THE EXTENDED SOFT X-RAY EMISSION REGIONS IN THE LMXB EXO 0748−676 AND AND THE CV UX UMA: GEOMETRIC CONSTRAINTS

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ABSTRACT

XMM-Newton observations have established the simultaneous presence of deeply eclipsed hard X-ray emissions and uneclipsed soft X-rays in the LMXB EXO 0748−676 and in the CV UX UMa. The eclipses in hard X-rays, as well as those in the optical and the UV, constrain the system geometry. This, in turn, can constrain the location and the size of the soft X-ray emitting region. We have explored spherical and cylindrical emission regions and identify two possible solutions for the geometry. In one, the soft X-ray region is larger than the binary, and hence does not suffer a significant eclipse. In the other solution, the emission region is relatively compact. In this solution, a large part of the soft X-ray emission region, the part which would suffer an eclipse, is permanently hidden from our view by the vertically extended structure of the accretion disk. Only the emission from the far side of the disk, which is not subject to an eclipse, reaches the observers above the disk rim.

Key words: Eclipse; Accretion Disk Corona.

1. INTRODUCTION

The study of accretion disks and associated phenomena around protostars, compact stellar objects, and supermassive black holes are a central theme of X-ray astronomy. From a multi-wavelength perspective, accretion disks are most easily observed in nearby binary systems, such as cataclysmic variables (CVs) in which a white dwarf accretes from a late-type companion. The observations of eclipsing CVs can be used to put a tight constraint on the shapes and the temperature distributions of their disks, which often are the main source of the UV/optical light. Detailed optical observations of CVs, combined with innovative techniques such as eclipse mapping and Doppler tomography, were essential in validating the standard model of optically thick, geometrically thin accretion disks. This Shakura-Sunyaev model provides the basic framework that can be used to explain what happens *in* an accretion disk.

However, much happens *above* an accretion disk. For example, observed power-law X-ray continua of AGN do not come from the surface of their accretion disks, which are too cool to generate X-rays (except, perhaps, some soft excess well below 1 keV). Instead, these soft photons are Compton up-scattered in hot coronae. There are different theories as to where these coronae are located and how exactly they are heated, and existing observations cannot discriminate among them. The geometry of the corona, in turn, is a key ingredient in modeling the relativistic Fe Kα line from the AGN disks, the exact parameters of which have been subject of lively debate in recent years. Similar Comptonized continuum are also known in X-ray binaries (both black hole and neutron star systems).

When a binary system displays an eclipsed X-ray component and an uneclipsed X-ray component, the latter must be extended. Although a unique solution of its geometry cannot be obtained from an uneclipsed light curve, a family of solutions may be. One can combine this with consideration of its X-ray spectrum and the energy budget to gain insight into the physics of accretion above the disk plane. In this paper, we report on the possible geometry of soft X-ray emission regions in the LMXB, EXO 0748−676, and the CV, UX UMa.

2. EXO 0748−676: DISCOVERY TO *XMM-NEWTON* OBSERVATIONS

The low-mass X-ray binary (LMXB) EXO 0748−676 was discovered with *EXOSAT* as a new transient in 1985, and is an eclipsing, dipping, and bursting source (Parmar et al. 1986). The presence of type I X-ray bursts establishes the accreting object as a neutron star. The eclipses recur on the 3.82 hr orbital period; the mass donor (estimated to be a ~0.45 $M_\odot$ star) must therefore eclipse the neutron star and the inner accretion disk, where the bulk of the X-rays are believed to originate. The dips recur on

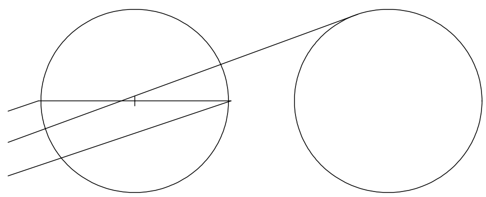

Figure 1. A schematic view of a possible geometry. The circle on the right represents the secondary; the circle on the left represents an X-ray emission region of the same size. The horizontal line through the latter represents the accretion disk; the shadows cast by the secondary, as well as the disk, are represented by the diagonal lines.

the same 3.82 hr period but are variable in details from orbit to orbit, and thought to be caused by azimuthal structures of the accretion disk. The phasing of dips relative to the eclipse implicates the impact of the mass transfer stream on the accretion disk as a likely cause of the structures.

