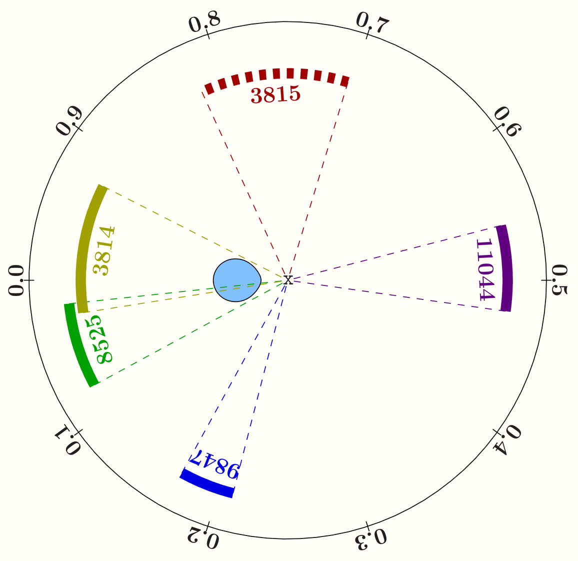
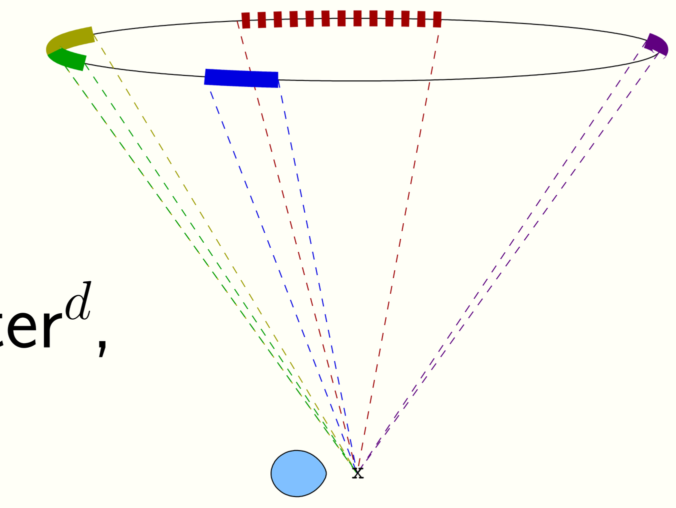


Low charge states of Si and S: from Cygnus X-1 to the lab and back



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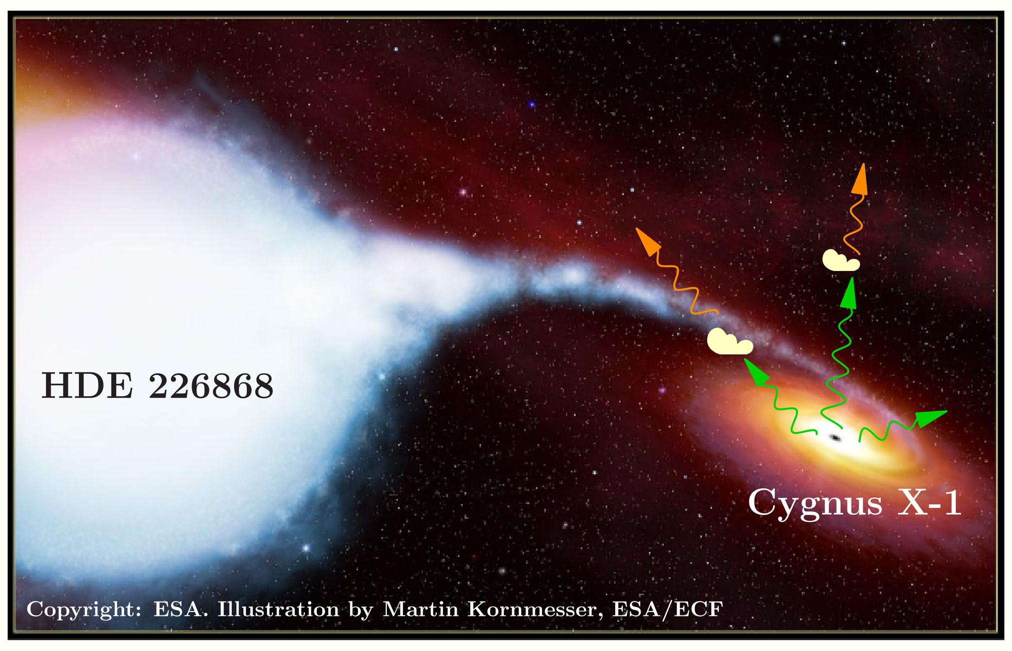
Abstract

