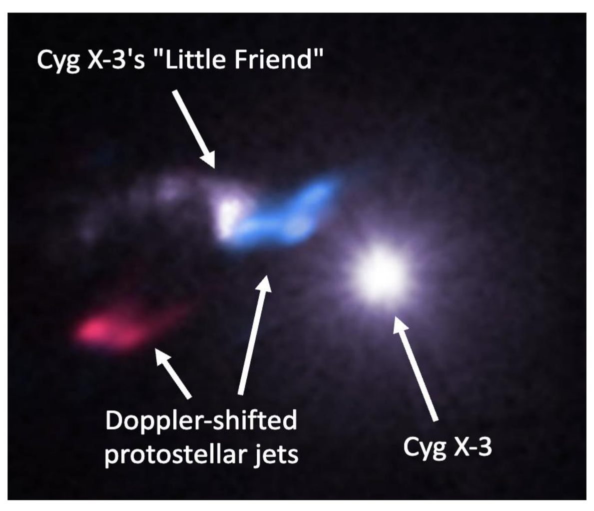
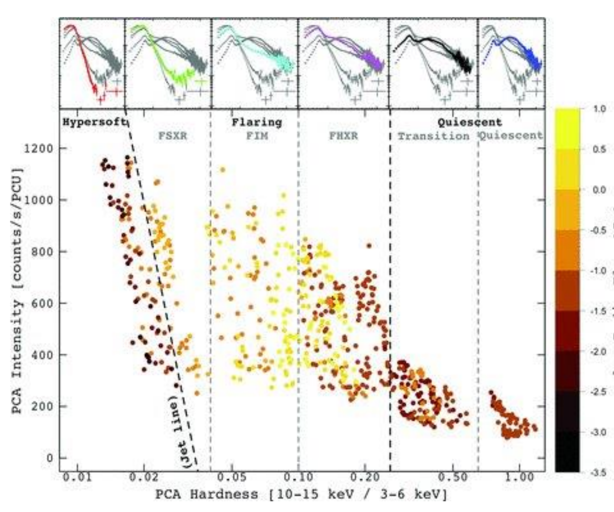
Phase-Resolved Spectral Analysis of Cygnus X-3 during Quiescent State with Chandra

Josephine Wong, Michael McCollough
Center for Astrophysics | Harvard & Smithsonian

Cygnus X-3: An Astronomical Puzzle

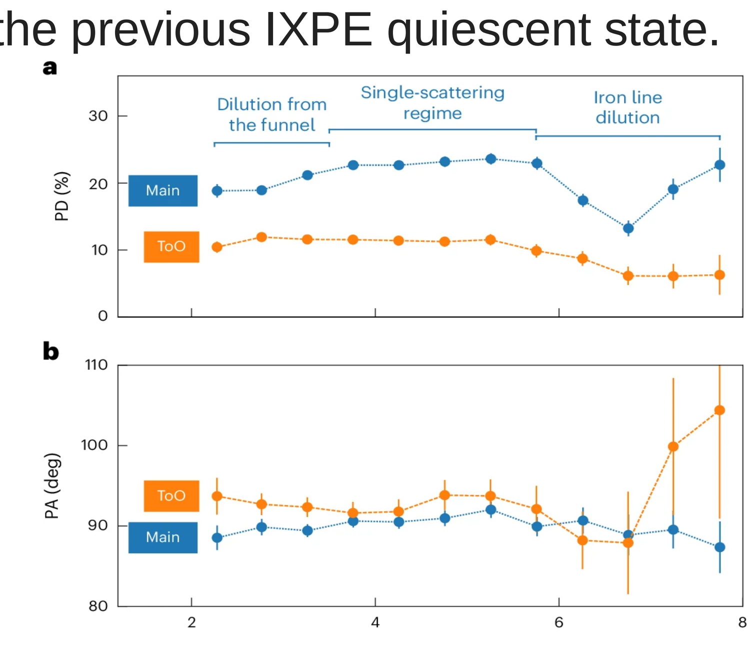




Cygnus X-3 is a **high mass X-ray binary (HMXB)** located about 10 kpc away. It is one of the earliest discovered X-ray sources, detected by an Aerobee sounding rocket in 1966. The nature of the compact object has not been definitely determined, but it exhibits spectral transitions similar to those seen in **black hole X-ray binaries (BHXBs)**. About 50% of the time, Cygnus X-3 is in a **quiescent state**, characterized by low, hard X-ray flux and radio emission at the level of ~10s mJy. Roughly once every 2–3 years, it is in a **major flaring state**, where the radio flux reaches ~10 Jy. During these flaring states, extended bipolar jets have been seen by the VLA.

