High-mass X-ray Binaries: Illuminating the Passage from Massive Binaries to Merging Compact Objects
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The young Be-star binary Circinus X-1

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Abstract. Cir X-1 is a young X-ray binary exhibiting X-ray flux changes of four orders of magnitude over several decades. It has been observed many times since the launch of the Chandra X-ray Observatory with high energy transmission grating spectrometer and each time the source gave us a vastly different look. At its very lowest X-ray flux we found a single 1.7 keV blackbody spectrum with an emission radius of 0.5 km. Since the neutron star in Cir X-1 is only few thousand years old we identify this as emission from an accretion column since at this youth the neutron star is assumed to be highly magnetized. At an X-ray flux of 1.8×10^{-11} erg cm^{-2} s^{-1} this implies a moderate magnetic field of a few times of 10^{11} G. The photoionized X-ray emission line properties at this low flux are consistent with B5-type companion wind. We suggest that Cir X-1 is a very young Be-star binary.

Keywords. stars: neutron, X-rays: binaries, techniques: spectroscopic

1. Introduction

Cir X-1 has shown a large range of brightness levels, variability patterns, and spectral changes in its X-ray emissions since its discovery a few decades ago (Margon *et al.* 1971). The true nature of this X-ray binary, one orbit lasts about 16.5 days (Kaluzienski *et al.* 1976), always was somewhat mysterious as the identification of its companion remained exceedingly unclear. We do know that the compact object is a neutron star because of direct observations of type I X-ray bursts (Tennant *et al.* 1986, Linares *et al.* 2010, Papitto *et al.* 2010). Whelan *et al.* (1977) suggested the companion star to be an early-type emission line or symbiotic star, while Moneti (1992) found three heavily reddened objects as possible counterparts. Photometric variability of a suggested optical counterpart, better determination of its orbital parameters, as well as X-ray spectral and timing patterns seemed to point to low-mass X-ray binary (LMXB) nature (Brandt & Podsiadlowski 1995, Tauris *et al.* 1999, Tennant 1987, Shirey *et al.* 1999).

Jonker *et al.* (2007) determined that the companion is very likely a massive supergiant of A0 to B5 type, which leads to an orbital eccentricity (e $\sim$ 0.45) and makes Cir X-1 a high-mass X-ray binary (HMXB). Such a companion would be consistent with an earlier tentative identification by Whelan *et al.* (1977). However, the Jonker *et al.* study could not entirely rule out effects caused by absorption in the accretion disk with respect to the supergiant nature.

Perhaps the most striking recent result is the discovery of the X-ray supernova remnant associated with Cir X-1 (Heinz *et al.* 2013). This allowed to place an upper limit of 4600 yr on its age making it the youngest known X-ray binary. Such a young age is also quite consistent with an earlier assessment of X-ray dip periodicity that Cir X-1 is a state of dynamical evolution as in a very young post-supernova system (Clarkson *et al.* 2004). This has striking consequences on the nature of Cir X-1. The observation of type I X-ray bursts on the surface of the neutron star indicates that the magnetic field is not very high suggesting either the possibility that accretion can rapidly de-magnetize a neutron star or there is the possibility that neutron stars can be born with low magnetic fields (Heinz *et al.* 2013). However, neither to date is further supported by theory and observations. In fact, all we know about young neutron stars is that they have magnetic fields or the order of 10^{12} Gauss (see Kaspi 2010, Reig 2011 and references therein). In Schulz *et al.* (2018) we argue that under the assumption that young neutron stars have high magnetic fields, Cir X-1 should as well. Under the further assumption that then the most likely emission site for a 1.7 keV blackbody with an emission radius of 0.5 km is the accretion column, that study estimates a magnetic field strength of the order of 10^{11} G. Furthermore, from blueshifted X-ray lines consistent with a B5 stellar wind, it was concluded that Cir X-1 is a HMXB, maybe a Be-star X-ray binary. In the following we discuss how such a binary nature holds up with what we know about X-ray binaries.

