The True Nature of Cygnus X-3's "Little" Friend

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Abstract

In 2006, Chandra observations of Cygnus X-3 reveled our best view to date of an unique feature associated with this well know microquasar. Extended emission located 16" from Cygnus X-3 was found to be varying in (anti)phase with Cygnus X-3. Also from previous Chandra observations it is shown that the total flux from the feature varies with Cygnus X-3's total flux. If both this feature and Cygnus X-3 lie at the same distance the separation between the two would be 2.4 light years (assume a distance of 9 kpc).

From a study of the spectra, flux and time variations of this feature we believe that this feature is a dust cloud that is located along our line of sight to Cygnus X-3. From these observations we are able to deduce the location, size, and properties of this cloud. We will present this analysis and the insights that this give us into the nature of Cygnus X-3 and its environment. We will also present models which will explain why this phenomenon has only been observed, by Chandra, for one X-ray binary. This object represent a discovery that was only possible due to the unprecedented spatial resolution that is only possible with Chandra.

Introduction

Cygnus X-3 is an unusual X-ray binary containing a compact object and a Wolf-Rayet (WR) companion, making it a high mass system. But its orbital period (4.8 hrs) is typical for a low mass system. It is a strong radio source routinely producing radio flares of over a Jy and up to ~ 20 Jy. Even during radio quiescence it can be relatively bright in the radio (60-100 mJy). It has been shown to produce radio jets and also demonstrates correlations of the Radio with both the X-ray and hard X-ray (McCollough et al. 1999, Szostek et al. 2008) .

Using Chandra observations, taken in 2000, extended X-ray emission was discovered associated with Cygnus X-3 (Heindl et al. 2003) . Their analysis pointed to this feature as being a jet impact region. In 2006 a longer Chandra observation during a Cygnus X-3 high state has given us a much better understanding of the nature of this emission.

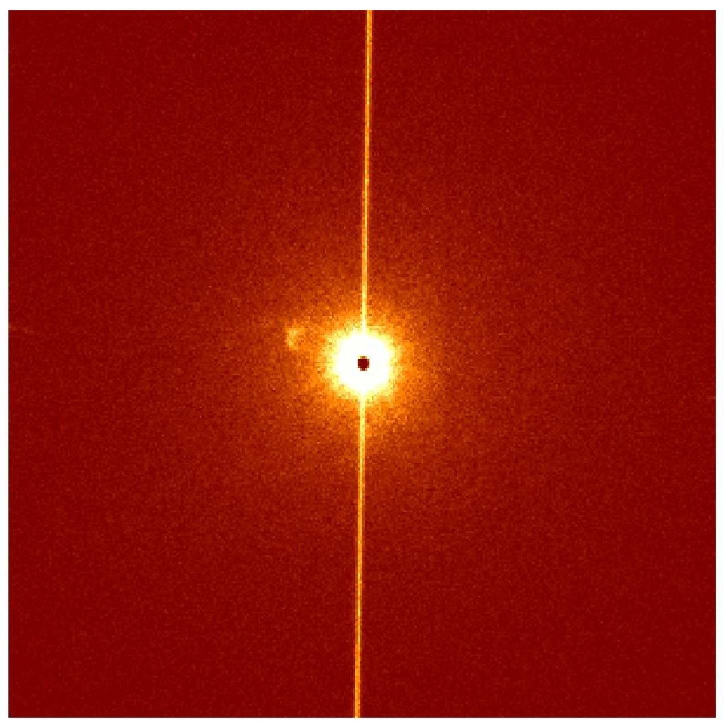

Fig. 1: A zero order Chandra grating image of Cygnus X-3 and its "little" friend.

Observations

In early 2006 Cygnus X-3 entered into a radio/hard X-ray quenched state (X-ray: high/soft state) after nearly four years in a radio quiescent state. During this quenched state a 50 ksec Chandra observations (OBSID: 6601) was performed as part of an international observing campaign to study major flaring activity in Cygnus X-3. The Chandra observations were grating observations designed to study the strong stellar winds that are associated with Cygnus X-3.