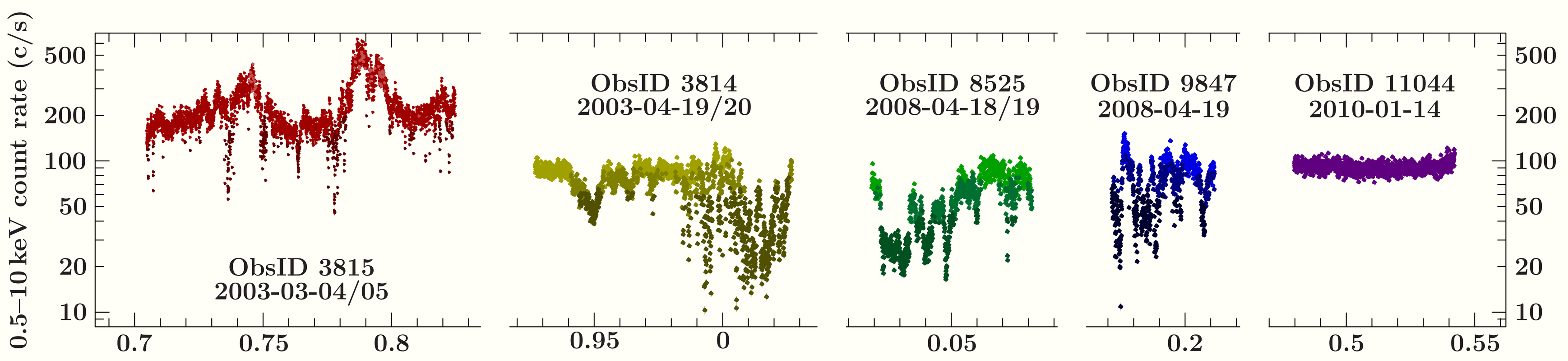
The X-ray light curves of the high mass X-ray binary (HMXB) Cygnus X-1 are shaped by strong, relatively short, absorption dips. While spectra extracted from the dip free phases are dominated by absorption lines of the Rydberg series of H- and He-like ions, 1s–2p transitions of lower ionized Si and S appear in the dip spectra. This shift in charge balance suggests that we probe "clumps" of cold material embedded in the companion's stellar wind as they cross our line of sight. Determining the bulk motion of these clumps by measuring the Doppler shifts of these lines as a function of dipping strength and ionization state can confirm this theory. Unfortunately, the predicted uncertainty for theoretical calculations – if available at all – is of the order of the expected shifts in the system. To overcome this lack of reliable reference wavelengths, we measured the Kα spectra of H- through F-like Si and S with the EBIT Calorimeter Spectrometer (ECS) and the Lawrence Livermore National Laboratory electron beam ion trap EBIT-I. We then directly apply these new line centers to calculate the Doppler shifts of the lines observed in Cygnus X-1. With this approach, we find shifts consistent with constant velocity of the absorber throughout all ionization states and, hence, provide evidence for an onion-like ion structure of the clumps.

