CYGNUS X-3’S LITTLE FRIEND

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ABSTRACT

Using the unique X-ray imaging capabilities of the Chandra X-ray observatory, a 2006 observation of Cygnus X-3 has provided insight into a singular feature associated with this well-known microquasar. This extended emission, located \( \sim 16'' \) from Cygnus X-3, varies in flux and orbital phase (shifted by 0.56 in phase) with Cygnus X-3, acting like a celestial X-ray “mirror.” The feature’s spectrum, flux, and time variations allow us to determine the location, size, density, and mass of the scatterer. We find that the scatterer is a Bok Globule located along our line of sight, and we discuss its relationship to Cygnus X-3. This is the first time such a feature has been identified with Chandra.

Key words: X-rays: binaries – X-rays: individuals (Cygnus X-3) – X-rays: ISM

Online-only material: animation, color figures

1. INTRODUCTION

At a distance of 9 kpc (Predehl et al. 2000), Cygnus X-3 is an unusual microquasar in which a Wolf–Rayet companion (van Kerkwijk et al. 1992) orbits a compact object with an orbital period of 4.8 hr. It is a strong radio source routinely producing radio flares of 1 to \( \sim 20 \) Jy (Waltman et al. 1995). It has been shown to produce radio jets and the radio emission correlates with both the soft X-ray and high X-ray emissions (Mioduszewski et al. 2001; Miller-Jones et al. 2004; Szostek et al. 2008; McCollough et al. 1999). In 2000, Chandra observations found extended X-ray emission that is believed to be associated with Cygnus X-3 (Heindl et al. 2003). In this paper, we analyze a 2006 Chandra observation of Cygnus X-3 and re-examine the previous Chandra observations discussed in Heindl et al. (2003). In particular, we take a careful look at the timing and spectral properties of the extended feature and how they related to Cygnus X-3.

2. OBSERVATIONS AND ANALYSIS

Between 1999 and 2006, Cygnus X-3 was observed six times by Chandra using the ACIS-S/HETG with a timed event (TE) mode and covered a range of source activity (see Table 1). These observations provided grating spectra of Cygnus X-3 and on-axis zero-order images which allow for spatial and spectral analysis of Cygnus X-3 and its surroundings.

The primary observation used for this analysis was a 50 ks quenched state observation (ObsID: 6601 hereafter referred to as QS) obtained during a period of high X-ray activity. At the time of the observation, the RXTE/ASM (2–12 keV) count rates were \( \sim 25–30 \) counts s\(^{-1}\), Swift/BAT (15–50 keV) had an average count rate of \( \sim 0.0 \) counts s\(^{-1}\), and the Ryle radio telescope (15 GHz) showed radio fluxes of \( \sim 1 \) mJy, all values typical of a Cygnus X-3 quenched state (Szostek et al. 2008; McCollough et al. 1999; Waltman et al. 1996). This observation has the longest duration of any of the observations and the feature has the greatest number of photons of any of the observations.

Since this analysis involves a region near a bright point source we also need to determine the impacts of pileup on the data. This can be determined by looking at the average number of counts per detection island (9 pixel region, see the Chandra POG 2011) per observing frame. We do this by taking a series of annul centered on Cygnus X-3 for the highest count rate observation (QS). Each annulus has a radial thickness of 2 ACIS pixels (\( \sim 1'' \)) with the readout streak regions excluded. We then sum the counts in each annulus and divide by the number of observation frames\(^3\) and the of number detection islands (the area of the annulus in pixels divided by 9 pixels). Figure 1 shows a plot of counts/frame as a function of radial distance from Cygnus X-3, with the solid line representing the entire observation and the dotted line the times of peak count rate. From Davis (2007), we have taken the counts/frame values for which one would expect pileup of 1%, 5%, and 10% and plot them in Figure 1. We see that at a radial distance of greater than \( \sim 8'' \) pileup should not be an issue and will not impact our analysis.

In our analysis of these observations, we used version 4.3 of the CIAO tools. The Chandra data retrieved from the archive were processed with ASCDS version 7.7.6 or higher. All event files were filtered by their good time intervals and barycenter corrected using the CIAO tool axbary.

2.1. The Feature and its Characteristics

For each observation, we have extracted a zeroth-order image between 1 and 8 keV binned at the nominal ACIS-S resolution (\( \sim 0.49'' \)). Figures 2 and 5 show images for the QS observation. In each individual image, there is a bright, unresolved core with strong radial point-spread function (PSF) wings and a strong scattering halo (Predehl et al. 2000). In each observation, the feature reported by Heindl et al. (2003) is present at the same location. An analysis of the QS observation shows that the feature (R.A.: 20\(^{h}\)32\(^{m}\)27.1, decl.: +40\(^\circ\)57\('\)33\('.\)8\) lies at an angular distance of 15''6 from Cygnus X-3 at an angle of 68''5 from the orientation of the observed radio jets of Cygnus X-3. The feature is extended and was fit using CIAO/SHERPA with a two-dimensional Gaussian with axes of 3''6 and 5''5 and a

\(^3\) The number of observation frames can be determined either by extracting the keyword TIMEDEL from the event file header and dividing the exposure time by its value or using the acisf06601_000N001_stat1.fits file found in the Chandra secondary data products, which contains a record of all of the frames in the observation. This file must also have applied all the time corrections and filtering that were applied to the event file and correct CCD selection needs to be made.
Figure 1. Plotted are the counts/frame for the QS observation as a function of radial distance from Cygnus X-3. The solid line is for the entire observation and the dotted line is for the times of the highest count rates (Cygnus X-3 phases 0.6–0.7). The counts/frame for various levels of expected pileup are given (Davis 2007). The long dashed vertical lines show the location of the feature and the shaded region gives the feature’s radial extent. Pileup should not be an issue for the observations used in this analysis.

