Optical/IR counterpart to the resolved X-ray jet source CXO J172337.5−373442 and its distance

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ABSTRACT
We present results of observations in the optical to mid-infrared wavelengths of the X-ray source CXO J172337.5−373442, which was serendipitously discovered in the Chandra images and was found to have a fully resolved X-ray jet. The observations include a combination of photometry and spectroscopy in the optical using ground-based telescopes and mid-infrared photometry using Spitzer. We detect the optical/IR counterpart of CXO J172337.5−373442 and identify it to be a G9 V star located at a distance of 334 ± 60 pc. Comparable values of the hydrogen column densities determined independently from the optical/IR observations and X-ray observations indicate that the optical source is associated with the X-ray source. Since the X-ray luminosity cannot be explained in terms of emission from a single G9 V star, it is likely that CXO J172337.5−373442 is an accreting compact object in a binary system. Thus, CXO J172337.5−373442 is the nearest known resolved X-ray jet from a binary system, which is not a symbiotic star. Based on the existing X-ray data, the nature of the compact object cannot be confirmed. However, the low luminosity of the X-ray point source, 7.1 × 1030 L⊙, combined with estimates of the age of the jet and a lack of detection of bright outburst, suggests that the X-ray jet was launched during extreme quiescence of the object. The measured low X-ray luminosity of the jet suggests the likelihood of such jets being more ubiquitous than our current understanding.

Key words: techniques: photometric – techniques: spectroscopic – infrared: stars – X-rays: binaries – X-rays: individual: CXO J172337.5−373442.

1 INTRODUCTION
Collimated outflows, or jets, are observed from a wide range of accreting astronomical objects, starting from supermassive black holes (BHs) in active galactic nuclei (AGNs) to protostars (Bridle & Perley 1984; Mirabel & Rodríguez 1999; Fender 2006; Körding et al. 2008; Güdel et al. 2009). This ubiquity along with the examples of association of accretion and jet launching in BH systems (Greiner, Morgan & Remillard 1996) and in AGNs (Marscher et al. 2002) strongly suggest that the accretion and the jet launching are coupled. Although being a universal phenomenon this disc–jet coupling is a fundamental topic of interest in astrophysics, it is still poorly understood. Jets from accreting compact stars [stellar mass BHs, neutron stars (NSs) and even white dwarfs (WDs)] are additionally interesting, because they (1) are launched from regions of intense gravitational fields; (2) are useful to probe much shorter time-scales in comparison to those of AGN jets and (3) can be used to probe the physics of accreting binaries. For example, although fossil jets have been observed from quiescent binaries, with luminosities that are several orders of magnitude lower than their bright-state luminosity (Angelini & White 2003), jets have not been observed to originate due to the quiescent activities. In binaries, jets in the X-ray wavelengths are known to originate from synchrotron and/or thermal bremsstrahlung emissions (Soleri et al. 2009). The X-ray jets thus provide essential high-energy information, which is complementary to that extracted from the more commonly encountered radio jets. Jets are typically detected from resolved structures, or from spectral analysis (Migliari et al. 2007a,b). However, resolved X-ray jets from BH and NS binaries are rare, and the nearest

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of them is at least 4 kpc away from the sun (Liu, van Paradijs & van den Heuvel 2006, 2007). The nearest X-ray jets observed so far are from the symbiotic stars (SSs) RH Cygni (Galloway & Sokoloski 2004) and R Aquarii (Kellogg et al. 2007), both located between 200 and 250 pc. We present observations which suggest that the X-ray jet from CXO J172337.5–373442 is by far (by more than one order of magnitude) the nearest resolved X-ray jet from an accreting compact star that is not an SS.

The faint X-ray point source CXO J172337.5–373442 with a prominent jet ($\alpha_{2000} = 17^h23^m37^s53.2$, $\delta_{2000} = -37^\circ34'41''.97$) was discovered in a Chandra image in 2008 (Bhattacharyya 2008). However, this image alone was insufficient to either conclusively decide on the nature of the source, or to measure its distance. Here we use a combination of photometric and spectroscopic observations in the optical and infrared (IR) in order to identify CXO J172337.5–373442, as well as to measure its distance. We find that this source is a compact star accreting from a G9 V star located at a distance of $334 \pm 60$ pc.