An image of the observation (zero order of the grading observation) is shown in Fig. 1. The feature (RA:20^{h}32^{m}27.06^s, DEC:+40^{o}57'33.78") lies at a distance of 15.62" from Cygnus X-3 at an angle of ~68.5° . from the orientation of the radio jets that have been observed in Cygnus X-3. The direction of the radio jets corresponds roughly to the direction of the instrumental readout streak. The feature is extended and can be fit with a 2D-Gaussian with axes of 3.65" and 5.54" and a rotation angle of ~78.7°. If the feature and Cygnus X-3 are at the same distance then their separation is 2.4 D_9 light-years (D_9: distance in units of 9 kpc). The feature is a factor of ~2000 times fainter than Cygnus X-3. As can be seen in Fig. 2 this feature has existed throughout the Chandra mission (1999 to present).

In Fig. 3 is shown the same image with as Fig. 1 but with the PSF of Cygnus X-3 removed. It now can be seen that the feature appears to be part of a larger arc-like feature which extends either from or across Cygnus X-3.

Phase Relationship with Cygnus X-3

An examination of the temporal properties of the feature show that there is a phase relationship between it and Cygnus X-3. This can be seen in the "phase" image in Fig. 4. In this image events of certain phases were assigned a color and combined to form a color coded phase image. The bands were: (red) 0.3-0.63, (green) 0.63-0.96, and (blue) 0.96-0.3. Note the blue color of the feature. This indicates that bulk of the photons are arriving in the 0.96-0.3 phase range. It is also important to note that no background subtraction was done and hence there is no issue with the background subtraction creating a false time/phase variation of the feature. In Fig. 5 are two images made at phase minimum and maximum for the feature.

In Fig. 6 is the phase folded light curves of the halo (due to Cygnus X-3's PSF) and the feature. It can clearly be seen that the feature exhibits the same slow rise and rapid drop that one sees in Cygnus X-3 but with a phase lag. From centroid fits to the peaks of a cross correlation between the background and the feature a phase lag of 0.551 +/- 0.003 is found. It should be noted that all of the Chandra data sets show an anti-correlation between the light curve of the feature and background.

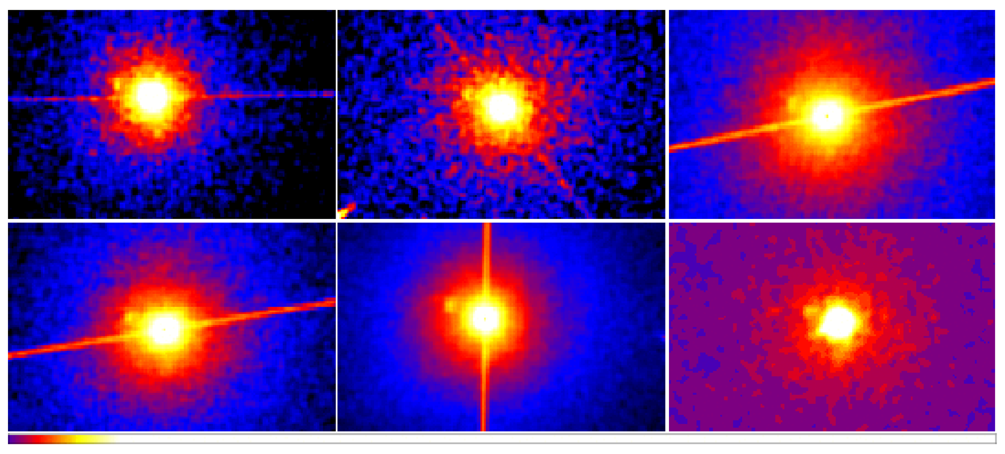

Fig. 2:Chandra observations spanning 1999-2006. Note the different spacecraft rolls.