Table 1

| ObsID | Date (MJD) | Instrument | Data Mode | Exp Mode | Exposure (ks) | Count Rate$^a$ (counts s$^{-1}$) | State |
|-------|------------|------------|-----------|----------|---------------|-----------------------------------|-------|
| 101$^b$ | 51471 | ACIS-S | FAINT | TE | 1.95 | 35.8 | t/mf |
| 1456 (obi 0)$^b$ | 51471 | ACIS-S | FAINT | TE | 12.12 | 27.7 | t/mf |
| 1456 (obi 2) | 51531 | ACIS-S | FAINT | TE | 8.42 | 18.0 | q/qi |
| 425$^c$ | 51638 | ACIS-S | GRADED | TE | 18.54 | 88.2 | fs/mrf |
| 426$^c$ | 51640 | ACIS-S | GRADED | TE | 15.68 | 71.0 | h/mrf |
| 6601 | 53761 | ACIS-S | FAINT | TE | 49.56 | 106.6 | h/qu |

Notes. The states are given as $k/s$ where: $k$ are those of Koljonen et al. (2010) (q: quiescent, t: transition, fh: FHXR, fi: FIM, fs: FSXR, and h: hypersoft) and $s$ are those of Szostek et al. (2008) (qi: quiescent, mf: minor flaring, su: suppressed, qu: quenched, mrf: major flaring, and pf: post flaring).

$^a$ This is calculated by taking the total number of 1–8 keV events in the observation and dividing it by the exposure.

$^b$ The observation end time of ObsID 101 is identical to the observation start time of 1456 (obi 0). For the purpose of the analysis in this paper these two ObsIDs will be taken to be a single observation.

$^c$ ObsIDs 425 and 426 were done in alternating exposure mode. The shorter frame time observation (0.3 s) resulted in an additional 0.4 ks (425) and 0.3 ks (426) exposure. For this analysis only the observations with the longer frame time (1.8 s) were used.

position angle of 78°7, measured counterclockwise with the top of the image being 0°. If the feature and Cygnus X-3 are at the same distance, then their separation is $2.2D_9$ lt-yr ($D_9$: distance in units of 9 kpc). This feature is present in all observations of Cygnus X-3 made throughout the Chandra mission (1999 to present).

2.2. Temporal Behavior

The feature is located amidst a high background region. This high background is due to the telescope PSF and a dust scattering halo. The majority of the photons in the background have energies above 2 keV and as such arise from scattering off microroughness in the telescope optics; see the discussion in Predehl et al. (2000). In order to examine the temporal variability of the feature we need to subtract the background flux from the region of the feature. To do this, we used segments of annuli centered on Cygnus X-3 for the feature and background regions to extract the light curve for the feature and the background (see Figure 2). The annuli were chosen to maximize the number of counts for the feature as well as have the feature and background regions sample the same radial region of the PSF/dust halo while avoiding the readout streaks. All data extraction was done with the CIAO tool dmextract.

2.2.1. Phase-folded Analysis

The phase-folded (1–8 keV) light curves of Cygnus X-3, the background region, and background-subtracted feature region are shown in Figure 3. As might be expected the background, which is mainly due to the scattered PSF emission, demonstrates the same 4.79 hr orbital variation with the slow rise and rapid observed drop in Cygnus X-3. This is also reinforced in Figure 4 (top panel) which shows no observed lag in the cross-correlation between Cygnus X-3 and the background. However, the feature surprisingly shows the same orbital modulation but with a phase shift of $\sim$0.6. Phase-selected images reveal how this feature
Figure 2. Segments of annuli centered on Cygnus X-3 were used for the feature and background regions to extract the light curve and spectrum for the feature (black; blue online) and the background (gray; green online). The inner edge of the annuli is 11′′₂ from Cygnus X-3 and the outer edge is 20′′₀.

(A color version of this figure is available in the online journal.)

varies relative to Cygnus X-3 (see Figure 5), which can be seen more dramatically in the movie which accompanies this paper (see online version). This is also confirmed in the cross-correlation between Cygnus X-3 and the feature seen in Figure 4 (lower panel) which shows a clear lag that peaks around 9460 s which corresponds to a phase lag of ~0.55.

Fitting phase-folded light curves. To address questions of a possible issue with background subtraction (oversubtraction) we took the light curve from feature annulus and fitted it using the following model:

\[ C_{lf}[i] = C_{bkgd}[i] + a \times C_{bkgd}[\text{shift}(i, j)], \]

where \( C_{lf}[i] \) is the count rate for the feature’s region in phase bin \( i \), \( C_{bkgd}[i] \) is the count rate from background region (scaled to the feature’s region size) in phase bin \( i \), and the last term \( a \times C_{bkgd}[\text{shift}(i, j)] \) is the count rate of the background region scaled by \( a \) and shifted by \( j \) in phase. The fit parameters are \( a \) and \( j \). We used the IDL routine MPFIT (Markwardt 2009) to fit the light curve. We did multiple fits of the light curve using a number of different phase binnings and found good fits for all binnings with consistent fit values (see Table 2). Our best fit gave \( a = 0.29 \pm 0.01 \) and \( j = 0.56 \pm 0.02 \) (see Figure 6).

