Chandra Observations of Cygnus X-3 Over the Last 25 Years

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Abstract

Cygnus X-3 (Cyg X-3) is a microquasar which is composed of a Compact Object (likely Black Hole) and a Wolf-Rayet Companion (the only known BH-Wolf-Rayet X-ray binary in our Galaxy). It has a short orbital period of 4.8 hours which imply an orbital separations of ~ 4 $R_{\odot}$. The system routinely goes through a number of state changes (quiescent, quenched/hypersoft, major flaring, and minor flaring) which show correlated changes in the radio, X-ray, hard X-ray, and gamma-ray. It is know to produce relativistic jets which align close (< 10 deg.) to our line-of-sight. This presentation will review the discoveries made from Chandra observations of Cyg X-3. This will include X-ray imaging of Cyg X-3 and the discovery of the Cyg X-3's Little Friend (first X-ray detection of a Bok globule) and its large (~0.5 deg.) scattering halo. Also discussed will be the Chandra HETG observations made of Cyg X-3 in various states and orbital phases. The state of Cyg X-3 spectral observations will be noted.

Chandra Images of Cygnus X-3

Chandra has sub-arcsecond imaging capabilities. Cyg X-3 been observed multiple times in an imaging mode. Among the things discovered were:

- **Scattering Halo:** The mosaic of the Cyg OB2 association shows that Cyg X-3 has a large scattering halo (see Fig. 1 (left)). It is over 24 arcminutes across (~ 0.5 deg.)
- **Cyg X-3's Little Friend:** In the zero order image of a grating observations was discovered an extended object (3x6 arcsecond) located 16 arcseconds away from Cyg X-3 (see Fig. 1 (right)). This object showed the same 4.8 hour variation that Cyg X-3 shows (see Fig. 2 (middle)). The analysis shows what we are seeing is X-ray scattering from a small molecular cloud. This is first detection of a Bok globule in the X-ray (McCollough, Smith, and Valencic 2013).
- **CO Emission from the Little Friend:** Follow up SMA observations confirmed the nature of source with CO emission. In addition the Bok globule showed evidenced of CO jet emission indicating ongoing star formation (see Fig. 2 (right and left) (McCollough, Corrales, and Dunham 2016).

Fig. 1: (left) A mosaic of Cyg OB region and Cyg X-3. Note Cyg X-3's large (~0.5°) scattering halo. The colors are CSC bands (Red: 0.5-1.2 keV, Green: 1.2-2.0 keV, Blue: 2.0-7.0 keV). (right) A zero order image (Obsid: 6601) showing Cyg X-3 and its Little Friend (LF). The color coding reflects orbital phase. This shows that the flux from the LF has a 0.5 phase shift.