Bonnet-Bidaud et al. (2001) presented their analysis of the early *XMM-Newton* observations of this object. A key discovery is that, while the hard (E>2 keV) X-rays are indeed eclipsed, a significant fraction of the soft (E<2 keV) X-rays remains uneclipsed. Strong, flare-like variability in the soft band is observed well outside the eclipse phases, making a quantitative measurement of the eclipse fraction somewhat subjective. Nevertheless, Bonnet-Bidaud et al. concluded that the emitting region was significantly greater than the companion star.

Homan et al. (2003) present further *XMM-Newton* observations of EXO 0748−676. They find that a clear soft eclipse is seen in some observations, but not in others. They argue, moreover, that the pronounced variability in the soft band should be seen as dips. Dips are deeper and cover wider phase intervals at lower energies, to such an extent that the dip-free intervals are rare and catch the eyes as "soft flares." If an eclipse happens during a dip-free interval, then soft X-rays are eclipsed. The soft emission that is visible even during deep dips have an extended origin and is not eclipsed by the companion.

3. UX UMA: UV/OPTICAL PHOTOMETRY AND *XMM-NEWTON* RESULTS

The cataclysmic variable (CV) UX UMa is the brightest eclipsing nova-like system in the optical and in the ultraviolet, with an orbital period of 4.72 hr. The eclipse mapping method has been used on high quality optical and UV data (see, e.g., Baptista et al. 1995) to infer the temperature distribution of the accretion disk in UX UMa, which appears consistent with theoretical expectation for a steady-state, high accretion rate disk. While it is clear

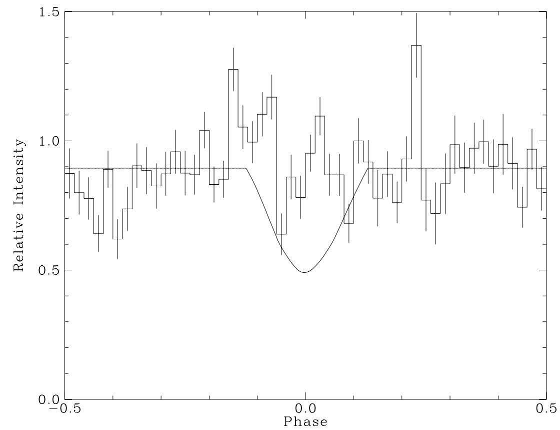

Figure 2. Comparison of observed and simulated light curves. The histogram with error bars is the folded XMM-Newton soft-band light curve of UX UMa. The smooth line is the partial eclipse predicted by the geometrical model sketched in Figure 1.

that the eclipse of the inner disk is seen, there are conflicting claims as to whether the eclipse of the white dwarf itself is seen in its UV light curves (Baptista et al. 1995; Froning et al. 2003).

Despite the deep eclipses in the optical and the UV, no eclipse was detected in the *ROSAT* observations (Wood et al. 1995). Pratt et al. (2004) observed UX UMa with *XMM-Newton* in 2002 June, in part to confirm this earlier result. Their spectral and timing analysis show that the X-ray emissions from UX UMa consist of two components. One is a newly discovered hard component that is heavily absorbed. Their spectral analysis suggests that this component contributes little counts below 2 keV. The other is the soft component that is consistent with the *ROSAT* detection, unabsorbed, and contributes only a small fraction of the counts above 3 keV.

Moreover, Pratt et al. have discovered an eclipse of the hard component, while confirming the lack of eclipse of the soft component. The hard component presumably originates from the vicinity of the accreting white dwarf. The soft component must originate in an extended structure to remain uneclipsed. In this respect, the CV UX UMa is strikingly similar to the LMXB EXO 0748−676.