As a further test we replaced the second term in Equation (1) with a constant term which was used as a fit parameter. We found no acceptable fits for any of the binnings (see Table 2). This result is consistent with the feature varying with the same period as Cygnus X-3 but shifted in phase.

Phase image. Finally, as another way to check whether background subtraction could be an issue for each Chandra detected event, a “Cygnus X-3” phase value was determined from its arrival time. Photons falling into certain phase ranges were broken in separate “phase” images. These images were assigned a certain 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. The image is shown in Figure 7; note the blue color of the feature. This indicates that the bulk of the
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Figure 4. Cross-correlation plots: the dashed vertical line corresponds to a lag of half of Cygnus X-3’s period and the dot-dashed line corresponds to a lag of Cygnus X-3’s period. Top: the cross-correlation between Cygnus X-3 (grating data) and the background region (1–8 keV) using 600 s time samples. Note that there is no lag between them. Bottom: the cross-correlation between Cygnus X-3 (grating data) and the feature (background subtracted) using 172 s time samples (~0.01 of Cygnus X-3’s period). Note the lag of 9460 s which corresponds to a phase shift of ~0.55.

Figure 5. These phase-selected images were created from the zero-order image Chandra grating observation (QS) using photons with energies between 1 and 8 keV. The count range and color scales are identical for both images. The bright readout streak caused by the ACIS CCD readout and the “cratering” of the central source due to pileup are both instrumental effects. Left: phase range 0.96–0.3 image. The feature is prominent. Right: phase range 0.5–0.8 image. The feature is very weak. To better visualize the phase relationship between the feature and Cygnus X-3 a movie was created. For all of the events detected in QS a Cygnus X-3 orbital phase based on their arrival time was determined. The data were filtered to only include 1–8 keV energy photons. For the image a 256 by 256 pixels region centered on Cygnus X-3 was used. A set of images were created based on phase intervals, starting at 0.0 phase and with a duration of 0.20 of Cygnus X-3’s phase. Each image was successively shifted by a 0.01 of Cygnus X-3’s phase until images for the full Cygnus X-3 period were created and compiled to form the movie. The duration of the observation (50 ks) corresponds to 2.96 orbits of Cygnus X-3, so phase coverage is relatively uniform. The duration of each image (0.2 phase) corresponds to an integration time of ~10^4 s. (An animation and a color version of this figure are available in the online journal.)

photons are arriving in the 0.96–0.3 phase range. If the feature was constant we would expect it to be white (equal amounts of each color). It is also important to note that no background subtraction was done in this approach and hence there is no issue with the background subtraction creating a false time-phase variation of the feature.

2.2.2. Longer Timescale Variability

To examine the temporal behavior of the feature on longer timescales we determined the flux^4 of Cygnus X-3 and the feature for each of the Chandra/ACIS observations (see Table 1).

^4 The spectral fits and corresponding fluxes estimates are given and discussed in Sections 2.3 and 3.1.
Figure 6. Fits to the phase-folded 1–8 keV light curves of the feature with no background subtraction. Top: phase-folded light curve of Cygnus X-3 (50 phase bins) with a fit to the light curve (dotted line). Middle: data minus model fit divided by the data error bars, with $\pm 1\sigma$ error bars. Bottom: the model of the phase-folded light curve of the feature from the fit.

Table 2
Phase-folded Light Curve Fitting Parameters

| Model   | Binning | Amplitude | Phase Shift | $\chi^2$/dof |
|---------|---------|-----------|-------------|--------------|
| Phase shift | 10      | 0.29 ± 0.01 | 0.60 ± 0.10 | (9.24/8)     |
|         | 20      | 0.29 ± 0.01 | 0.55 ± 0.05 | (23.74/18)   |
|         | 40      | 0.29 ± 0.01 | 0.55 ± 0.03 | (50.82/38)   |
|         | 50      | 0.29 ± 0.01 | 0.56 ± 0.02 | (51.17/48)   |
|         | 100     | 0.29 ± 0.01 | 0.56 ± 0.02 | (104.60/98)  |

| Constant | 10      | 0.069 ± 0.002 | ... | (66.34/9) |
|          | 20      | 0.068 ± 0.002 | ... | (80.81/19) |
|          | 40      | 0.068 ± 0.002 | ... | (108.07/39) |
|          | 50      | 0.068 ± 0.002 | ... | (110.38/49) |
|          | 100     | 0.067 ± 0.002 | ... | (166.39/99) |

Notes. The phase-shifted model is the one given in Equation (1). The constant model is the same as the phase-shifted model except that the shift term has been replaced with a constant which is used as a fit parameter.

When Cygnus X-3’s flux is plotted versus the flux from the feature there appears to be a correlation (see Figure 8) where the dashed line is a linear fit to the data. A Pearson’s correlation test of the data yields a correlation coefficient of 0.98 indicating a linear correlation between the feature and Cygnus X-3.

2.3. Spectrum

The annuli used to extract the light curves (see Figure 2) were also used to extract spectra for the feature and background region. The final background-subtracted spectra of the feature contained from 78 to 3216 counts in the 1–8 keV band. Table 3 shows fits to the spectrum using simple absorbed power-law and blackbody models, all of which yield acceptable fits to the spectrum.