2. Properties of X-ray Binaries

Generally X-ray binaries containing a neutron star can be divided into low- and high-mass systems depending whether the mass of the donor star is below about 2 $M_\odot$ or above about 8 $M_\odot$, respectively. LMXBs are old systems with ages beyond 10^9 yr (Cowley *et al.* 1988). With their magnetic fields to be decayed down to about 10^8 G, mass accretion onto the neutron star is hardly affected by this field. Accretion from low-mass companion stars happens effectively via Roche-lobe overflow resulting in various X-ray spectral variation patterns depending on mass accretion and luminosity (Schulz, Hasinger & Truemper 1989) accompanied by distinct quasi-periodic timing patterns (Hasinger & van der Klis 1989). The brightest X-ray sources radiate close to the Eddington limit and due to their variation pattern in the X-ray color-color diagram are called Z-sources. Sources with X-ray luminosities more than an order of magnitude lower are called atoll sources due to their different and more disjunct pattern consisting of island and banana states. LMXBs also show a zoo of distinct features in their lightcurves and spectra such as type I and II X-ray bursts, accretion disk coronae, dips and in more rare cases eclipses. Type I X-ray bursts are thermonuclear explosions on the surface of the neutron star, type II X-ray bursts occur due to instabilities in the accretion disk (see Lewin, van Paradijs & van den Heuvel 1995 for a review). X-ray spectra can usually be modelled by multi-component models involving blackbody functions, multi-temperature disk blackbody functions, power laws, bremsstrahlung, reflection and Comptonisation.

In contrast, HMXB are comparatively young due to the fact that massive stars have much shorter life times, i.e. less than a few 10^7 yr. They divide further into supergiant X-ray binaries (SGXB) and Be X-ray Binaries (BeXB) depending on the evolutionary status of the optical companion (see Reig 2011 for a more recent review). SGXBs usually contain companions with a luminosity class I - II, BeXBs luminosity classes III - V. Most SGXBs are not known to have significant accretion disks and the bulk of accretion happens through Bondi Hoyle wind accretion. Prime examples are Vela X-1 and 4U 1700-37, rare exceptions are Cen X-3, LMC X-4, and SMC X-1. In BeXBs the massive

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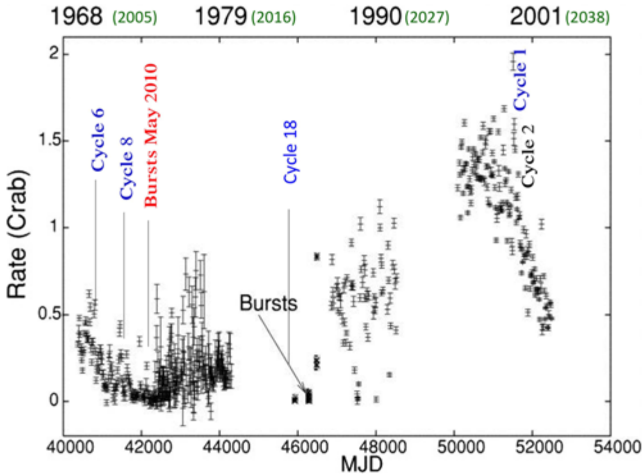

Figure 1. Long-term lightcurve from Parkinson *et al.* (2003). We marked the locations of Chandra observations so far as well as the locations of type I X-ray bursts.

companion star is a fast-rotating B-type star, optically identified through spectral line emission, which have their origin in a circumstellar disk formed from wind material expelled from a rapidly spinning B-star.

3. Where does Cir X-1 fit in?

Cir X-1 has given us many appearances throughout the decades. Figure 1 shows the long-term lightcurve from Parkinson *et al.* (2003). During its brighter X-ray phases in the late 1990s it behaved like a Z-source (Shirey *et al.* 1999), during its rapid decay in the early 2000s it looked more like an atoll source (Schulz *et al.* 2008), usually accretion trademarks of LMXBs. However, Homan *et al.* (2010) showed in recent studies of transient sources that sources do morph through Z- and atoll stages during their rise and decline in source brightness making these patterns more an imprint of Roche-lobe overflow accretion rather than defining a distinct X-ray binary type. If Cir X-1 is a LMXB, its neutron star was formed in an accretion induced collapse (AIC, Bhattacharya & van den Heuvel 1991) of a white dwarf. The analysis of the X-ray remnant could neither rule out nor confirm an AIC scenario (Heinz *et al.* 2013). However, the high eccentricity of the binary orbit together with the fast orbital evolution of the system are at odds with such an event. Neutron stars in AIC events like the ones from electron capture supernova events hardly receive an kick during these events and their binary orbits are not significantly affected (Tauris *et al.* 2013).

