CLOUDS, WINDS, AND JETS IN THE LUMINOUS X-RAY SOURCE CIRCINUS X-1

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ABSTRACT

One of the early highlights of high resolution X-ray spectroscopy was the discovery of P Cygni lines in the highly variable and luminous X-ray source Circinus X-1 during the early days of the Chandra mission. By adapting the preceding paradigm established from ASCA observations that the accretion disk around the neutron star is viewed edge-on, the the complex line structure was interpreted as a combination of accretion disk coronal line emission and absorption from a radiatively driven equatorial disk wind. The detection of ultra-relativistic radio jets at about the same time seemed to support the image of Circinus X-1 as a powerful microquasar, but also casted some doubt on the assumption that the source is viewed edge-on, but instead featured a face-on view. This not only challenges the current model for the observed X-ray emission, it could also force a complex scenario involving jets, winds, and clouds that seems quite unique among accreting compact sources. Furthermore the X-ray emission of Circinus X-1 has undergone radical changes since then as it gradually slipped into a low intensity state which is even at times devoid of the typical outburst pattern with its binary orbit. We observed Circinus X-1 several times with the Chandra HETG spectrometer during this transition. We show some preliminary results from the first of these observations, which provided the unobstructed high resolution X-ray image of this source as well as an X-ray spectrum that is devoid of P Cygni lines but shows line emission as expected from ADC sources. We discuss the results in conjunction with its long-term lightcurve and investigate possible scenarios with respect to its line of sight.

Key words: Binaries; Neutron Stars; Spectroscopy; X-rays.

1. INTRODUCTION

The nature of Cir X-1 in general is still poorly understood and, despite advances in recent years, there remains great uncertainty about even the most basic properties of this system. Since its discovery (Margon et al., 1971), it has appeared bright and variable in X-rays exhibiting a period of 16.6 days (Kaluzienski et al., 1976). The compact object in the Cir X-1 system is thought to be a neutron star (Tennant, Fabian, & Shafer, 1986) that can radiate at super-Eddington luminosities. Its heavily reddened optical counterpart (e.g., Moneti (1992)) shows strong, asymmetric Hα emission. The system shows two arcminute-scale radio jets (Stewart et al., 1993), and an arcsecond-scale asymmetric jet (Fender et al., 1998) suggesting the presence of relativistic outflow from the source, a claim that was confirmed by the latter authors in early 2004 (Fender et al., 2004). Cir X-1 is now included among the "Galactic Microquasar" X-ray binaries (Mirabel, 2001), although its behavior favors more a Z-source type binary rather than that of a black hole binary (Tennant, Fabian, & Shafer, 1986; Shirey et al., 1999a). The identification by Tennant, Fabian, & Shafer (1986) as an accreting neutron star is based on the detection of several type I X-ray bursts in the field of view with *EXOSAT*, which not only appeared to come from a consistent position but also varied in properties in response to changing source flux. Its identification as a neutron star clearly impacts on the question whether accretion powered X-ray sources containing a neutron star can generate ultra-relativistic jets (Fender et al., 2004).

The existence of the P Cygni lines demonstrated the presence of a high-velocity accretion disk wind with velocities between 400 and 2000 km (Brandt & Schulz, 2000). Unlike in cataclysmic variables, which generally feature polar outflows (Córdova & Horwarth, 1987), the wind is considered to be equatorial. Previous X-ray studies strongly suggested that the spectral variability caused by the observed X-ray absorption is best explained by a model with a nearly edge-on view (Brandt et al., 1996;

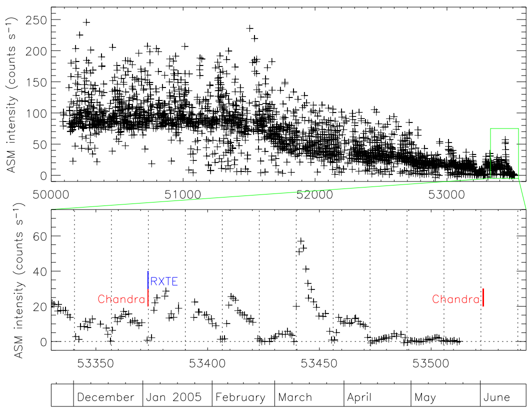

Figure 1. RXTE ASM *lightcurve of Cir X-1 from 1996 until the middle of May 2005 (upper panel). A close-up for 2005 (lower panel) still shows the regular flux dips at zero orbital phase and irregular flare events soon after zero phase. Marked are the most recently obtained* Chandra *observations.*

Shirey et al., 1999b; Schulz & Brandt, 2002). Such accretion disk winds have been discussed both theoretically and observationally (e.g. Begelman, McKee, & Shields (1983); Raymond (1993); Chiang (2001); Proga & Kallman (2002)) and quite recently, the existence of such winds was established as a viable explanation of *Chandra* HETGS (Canizares et al., 1995) observations of black hole X-ray binaries which have now revealed variable, blue-shifted absorption lines (Miller, 2005).