Figure 7. Color-coded phase image of Cygnus X-3 region. 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.

All of the Chandra/ACIS observations were HETG grating observations. The ± first-order HEG spectra were combined and fit for each observation (see notes in Table 1). The continuum for Cygnus X-3 is complex and dependent on the state of activity
Figure 8. Plotted is the 1–8 keV flux of Cygnus X-3 (determined from the grating data) vs. the 1–8 keV flux of the feature for each of the ACIS observations using the scattering model. The dashed line is a linear fit to the data.

Table 3
Spectral Fit Parameters for the Feature

| ObsID:         | 101+1456(0) | 1456(2) | 425  | 426  | 6601 |
|---------------|-------------|---------|------|------|------|
| Net counts:   | 163         | 78      | 750  | 697  | 3216 |
| Absorbed power law |            |         |      |      |      |
| \(N_h\) (10^{22} \text{ cm}^{-2}) | 7.3^{+16.7}_{-7.3} | 6.0^{+36.6}_{-5.5} | 12.5^{+6.7}_{-4.2} | 13.3^{+6.9}_{-4.5} | 10.6^{+12.1}_{-1.8} |
| \(\Gamma\)    | 1.7^{+4.2}_{-2.9} | 2.8^{+4.5}_{-2.8} | 4.8^{+2.0}_{-1.5} | 3.8^{+4.6}_{-1.2} | 4.0^{+5.6}_{-0.6} |
| Flux \(^b\)   | 6.6 \times 10^{-13} | 3.6 \times 10^{-13} | 2.6 \times 10^{-12} | 2.6 \times 10^{-12} | 3.7 \times 10^{-12} |
| \(\chi^2/dof\) | 5.8/8       | 7.7/13  | 14.5/13 | 17.2/13 | 15.2/17 |
| Absorbed blackbody |            |         |      |      |      |
| \(N_h\) (10^{22} \text{ cm}^{-2}) | 1.8^{+13.1}_{-1.8} | 2.3^{+24.4}_{-2.2} | 7.3^{+4.5}_{-2.7} | 7.5^{+4.5}_{-2.8} | 5.6^{+13.1}_{-1.1} |
| \(T\) (keV)   | 2.4^{+0.9}_{-0.1} | 1.1^{+1.6}_{-0.6} | 0.7^{+0.2}_{-0.2} | 1.0^{+0.3}_{-0.2} | 0.9^{+0.1}_{-0.1} |
| Flux \(^b\)   | 7.1 \times 10^{-13} | 3.8 \times 10^{-13} | 2.5 \times 10^{-12} | 2.6 \times 10^{-12} | 3.5 \times 10^{-12} |
| \(\chi^2/dof\) | 5.9/9       | 7.3/13  | 13.6/13 | 16.4/13 | 15.5/17 |

Notes.
\(^a\) Net number of counts in 1–8 keV part of the spectrum.  
\(^b\) Measured flux in erg s\(^{-1}\) cm\(^{-2}\) in the 1–8 keV band.

(Hjalmarsson et al. 2008, 2009; Koljonen et al. 2010). In the X-ray (0.5–10 keV), the continuum can be modeled by a partially covered disk blackbody during flaring/quenched states (Koljonen et al. 2010) and during the quiescence/transition states we found that the continuum was best approximated by an absorbed power law. In all cases, a large number of spectral features were added (see Table 4) to improve the spectral fit.

We note that all of the spectra of the feature are more absorbed and very steep/soft, relative to the corresponding Cygnus X-3 spectra (see Tables 3 and 4). As Cygnus X-3 transitions from a quiescent (hard) to a flaring/quenched state (soft) its spectrum becomes softer. The spectrum of the feature is shown to follow suit and becomes steeper/softer as Cygnus X-3’s spectrum does.

3. NATURE OF THE FEATURE

To understand the feature’s nature the following must be explained: (1) it is clearly extended, (2) its flux varies in phase with Cygnus X-3 with a phase shift of 0.56, (3) the flux from the feature shows a correlation with the flux from Cygnus X-3, (4) the phase-averaged flux of the feature is \(\sim 10^{-3}\) of Cygnus X-3’s flux, (5) the time variation is 4.8 hr but the separation between the feature and Cygnus X-3 is at least 2.2\(D\) lt-yr, and (6) its spectrum is heavily absorbed and lacks hard X-ray flux relative to Cygnus X-3.

Jet emission. It is natural to try to associate this feature with the Cygnus X-3 jet emission. However, Cygnus X-3 was in a quenched state throughout the Chandra observation and
for several days before and after, during which jet activity is strongly suppressed. Additionally, over a three-year period prior to this observation, Ryle/AMI-LA observed no radio flare exceeding 0.5 Jy (Pooley 2011). Furthermore, in earlier Chandra observations where there is jet activity, the feature is fainter. If the X-ray emission of the feature was due to the jet one would expect this to be synchrotron emission and would not generally expect the spectrum to be so steep and heavily absorbed. Also, the misalignment of the feature relative to the jets observed in the radio complicates this picture.

Jet impact area. Problems with this being a jet impact area have been noted by Heindl et al. (2003): the location relative to the radio jets, jet precession, and jet collimation. In addition the observed flux correlation between the feature and Cygnus X-3 provides problems given a likely separation of 2.2 D₀ lt·yr. The strong phase modulation of the feature (varying as

Cygnus X-3 by a factor of two), combined with a periodicity exactly matching that of Cygnus X-3, would be difficult to understand. One would expect that the continuing impact of the jet would give rise to a brighter constant flux from the feature and drastically reduce the modulation that is observed.

