EVIDENCE OF A PARSEC-SCALE X-RAY JET FROM THE ACCRETING NEUTRON STAR CIRCINUS X-1

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1. INTRODUCTION

Circinus X-1 is an unusual, highly variable X-ray binary. Beyond variability at the 16.5 day orbital period, which includes deep dips near orbital phase 0, its long-term light curve can reach peak fluxes between 1 and 2 crab, but it also shows several long excursions into a very deep low-flux state. The compact object in this system is believed to be a neutron star, based on observed type I X-ray bursts (Tennant et al. 1986), putting the source at a likely distance of $\sim 7.8-11$ kpc (Jonker & Nelemans 2004; Jonker et al. 2007), roughly consistent with the estimated hydrogen absorption column of $N_H \approx 2 \times 10^{22}$ cm$^{-2}$ (e.g., Schulz & Brandt 2002). We will adopt a distance of $D = (7.8 \; \text{kpc}) D_{7.8}$ throughout this Letter.

The arcminute-scale jets are clearly curvature within the radio emission, suggesting that it originates within the jet itself or in the shock that the jet is driving into its environment. This makes Circinus X-1 the first neutron star for which an extended X-ray jet has been detected. The kinetic jet power that we infer is significantly larger than the minimum power required for the jet to inflate the large-scale radio nebula.

Subject headings: ISM; jets and outflows — stars: neutron — X-rays: binaries

2. OBSERVATIONS AND ANALYSIS

Circinus X-1 was observed with the High Energy Transmission Grating Spectrometer (HETGS; Canizares et al. 2005) on board the Chandra X-Ray Observatory on 2005 June 2 (04:13:01 UT, ObsID 5478) as part of a campaign to obtain high-resolution X-ray spectra of the source during its extremely low long-term X-ray flux state. The observation lasted 50 ks and occurred at orbital phases 0.06–0.10. As a by-product of this observation, we obtained a zero-order image of the source. The source flux was exceptionally low, and the point-spread function (PSF) is almost completely pileup-free due to the application of a 1/2 subarray mode that held the CCD frame time to 1.7 s.

The upper panels of Figure 1 show the zero-order image. The colors represent increasing count levels from black (low) to white (high). With the HETG in place, the zero-order image is affected by various artifacts. Visible are the four dispersion arms of the positive and negative orders of the medium- and high-energy gratings. These lies at position angles of $\sim 26^\circ$ and $36^\circ$, and the same at 180$^\circ$ rotation (position angles throughout this Letter are measured counterclockwise from due west to the point source and abbreviated as PA), outward of about 1.3$'$. Furthermore, the spectrometer shields some of the soft X-ray photons below 0.7 keV and reduces the overall throughput in an azimuthally uniform fashion. The zero-order PSF is otherwise not affected by the spectrometer. For brighter sources, the CCD readout streak (a charge trace along the PSF centroid column) becomes prominent. In order to enhance contrast in the PSF wing areas, the core of the PSF in Figure 1 is overexposed.

2.1. The X-Ray Jet

Figure 1 shows a distinctive surface brightness excess in the northwestern quadrant that does not line up with any of the known PSF artifacts (see white arrow). The morphology of the feature resembles two filaments pointing away from the point source at...
PAs 22.5° and 54.5°. The bottom panel of Figure 2 shows a combined radial surface brightness profile along two 15°-wide sectors centered on those two PAs (see insert for extraction region), clearly showing the excess emission in the region from about 0.45' to 0.9'. The formal statistical significance of the excess over the azimuthally smoothed background emission is 7.1σ. A Gaussian fit yields a centroid distance of $r_{\text{peak}} \approx 0.64' \pm 0.03'$ from the point source and $\sigma \approx 0.13' \pm 0.02'$. In order to illustrate the excess more clearly, we adaptively smoothed the central region of the zero-order image after removing all the gratings and CCD artifacts, subtracted the azimuthally averaged profile $\Sigma_{\text{rad}}$, and divided the difference image by $\Sigma_{\text{rad}}$ to create a normalized difference image (the bottom left panel in Fig. 1). The adaptive smoothing length was chosen to vary only with radial distance from the point source to provide an average significance of 5σ per smoothing length.