2 DATA AND OBSERVATIONS

2.1 Mid-Infrared photometry using Spitzer

The field containing the source CXO J172337.5–373442 was observed by the two Legacy programmes of Spitzer: the Galactic Legacy Infrared Mid-Plane Survey Extraordinary (GLIMPSE) using IRAC at 3.6, 4.5, 5.8 and 8.0 $\mu$m and MIPS GAL, a 24 and 70 Micron Survey of the Inner Galactic Disc with MIPS; all data are available at the NASA/IPAC Infrared Science Archive (IRSA). Using accurate photometric analysis we detect the source clearly in the four IRAC bands and do not detect it with MIPS at 24 $\mu$m. The mean position of the source in the four IRAC bands is $\alpha_{2000} = 17^h23^m37^s52.8$, $\delta_{2000} = 37^\circ34'42''.2$ with an uncertainty of 1 arcsec. Thus the position of the IR source is in excellent agreement with the Chandra point source discussed by Bhattacharyya (2008).

2.2 Optical spectroscopy

Two 1800-s medium-resolution optical spectra between 3850 and 7200 Å of CXO J172337.5–373442 were acquired starting at 20:52 UT of 2009 August 8 with the 1.9-m ‘Radcliffe’ telescope in Sutherland, Southland, South Africa. A spectrograph equipped with a 266 $\times$ 1798 pixel SiTe CCD is mounted at the Cassegrain focus of this telescope. Using the Grating #7 and a slit of 1.8 arcsec, we obtained a nominal spectral coverage between 3850 and 7200 Å and a dispersion of 2.3 Å pix$^{-1}$.

The spectra were optimally extracted (Horne 1986) using IRAF$^1$ after performing flat-fielding, bias-subtraction, cosmic-ray rejection and background subtraction. On each spectrum, wavelength calibration was performed using Cu–Ar lamps, while flux-calibration was done using the spectrophotometric standard LTT 9239 (Hamuy et al. 1992). We estimate the wavelength-calibration uncertainty to be $\sim 0.5$ Å using the positions of background night sky lines. The two spectra were stacked together to increase the signal-to-noise ratio.

Table 1. Results of optical and IR photometry of CXO J172337.5–373442.

| $g'$  | $i'$ | $i'′$ | $z'$ | $J$ | $H$ | $K$ | $F_{3.6}$ | $F_{4.5}$ | $F_{5.8}$ | $F_{8.0}$ | $F_{24}$ |
|------|------|-------|------|-----|-----|-----|----------|----------|----------|----------|---------|
| (mag)| (mag)| (mag) | (mag)| (mag)| (mag)| (mag)| (mJy)    | (mJy)    | (mJy)    | (mJy)    | (mJy)   |
| 17.1 | 15.5 | 14.8  | 14.3 | 13.5 | 13.2 | 13.3 | 7.46     | 3.75     | 2.50     | 1.80     | <1.24   |
| ±0.1 | ±0.1 | ±0.1  | ±0.1 | ±0.1 | ±0.1 | ±0.1 | ±0.02   | ±0.02   | ±0.02   | ±0.03   |

1 IRAF is the Image Analysis and Reduction Facility made available to the astronomical community by the National Optical Astronomy Observatories, which are operated by AURA, Inc., under contract with the US National Science Foundation. It is available at http://iraf.noao.edu/

2.3 Seven-band optical and near-Infrared photometry using GROND

We acquired simultaneous photometric data (Table 1) in seven optical and near-IR wavebands by observing CXO J172337.5–373442 in $g'i'z'JHK$, using Gamma-Ray Burst Optical/Near-infrared Detector (GROND; Greiner et al. 2008) mounted at the 2.2-m ESO/MPI telescope at La Silla Observatory (Chile). The observations were performed on 2010 February 3. We converted the $g'i'z'$ photometry to BVRI magnitudes using the following transformation equations (Lupton 2005):

$$B = g' + 0.3130(g' - r') + 0.2271,$$

$$V = g' - 0.5784(g' - r') - 0.0038,$$

$$R = r' - 0.2936(r' - i') - 0.1439,$$

$$I = i' - 0.3780(i' - z') - 0.3974.$$
counterpart of the source is a G-type star (Hernández et al. 2005). Other prominent spectral features identified in the spectrum are marked in Fig. 1. The fact that the Ca I (4226 Å) line is significantly stronger than the Hγ and the Hδ lines further shows that the star is of a later type than G5. Based on a more precise comparison with stellar spectra from the library by Jacoby, Hunter & Christian (1984) we have identified the source to be a star of spectral type G9 V.