Wind interaction. The strongest arguments which were made by Heindl et al. (2003) for the feature’s nature are that it is due to a wind/interstellar medium (ISM) interaction. The feature’s distance, flux correlation, and phase modulation with Cygnus X-3 make such a model difficult to reconcile with the observations. In this interpretation, the feature is created over timescales that are long (~2000 yr) compared to the observed orbital modulation. Also, the direct change in the flux of the feature with Cygnus X-3 flux is difficult to reconcile with such a model.

3.1. Scattering Solution

A natural explanation for the feature’s time variable behavior is that it is a result of scattering from a cloud (which acts as a kind of interstellar X-ray “mirror”) between Cygnus X-3 and the observer. This explanation would naturally lead to the observed phase difference between light curves as a difference in the path length of the scattered photons (Trümpler & Schönfelder 1973). This could also explain the flux correlation (see Figure 8) and overall flux difference (~10⁻²) since only a small fraction of the total flux will be scattered toward the observer. In Figure 9, a diagram of the expected geometry for the scattering from a cloud is shown.

The spectrum of the feature can also be modeled as a scattered version of Cygnus X-3’s spectrum. At these energies scattering will modify the spectrum by A * E⁻² (Smith et al. 2002), due to the reduced scattering efficiency at higher energies (Overbeck 1965). There will be an additional reduction at low energies caused by absorption in the cloud (Nₜ) and multiple scattering. We can then model the feature’s spectrum due to scattering as

\[ S_{lf} = e^{-\sigma(E)N_0(lf)} * A * E^{-\alpha} * S_{cont}. \]  

(2)

where \( S_{lf} \) is the scattering model for the feature, \( e^{-\sigma(E)N_0(lf)} \) is the additional absorption due to the cloud (modeled using phabs in XSPEC), \( A * E^{-\alpha} \) represents the high energy attenuation due to scattering (modeled using phabs from XSPEC), and \( S_{cont} \) is Cygnus X-3 continuum model determined from the grating data (see Table 4). The resulting fit parameters for the observations are shown in Table 5 and the fit to the QS observation’s spectrum.
the observed orbital period of Cygnus X-3, but we have an ambiguity in the total number orbital period offsets ($n$). Using $\Delta t = 0.56 \times t_{\text{cx3}} = 9.66$ ks, $D = 9$ kpc, and $\Theta = 15^\prime$, the resulting fractional distance is $x = 0.79$. This means that the cloud is close to Cygnus X-3 (within 1.9 kpc) and if $n > 0$, this distance could be smaller.

This degeneracy ($n$) can be removed using the fact that the feature is extended. From Equation (3) we would expect that the delay that the scattered photons experience increases as a function of angle from Cygnus X-3. If we take the inner and outer edges of the feature to be $13^\prime.8$ and $17^\prime.4$ respectively then for $x = 0.79$ we would get a time delay of $\sim 1.2$ hr across the feature. For locations closer to Cygnus X-3 we would expect the delay across the feature to increase. To test this we have taken the extraction and background annuli (see Figure 2) and divided them into an inner and outer set of annuli ($11^\prime.2$–$15^\prime.6$ and $15^\prime.6$–$20^\prime.0$, respectively). In Figure 11, we show a cross-correlation of the inner and outer light curves (for the QS observation with 5 minute time resolution) which shows a significant lag (at the 99% confidence level) at 0.79 hr. This would correspond to the $n = 0$ case. Figure 12 shows the phase-folded light curves of the inner and outer regions, in which one can see

\begin{equation}
\Delta t = \frac{\Theta^2}{2c} \frac{D}{1-x} = 1.15\Theta^2 \frac{D}{1-x},
\end{equation}

where $\Delta t$ is the time delay (in seconds), $D$ is the distance (in kpc) to the source, $\Theta$ is observed angular distance (in arcsec) from the source, $x$ is the fractional distance of the scatter to the observer (see Figure 9), and $c$ is the speed of light. From the observed phase offset, we know that the time delay is given by $\Delta t = (0.56 + n)t_{\text{cx3}}$ where $t_{\text{cx3}} = 17.25$ ks is

![Figure 10](image-url). Extracted spectrum of the feature, taken from QS, is shown above. Also given is the fit (gray; red online) and residuals of a scattering model. A good agreement is found between the data and the model.

(A color version of this figure is available in the online journal.)

### Table 5

| ObsID       | 101+1456(0) | 1456(2) | 425  | 426  | 6601 |
|-------------|-------------|---------|------|------|------|
| $N_{\text{cl}}$ (10$^{22}$ cm$^{-2}$) | 6.4$^{+15.5}_{-4.19}$ | 0.0$^{+7.8}_{-0.0}$ | 3.1$^{+1.6}_{-1.3}$ | 4.0$^{+6.4}_{-4.0}$ | 5.0$^{+12.0}_{-7.7}$ |
| $A$         | 1.4$^{+0.5}_{-0.5}$ | 1.5$^{+0.7}_{-0.7}$ | 1.1$^{+0.2}_{-0.2}$ | 1.1$^{+0.2}_{-0.2}$ | 1.4$^{+0.1}_{-0.1}$ |
| $\alpha$    | 2.0$^a$ | 2.0$^a$ | 2.0$^a$ | 1.8$^{+1.6}_{-1.2}$ | 1.0$^{+0.6}_{-0.6}$ |
| Flux$^b$    | 6.0 $\times$ 10$^{-13}$ | 3.9 $\times$ 10$^{-13}$ | 2.7 $\times$ 10$^{-12}$ | 2.6 $\times$ 10$^{-12}$ | 3.6 $\times$ 10$^{-12}$ |
| $\chi^2$/dof | 6.4/8 | 7.8/13 | 15.8/13 | 16.7/12 | 14.7/16 |

**Notes.**

$^a$ Fixed.