The nearly edge-on view of Cir X-1 is currently challenged by the observations of jet emissions in the Radio band (Fender et al., 2004). The suggested energetics of the observed Radio emission not only hinted the existence of an ultra-relativistic jet with $\Gamma \sim 10 - 15$, but also constrained the angle of emission within the line of sight. Under the assumption that the jet is launched perpendicular to the accretion disk and that the X-ray flare at zero phase of the same orbit is providing the energy, an inclination of not more than 5° towards the line of sight is the consequence, suggesting a face-on view of the system. Recent studies of a soft X-ray excess in *BeppoSAX* data seemed to slightly revise the distance towards the source thus relaxing the inclination constraint from the Radio emission slightly, but not dramatically (Iaria et al., 2005).

In the following we present new X-ray spectra obtained recently with the HETGS, which again seem to support a more edge-on interpretation. We also summarize the difficulties as well as advantages of both views, edge-on versus face-on, with respect to the observations so far.

2. THE LONG-TERM LIGHTCURVE

Recently Parkinson et al. (2003) compiled the X-ray lightcurve from archival data of a large variety X-ray

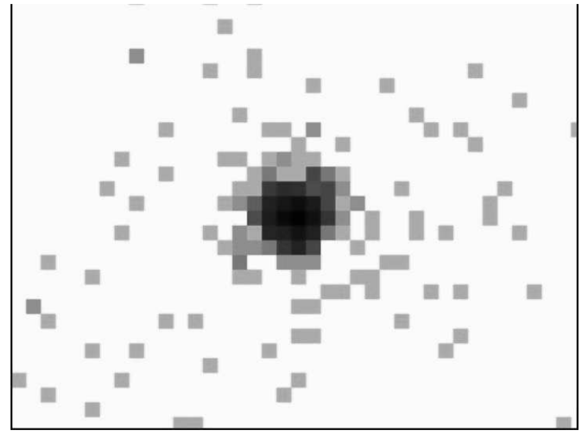

Figure 2. Zero order image of Cir X-1 from obsid 6148. An event filter placed on the zero order point spread function to avoid telemetry overflow allowed to transmit only every 10th photon reducing the effective exposure from 25 ks to 2.5 ks. Each pixel in the image has the size of 0.5 arcsec, the lightest grey is 1 count, the black peak in the middle 83 cts total.

satellites spanning over 30 years between 1968 and 2002. It shows a transient-like behaviour where source activity seemed to quiet down for some period during the early 1980s and its X-ray flux dropped well below 100 mCrab. During this time period Tennant, Fabian, & Shafer (1986) detected the type I X-ray bursts in *EXOSAT* data. Since then the source flux steadily increased to about a flux of 1.5 Crab with intermittent periods of high flaring activity. This high flux was maintained at least throughout the second half of the last decade unitl the flux started to decline again starting by the year 2000 falling below 100 mCrab in 2005. Whether this long-term behaviour is cyclic needs to be seen, it should be noted, though, that there seems to be a similar decline during the early phases of the archival coverage.

Figure 1 shows the *RXTE ASM* lightcurve that covers the period between 1996 and mid-2005 indicating a steady flux near 100 cts s^{-1} between 1996 and 2000 and the steady decline after that. During the high flux periods the source received massive attention from observers with *ASCA*, *BeppoSAX*, *RXTE*, *Chandra* and *XMM-Newton* (Brandt et al., 1996; Shirey et al., 1999a,b, 2001; Iaria et al., 2001, 2005; Brandt & Schulz, 2000; Schulz & Brandt, 2002). The HETG observation in Junuray 2005 (obsid 6148) was performed during exactly the same orbital phase than the one during June 2000, while it still was at a high flux level. We thus can directky compare spectra of very similar orbital phase between high and low long-term flux levels.