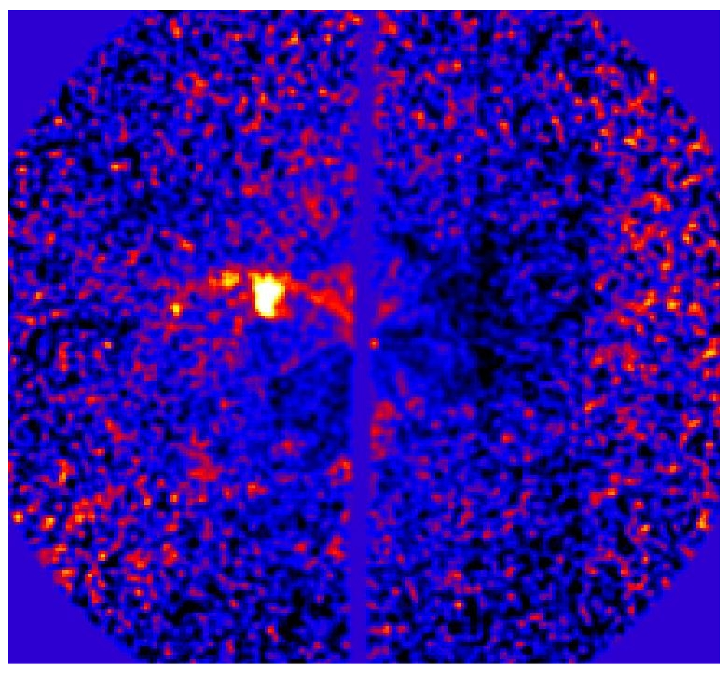

Fig. 3: A PSF subtracted image of Cygnus X-3 . Note that the feature is part of an arc-like structure.

The "Little" Friends Spectrum (Simple Fits)

Choosing an optimized extraction region the feature yields a spectrum of ~3000 counts which is shown in Fig. 7. Several different simple fits yield good fits:

Absorbed power law -> Γ: 4.02 N_h : 10.6 x 10^{22} cm^{-2}
Absorbed blackbody -> T(keV): 0.87 N_h : 5.5 x 10^{22} cm^{-2}
Absorbed bremsstrahlung -> T (keV): 2.00 N_h: 8.2 x 10^{22} cm^{-2}

A Raymond-Smith or Mekal model does not fit the spectrum well.

All these fits point to a heavily absorbed source (factor of 2-5 times greater than Cygnus X-3) and have a very soft/steep spectrum. The softness of the spectrum and the location of the feature relative the direction of jets observed in this system are difficult to reconcile with a jet impact or beamed emission model for this feature.

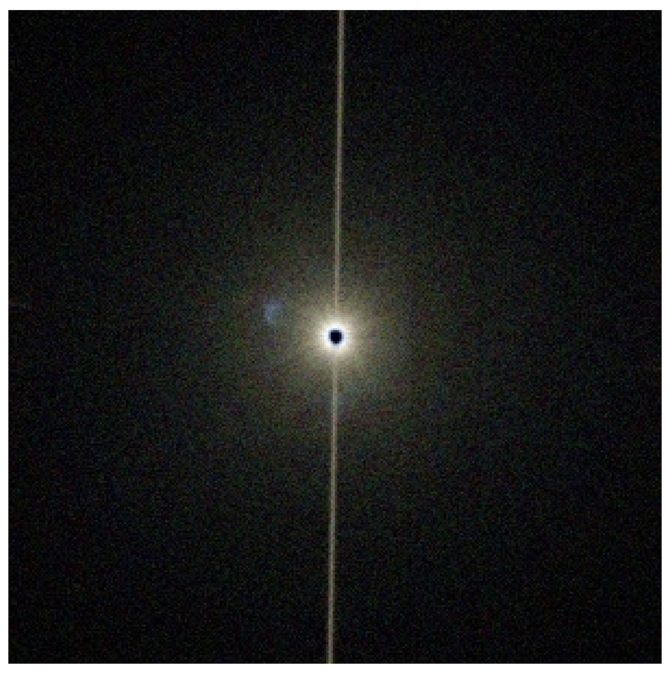

Fig. 4: A color coded phase image of Cygnus X-3 area. Note the blue color of the feature which indicates that the bulk of the photons are arriving in the 0.96-0.3 phase range.