The most likely scenario is that Cir X-1 was born in a core collapse supernova event of a massive star. In that case the companion cannot be a low mass star for simple evolutionary reasons. Here it has to be a massive star of similar or somewhat later type than the progenitor type of the neutron star. The study by Jonker *et al.* (2007) suggests that the companion is a massive star of A0 to B5 type, which does fit into that paradigm. In order to produce a neutron star in a core collapse explosion, that progenitor star has to have had a mass of higher than 8 to 10 $M_{\odot}$demanding at least an early B-type nature, i.e. B3 or earlier (Behrend & Meader 2001). The X-ray line centroid shifts measured in Schulz *et al.* (2018) narrows possibilities down to a companion being a B5 star (Fig. 2). Later type B-star winds have much lower velocities. The lines are attributed to the companion wind as they are observed at periastron, but not at apastron. If the identification by Jonker *et al.* (2007) for the companion to be of supergiant nature is correct, then this is

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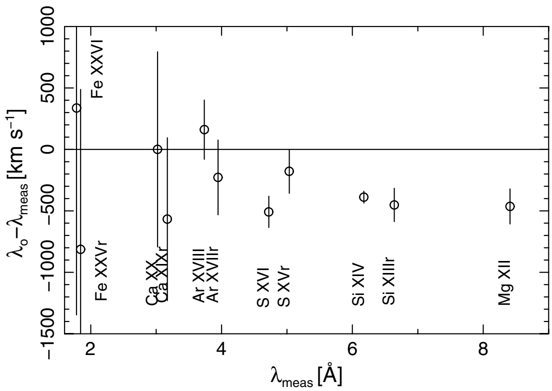

Figure 2. X-ray line centroids from the low flux state observations in Chandra cycle 8 and 18. The most prominent and significant lines of at least one photoionized plasma spectral components in the spectral fits are blueshifted by about 400 km s^{-1}(data from Schulz *et al.* 2018).

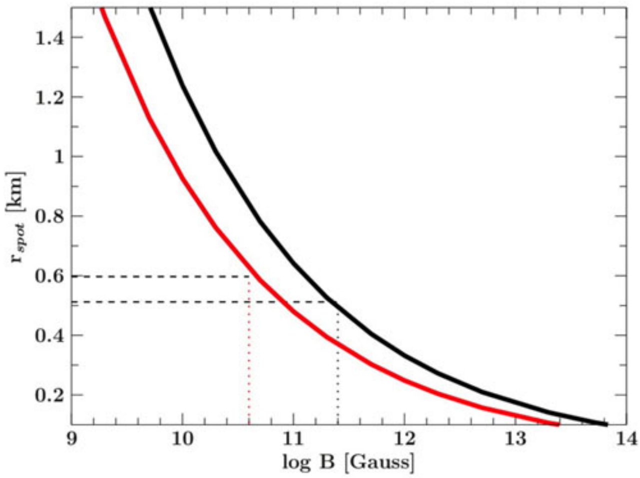

Figure 3. The magnetic field strength of Cir X-1 in dependence of the measured blackbody emission radii (from Schulz *et al.* 2018). From a range of radii between 0.5 and 0.6 km follows a range of magnetic field strength between 4×10^{10} G and 2.5×10^{10} G assuming that very young neutron stars have high magnetic fields.

almost the only choice left because any later type would not have had enough time to evolve that far. Under all these circumstances the most likely nature of Cir X-1 is that of an HMXB.

At this point we also want to put some attention onto the fact that the neutron star in Cir X-1 is extremely young and by that fact should have a high magnetic field. Heinz *et al.* (2013) argued that maybe neutron stars can be born with very low ($<10^{10}$ G) magnetic fields or that accretion could de-magnetize a neutron star on very short time scales. However, this has never been observed before nor is there any theoretical backup for such a scenario. All we know is that neutron stars are born with high magnetic fields. How high is relative, most young neutron stars have magnetic fields as high as 10^{12} G and beyond. Halpern & Gotthelf (2010) presented an example of a young neutron star in Kes 79 of much less than 10^{11} G proposing the existence of 'anti-magnetars', i.e. neutron stars born with moderately high magnetic fields. Figure 3 shows the magnetic

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field range determined for Cir X-1 from the blackbody emission radii measured in Schulz *et al.* (2018) from very low X-ray flux data. This would indicate that the neutron star in Cir X-1 has a more moderate magnetic filed. This is an interesting possibility because it would allow the scenario for a very young accreting neutron star to exhibit type I X-ray bursts, an process only known to be effective in low magnetic fields of old LMXBs.