3. THE *CHANDRA* IMAGE

The observation on January 3rd 2004 showed the source within 0.5 arcsec of the expected position given by (Ar-

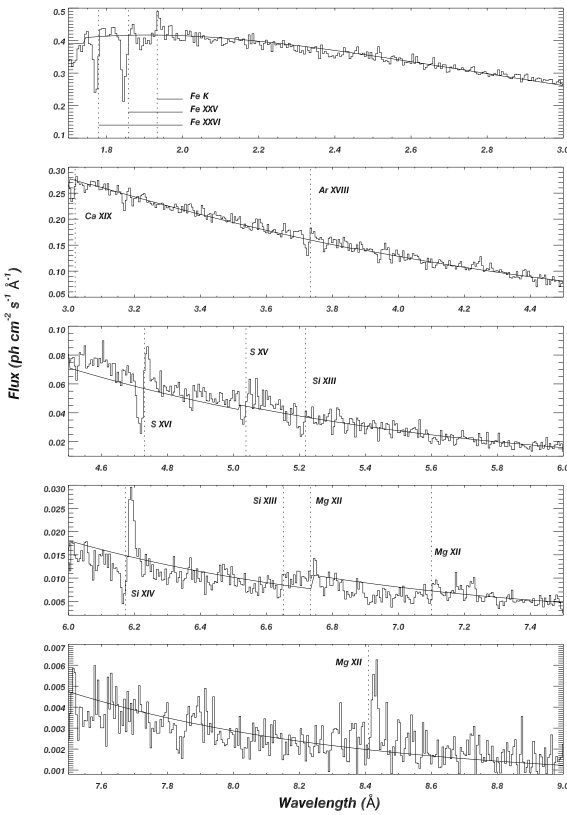

Figure 3. HETG spectrum of Cir X-1 from an observation in 2000 while it still was at its high flux level. The observation was performed during an intensity dip just before the source reached its orbital phase zero (from Schulz & Brandt (2002)).

gue et al., 1984). How well this position confirms the association of Cir X-1 with the faint red counterpart suggested by Moneti (1992) still needs to be seen once a more vigorous analysis of the *Chandra* point spread as well as an *ACIS* subpixel analysis has been performed. The image itself has an effective exposure of 2.5 ks over a period of 25 ks and provides some sensitivity down to $\sim 3 \times 10^{-12}$ erg cm^{-2} s^{-1}. Figure 2 shows the image, which is an agreement with a single point source. So far, no significant features within the sensitivity limit are observed.

4. HETGS SPECTRA

The properties of the X-ray lines and their relation with the underlying continuum are rather intriguing and spectra so far have already revealed a great deal of detail (Brandt & Schulz, 2000; Schulz & Brandt, 2002). Figure 3 shows a photon spectrum in the X-ray band between 1.7 Å and 9 Å containing a variety of H- and He-like lines from Mg to Fe. All P Cygni profiles show specific types of variability. The first type is a complex relationship of the equivalent widths of the absorbing as well as the emitting parts of the line profiles with the shape of

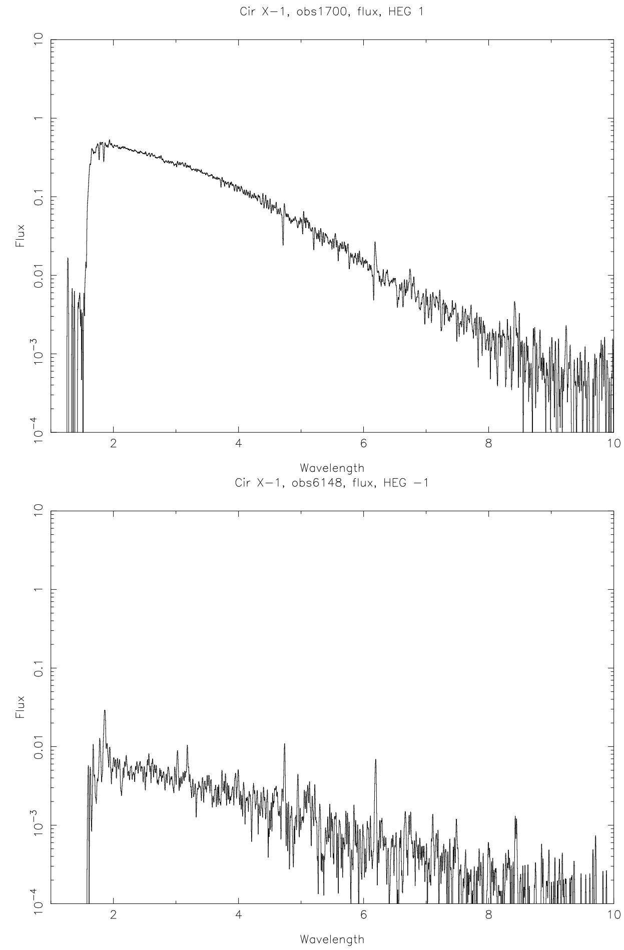

Figure 4. Two HETG spectra taken during the dip just before zero orbital phase. The top spectrum is from the high flux state (obsid 1700), the bottom spectrum from the low flux state (obsid 6148).

the underlying continuum. Schulz & Brandt (2002) interpret this variability as fluctuations in the ionization fraction of the wind triggered by spectral hardness changes of the incident spectrum emitted from the central source on a time scale of ~ 8 hours. A second type of variability is seen around the orbit where the strengths of the profiles diminish with increasing orbital phase. Here very faint lines are seen only during the first half of the orbit, the spectrum is devoid of lines during the rest of the orbit (Galloway, Schulz, & Brandt, 2005).