4. GEOMETRICAL CONSTRAINTS

We begin with the schematic shown in Figure 1. In this, the soft X-ray emission region is assumed to be a sphere whose radius is identical to that of the secondary (also approximated by a sphere). It is immediately obvious that such a geometry should result in a significant partial eclipse. The geometry in both EXO 0748−676 and UX UMa is such that the central object (represented by

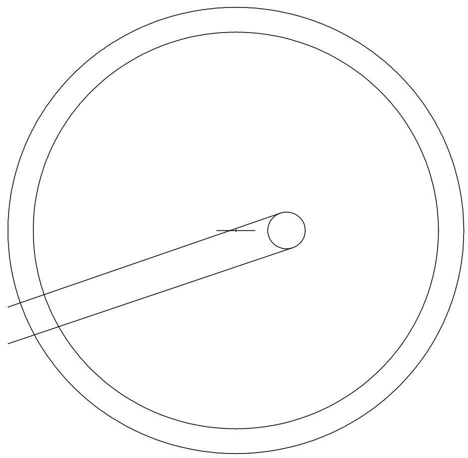

Figure 3. A schematic view of a very extended emission region. The central binary is represented by the small circle (for the secondary) and a ¤at accretion disk. In this scenario, an extended shell (represented by the large circles) scatters the soft X-ray photons from a central source into our line of site.

a small cross) is eclipsed, which naively would predict a deep, though partial, eclipse of the soft X-ray component as well. Even when we take the shadowing by the accretion disk into account — this would permanently hide a fraction of the lower half of the region from our view — we should still see a partial eclipse. We have simulated the light curve expected for a geometry sketched in Figure 1 (and several like it, changing only the radius of the emission region), and show a comparison with the observed *XMM-Newton* soft-band light curve of UX UMa. Clearly, we do not see the partial eclipse that is predicted by this model.

4.1. A Very Extended Solution

It is possible to create an uneclipsed component by invoking a shell that is larger than the entire binary (Figure 3). In this geometry, a small fraction of the shell is always eclipsed by the secondary; this fraction varies somewhat from phase to phase, because the secondary is off-center (the shell is assumed to be centered on the compact object), but such a variation is small enough to be undetectable. We have explored a range of cylindrical emission regions and reach a similar conclusion: the emission region must be larger than the binary to escape an eclipse.

Such a model is used to explain the uneclipsed EUV component in similar systems. Notably, Mauche & Raymond (2001) have successfully modeled the EUV spectrum of the dwarf nova OY Car in superoutburst as due to scattering of the central source by the accretion disk wind. In this case, the EUV line width (FWHM $\sim$ 1Å), which is similar to those of the UV (accretion disk wind) lines, is a strong evidence in favor for this model.

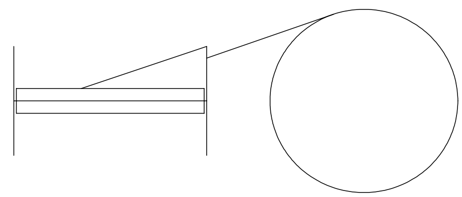

Figure 4. A schematic view of a compact emission region that would nevertheless be uneclipsed. In addition to the secondary, the accretion disk with an outer "wall" restricts our view of the soft X-ray emission region, which is depicted as cylindrical slabs above and below the disk. The outer wall hides a large part of the soft X-ray emitting region, including all the areas that would be eclipsed by the secondary.

In fact, Pratt et al. (2004) also adopted this solution for the soft X-ray component in UX UMa. Further considerations reveal a problem of energetics, however: the soft X-ray emission from the compact object in UX UMa is probably not strong enough for this explanation to work. The extrapolation of the absorption-corrected hard X-ray component is insuf£cient. The EUV component that powers the wind-scattered component in OY Car is too soft, and is not expected to be bright above 0.5 keV. Further argument against this interpretation for CVs can be found in Wheatley & Mauche (2005; see also Wheatley, this volume).

In the case of EXO 0748−676, the *Chandra* HETG observations show that the lines have modest widths (750 $\mathrm{km\,s^{-1}}$; Jimenez-Garate et al. 2003). Such a modest width argues against an accretion disk wind origin. Moreover, the soft X-ray emitting plasma strongly resembles the intrinsic absorber in our line of sight to the central object (Cottam et al. 2001). Thus, the soft X-ray emission region in EXO 0748−676 is probably very close to the accretion disk. How can this be reconciled with the lack of an eclipse?