4. Cir X-1 as a BeXB

There are some inconsistencies in the identification whether Cir X-1 is a young SGXB or BeXB. One is the fact that in none of the known SGXB the massive star is of Be-type. The other one is that none of the companions in known BeXBs are later than of B2 type. While the latter might be an observational bias, the former needs more evolutionary understanding of Be stars. The orbital period of 16.5 days as well as the eccentricity of 0.45 are now consistent with kick velocities of several hundred km s^{-1}as observed in other post supernova HMXBs, specifically BeXBs (Reig 2011). BeXBs typically show low persistent X-ray luminosities of $\sim 10^{34-35}$ erg s^{-1} (Reig & Roche 1999). However, BeXBs with higher eccentricities also show two patterns of outbursts. One pattern consists of regular and periodic outbursts near periastron passage of the neutron star, another more longterm pattern involves X-ray flux increases of 10^3 - 10^4 times the quiescence flux. Both types of patterns as well as the range of luminosities are observed in Cir X-1, Fig. 1 shows the second pattern spanning over 30 yr.

In the case of Cir X-1 we invoke a longterm Be-star disk precession. Precessing Be-star disks may be rare, but not unheard of. Cir X-1 as a BeXB has the potential to explain the ∼30 yr transient flux behavior as shown in Fig. 1. The requires to propose a precession period for the Be-star disk. Similar but physically different scenarios have been suggested by Brandt & Podsiadlowski (1995) and Heinz *et al.* (2013). The former study suggested an accretion disk precession, while the latter discussed spin-orbit coupling effects between the neutron star spin and the binary orbit. This is not unrealistic as super-orbital periods in accretion disks are not unusual in X-ray binaries. Examples of such super-orbital disk precession periods are the ones in Her X-1, LMC X-4, and SMC X-1. Another X-ray binary microquasar which has been compared to Cir X-1 many times before and resides in the a young remnant (W50) is SS 433. Even though we do not have direct knowledge of its compact object mass, much evidence points to a black hole accreting from a highly evolved supergiant primary (Blundell *et al.* 2008). This system also has high dynamical features in form of a helical precessing jet. Seward *et al.* (2012) identified a likely HMXB in the LMC remnant DEM L241, which consists of a O5III(f) star and an undetermined compact object. Another example in this context is SXP 1062, a BeXB in the SMC, which appears to be embedded in a shell-like structure, likely a SNR (Hénault-Brunet *et al.* 2012). More recently Lau *et al.* (2016) presented evidence of a precessing helical outflow from the massive star WR102c. Even though it is a single star, it shows that dynamic outflows can happen from a precessing massive star. All this shows that we now have plenty of observational evidence of young high mass systems in young remnants exhibiting precession action.

5. Conclusions

We now have a surmounting amount of evidence that the neutron star in Cir X-1 is not only very young but the system itself is a HMXB. Even though the companion has been identified as a supergiant, it phenomenologically shows many features and traits linked to BeXBs. More observations and modeling are needed, but a precessing Be-star disk provides an intriguing mechanism to explain the vast longterm X-ray flux variations.

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Discussion

K. Postnov What is the spin of the neutron star?

N. S. Schulz This is a very important point as for a young pulsar one should expect a spin period of a few tens of millisecond. To date no spin period has been found. However, we also point out that at these moderate fields there is quite a range of angles between the magnetic axis with repect to the rotation axis, where the detection of such a period is very difficult if not impossible. There are a few Be-star binaries where no period has been detected so far.

S. Chaty If a low magnetic field is consistent with young neutron stars, how low do you reconcile this low magnetic field with young neutron stars?

N. S. Schulz There is not much theory tells us at this point. From observations we know the lowest field to be a few times 10^{10} G. The suggested field strength for Cir X-1 is consistent with that.

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