Figure 4 compares the spectra obtained during the pre-zero orbital phase dip (see Figure 3) at the high flux to the one now obtained during low flux. The source emission between the two observations differs by more than two orders of magnitude. Striking in the low flux case is the absense of P Cygni lines. This, however, only applies to the absorption part. The strengths of the emission lines, on the other other hand, is of similar magnitude. In the high flux case, Schulz & Brandt (2002) reported of line strengths for the major H-like (Lyα) lines of Fe, S, and Si values of 3.35, 6.15, and 3.14 $\times 10^{-4}$ photons cm^{-2} s^{-1}, respectively. Preliminary line fits of the spec-

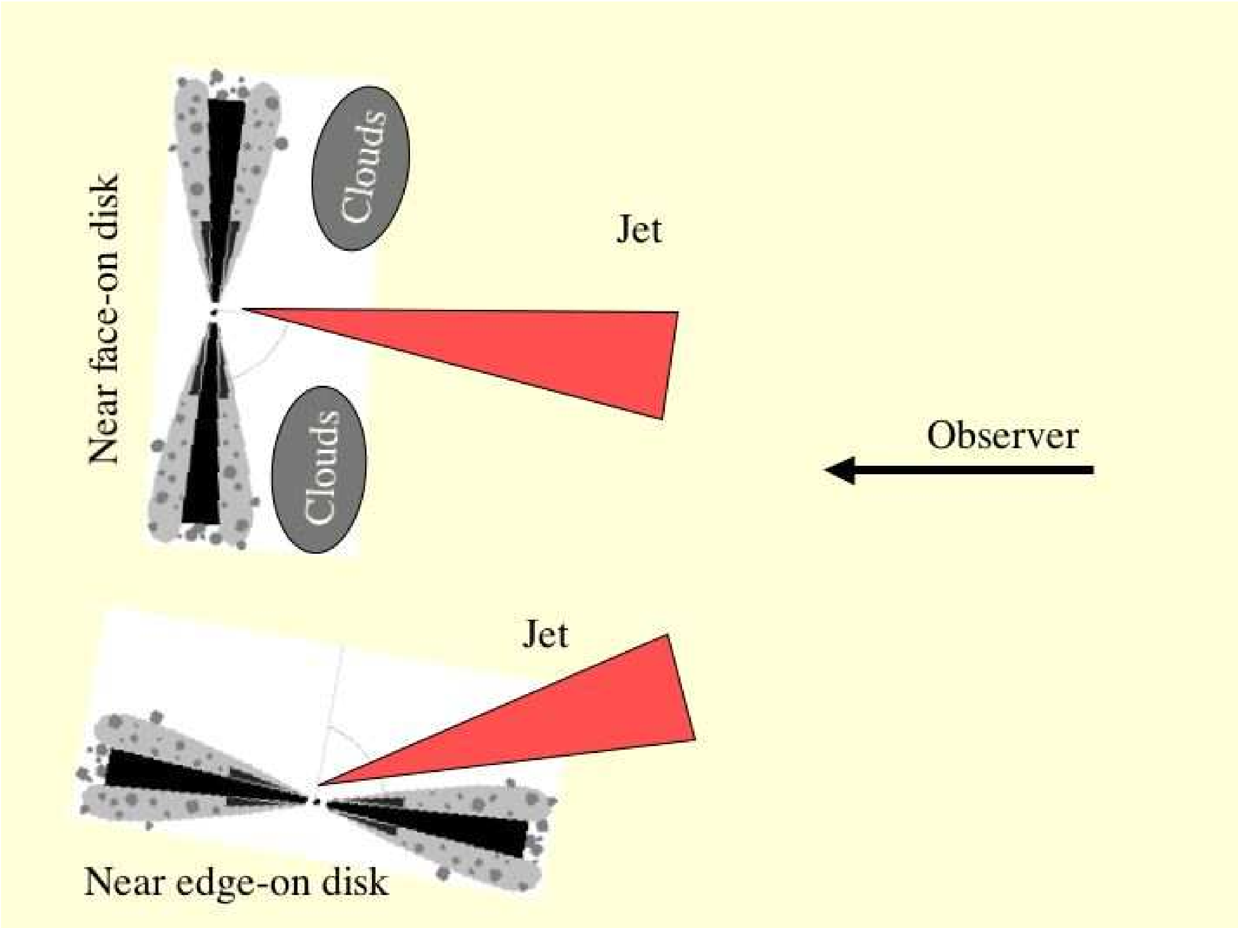

Figure 5. Two possible scenarios involving either a face-on or edge-on view towards the X-ray source in Cir X-1. The face-on view is argued for by the energetics of recent radio jet events. The near edge-on veiw is favored by X-ray observations.