4.2. A Compact Solution

As it turns out, there is a solution that involves a relatively compact emission region. For this model to work, we only require a structure that hides all regions that are subject to an eclipse by the secondary. In our £nal sketch (Figure 4), this is represented by a wall at the outer edge of the accretion disk. In fact, we know something like this wall must exist both in EXO 0748−676 and in UX UMa: the hard X-rays suffer strong intrinsic absorption in both systems. This "wall" is thick enough to absorb all soft X-rays ($<$2 keV) but let through the harder X-rays. We postulate a cylindrical emission region, a large fraction of which remains hidden from our view by this wall.

The remaining, observable part of the emission region is then never eclipsed. It also represents a small fraction of the total. Assuming a sensible set of symmetries, only the far side of the region above the disk remains visible, so we observe at most 25% of the intrinsic soft X-ray emission.

We have little direct constraint on the detailed shape of the wall or of the emission region. It is probably more natural to think in terms of a strongly ¤ared disk (the ¤ared edge playing the role of the wall) with something like an accretion disk corona. For the moment, we content ourselves with a simple sketch shown in Figure 4.

5. DISCUSSION

The above, more compact, geometry almost certainly applies to EXO 0748−676. The wall, in this case, is the dip-causing structure. During *XMM-Newton* observations, the soft X-ray emission from the central region is dipped out except during certain orbital phases. There is an extended soft X-ray emission region, but interior to the dip-causing structure, that is the origin of the un-dipped, un-eclipsed soft X-ray emission.

This geometry is also consistent with all the available X-ray data on UX UMa. We do not have a conclusive evidence for this interpretation yet, however. A long observation with a *XMM-Newton* or *Chandra* grating instrument can provide the kinematic constraint and will allow us to choose between the very extended and the relatively compact geometries.

If we can prove that the latter is true in UX UMa, that would have important implications. First, CVs — whose accretion disks are generally considered too cold to be X-ray sources — do indeed emit X-rays from the outer accretion disk. This component may also contribute to the observed X-rays from non-eclipsing CVs, so the previous X-ray spectral £ts may need to be re-interpreted.

Second, it would imply that an accretion disk around a white dwarf is capable of elevating and heating materials to X-ray emitting temperatures. If so, this is likely to be an intrinsic property of the accretion disk, unrelated to the nature of the compact object. Perhaps all accretion disks generate an accretion disk corona (ADC). In the outer regions of a CV disk, the ADC simply emits soft, thermal X-rays. Deeper in a gravitational potential well, the predominant cooling mechanism of the same ADC might switch to Comptonization of soft, seed photons. In the outer part of a neutron star of a black hole accretion disk, the energetics of the ADC will be dominated by irradiation instead.

However, this remains a speculation at the moment. We believe that further observations of extended soft X-ray emissions in CVs, away from the contaminating in¤uence of neutron stars or black holes, will play an essential role in our understanding of accretion ¤ow well above the disk plane.

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REFERENCES

Baptista, R., Horne, K., Hilditch, R.W., Mason, K.O. & Drew, J.E. 1995, ApJ, 448, 395

Bonnet-Bidaud, J.-M., Haberl, F., Ferrando, P., Bennie, P.J. & Kendziorra, E. 2001, A&A, 365, L282

Cottam, J., Kahn, S.M., Brinkman, A.C., den Herder, J.W. & Erd, C. 2001, A&A, 365, L277

Froning, C., Long, K.S. & Knigge, C. 2003, ApJ, 584, 433

Homan, J., Wijnands, R. & van den Berg, M. 2003, A&A, 412, 799

Jimenez-Garate, M.A., Schulz, N.S. & Marshall, H.L. 2003, ApJ, 590, 432

Mauche, C.W. & Raymond, J.C. 2001, ApJ, 541, 924

Parmar, A. White, N.E., Giommi, P. & Gottwald, M. 1986, ApJ, 308, 199

Pratt, G.W., Mukai, K., Hassall, B.J.M., Naylor, T. & Wood, J.H. 2004, MNRAS, 348, 49

Wheatley, P.J. & Mauche, C.W. 2005, ASP Conf. Ser. 330, 257

Wood, J.H., Naylor, T. & Marsh, T.R. 1995, MNRAS, 274, 31