A CHANDRA OBSERVATION OF THE DIFFUSE EMISSION CENTERED ON THE LOW-MASS X-RAY BINARY 4U 1755–33

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Received 2004 August 30; accepted 2004 November 19; published 2004 December 2

ABSTRACT

We present an analysis of a Chandra observation of the field surrounding the low-mass X-ray binary 4U 1755–33, which has been in quiescence since 1996. In 2003, Angelini & White reported the appearance of a narrow 7'-long jetlike feature centered on the position of 4U 1755–33 using the XMM-Newton telescope. Although the source and jet are not visibly apparent in our Chandra ACIS-S image, there is a significant excess (4–6 σ) of counts in a region that encloses the jet when compared to adjacent regions. We examined a knot of emission in the jet that was detected by XMM-Newton but not by Chandra and calculated that if the knot flux observed by XMM-Newton was concentrated in a point source, Chandra would have easily detected it; we therefore conclude that this knot of emission is diffuse. In summary, we suggest that the jetlike feature found previously in the XMM-Newton data is quite diffuse and likely a true jet and that it is not due to a chance alignment of discrete point sources or pointlike regions of emission associated with internal shocks.

Subject headings: binaries: close — stars: individual (V4134 Sagittarii, 4U 1755–33) — X-rays: stars

1. INTRODUCTION

4U 1755–33 is a low-mass X-ray binary (LMXB) and black hole candidate located in the direction of the Galactic center. It was first discovered by the Uhuru satellite’s all-sky X-ray survey in 1970 (Giacconi et al. 1974) with a flux of ~100 μJy. The X-ray source remained bright and persistent until 1996 January, when the Rossi X-Ray Timing Explorer discovered that the source had turned off, with a flux of ≤1 μJy (Roberts et al. 1996). The source has remained quiescent since then, to the time of writing.

The X-ray spectrum of 4U 1755–33 was observed to be “ultrastiff” (kT ~ 2 keV) when the source was bright (Jones 1977; White & Marshall 1984; White et al. 1984), and a hard X-ray tail above ~6–10 keV was observed by Pan et al. (1995); both spectral aspects indicate that the primary may be a black hole (Tanaka & Lewin 1995). Seon et al. (1995) also noted the appearance of an iron emission line centered at 6.7 keV, as found in many black hole candidates (Miller et al. 2002a, 2002b; Park et al. 2004).

The optical counterpart of 4U 1755–33 was identified as a faint, blue star with a featureless spectrum by McClintock et al. (1978). When the X-ray source was active, the optical counterpart was a V ~ 18–19 mag object. Since turning off, the counterpart has dimmed to V > 22 (Wachter & Smale 1998). A regular, periodic dipping in the X-ray light curve of the source was observed by White & Marshall (1984), suggesting that the source is being observed at high inclination. A 4.4 hr orbital period was determined from the dipping (White et al. 1984) and confirmed by the photometric variations in the optical counterpart by Mason et al. (1985). This period, along with the period-mass relation (Frank et al. 2002, p. 398), suggests a mass of ~0.5 M⊙ for the secondary star. The distance to this source is thought to be between 4 and 9 kpc (Wachter & Smale 1998).

In 2003, Angelini & White (2003, hereafter AW03) reported the XMM-Newton discovery of a narrow X-ray-emitting jetlike feature that is 7′ in extent and centered at the position of 4U 1755–33. They suggest that it has existed since the source entered quiescence and note that the 3.5 half-length of the jet corresponds to 4 pc for an assumed distance of 4 kpc. Given that the source was active for at least 25 years, it is plausible that a relativistic jet could have expanded to this length. They also report the existence of a hole developing near the LMXB, which is consistent with the scenario that the source has not been feeding the jet during the past 8 years of quiescence. Although jets are not seen exclusively in black holes binaries, they are relatively common in such systems (e.g., Mirabel 2003). Confirmation that this extended emission feature is a true jet would provide further evidence that 4U 1755–33 may contain a black hole. In this Letter, we present a Chandra observation of 4U 1755–33 and report on the diffuse appearance of the jetlike feature.