Stellar Wind in High Mass X-ray Binaries (HMXB)



- Cyg X-1 with his supermassive O-type companion among best studied black hole HMXB
- accretion of coronal material ejected by strong stellar winds and partially focused towards BH (Friend and Castor, 1982)
- accreted material loses potential energy through emission of X-rays
- **highly structured wind** photo-ionized by X-rays
- "clumps" from density and temperature variations (Dessart, 2004) cause **absorption dips** in light curves when passing through the line of sight

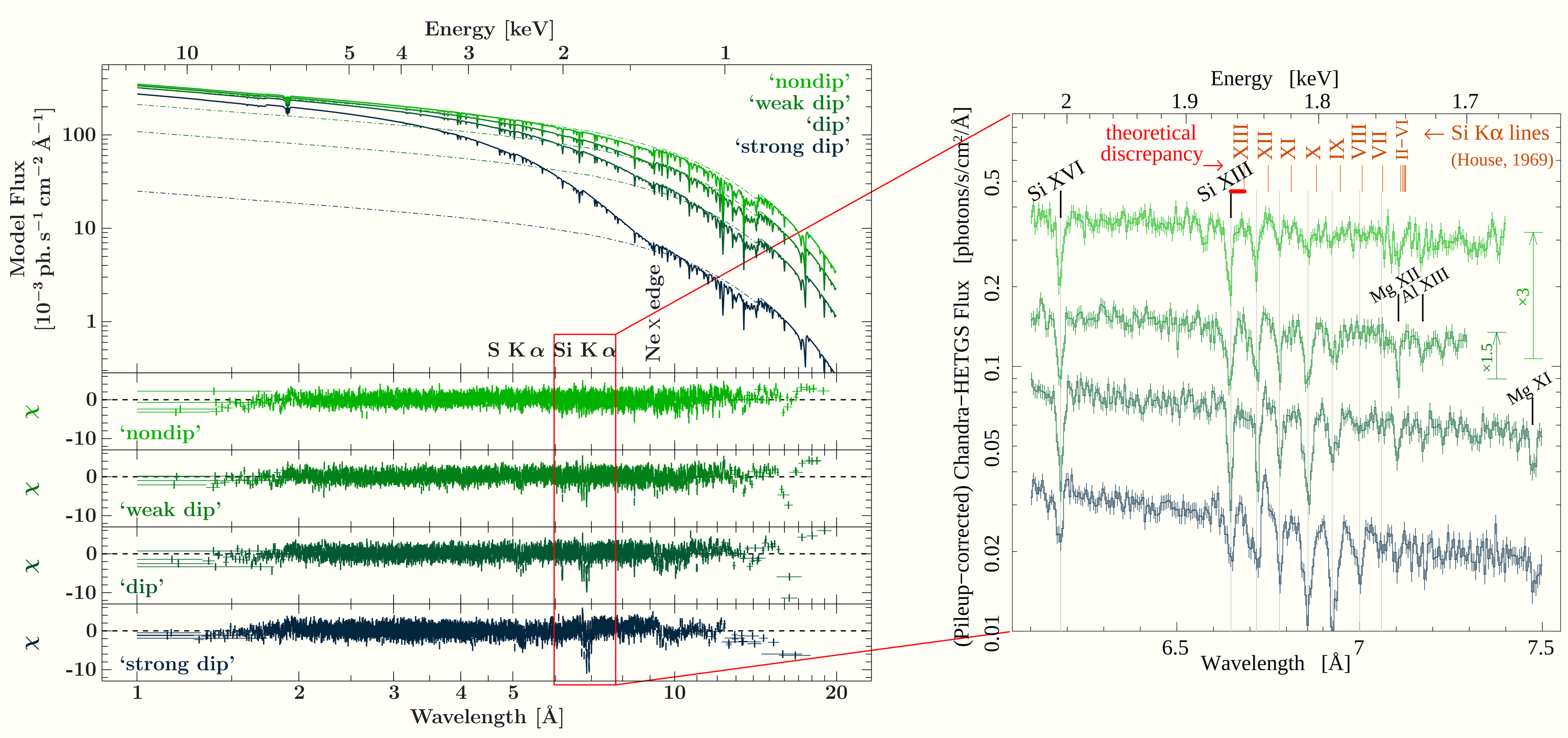
Chandra's view of Cyg X-1: $\phi_{\rm orb} \sim 0.75, 0.95, 0.05, 0.2$, and 0.5



Orbital phase ϕ (At ϕ=0, Cyg X-1 is only seen through the densest part of the donor's stellar wind.)