trum during the low flux produced values of 1.96, 3.59, and 1.91×10^{-4} photons cm^{-2} s^{-1} for these lines, respectively. Not only are the flux ratios between these lines remarkably similar, the line fluxes between the two source states are well within a factor of two, whereas the overall source flux changed by two orders of magnitude (see Figure 4). Under the premise that these lines are photoexcited emissions from either the accretion disk itself or some atmospheric layer on top of the accretion disk, this clearly indicates that the illuminating source onto the line emitting region did not change significantly between the two flux states. Consequently, the overall reduction in total luminosity seems more likely a result of absorption or obscuration by material in the line of sight. Brandt et al. (1996) fitted two spectral components to the spectral continuum, both with partial coverage in absorption. One idea for the interpretation of the low flux continuum spectrum is that one or both spectral components exhibit higher absorption or one of the components has vanished entirely. A very preliminary analysis indicats the latter, though more detailed studies of the phenomenon is under way.

5. IMPLICATIONS

The analysis of these new spectra is clearly work in progress and, at this point, we abstain from an indepth discussion of the nature and detailed physics behind these ionized outflows as much has already been outlined in the introduction. Figure 5 shows cartoons of the two extreme scenarios incolving the line of sight towards the X-ray source. Although we do not entirely rule out a solution in between, it is clear that this would render viable explanation for both, the X-ray emission as well as the energetics of the Radio jets, rather complex.

The near face-on view of the X-ray source (top cartoon in Figure 5) seems favored by the most simplistic solution with respect to the implied jet dynamics observed in the Radio band (Fender et al., 2004). In this case the jet is directly associated with the X-ray flare before the Radio brightening. Viable solutions for the intrisic jet velocity imply an angle to the line of sight of $< 5^{\circ}$. In this case the interpretation of the observed X-ray absorption, line emission, and the origin of the P Cygni lines (Brandt & Schulz, 2000) need to be revised. The interpretation of the blue-shifted ionized line absorption would need to be be explained in the context of polar winds as observed in cataclysmic variables. The face-on view also implies a somewhat complex scenario for the observed neutral absorption as well as the line emission as one has to invoke an additional absorber into the line of sight that still provides partial view of the line emitting region. Material ejected from the jet itself seems insufficient as X-ray dips near zero phase are observed even in the case of Radio quiecence.

The near edge-on view of the X-ray source (bottom cartoon in Figure 5) provides a rather straight-forward solution for the observed X-ray emissions as here the accretion disk and its atmosphere provide a natural absorber medium. X-ray dips in the lightcurve associated with absorption and broad line emission from accretion disks have mostly been associated with edge-on views of disks, specifically for sources like 4U1822-37 (Cottam et al., 2001) or EXO0748-676 (Jimenez-Garate et al., 2003) to name a few. The spectrum we observed in January 2005 during the source's low flux period clearly falls into this category. Arguments for equatorial winds also emerge from more recent *Chandra* observations of black hole binaries which show similar blue-shifted line absorption as observed Cir X-1 and edge-on views have been established by other means (Miller, 2005). On the other hand, this may leave a fundamental problem with the interpretation that the jet in Cir X-1 is highly relativistic. There are ways around, though they require quite complex solutions. A scenario where the jet itself is not perpendicular to the disk, or may even be strongly bend might come into play as well the realization that the connection between the Radio emergence and the X-ray flares at zero phase is not as straight-forward as being assumed.

Both cases outlined above leave ample room for interpretation and modeling. However, from the X-ray spectra a near edge-on view is clearly preferred. Future analysis should focus on the interplay of absorption in the spectra of various flux states, but also the emission line properties. Throughout these dramatic flux changes, the emission lines near zero phase seem to be the only features that remain relatively unaffected by whatever changes affect the system. Likely originating from the accretion disk they are a valuable diagnostics and are sensitive to geometry such as inclination. Finally, we need to better understand and monitor the X-ray and radio emission, specically the relation between X-ray flaring and Radio brightness.

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