$^b$ Measured flux in erg s$^{-1}$ cm$^{-2}$ in the 1–8 keV band.
that the light curve for the outer region is lagging the inner by \( \sim 0.2 \) in phase. This corresponds to a lag of \( \sim 1 \) hr. This puts the feature at a distance of 1.9 kpc from Cygnus X-3, making its observed dimensions 0.12 by 0.19 parsecs.

**Density of the cloud.** From the spectral fit to the feature for the QS observations we have an absorbing column density of the feature of \( 5.0^{+1.7}_{-1.5} \times 10^{22} \) cm\(^{-2} \). This value is consistent with the column density determined from spectral fits to the other observations (see Table 5). The column density of the feature can also be estimated from the flux ratio of the feature to Cygnus X-3 using the following relationship (see the Appendix for its derivation):

\[
\frac{F_{\text{cx3}}}{F_{\text{cx3}}} = N_{H}(\text{lf}) \frac{\pi \tan \alpha_1 \tan \alpha_2 \cos^2(\theta_1 - \theta)}{(1 - x)^2} \times \sum_{i=g,s} \int_{E_1}^{E_2} S(E) e^{-\sigma(E)N_{H}(\text{lf})} a^{-3.5} \times \left( d\sigma(E, a, \theta_1) \right) d\alpha dE.
\]

The flux ratio is equal to the product of three quantities. The first \((N_{H}(\text{lf}))\) is the column density of the feature, the second is a solid angle term which relates to the fraction of Cygnus X-3’s flux that is intercepted by the feature, and the final term is a scattering term which is a measure of the flux scattered by the dust in the cloud (this is solved for by numerical integration over the energy range and grain distribution). The last two terms depend on \( x \), the fractional distance between the observer and Cygnus X-3. Figure 13 shows a plot of the last two terms and their product as a function of \( x \). The solid line is for scattering due to silicates and the dotted line for scattering due to graphite. Equation (4) can be solved for the column density of the feature as a function of \( x \) as shown in Figure 14. The parameters used to create these curves are given in Table 6. Also included are lines representing the column density from the spectral fit of QS with its uncertainties and a vertical line representing its location from the observed time delay. What we find is good agreement with the column density determined from the spectral fits and the column density \((N_{H} = 3.6 \times 10^{22} \text{ cm}^{-2})\) necessary to produce the observed flux ratio.

If we assume that path length along the line of sight through the cloud is similar to the observed dimensions of the feature \((3.7\times5.9) \times 10^{17} \text{ cm})\) we can make an estimate of the density of the feature. Taking the column density to be \( 5.0^{+2.0}_{-1.5} \times 10^{22} \text{ cm}^{-2} \) we arrive at a density range of \((0.6\times1.9) \times 10^{5} \text{ cm}^{-3} \) making the feature a dense molecular cloud.

**Mass of the cloud.** From the estimate of the density of the cloud and the size determined from the X-ray measurements we can make an estimate of the mass of the cloud. Using the simplifying assumption of a spherical cloud with a diameter of between 0.12 and 0.19 pc with a density of \( 10^{5} \text{ cm}^{-3} \) we arrive, from X-ray observations alone, at an estimate of the mass of the cloud of \( 2\times24 M_{\odot} \).

From the cloud’s size, density, and mass the feature has all of the characteristics of a Bok Globule (Bok & Reilly 1947; Clemens et al. 1991), but instead of seeing this as a dark obscuring feature in the optical, we see it shining in scattered X-rays.

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**Figure 11.** Plot of the cross-correlation between the inner (11.2–15.6) and outer (15.6–20.0) regions of the feature (both background subtracted). The time resolution was 5 minutes for the light curves. The dashed horizontal lines correspond to a 99% confidence level. The dash, dot-dash, dots-dash, and large dot-dash vertical lines correspond to lags one would observe across the feature for \( n = 0, 1, 2, \) and 3, respectively. Note the prominent peak at \( \sim 1 \) hr corresponding to the \( n = 0 \) lag.

**Figure 12.** Plot of the phase-folded light curves of the inner (solid: blue online) and outer (dotted: red online) regions of the feature (both background subtracted). There is a noticeable lag in the outer relative to the inner of \( \sim 0.2 \) in phase which corresponds to \( \sim 1 \) hr in time.

(A color version of this figure is available in the online journal.)

