionization states (Miškovičová *et al* 2011, 2012). The latter can only be in equilibrium with the radiation field, if they exist in correspondingly dense clumps of material. It has been suggested that the outer layers of this dense material shield the inner parts from the ionizing X-radiation of the black hole, leading to the plasma in the center of the clumps being colder and less ionized. If true,

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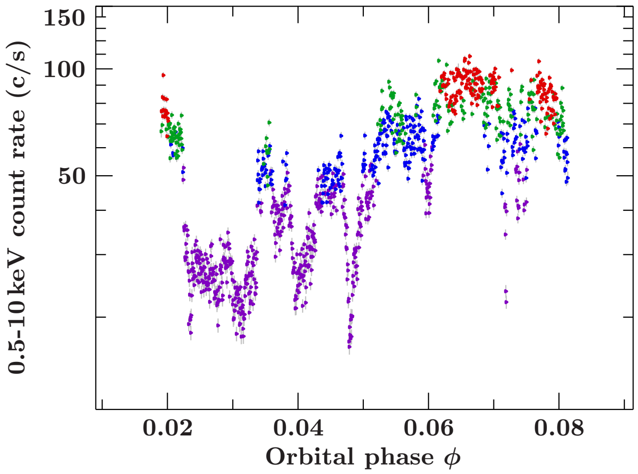

Figure 1. Thirty kiloseconds lightcurve of Cyg X-1 at orbital phase zero (*Chandra* ObsID 8525). Severe drops in count rate represent absorption dips. The colors in the figure depict different dipping stages (top to bottom: non-dip, weak dip, dip and strong dip) selected to extract spectra with equal signal to noise ratios.

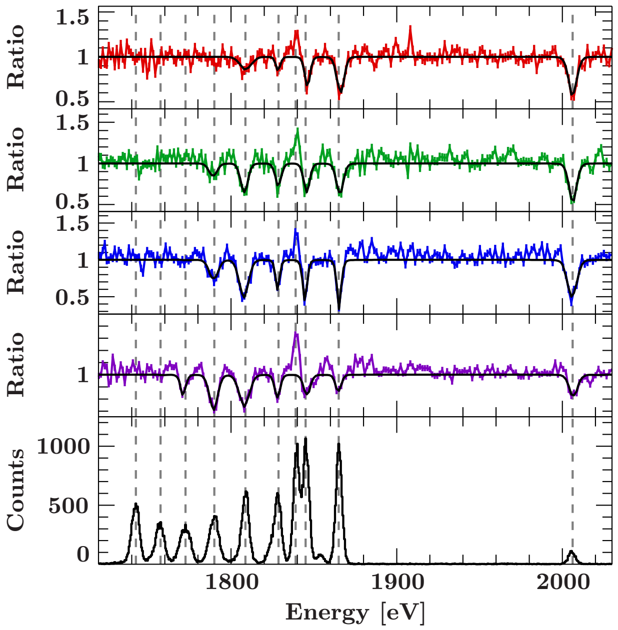

Figure 2. Upper four panels: ratio of spectrum and continuum model in the Si region of the spectra of ObsID 8525 for all stages from no dipping (top) to strong dips (bottom). Lower panel: EBIT measurement of the Si lines.

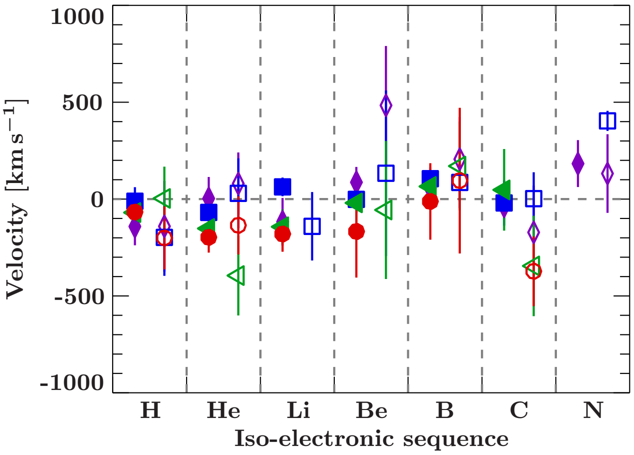

Figure 3. Doppler shifts for ObsID 8525 at orbital phase zero for all dipping stages (○: non-dip; △: weak-dip; □: dip; ◊: strong-dip) and ionization states of Si (filled) and S (empty).

all ionization states present in the clump would have the same Doppler shift. Figure 2 shows example spectra of the Si region from a *Chandra* observation of Cyg X-1 taken at orbital phase $\phi \approx 0$, where the black hole is in superior conjunction of its stellar companion.

2. Laboratory measurements

1s – 2ℓ (ℓ = s or p) transitions in L-shell ions below the Li iso-electronic sequence are scarcely available in spectral databases. Those calculations that can be found are generally believed to be accurate in their line position within 1–2 eV (Gu 2004, Palmeri *et al* 2008). In the Si/S regions around 2 keV this uncertainty translates to velocities of a few hundred km s^{-1}, i.e. of the order of the Doppler shifts expected in Cyg X-1 (Miller *et al* 2005, Miškovičová *et al* 2012). Following suggestions presented by Liedahl and Brown (2008), we used the EBIT-I electron beam ion trap (Levine *et al* 1988, Beiersdorfer 2003) at the Lawrence Livermore National Laboratory together with the EBIT Calorimeter Spectrometer (ECS; Porter *et al* 2008) to measure the Kα transition energies of the L-shell ions of Si and S (Hell 2012). The measured spectra (cf figure 2) have an energy resolution of roughly 4.5 eV, allowing us to determine line energies with a precision of less than 1 eV and for most lines even of better than 0.5 eV. To identify the line centers of the fitted Gaussians with the transitions contributing the most to the line, the line strength of each transition is simulated using the collisional radiative model (CRM) of the flexible atomic code (FAC; Gu 2004).

3. Velocity shifts

To find the Doppler shifts of the Cyg X-1 line emission measured by *Chandra* we used the FAC/CRM model with energies corrected using the measured laboratory values (Hell 2012). Figure 3 shows the distribution of the Doppler shifts determined using our laboratory corrected models for Si xviii–xiv and S x–xvi founding all dipping stages at phase $\phi \approx 0$. It is apparent that in the $\phi \approx 0$ observations the Doppler shifts of the lines are consistent with zero velocity and, more important, with each other throughout all ionization states in each dipping stage.

The velocity distribution being nearly identical for all ionization states during all dipping stages strongly supports the onion-like structure theory of clumps of cold, dense material embedded in the highly ionized wind of Cyg X-1. For a more detailed explanation of the 'onion-like' structure of the clumps and the Doppler shifts at other orbital phases, see Miškovičová *et al* (2012).

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