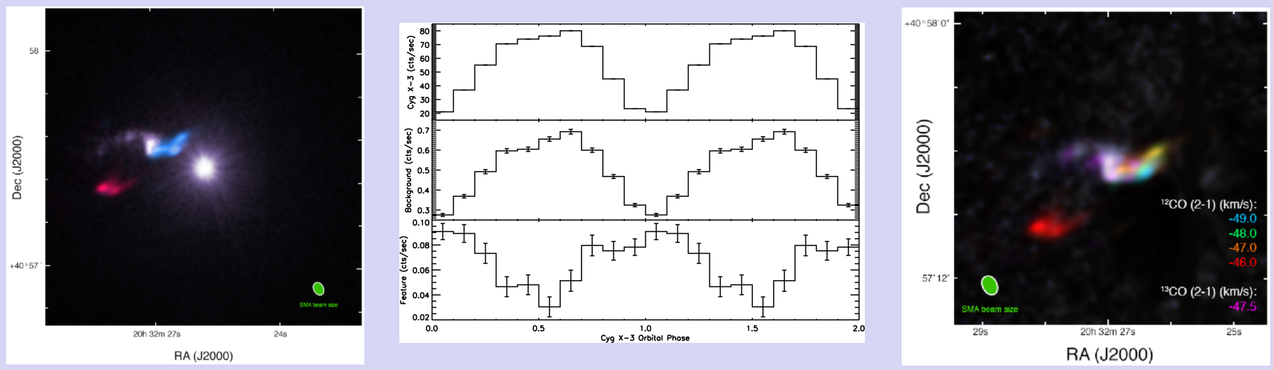


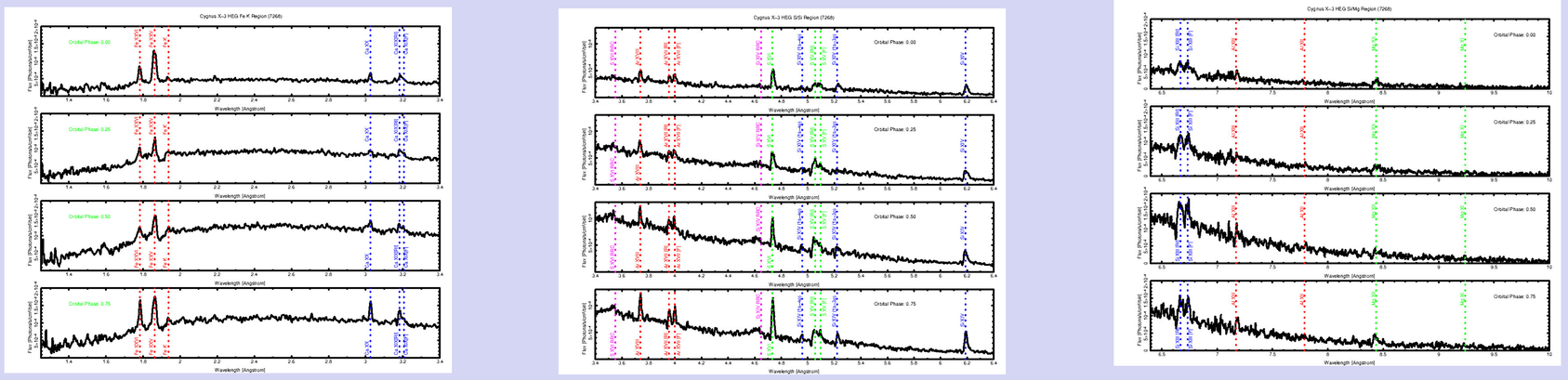
Fig. 2: (left) A composite Chandra (purple) and SMA (red and blue) image. Showing Cyg X-3, its LF, and the CO jets. (middle) The three panels should Cyg X-3 grating, zero order background, and LF phase folded data showing the orbital modulation and the LF phase shift. (right) A PSF subtracted image Chandra (1-8 keV) image with CO jets showing their velocity structure.

Chandra HETG Observations

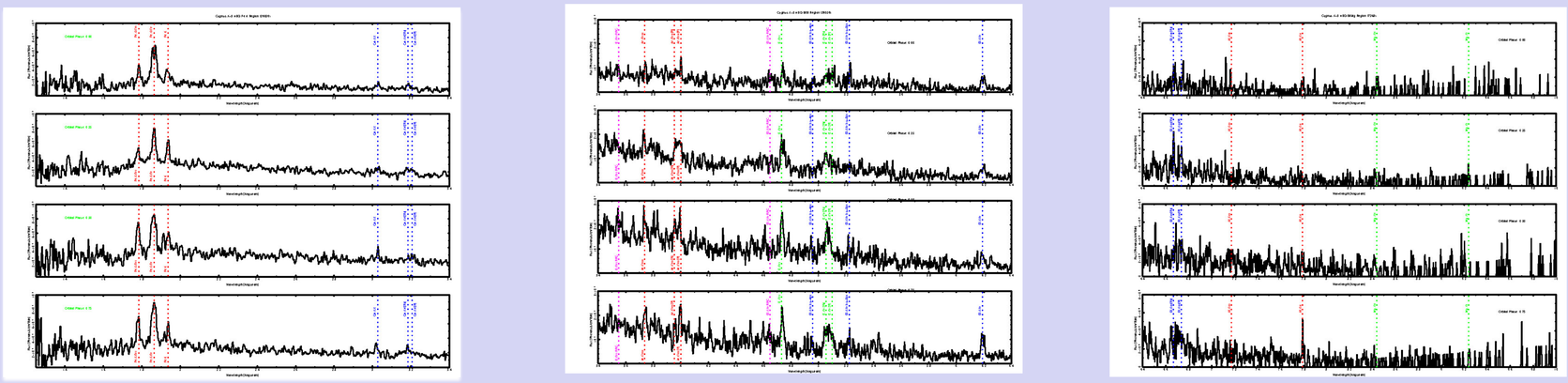
We note the following about the Chandra HETG observations (see Kallman et al. 2019):