### Table 6

| Parameter          | Value                                      |
|--------------------|--------------------------------------------|
| \( F_{\text{cx3}} \) (1–8 keV) | \( 9.12 \times 10^{-3} \) photons cm\(^{-2} \) s\(^{-1} \) (6.13 \times 10^{-9} \) erg cm\(^{-2} \) s\(^{-1} \) |
| \( F_{\text{cx3}} \) (1–8 keV) | \( 5.6 \times 10^{-4} \) photons cm\(^{-2} \) s\(^{-1} \) (3.6 \times 10^{-12} \) erg cm\(^{-2} \) s\(^{-1} \) |
| \( \theta \)         | 15/6                                       |
| \( \alpha_1 \)          | 2.57 (50 full width: 5.54)                |
| \( \alpha_2 \)          | 1.82 (50 full width: 3.65)                |
| \( D \)               | 9 kpc                                      |
| \( \rho (\text{graphite}) \) | 2.24 g cm\(^{-3} \)                      |
| \( \rho (\text{silicate}) \) | 3.5 g cm\(^{-3} \)                      |
| \( N_{d} (\text{graphite}) \) | \( 7.41 \times 10^{-16} \) grains m\(^{-2} \) |
| \( N_{d} (\text{silicate}) \) | \( 7.76 \times 10^{-16} \) grains m\(^{-2} \) |
| \( a_{\text{min}} \)   | 0.005 \() \)                               |
| \( a_{\text{max}} \)   | 0.25 \( \mu \)                            |
| \( E_1 \)             | 1.0 keV                                    |
| \( E_2 \)             | 8.0 keV                                    |

Note. \(^*\) The dust grain parameters were taken from Weingartner & Draine (2001).
Figure 13. Plots of the last two terms and their product of the flux ratio (see Equation (4)) as a function of $x$. Top: plot of the solid angle term which is a measure of the flux the feature intercepts. Middle: plot of the scattering terms which takes into account the fraction of the X-ray flux that is scattered to the observer. The solid line is for silicate scatters and the dotted line is for graphite scatters. Bottom: plot of the product of the solid angle term with the sum of the two scattering terms.

Figure 14. Plot of the scattering column density necessary to produce the observed feature/Cygnus X-3 flux ratio (see Equation (4)) vs. $x$. The vertical line (large dashes) is location for the feature determined from the time delay. The horizontal dashed lines represent the scattering column density determined from the spectral fit and the shaded region between the dashed-dotted lines represents its uncertainties. We find good agreement between values found for the flux ratio and the spectral fit.

4. RELATIONSHIP TO CYGNIUS X-3

What is the relationship of this feature to Cygnus X-3? Three possibilities present themselves.

1. **Random alignment.** Cygnus X-3 and the feature both lie in the Galactic plane ($l_{ii} = 79.845$, $b_{ii} = 0.700$). The Cygnus X region that hosts Cygnus X-3 is rich in molecular clouds (Schneider et al. 2006). So this may be just a chance alignment. If so, this gives us insight into the nature and structure of molecular clouds in the ISM. In this case, we would be looking across three Galactic arms (with Cygnus X near the Local Spur, the feature in the Perseus arm at $\sim 5$ kpc, and Cygnus X-3 in the Outer Arm at 7–9 kpc). Bringing Cygnus X-3 closer, to 7 kpc, does not greatly change the distance estimate to the feature or the need for three star-forming regions along the line of sight.

2. **Supergiant bubble shell.** These structures have been observed in other galaxies (Kim et al. 1999). They have typical radii of 0.5–1.0 kpc and are driven by the radiation and outflows from OB associations, supernovae and their remnants, and X-ray backgrounds. Molecular clouds have also been found to exist in these shells (Yamaguchi et al. 2001). Cygnus X-3 is a high-mass X-ray binary and likely still resides in such an OB association. This gives a natural explanation of the feature’s location along our line of sight. Given the distance of the feature from Cygnus X-3 this would be a bubble comparable to the H$\text{I}$ shell found in NGC 6822 (de Blok & Walter 2000).

3. **Microquasar jet-inflated bubble.** Within NGC 7793 a powerful microquasar is driving a 300 pc jet-inflated bubble (Pakull et al. 2010). Cygnus X-3 is a microquasar whose jets appear to be aimed along our line of sight (Mioduszewski et al. 2001; Miller-Jones et al. 2004). It is possible that rapid cooling near the working surface of the jet, in the shell of the cocoon, may allow a dense molecular cloud to form. This would explain the nature of the feature as well as its alignment with Cygnus X-3. However, it should be noted that there is research which suggests that the jet may not be
close to the line of sight (Martì et al. 2001), which would make this a less likely option.

Finally, it should be noted that a combination of both (2) and (3) may be possible. The radiation and outflows from the OB association may create a large low-density cavity in which the microquasar jet can more easily propagate. Evidence for large-scale cavities surrounding other microquasars has been noted (Hao & Zhang 2009). This could explain the large distance of the feature from Cygnus X-3 (1.9 kpc) and reduce the energetics of the OB cloud.

The feature has been fitted with an elliptical Gaussian with semimajor and semiminor axes of r1 and r2, respectively. For a distance of xD one can use the angular measurements of the semimajor and semiminor axes, α1 and α2, respectively, to give the surface area of the feature as A_{gf} = πx^2 D^2 tan α1 tan α2. For a scattering volume of the feature we can determine the total count rate and flux for the feature as

\[ F_{lf}(a, E) = \frac{C_{int}(E)}{A'} = \frac{n_g(a)L_{c3}(E)\int d\sigma_s}{4\pi r_s^2} \frac{d\sigma_s}{d\Omega} \frac{A_{lf}}{r_s^2} \]  

where \( n_g(a) \) is the number of dust grains per unit area.

