Progressive Covering of the ADC during Dipping in the LMXB XBT 0748-676

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ABSTRACT

We report results of analysis of the ASCA observation of 1993, May 7th of the dipping LMXB source XBT 0748-676, and propose a new explanation of the spectral evolution in dipping in this source. The behavior of the source was very unusual in that, in the band 1 - 3 keV, dipping extended around most of the orbital cycle with almost no non-dip intensity evident and the depth of dipping reached 100%. At higher energies, eg 3 - 10 keV, the depth of dipping was less than 100%, and there were marked increases in hardness in dipping. We show that the non-dip and dip spectra in several intensity bands are well fitted using the same physical model that we have previously shown gives good explanations of several dipping sources, consisting of point source blackbody emission from the neutron star, plus extended Comptonised emission from the accretion disk corona (ADC), with progressive covering of the ADC during dipping. Best fit values of $kT_{bb} = 1.99\pm0.16$ keV and power law photon index $\Gamma = 1.70\pm0.16$ are found. The strong excess below 1 keV was well fitted by a Gaussian line at 0.65 keV. In dipping, good fits were obtained by allowing it to be covered by the same progressive covering factor as the extended continuum emission, providing strong evidence that the line originates in the ADC. Our approach of applying the two-component model, and explicitly including progressive covering of the Comptonised emission, differs radically from the “absorbed plus unabsorbed” approach previously used extensively for XBT 0748-676 and similar sources, in which the normalisation of the unabsorbed peak in dip spectra is allowed to decrease by a large factor in dipping. This decrease has often been attributed to the effects of electron scattering. By using our two-component model we show that the unabsorbed component is the uncovered fraction of the Comptonised emission, and in the band 1 - 10 keV, we do not need to invoke electron scattering to explain dipping.

Subject headings: accretion, accretion disks — scattering — (stars:) binaries: close — stars: circumstellar matter — stars: individual (XBT 0748-676) — X-rays: stars

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1. Introduction

There are \( \sim 10 \) Low Mass X-ray Binaries (LMXB) that exhibit absorption dips in X-ray intensity at the orbital period, and it is generally accepted that these are due to absorption in the bulge in the outer accretion disk where the accretion flow from the Companion impacts (White and Swank 1982). XBT 0748-676 is an important member of the dipping class, discovered and observed extensively with Exosat, exhibiting dipping, bursting and eclipsing (Parmar et al. 1986). Since then, it has undergone strong variations in brightness. The Exosat observations showed that both dips and interdips were present, and that the depth and extent of dipping varied markedly from orbit to orbit. Eclipses showed that the inclination was high, and during these, about 4% of the non-dip emission in the band 2 - 6 keV remained, indicating the presence of an extended emission component. Using the eclipses as fiducial markers, Parmar et al. (1986, 1991) found a very accurate value for the orbital period and a decreasing period. Asai et al. (1992) and Corbet et al. (1994) showed evidence that the period is modulated sunsoidally, but this pattern was not continued when RXTE data was added (Hertz et al. 1997). However all determinations agree on the period to \( \sim 0.01 \) s, ie 13766.78 s.

The dipping sources do not, in general, have the spectral evolution expected for photoelectric absorption of a single emission component in the bulge in the outer accretion disk, ie a strong hardening of the spectrum. For example, X 1624-490 shows a softening of the spectrum (Church and Balucinska-Church 1995), and X 1755-338 shows energy independence (White et al. 1984; Church and Balucinska-Church 1993). We have previously proposed a physical model for the dipping sources which explains the spectral evolution in these two sources (Church and Balucinska-Church, 1995). In this model, emission consists of two components: blackbody emission from the neutron star plus extended Comptonised emission from the accretion disk corona (ADC) represented as a power law at energies well below the Comptonisation break. X 1624-490 is also important because dipping reaches a “saturated” lower level which is strong evidence that two emission components are present (Church and Balucinska-Church 1995). The differences between the two sources above are mainly due to differences in blackbody temperature. In X 1624-490, \( kT_{bb} \) is relatively high, and as dipping consists predominantly of absorption of the point-like blackbody emission, this leaves the residual spectrum softer. In X 1755-338, \( kT_{bb} \) is smaller, with the peak emission at \( \sim 3 \) keV, so that removal of the blackbody leaves the spectrum neither harder nor softer in the band 1 - 10 keV.