IXPE Spectropolarimetric Analysis of Cygnus X-3

In Oct & Nov 2022, IXPE observed Cygnus X-3 in the quiescent state. In their energy-resolved analysis, they found that the polarization degree (PD) is relatively constant from 2 – 8 keV, except for a drop between 6 – 8 keV, which they speculated was due to dilution from strong, unpolarized iron emission lines. The polarization angle (PA) is roughly constant at 90°, consistent with scattering off a collimated medium aligned with the north-south jet. Another IXPE observation was taken Nov 17 – 23, 2023 during quiescence. Initial analysis appears to be similar to the previous IXPE quiescent state.



Investigating the Iron Line Fluxes with Chandra

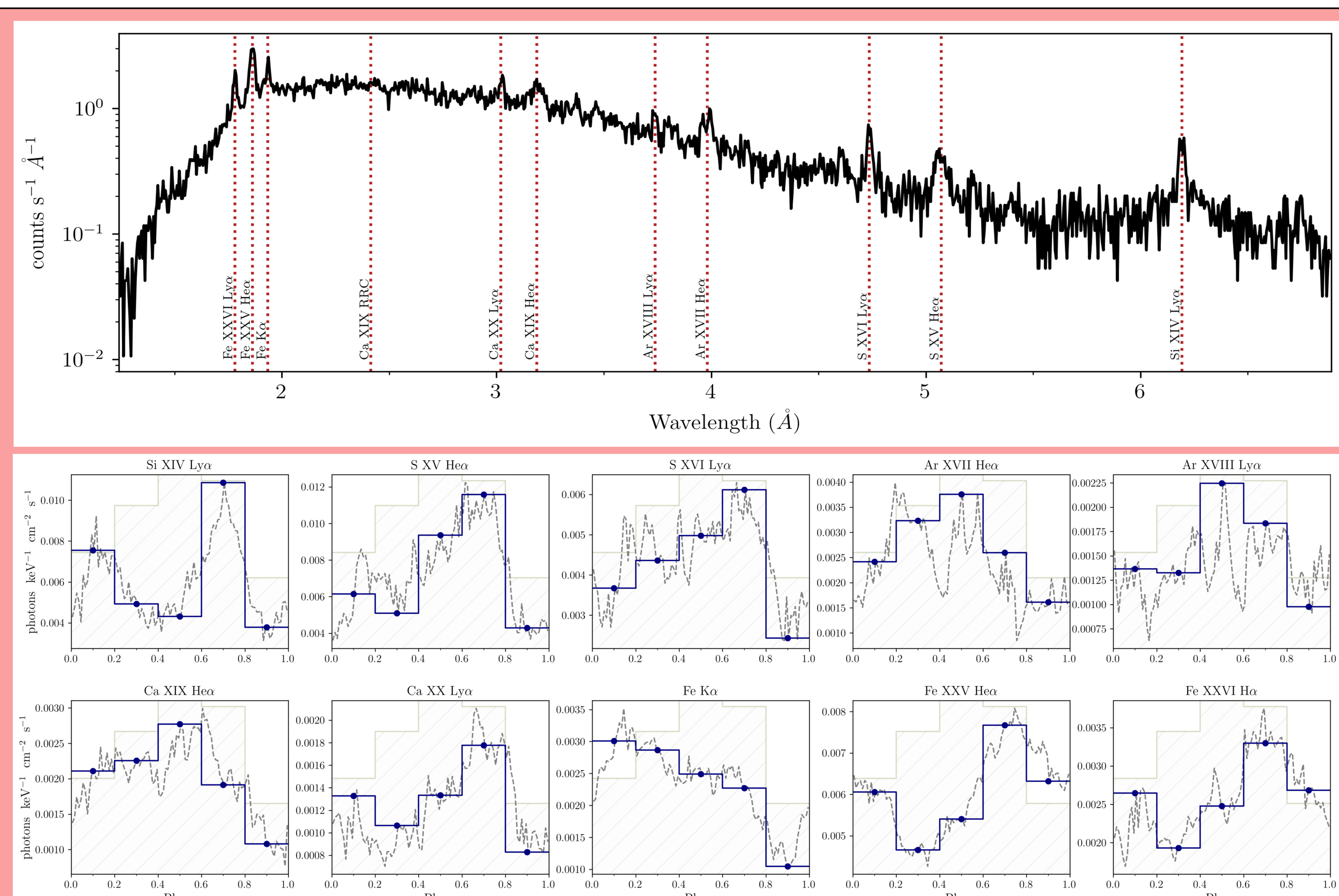
Chandra X-ray Observatory (CXO) observed Cygnus X-3 for about 20 ks during quiescence on November 22, 2023. Due to its excellent spectral resolution (E/ΔE = 200 @ 6 keV), we were able to resolve the individual iron emission lines: "neutral" Fe Kα (~6.4 keV), He-α (~6.67 keV), and Hα (~6.97 keV). We measured the unabsorbed fluxes of each line as well as the power-law continuum. Under the assumption of PD = 20% for the continuum and unpolarized lines, we calculated the expected polarization in 0.5-keV energy bins between 6 – 7.5 keV. Our values are consistent with those measured by IXPE in 2022.