5. CONCLUSION

This feature and its temporal relationship to Cygnus X-3 have unveiled the unique interaction between a microquasar and its environment. It has given us a tool to probe the nature and structure of molecular clouds, providing information on their size and shape, possibly due to the microquasar interaction or the presence of ordered magnetic fields in the ISM. It has also given us our first X-ray view of a Bok Globule.

To date this is the first such feature found with Chandra. If the feature is indeed due to a microquasar interacting with the X-ray and the need for the lobes and associated molecular clouds to be aligned close to our line of sight. Depending on the nature of these sources the best candidates for future detections would be high-mass X-ray binaries (because of their young age and hence likely relationship with OB association and star-forming regions) with relatively short orbital periods.

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APPENDIX

DERIVATION OF SCATTERING RELATIONS FOR CYGNUS X-3 AND THE FEATURE

It is possible to derive some of the scattering properties by comparison of the fluxes of Cygnus X-3 and the feature. This derivation is similar to that done for the scattering halo intensity of Smith & Dwek (1998). The geometry being used can be found in Figure 9. If we take the unabsorbed luminosity of Cygnus X-3 as a function of energy to be \( L_{c3}(E) \) then the X-ray luminosity at the feature is given by

\[ L_{lf}(E) = \frac{L_{c3}(E)\int d\sigma_s}{4\pi r_s^2}, \]  

where \( d\sigma_s/d\Omega \) is the differential scattering cross section (see Mathis & Lee 1991; Mauche & Gorenstein 1986).

For a telescope with collecting area \( A' \) we can choose \( d\Omega \) such that \( A' = r_s^2 d\Omega \), where \( r_s \) is the distance from the scatter to the observer.

The photon count rate that the observer will detect from scattering from a single dust particle is given as

\[ C_s(E) = L_s(E)e^{-\sigma(E)N_{lf}(r_s)} \left( \frac{d\sigma_s}{d\Omega} \right) A' \frac{d\sigma_s}{d\Omega} A' \frac{d\sigma_s}{d\Omega} \]  

where \( N_{lf}(r_s) \) is the column density between the observer and Cygnus X-3.

Finally, from the scattering geometry (see Figure 9), we have

\[ \frac{1}{r_s} = \frac{\cos(\theta_e - \theta)}{D(1 - x)}, \]  

where \( d\sigma_s/d\Omega \) is the differential scattering cross section (see Mathis & Lee 1991; Mauche & Gorenstein 1986).

For a telescope with collecting area \( A' \) we can choose \( d\Omega \) such that \( A' = r_s^2 d\Omega \), where \( r_s \) is the distance from the scatter to the observer.
where $x$ is the projected distance along the path between the observer and Cygnus X-3. The measured angle of the feature ($\theta$) and the scattering angle ($\theta_s$) are related to the projected distance $x$ by $\theta = (1 - x)\theta_s$. Using the above relations we arrive at the following substitution:

$$\frac{L_{\text{cx}3}(E)}{4\pi r_s^2} \approx \frac{F_{\text{cx}3}(E) e^{-\sigma(E)N_{\text{H}}(\text{IF})} \cos^2(\theta_s - \theta)}{(1 - x)^2}. \quad (A9)$$

If we integrate over energy bandpass and replace $F_{\text{cx}3}(E)$ by $F_{\text{cx}3}S(E)$ where $F_{\text{cx}3}$ represents the measured flux from Cygnus X-3 and $S(E)$ is its spectral form (normalized to one) we can write the flux relationship of the feature to Cygnus X-3 as

$$\frac{F_{\text{IF}}}{F_{\text{cx}3}} = \frac{\pi \tan \alpha_1 \tan \alpha_2 l_s \cos^2(\theta_s - \theta)}{(1 - x)^2} \times \int_{E_1}^{E_2} S(E)e^{-\sigma(E)N_{\text{H}}(\text{IF})} \int_{\text{dmin}}^{\text{dmax}} n_g(a) \times \left( \frac{d\sigma_g(E, a, \theta_s)}{d\Omega} \right) d\Omega dE. \quad (A10)$$

Assuming an MRN grain size distribution (Mathis et al. 1977; Weingartner & Draine 2001) then we have

$$n_g(a) = n_h \sum_{i=g, s} N_i^d a^{-3.5}, \quad (A11)$$

where $n_h$ is the hydrogen number density of the cloud, $a$ is the radius of the grain, and $N_i^d$ are the normalization in (grains/H atom)/µm for graphite (g) and silicates (s). If we also note that $n_{\text{H}} l_s$ is simply the column density of the cloud $N_{\text{H}}(\text{IF})$, substituting $n_g(a)$ into Equation (A10) gives us

$$\frac{F_{\text{IF}}}{F_{\text{cx}3}} = N_{\text{H}}(\text{IF}) \left[ \frac{\pi \tan \alpha_1 \tan \alpha_2 \cos^2(\theta_s - \theta)}{(1 - x)^2} \right] \times \left[ \sum_{i=g, s} N_i^d \int_{E_1}^{E_2} S(E)e^{-\sigma(E)N_{\text{H}}(\text{IF})} \int_{\text{dmin}}^{\text{dmax}} a^{-3.5} \times \left( \frac{d\sigma_g(E, a, \theta_s)}{d\Omega} \right) d\Omega dE \right]. \quad (A12)$$

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5 We note that this equation is similar to Equation (A5) in Smith & Dwek (1998). However, in that paper, one factor of $\cos(\theta_s - \theta)$ was omitted in error, although this makes no difference to either their or our final results.