- observations at phases $\phi_{\rm orb} \sim 0.75, 0.95, 0.05, 0.2$, and $0.5 \Rightarrow$ **probe all prominent parts of the wind of Cyg X-1** (see title left)
- violent **absorption dips** at $\phi_{\rm orb}\sim 0$
- (shorter and weaker) dip events already at $\phi_{\rm orb}\sim 0.75$ and still at $\phi_{\rm orb}\sim 0.2$
- ObsID 11044 at $\phi_{\rm orb}\sim 0.5$ totally **free of dips**
- **non-dip** level: **hot, ionized wind**
- **dip** levels: **clumps**
- Different stages of dipping (as color-coded) analyzed separately

Dip Spectra: Low Ionization stages



- left: observation with the strongest dips, ObsID 8525, split into four spectra for analysis
- non-dip: good description with warm absorber model, i.e., **absorption through H- and He-like ions**
- increasing dipping strength: **additional strong absorption lines** $\Rightarrow$ Kα transitions of lower ionized **Si XII–VIII** and **S XIV–X**
- right: Si line evolution with dipping
- non-dip and weak dip spectra shifted for visual clarity, further reduction in flux is real
- increasing strength of the low-ionization lines with dipping suggests their relation to **high-density clumps at lower temperatures**
- analysis of Doppler shifts can reveal clump structure