The intrinsic colour \((B-V)_0\) of a G9 V star is 0.81 (Binney & Merrifield 1998) and from GROND the observed colour is \((B-V) = 1.66\), resulting in \(E(B-V) = 0.85\). We thus obtain a visual extinction of \(A_V = 2.7 \pm 0.4\), considering 0.1 mag error in each of the two optical magnitudes. This \(A_V\) value corresponds to a neutral hydrogen column density \((N_H) = (5.1 \pm 0.8) \times 10^{21} \text{ cm}^{-2}\) (using the empirical formula of Predehl & Schmitt 1995), which is consistent with the Chandra X-ray data analysis best-fitting value \(3.7^{+0.4}_{-1.2} \times 10^{21} \text{ cm}^{-2}\) within 90 per cent confidence level. Using the calculated V-band magnitude, the estimated \(A_V\) and the absolute magnitude of a G9 V type star (5.9; Binney & Merrifield 1998), we estimate the distance to CXO J172337.5–373442 to be 334 ± 60 pc. Note that the comparison of a reddened model stellar atmosphere (Kurucz 1993) for G9 V type star \((T_{\text{eff}} = 5250 \text{ K})\) with all the observed optical, near- and mid-IR data (Fig. 2) shows that such a model reproduces the observed spectral energy distribution reasonably well, with the photospheric emission at 24 μm below the detection limit in the MIPS map.

4 DISCUSSION

Here we explore the nature of the compact X-ray source. Since the IR/optical counterpart of CXO J172337.5–373442 is a G9 V star, this source is not a protostar or a pulsar wind nebula or a SS, and is either a low-mass X-ray binary (LMXB) or a cataclysmic variable (CV). Note that Bhattacharyya (2008) excluded the plausible AGN identification of the source based on the observed low \(N_H\) value.

For a Roche lobe filling main-sequence G9 V star, the orbital period of the system is \(\approx 6.3 \text{ h}\) (using equation 3.45 of Bhattacharyya & van den Heuvel 1991). For the estimated \(N_H\), an unabsorbed flux of \(5.31 \times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1}\) in 0.3–10.0 keV range implies a low X-ray luminosity of the point source (\(\sim 7.1 \times 10^{30} \text{ erg s}^{-1}\); assuming isotropic emission). In contrast the luminosity of the jet is only \(3.9 \times 10^{29} \text{ erg s}^{-1}\). We note that the expected X-ray emission of a G9 star is soft and of the order of \(10^{29} \text{ erg s}^{-1}\). Since the expected Eddington luminosity of an LMXB is \(\sim 10^{38} \text{–} 39 \text{ erg s}^{-1}\), CXO J172337.5–373442 should have been in an extreme quiescent state during the observation, if this source is an LMXB. Even if this source is a CV, its low luminosity indicates a quiescent level. In this state, the optical and IR emission from the star can be much more than X-ray emission due to accretion: this is consistent with the results shown in fig. 4 of Bhattacharyya (2008). As a result, the signatures of accretion (e.g. broadened Balmer lines and He II 4686 Å, all in emission) may not be discernible in the optical spectrum, which is consistent with the observation. The compact star
of CXO J172337.5–373442 can thus be a BH or an NS or a WD. Although Bhattacharyya (2008) did not detect a soft thermal X-ray spectral component from the point source, which is a typical signature of quiescent NS LMXBs (McClintock, Narayan & Rybicki 2004), such a thermal component cannot be completely ruled out based on the available Chandra data. The estimated upper limit of the flux of the thermal component is about 50 per cent of the total flux.