- Chandra HETG: Observations were made during hypersoft, flaring and quiescent states. They show feature rich spectra.
- Continuum: Can be modeled by absorbed disk-blackbody.
- Absorption: Cyg X-3 is heavily absorbed with limited flux below 1 keV. Most of flux below 1 keV is due to scattering.
- X-ray Lines: Strong H-like and He-like lines from Fe to Mg.
- Fe Kα: The Fe Kα (6.4 keV) is present in all spectra. But varies from being very week in the hypersoft and flaring states to being very strong during quiescent states.
- RRCs: Radiative Recombination Continua are observed in all spectra. They indicate gas temperatures of ~ (7-8) x 10^4 K.
- P Cygni Profiles: During the hypersoft and flaring states many of the lines show P Cygni profiles.
- Absorption Feature: Also during the hypersoft and flaring states there is the appearance of an absorption feature located between He-like Fe and Fe Kα.
- Orbital Variations: The spectral features display variations as a function of orbital phase. These variations can be in intensity, velocity shift, and the presence of multiple components.
- Different Variations: Fe line region and the lines due to lighter elements show a different orbital modulation. Also a difference in the modulation of Fe Kα and the H-like and He-like lines.
- Multiple Ionizing Sources: There has to be two sources of ionization in order to produce the Fe lines and another to produce the H-like and He-like lines of the lighter elements.
- Bow Shock: Much of what is seen is driven by the interaction of the compact object with the wind from the WR companion.

Phase Resolved 1ST Order HETG Spectrum during a Hypersoft State (Obsid: 7268)



Phase Resolved 1ST Order HETG Spectrum during a Quiescent State (Obsid: 29059)



Cyg X-3 Spectra from the Past to Future

Over the 25 years of Chandra the spectral resolutions of Cyg X-3 have dramatically improved. From Swift (~140 eV @ 6 keV) to NICER (~137 eV @ 6 keV) with higher effective area. Chandra HETG observations result in even higher resolution (~30 eV @ 6.5 keV) which allows one to probe X-ray line emission and absorption in detail With the beginning of observations with XRISM (~5 eV @ 6.5 keV) a new era of X-ray spectroscopy has been opened. Below are examples of Cyg X-3 spectra from these four missions.

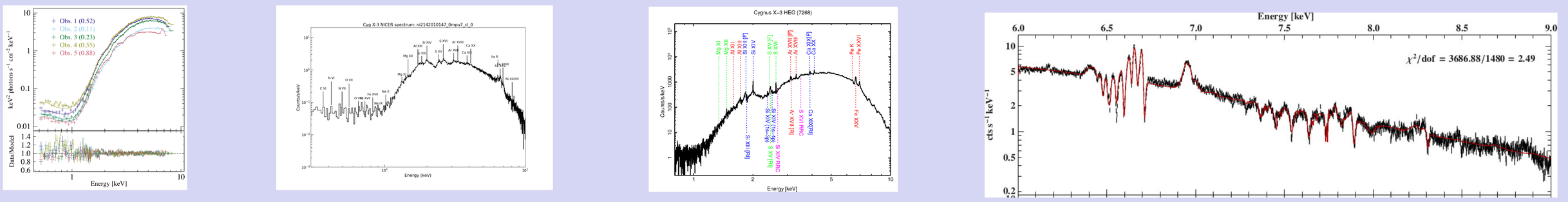


Fig. 3: (a) Cyg X-3 Swift/XRT spectra from a flaring state. (b) Cyg X-3 NICER observations taking during a flaring state. (c) Cyg X-3 Chandra HETG observations taken during a hypersoft state. (d) Cyg X-3 XRISM observation taken during a Cyg X-3 hypersoft state (see https://arxiv.org/pdf/2422.00597)