Missing reference lines

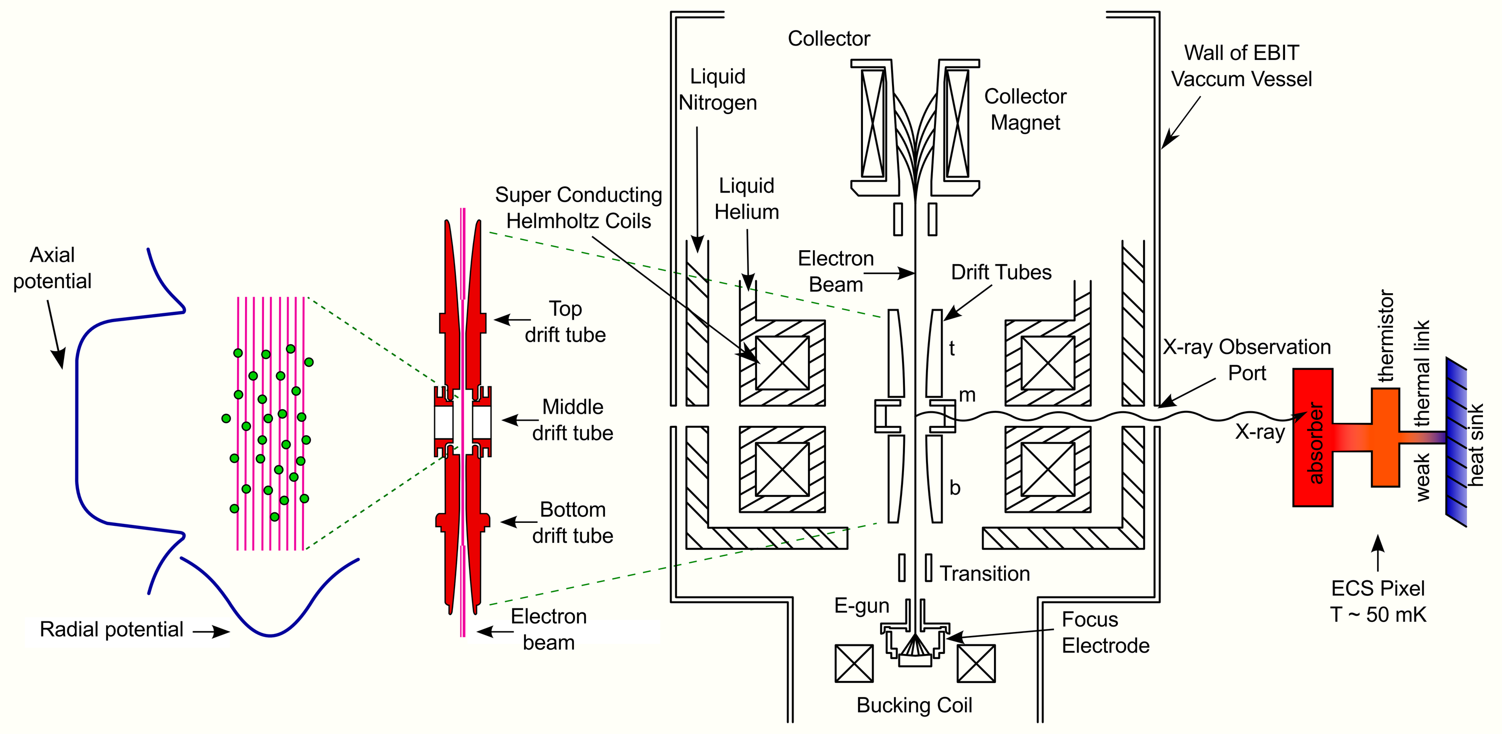
Deriving Doppler shifts requires **accurate reference line energies**. Calculations are usually only accurate within 1–2 eV, or a few hundred km s^{-1}, i.e., what is expected in Cyg X-1 (Miller et al., 2005). Hence, we **measured the Si and S Kα series** with the LLNL electron beam ion trap EBIT-I and the NASA/GSFC EBIT Calorimeter Spectrometer (ECS).

Acknowledgements

Friedrich-Alexander-Universität Erlangen-Nürnberg
ECAP Erlangen Centre for Astroparticle Physics
Lawrence Livermore National Laboratory