Fitting the jet X-ray spectrum with a thermal bremsstrahlung model gives an unphysically high best-fitting temperature ($\approx 200$ keV). Therefore, assuming a synchrotron origin of the jet, we follow Longair (1994) and Fender (2006) to estimate the minimum-energy associated with CXO J172337.5–373442. The jet length of $\approx 48$ arcsec and a width of $\approx 13$ arcsec roughly give a volume of $1.0 \times 10^{50}$ cm$^3$, and hence a minimum jet energy $E_{\text{min}} \geq 1.5 \times 10^{41}$ erg. This minimum-energy condition is achieved when there is an equipartition of energy in particles and the magnetic field. The corresponding magnetic field is $B_{\text{E}} = 28.4$ $\mu$G and the Lorentz factor $\gamma$ of the energetic electrons which emit the synchrotron radiation is $1.6 \times 10^5$. Note that this is not the Lorentz factor corresponding to the bulk motion of the material in the jet.

An important question is whether the resolved X-ray jet was ‘fossil’ or it originated from quiescent activities. In order to find out, we assume that the intensity difference between the approaching jet (observed) and a plausible receding jet (not detected) is solely because of Doppler boosting and deboosting. Unlike many pulsars the speeds of binary systems are known to be small, the only two exceptions being XTEJ1118+480 and GRO J1655–40 (Mirabel et al. 2001, 2002). Hence one of the jets of CXO J172337.5–373442 should not be destroyed by the collision with ISM (as might have happened for the Geminga pulsar; Pavlov, Sanwal & Zavlin 2006) and our assumption of the intensity difference arising only due to Doppler boosting and deboosting is reasonable. With this assumption, the photon flux ratio of the approaching jet to the receding jet is given by $[(1 + \beta \cos \theta)/(1 - \beta \cos \theta)]^{2.17}$, where $\beta$ is bulk speed of jet in the unit of the speed of light in vacuum, $\theta$ is the angle between the approaching jet’s direction and the observer’s direction and $\Gamma$ is the photon index for a spectral fitting with a power law. Since the receding jet was not detected (Bhattacharyya 2008), we consider the maximum possible limit of $\beta \cos \theta$, which is 1. This implies that the upper and lower limits of $\beta$ and $\theta$ are 1 and 0°, respectively. In order to calculate the opposite limits, we use the $3\sigma$ upper limits of $\Gamma$ ($=2.17$) and the receding jet photon counts ($=9.97$). This gives a lower limit of $\beta \cos \theta = 0.1$, implying $\beta > 0.1$ and $\theta < 84°$. The nearest detected part of the jet was $\approx 14.5$ arcsec away from the point source during the 2001 September 4 Chandra observation. Hence, for $\theta > 11.5$ (which has 98 per cent probability of occurrence assuming $\theta$ could have any random value in $0°$–$90°$) and the measured source distance ($=334$ pc), this nearest detected part was ejected less than 3.6 yr before 2001 September. CXO J172337.5–373442 definitely did not become bright (non-quiescent) after 1998 January, because otherwise the Rossi X-ray Timing Explorer (RXTE) ‘All Sky Monitor’ and RXTE ‘Proportional Counter Array’ Galactic bulge scan would have detected it. The X-ray jet of this source was most likely launched by the quiescent activities. Furthermore, the ratio of the jet power to the (quiescent) accretion power is $\approx 0.055$ for CXO J172337.5–373442 in the 0.3–10 keV spectral range (assuming isotropic emission), which is within the same order of magnitude of the typical ratio ($\approx 0.1$) for a range of astrophysical objects (Körding et al. 2008).

5 SUMMARY

We have identified the optical/IR counterpart of the X-ray source CXO J172337.5–373442 as a G9 V star and determined the distance to the source to be $334 \pm 60$ pc. Based on the comparable values of hydrogen column densities measured independently towards the optical/IR source and the X-ray source, we conclude that these two most likely form a binary. Barring the two SSRs RH Cygni and R Aquarii no other binary system with resolved X-ray jet has been observed at such short distances from us. The currently available X-ray data do not allow us to determine the nature of the compact object.

In the event of CXO J172337.5–373442 being an BH LMXB, it would be the nearest known BH. The low X-ray luminosity of the point source, $7.1 \times 10^{30}$ erg s$^{-1}$, suggests that the jet is most likely launched during quiescent activity. Further, the low luminosity of the jet, $3.9 \times 10^{29}$ erg s$^{-1}$, implies that such jets could be significantly more ubiquitous than are currently known to be, since being located at large distances they are not likely to be detected easily.

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