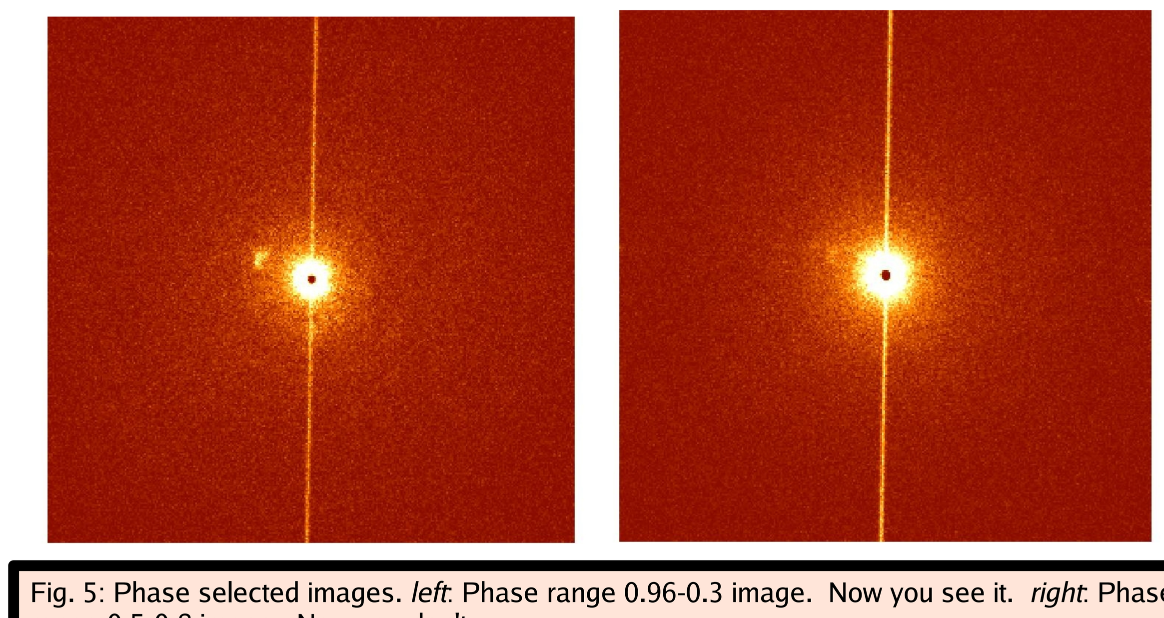

Fig. 5: Phase selected images. *left*: Phase range 0.96-0.3 image. Now you see it. *right*: Phase range 0.5-0.8 image. Now you don't.

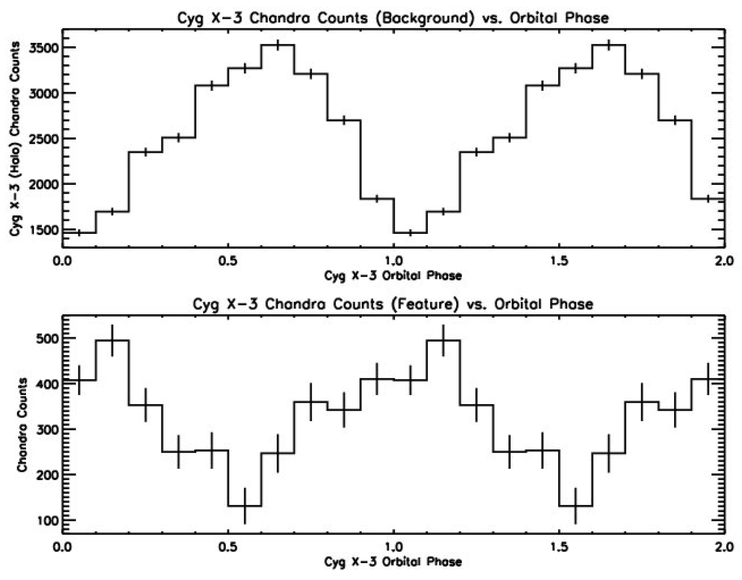

Fig. 6: Folded light curves. *Top*: Phase folded light curve of the halo. *Bottom*: Phase folded light curve of the feature. Note the similarity of the light curves and the 0.5 phase shift.

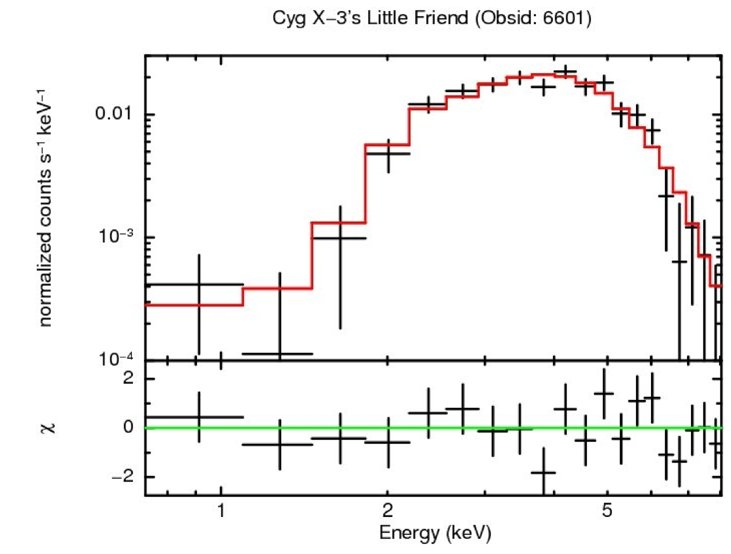

Fig. 7: The spectrum of the feature. The model fit and residuals are those of the Scattering model.