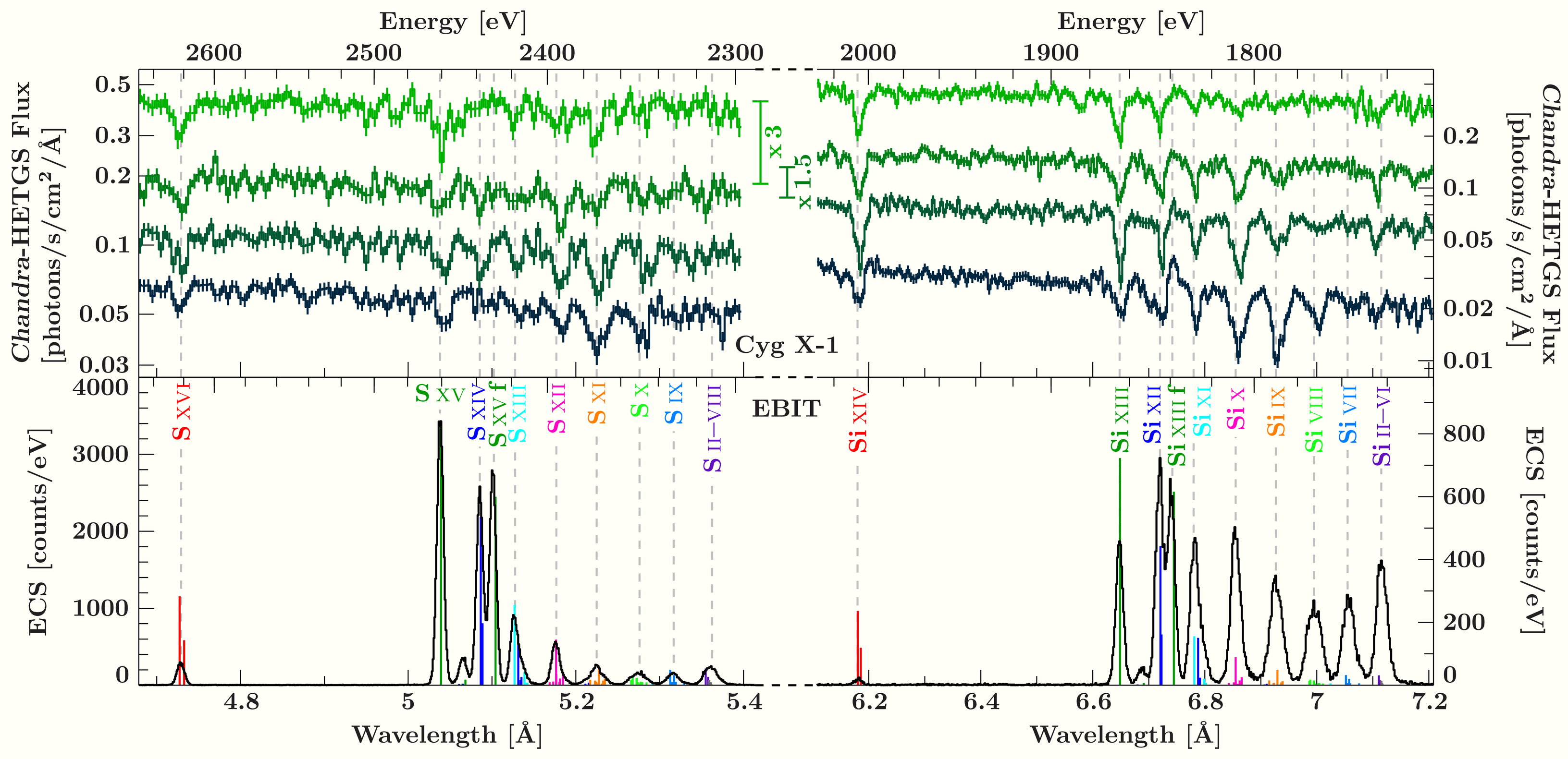
We acknowledge funding by BMWi under DLR grant 50 OR 1207 and from the EU under grant agreement number ITN 215212 "Black Hole Universe". This work was partially completed by LLNL under Contract DE-AC52-07NA27344, and is supported by NASA grants to LLNL and NASA/GSFC.

Electron Beam Ion Trap



- (neutral) gas is injected into the trap region
- atoms are ionized and excited through collisions with beam electrons
- plasma trapped by set of three drift tubes
- calorimeter (ECS) observes line emission through ports in middle drift tube