Figure 2 also shows an azimuthal surface brightness profile across an annular sector covering the excess emission. The filaments show clear lateral extent. For comparison, Figure 2 also shows an azimuthal profile across the readout streak, which is representative of the image resolution and is much narrower. Fitting two Gaussians to the excess yields centroid angles of 22.5° ± 0.6° and 54.5° ± 0.5° and widths of $\sigma \sim 2.3° \pm 0.6°$ and $\sigma \sim 2.0° \pm 0.5°$, respectively, spanning an angle of 32°.
from peak to peak. Since the inclination angle $i$ of the feature (angle to the line of sight) is unknown, this is an upper limit on the opening angle.

It is noteworthy that even the azimuthally symmetric emission is well in excess of the PSF estimate derived from Marx ray tracing. However, calibration observations show that the ray-traced PSF underestimates the true PSF by a factor of order 2–3, especially at high energies, making this excess emission marginal at best. It is possible that such excess emission stems from the large-scale synchrotron nebula around the source. However, given the questionable significance, detailed discussion of this spherical excess is beyond the scope of this Letter.

2.2. Comparison with the Radio Jet

The excess emission is generally aligned with the northwestern arcminute-scale radio jet. Multiple epochs of radio observations with varying resolution exist of the Circinus X-1 jet. Stewart et al. (1993) presented 1991 Australia Telescope Compact Array (ATCA) observations (12” resolution) that show diffuse extended emission on arcminute scales and a jetlike enhancement in the southeast to northwest direction. On the scale of the observed X-ray feature, we estimate the jet PA to be roughly $33^\circ \pm 9^\circ$, with significant bending toward larger PAs on larger scales. Tudose et al. (2006) presented recent ATCA observations on the same scales as Stewart et al. (1993). In the highest resolution image (2004 epoch), we estimate a PA of $40^\circ \pm 15^\circ$. Finally, Fender et al. (2004) presented a series of well-resolved jet images (2000 October–2002 December) on scales of about 10” with a...
image of the inner region, indicating that the jet emission has a significantly softer X-ray color than the background (red: 2–4 keV, green: 4–7 keV, blue: 7–10 keV). Note that the other region with visibly softer spectrum is the southeastern quadrant, close to where we would expect to find the approaching jet (see § 3.2 for a brief discussion of the southeastern emission).

The background-subtracted count rate from the jet is 3.5 $\times$ 10$^{-3}$ s$^{-1}$, giving roughly 175 counts from the jet over 480 background counts. Given the limited number of counts, we restricted fitting to the simplest possible models. The first model that we fitted was an absorbed power law, giving $N_H \approx 5.9 \times 10^{23}$ cm$^{-2}$ and $\Gamma \approx 3.0 \pm 0.3$. As it stands, the best-fit photon index is broadly consistent with the emission being of synchrotron origin (for which we would expect $1.5 \leq \Gamma < 2.5$). An absorbed thermal model can fit the data equally well, giving $N_H = 5.4 \pm 0.2 \times 10^{22}$ cm$^{-2}$ and $T = 2.2\pm0.1$ keV.

Taking the best-fit spectral parameters at face value, we can estimate the unabsorbed 2–10 keV source flux to be roughly $F_{2-10} \approx 1.7 \times 10^{-13}$ ergs cm$^{-2}$ s$^{-1}$, corresponding to an X-ray luminosity of $L_{2-10} \approx 1.2 \times (10^{39}$ ergs s$^{-1})D_{7.8}^2$.

3. DISCUSSION

3.1. Interpretation and Physical Parameters

The V-shape morphology of the X-ray jet suggests limb-brightened emission from the surface of a conical volume. The length of the X-ray jet is roughly $l_{\mu} \approx (1.6$ pc) $D_{7.8} / \sin \alpha$. Given the half-opening angle of roughly $\alpha \approx 2.6 \sin \alpha$, the volume of the emitting cone is $V_{\text{em}} \approx 1.2 \times (10^{35}$ cm$^3)D_{7.8}^3 / \sin \alpha$. Since we can observe the radio and X-ray counterjet on arcminute scales, it is safe to assume that its motion is no longer ultrarelativistic, and we can neglect Doppler corrections. We propose two possible alternative explanations for the origin of the excess emission:

Synchrotron emission from the jet.—The X-ray emission could be limb-brightened emission from the conical walls of the jet itself. Assuming a synchrotron slope of $\Gamma \approx 1.5$ and a volume filling fraction of order unity, the equipartition particle pressure is $p_{\text{therm}} \approx 5 \times (10^{-12}$ ergs cm$^{-3})D_{7.8}^2 / (\sin \alpha)^{4/7}$. We can then estimate the minimum jet power in the counterjet to be roughly $W_{\text{jet}} \approx 5 \times (10^{36}$ ergs s$^{-1})D_{7.8}^{10/3} / (\sin \alpha)^{2/3}$, which is larger than, and thus consistent with, the lower limit on the time-averaged kinetic power ($W \approx 10^{35}$ ergs s$^{-1}$) from the large-scale radio nebula (Heinz 2002; Tudose et al. 2006).

Thermal emission.—The X-rays could also be due to thermal emission from the shock driven into the ISM by the propagation of the jet alongside the expanding cocoon. In this case, the required electron density would be $n_{\text{therm}} \approx (10$ cm$^{-3})D_{7.8}^{1/2} / (\sin \alpha)^{1/2}$, with a total emitting gas mass of $M_{\text{therm}} \approx (0.1 M_\odot)D_{7.8}^{2/3} / (\sin \alpha)$ and a very high pressure of $p_{\text{therm}} \approx 3 \times 10^8$. Since the shock velocity is fixed by the temperature, we can estimate the jet power required to explain the X-rays to be $W_{\text{therm}} \approx 5 \times (10^{36}$ ergs s$^{-1})D_{7.8}^{10/3} / (\sin \alpha)^{2/3}$, which is similar to the power estimated for the synchrotron case, making $W_{\text{therm}}$ a relatively robust estimate.

Inverse Compton emission.—In order for inverse Compton emission to explain the X-ray jet, potential seed photons would have to come from the diffuse radio lobe, from the radio jet (as synchrotron self-Compton), or from the binary. In all three cases, the pressure required to produce the observed X-ray flux falls into the range $p_{\text{sc}} \approx 0.001$–1 ergs cm$^{-3}$, which can be ruled out on energetic grounds. Thus, inverse Compton scattering is not a viable radiation mechanism.

3.2. The Southeastern X-Ray Jet

The radial surface brightness profile along the direction of the approaching jet in Figure 2 shows that a small excess over the average profile is visible from the plot, significant at the 4 $\sigma$ level. Given that the approaching jet is observed in the radio, the low intensity of the approaching X-ray jet is noteworthy and could have one or both of the following causes:

1. The dimness of the approaching jet could reflect differences in the environment on the near and far side of the source. Given the clear nonspherical appearance of the radio nebula, such an asymmetry in ISM density and/or pressure is likely present.

2. The difference between an approaching and a receding jet must reflect the light-travel time difference $\tau_{\text{light}} \approx 2D_{7.8}/c \cot \alpha \approx (10$ yr$)D_{7.8}$ at both sides if the jet is propagating close to the speed of light; $\tau_{\text{light}}$ is significantly longer than the variability timescale for state transitions. Thus, it is plausible that the absence of the approaching X-ray jet reflects different activity levels of the source over roughly a 10 yr period.

3.3. Broader Implications

Chandra found extended X-ray jets for a number of either identified or likely black hole X-ray binaries (XTE J1550–564, Corbel et al. 2002; SS 433, Migliari et al. 2002; H1743–322, Corbel et al. 2005; and Cygnus X-3, Heindl et al. 2003). Circinus X-1 is thus the first bona fide neutron star with an extended X-ray jet.

The minimum power of $W \approx 5 \times 10^{36}$ ergs s$^{-1}$ is roughly 4% of the Eddington luminosity for a neutron star. At peak flux, Circinus X-1 is only slightly super-Eddington, and because, unlike in black holes, mass cannot disappear into an event horizon, we can turn this into a lower limit on the jet production efficiency of $\eta \approx 0.5\%$; that is, upward of 0.5% of the accreted rest-mass energy must have gone into powering the X-ray jet. This makes Circinus X-1 as efficient as a black hole in making jets, despite its shallower potential. It also ties Circinus X-1 directly to the radio nebula, showing that the jets have more than enough power to inflate the large-scale lobes.

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