2. OBSERVATIONS AND ANALYSIS

We observed 4U 1755–33 with the Chandra X-Ray Observatory on 2003 September 25 from 17:21:18 to 23:51:50 UT, with 21,909 s of good time exposure. The incoming X-ray flux was read out by the Advanced CCD Imaging Spectrometer spectroscopic array (ACIS-S) with the very faint format in timed exposure mode. At the time of the proposal, it was not known that 4U 1755–33 might have a jetlike feature extending from it, and thus the source was placed at the standard aim point near the boundary between nodes 0 and 1 on the ACIS-S3 CCD chip. This aim point is not at the center of the chip, so, unfortunately, the S3 CCD did not capture the full length of the emission region. In order to avoid measurement errors due to the very different responses of the S3 and S2 chips, we chose to look only at ACIS-S3, cutting off about 15% of the region in question (see Fig. 1).

We compare the Chandra data with the XMM-Newton data for the same source, which were taken on 2001 March 8 in a 5 hr exposure using the two EPIC-MOS arrays operated in full frame mode and the EPIC-PN array in extended full frame mode (AW03). All three cameras observed the source with the “medium” optical blocking filter. The good time exposure in each camera was 18,127, 18,107, and 15,359 s for the MOS-1, MOS-2, and PN cameras, respectively.

The Chandra data were analyzed using standard processing...
tools from CIAO version 3.0.2 and filtered to make use of the VFAINT mode. No significant flaring was seen in the data, and the response files used were corrected for the gradual degradation in the low-energy response of the ACIS detector. We also reanalyzed the XMM-Newton data obtained through the HEASARC public data archive using the XMM-Newton Science Analysis System version 5.4.1 to properly compare the data between the two telescopes. Because the PN camera has less uniform coverage due to the gaps between the CCDs and bad pixel columns, we chose to use only the data from the two MOS cameras in our analysis. The difference in sensitivity between these two cameras is modest, and we found that the MOS-2 camera yielded greater flux values by at most 15%. For our analysis, we quote only the average of the two cameras.

The spectra of the data from both Chandra and XMM-Newton were binned to contain a minimum of 15 counts in each channel and analyzed in the 0.3–7.0 keV band using XSPEC version 11.2 (Arnaud 1996). The region of the jetlike feature was specified to be 7′ in length by AW03 and estimated by us to be 0′.6 in width from the XMM-Newton images. Because a feature 7′ in length centered on the source does not fit in the Chandra ACIS-S3 chip, we took the region length to be 6′ in our analysis of both the Chandra and XMM-Newton data (see Fig. 1) so that we could compare the fluxes using the exact same region. For consistency, we always use the same source and background regions in our analysis of both data sets. Errors on fluxes reported in this work are at 95% confidence; errors on counts are at 1 σ, and all other errors are at 90% confidence.

3. Results

In its quiescent state, 4U 1755–33 remained undetected by Chandra. We obtain an upper limit for the flux of the LMXB by finding an average of 1.0 background counts in a 2′ radius circle, the size of the aperture expected to contain 90% of the flux for an on-axis ACIS point source at 1.49 keV. With this mean background, the probability of detecting a source with 5 or more total counts is less than 0.001 according to Poisson statistics; using a power-law model (with parameters equal to

![Fig. 1.—Chandra ACIS-S3 chip image of the 4U 1755–33 region in the 0.3–7.0 keV band. The full rectangular region of length 7′ in the center of the image shows the extent of the jetlike emission observed by AW03 with XMM-Newton; the central cross denotes the position of 4U 1755–33. In the Chandra analysis, we consider only the upper 6′ of the emission (solid line) that was imaged by the ACIS-S3 chip. The circle within the rectangular region encloses the location of the knotlike feature observed by XMM-Newton. Neither this feature nor the jet itself is apparent in a visual inspection of the ACIS-S3 image. The smaller circles denoted by A–F are point sources detected by both Chandra and XMM-Newton.](image1)

![Fig. 2.—Chandra region counts. The central rectangle, which is identical to the solid-line rectangle shown in Fig. 1, encloses most of the jetlike feature observed with XMM-Newton. The four flanking rectangles enclose background comparison regions. The total number of counts detected after point source subtraction in each of the 0′.6 × 6′ regions is indicated. As in Fig. 1, the cross in the central rectangle marks the location of 4U 1755–33. The same rectangular regions were used in analyzing the XMM-Newton data.](image2)

| Table 1 | Region Counts |
|-----------------|---------------|
| **Jet** | **Knot** | **Background** |
| **XMM-Newton** | Total Counts | Net Counts | Total Counts | Net Counts | Total Counts (Total Counts) |
| 782.0 ± 28.0 | 277.8 ± 32.4 | 52.0 ± 7.2 | 34.4 ± 7.2 | 958.0 ± 31.0 |
| **Chandra** | 1264.0 ± 35.6 | 232.9 ± 42.5 | 48.0 ± 6.9 | 12.0 ± 6.9 | 1959.0 ± 44.3 |
| **Region size** | 0′.6 × 6′ | 0′.6 × 6′ | (0′.6 × 6′) (0′.6 × 5′) |