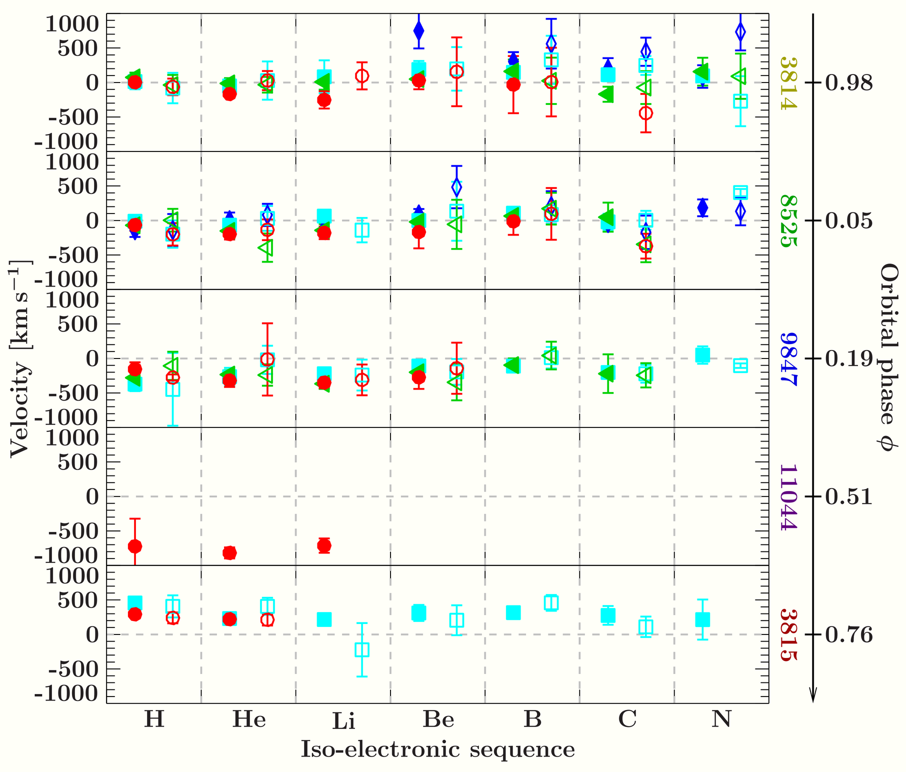
EBIT Measurements

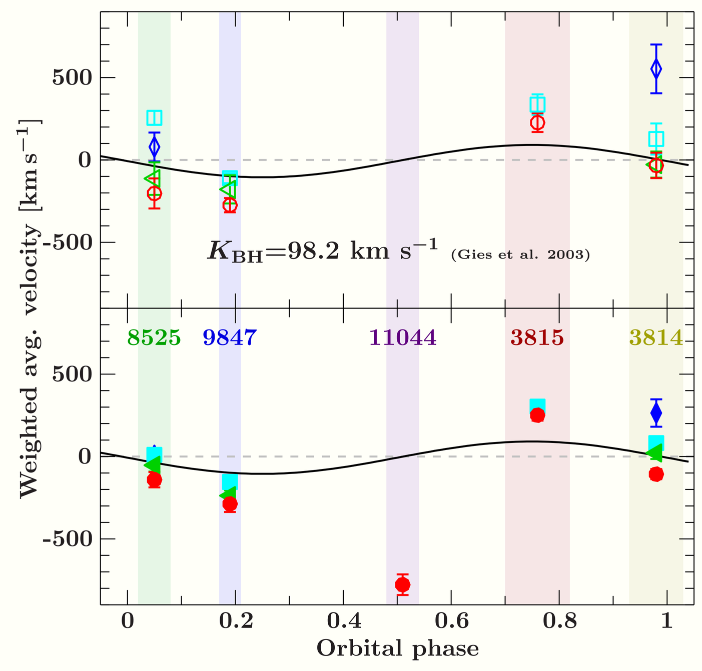


- spectra with $\sim$ **4.6 eV resolution**
- resolve 19 Si and 23 S lines
- **accuracy of better than 0.5 eV** for most line centers
- line identification: assigning the strongest components of a spectrum simulated with the plasma module of the Flexible Atomic Code (FAC, Gu 2003)

Velocity Distribution

Doppler shifts for all *Chandra* observations are derived using FAC spectra with energies corrected for laboratory values as reference.
Si (filled) and S (empty) for all dipping stages (●○ nondip, ◄◁ weak-dip, ■□dip, ♦◊strong dip).





- **Doppler shift is independent of dipping stage**
- lines originate from material in the same compact object (clumps)
- **outer layers shield the inner part from the ionizing radiation** of the BH
- weighted average velocities for each dipping stage projected onto the orbital phase of the observation
- average shifts roughly follow the projected orbital velocity of the BH (black sine curve, semi-amplitude $K_{\rm BH}$)
- **we probe material infalling onto the BH**

References

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