Energy Bin (keV)	Log10 Flux (erg/cm²/s)				Expected PD (%)
	"Neutral" Fe Kα	He-like Fe Kα	H-like Fe Lyα	Power Law	
6 – 6.5	-10.51	---	---	-9.68	17%
6.5 – 7	---	-10.15	-10.49	-9.58	14%
7 – 7.5	---	---	-9.78	-11.24	19%

Studying the Phase Variation of Cygnus X-3's X-ray Spectral Features

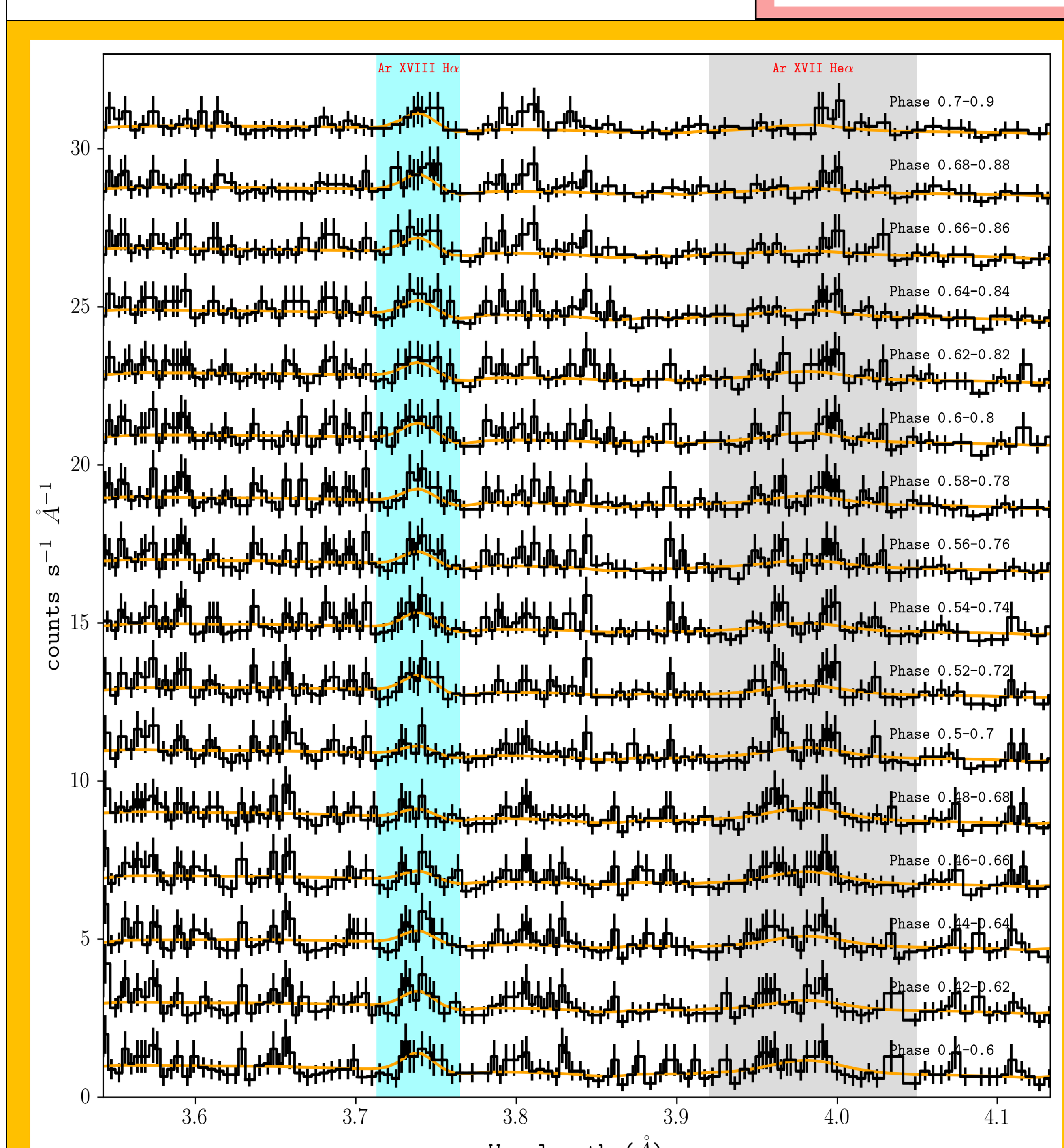
Photoionization of the Stellar Wind

Cygnus X-3 consists of a Wolf-Rayet star and a compact object in close binary orbit (orbital period ~ 4.8 hrs). The strong wind from the stellar companion is photoionized by hard X-rays from the compact object, leading to the production of various emission lines and radiative recombination continuua (RRCs) from H-like and He-like species (e.g. Mg, Si, S, Ar, Ca, Fe). In addition, the spectrum is affected by broadband absorption from the dust halo. Scattering from electrons in the stellar wind also produces P-Cygni profiles. The resulting spectrum is highly complex, as shown in the CXO spectrum on the right. Prominent emission features are labeled with the dotted lines.



Fitting within Sliding Window

Due to limited statistics, we used a sliding window to monitor the phase variation of the emission lines. The window has a width of Δ = 0.2 and was shifted with Δ_{shift} = 0.01. The continuum was modeled as an absorbed power-law subjected to additional absorption by a partially covering cloud. The emission lines were modeled as Gaussians with energies and widths fixed at the values obtained from fitting to the phase-integrated spectrum. The bottom panel shows the fitted normalizations in the sliding windows. Independent phase bins (5 total) are drawn in blue. The dotted gray line are the normalizations obtained in the sliding windows. For reference, a gray cross-hatched light curve (PL norm) is included.



Line Splitting in the Spectrum

Inspecting the He-α and Hα lines in the spectra, we see complex morphological changes with phase. At certain phases, the "line" can split into multiple peaks. For the He-α lines, we know that they consist of multiple lines (resonance, intercombination, and forbidden). It will be interesting to track the variation of these components with phase.

Left diagram: restricted to the 3 – 3.5 keV range for a closer look at the Ar He-α and Hα lines; Δ = 0.4 – 0.7 in increments of Δ_{shift} = 0.02

Right diagram: restricted to the 6 – 7.5 keV range for a closer look at the Fe Kα, He-α, and Hα lines; covers entire phase range with Δ_{shift} = 0.04

In both diagrams, the line morphology changes significantly with phase, especially for the He-α emission lines. Orange lines show the best-fit model for the spectrum at each phase bin.