Notes.—Counts for the jet, knot, and background regions of both telescopes in the 0.3–7 keV band. The XMM-Newton information is from a summed image of MOS-1 and MOS-2. The counts in the jet and knot regions were found using the central rectangular region and circular region in Fig. 1, respectively. The outer two regions in Fig. 2 were adopted as the background regions for both the knot and the jet, with the leftmost rectangle truncated to the upper 5′/4 to avoid contamination from counts from a point source.
those we used to analyze the jetlike emission, described in detail below) with WebPIMMS, the counts correspond to a flux upper limit of $2.24 \times 10^{-15}$ ergs cm$^{-2}$ s$^{-1}$. This is lower than the flux values obtained by AW03, although a direct comparison cannot be made because of the use of different models and energy bands.

### 3.1. Emission from the Jetlike Region

AW03 reported the detection of a 7$'$ jetlike feature of extended emission, centered on the position of 4U 1755$-$33 and at a position angle of $\sim$137$\degree$. 4U 1755$-$33 is located off the galactic plane at R.A. = $17^h58^m40^s.0$ and decl. = $-33^\circ 48' 27''$ (l = $357^\circ 21$, b = $-4^\circ 87'$), so the emission is not likely to be a feature in the plane. The plane is symmetric, as expected from a binary source observed at high inclination.

The jetlike feature is prominent in the XMM-Newton images of AW03 (see Figs. 1 and 2 of their paper). In the high-resolution Chandra image, however, the jet is not visually apparent. The Chandra image provides evidence that the emission may be diffuse: a rectangular area enclosing the extended emission due to a potential underestimate of the knot flux are large, we list only the upper limits for the knot region.

### 3.2. Emission in the Knot Region

Two bright knotlike regions were found in the XMM-Newton image in the southeastern end of the emission area. They appear to be broader than the XMM-Newton point-spread function of 9$''$ in radius at 1.5 keV for a region encircling half of the total energy. One of these regions was also imaged by Chandra (see Fig. 1). We analyzed this knot, at R.A. = $17^h58^m46^s.64$ and decl. = $-33^\circ 49' 49''$, using the same models described above. We selected a 12$''$ radius extraction aperture by comparing the net counts for a series of aperture sizes in 1$''$ increments in the XMM-Newton image. The most significant drop-off was between 12$''$ and 13$''$, with the net counts per area falling to two-thirds its previous value. A visual analysis of the smoothed imaged also suggests that 12$''$ is the most appropriate radius for the knot size.

The knot region had a greater concentration of net counts compared to the net counts in the region of jetlike emission in the XMM-Newton data, but the knot emission was not significantly detected in the Chandra data. XMM-Newton recorded

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**TABLE 2**

| Telescope      | Jet Region | Knot Region |
|----------------|------------|-------------|
| **Power-Law Model** |            |             |
| Chandra        | (1.22 $\pm$ 0.42) $\times 10^{-13}$ | 1.34 $\times 10^{-14}$ |
| XMM-Newton     | (0.96 $\pm$ 0.34) $\times 10^{-13}$ | 4.63 $\times 10^{-14}$ |
| **Bremsstrahlung Model** |            |             |
| Chandra        | (9.91 $\pm$ 3.43) $\times 10^{-14}$ | 1.12 $\times 10^{-14}$ |
| XMM-Newton     | (8.60 $\pm$ 3.08) $\times 10^{-14}$ | 4.01 $\times 10^{-14}$ |

**Note:** All fluxes are listed with 95% confidence errors in units of ergs cm$^{-2}$ s$^{-1}$ in the 0.3–7.0 keV band. Because the errors in the knot flux are large, we list only the upper limits for the knot region.