The "Little" Friends Spectrum (Scattering)

A natural explanation for the time variable behavior of the feature is that it is due to scattering from the cloud between Cygnus X-3 and the observer. If this is the case the spectrum of the feature should be Cygnus X-3's spectrum modified by being scattered. Scattering will modified the spectrum at high energies by A^*E^{-2} reduction and at the low energies there will be addition absorption (N_{cl} caused by the cloud and multiple scattering). Cygnus X-3's X-ray spectrum shows a photoionized spectrum whose continuum can be describe an absorbed partial covered disk blackbody. Using this Cygnus X-3's spectrum modified by scattering we get an excellent fit (see Fig. 7) with the following values:

N_{cl}:	4.99 x 10^{22} cm^{-2}
N_h:	2.66 x 10^{22} cm^{-2} (fixed by Cygnus X-3)
N_{pc}:	3.41 x 10^{22} cm^{-2} (fixed by Cygnus X-3)
f_{pc}:	0.63 (fixed by Cygnus X-3)
T (keV):	2.04 (fixed by Cygnus X-3)
A:	1.40
α:	2.00 (fixed)
F_x (feature: 1-8 keV):	3.57 x 10^{-12} ergs cm^{-2} s^{-1}
F_x (Cygnus X-3: 1-8 keV):	6.25 x 10^{-09} ergs cm^{-2} s^{-1}

Nature of the Beast

The most nature explanation the temporal behavior, spectrum, and extend nature of this feature is that it represents Cygnus X-3's scattered emission off of a cloud. Some of interesting implications:

Time Delay: If the time delay between the feature and Cygnus X-3 is a resulting of scattering then this feature has be be within 2 kpc of Cygnus X-3.

Flux: Using the flux ratio between the feature and Cygnus X-3 assuming the flux is that scattered from Cygnus X-3 puts the feature at a distance ~ 2 pc.

Extend Size: The combination of the variation in phase with the extend size of the feature implies that this cloud must be a thin sheet/shell type structure.

Solution

If we consider the mass donating companion in Cygnus X-3 we can come to an understanding of what we are observing. The mass donating companion is a WR star which with its high mass outflow (which is indicated in observations of Cygnus X-3) form a wind blow shells (WR stars typically produce 1-10 pc radii shells) about the star like the one shown in Fig. 8. Thus for Cygnus X-3 the "little" friend is simply a thin dust layer in the shell of a wind blown nebula surrounding Cygnus X-3. Also the fact that this has only been seen for Cygnus X-3 is also explain by the studies that have shown that we should only expect only one such system like Cygnus X-3 in our Galaxy at a given time. So the X-rays from the compact object are "X-raying" the structure of the surrounding nebula.

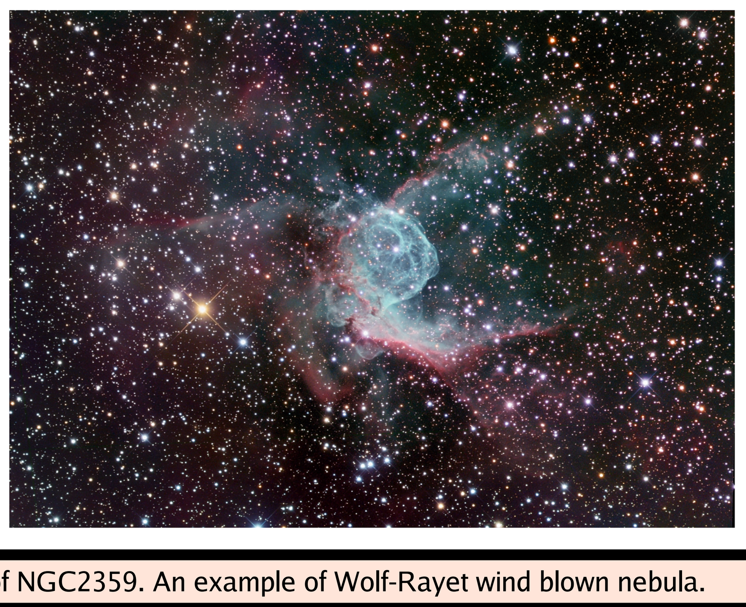

Fig. 8: An image of NGC2359. An example of Wolf-Rayet wind blown nebula.