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**TABLE 3**

| ID  | R.A.   | Decl.  | Net Counts |
|-----|--------|--------|------------|
| A   | 17 58 44.24 | $-$33 45 09.52 | 76.0 |
| B   | 17 58 44.06 | $-$33 46 11.83 | 54.3 |
| C   | 17 58 46.81 | $-$33 48 44.74 | 42.0 |
| D   | 17 58 51.17 | $-$33 49 13.58 | 92.7 |
| E   | 17 58 20.99 | $-$33 46 53.50 | 98.7 |
| F   | 17 58 20.15 | $-$33 49 04.03 | 15.3 |

**Notes:** Positions of the six point sources detected by both Chandra and XMM-Newton (epoch 2000). See Fig. 1 for an image. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. The net counts were taken from the Chandra observation.
The lack of visibility of the knot in Chandra suggests that the object may be diffuse. We verified this by comparing the ratio of the fluxes between the knot and the jet in XMM-Newton and Chandra. Assuming that $N_{\text{e}}$ and $\Gamma$ are the same for both the knot and the jet, and that the flux of the knot has not changed significantly in the 2.5 years between the two observations, the ratio between the knot and jet flux in XMM-Newton gives a predicted $28.8 \pm 8.7$ net counts for the knot in Chandra for the 0.3–7.0 keV band, which is consistent (within 1.5 $\sigma$) with the observed $12.0 \pm 6.9$ net counts in the Chandra image. The surface brightness sensitivity of Chandra may be too low to statistically detect the diffuse knot in the 0.3–7.0 keV band. If the 12 counts in the knot had been concentrated at a point source, the knot would be significant and immediately apparent in the Chandra image, since the 0.3–7.0 keV background in a typical 2'0 radius extraction aperture is only 1.0 counts (see Table 1). Thus, we suggest that the observed knot is most likely a real, but diffuse, feature.

Similarly, the jetlike emission is also likely a real feature. The agreement between the Chandra and XMM-Newton fluxes for the jet region suggests that the emission visibly seen in the XMM-Newton data must still be present in the Chandra data. Although the Chandra data had slightly longer good time exposure ($\approx 22,000$ s, compared to $\sim 18,100$ s for the MOS cameras aboard XMM-Newton), other factors have contributed to the lack of visibility of the jet and knot in Chandra, including XMM-Newton’s greater effective area: at 1.5 keV, the effective area of the MOS cameras is 1400 cm$^2$ compared to Chandra’s 700 cm$^2$. The background rates are also twice as high with Chandra, making significant detections of diffuse emission more difficult. Thus, if the emission were truly diffuse, it would have been more easily detected with the capabilities of the XMM-Newton instruments.

The emission is not likely to be due to an alignment of point sources, as multiple point sources were not found in the emission region by either telescope. Six point sources located outside the jet region were detected by both Chandra and XMM-Newton and are shown in Figure 1 with their positions and net counts listed in Table 3. Of course, a large enough assemblage of very faint point sources would have escaped detection as individual sources (e.g., 100 or more source with fluxes of $\sim 10^{-14}$ ergs cm$^{-2}$ s$^{-1}$ or less), although this scenario is unlikely. It is important to note that since one of the bright knotlike regions detected by XMM-Newton was off the S3 chip of Chandra, a simple scaling of the fluxes found in our analysis of the 0.6' x 6' region to the estimated true size of the jet of 7' may yield a slight underestimate of the actual flux in the region. However, we limited our XMM-Newton analysis to 6' regions for a more accurate and consistent comparison with the Chandra data.

5. CONCLUSIONS

While the Chandra image showed many point sources, emission from LMXB 4U 1755–33 in quiescence was not detected. We present the results of a comparative study using Chandra and XMM-Newton imaging data of a jetlike emission feature that is apparently emanating from 4U 1755–33. Although the jetlike feature is not directly visible in the Chandra image, though highly visible in the XMM-Newton images, Chandra does detect significant emission (4–6 $\sigma$) from the jet region. Furthermore, we find that the fluxes from the same 0.6' x 6' jet region as observed by Chandra and XMM-Newton agree within errors. The flux of a knotlike region embedded in the jet was detected by XMM-Newton but not by Chandra because of Chandra’s smaller area and higher background. We show that if this emission were due to a point source, then it would have been easily detected by Chandra. We therefore conclude that the emission from the knot is diffuse. Our analysis shows that the jetlike emission surrounding 4U 1755–33 is likely a true and diffuse jet, which appears to be devoid of pointlike regions of emission associated with internal shocks. Because jets evolve very rapidly in our Galaxy, compared with the slowly evolving larger scale jets of quasars and active galactic nuclei, studying the jets from 4U 1755–33 and other galactic sources may provide key information in understanding jet formation and propagation.

We thank W. Forman and M. Markevitch for discussions on the spatial structure of the ACIS background. J. M. M. acknowledges support from the NSF through its Astronomy and Astrophysics Postdoctoral Fellowship program. This work has made use of the information and tools available at the HEASARC Web site, operated by GSFC for NASA.