There is also an important group of dipping sources including XB 0748-676, XB 1916-053 and XB 1254-690 which have very similar spectral evolution in dipping, in that there is clearly part of the spectrum which is not absorbed. These sources also, do not fit a simple pattern of photoelectric absorption in the bulge in the outer accretion disk. Spectral evolution in dipping in these sources has been modelled using the “absorbed plus unabsorbed” approach (Parmar et al. 1986, Smale et al. 1988 and Courvoisier et al. 1986). In the case of XBT 0748-676, the non-dip spectrum was fitted with a cut-off power law model (Parmar et al. 1986). Dip data selected in intensity bands however, revealed a strong low energy excess, and the spectra could be fitted by dividing the non-dip model into two parts with the same form, one strongly absorbed and the other not absorbed. Good fits were obtained with the column density of the unabsorbed part fixed at the non-dip value and but with strongly decreasing normalisation as dipping progresses, whereas the absorbed component had increasing column density but with a normalisation remaining at about the non-dip value. The origin of the unabsorbed component has often in this group of sources been attributed to electron scattering producing an energy-independent decrease of intensity, although it is not clear that electron scattering should play an important role in the bulge in the outer accretion disk in competition with photoelectric absorption. In the case of XBT 0748-676, Parmar et al. (1986) concluded that the unabsorbed component was probably due to fast variations of column density which could mimic a soft excess.

In the case of XB 1916-053, we have shown that the ASCA spectra may be fitted well by our two-component model including progressive covering of the extended Comptonised emission (Church et al. 1997). The blackbody emission from the neutron star was covered rapidly. Very good fits were obtained in this way, with large increases in column density \( N_H \) for the blackbody and smaller increases in \( N_H \) for the Comptonised emission, which are averages across the absorber. The unabsorbed peak in the spectrum is the uncovered part of the power law component, and
the increase in the partial covering fraction from zero to unity in deepest dipping is the behavior represented by the decreasing normalisation in “absorbed + unabsorbed” modelling. This is however radically different from that type of modelling. Firstly, we are explicitly using partial covering of extended emission in the model which has not previously been done. Secondly, the emission model for the source has two terms, and is the same model that we have shown gives good explanations of other dipping sources. Dipping can be modelled well by photoelectric absorption alone, without the need for electron scattering, and calculations from the cross sections showed that scattering is not expected to be important in the absorbing bulge in competition with absorption below 10 keV (Church et al. 1997). The main aim of the present work was to test using the ASCA data whether this approach can also successfully describe spectral evolution in dipping in XBT 0748-676.

2. Observations

We present results for the observation of XBT 0748-676 made on 1993, May 7th with ASCA (Tanaka et al. 1994), which lasted 23 hours, during the performance verification phase. The GIS data were screened to remove regions of SAA passage, to restrict elevation above the rim of the Earth to more than 5°, particle rigidity to more than 6 GeV/c, the radiation belt parameter to less than 200 c/s and angular deviation of the telescope pointing to less than 0.014°. The calibration source and outer ring were removed from the image, and rise-time rejection applied. Source data were selected from a circle of radius 6′ centered on the source. Background data were also obtained from a circular region of radius 6′ which provided a sufficiently large background count to use for sensible subtraction from the spectra. SIS0 data were extracted similarly and ‘faint’ data converted to ‘bright’ mode data. The data were screened, and cleaned to remove the effects of hot pixels. The main spectral fitting results were however obtained by adding GIS2 and GIS3 spectra to improve the quality of the spectra.

3. Results

The GIS2 light curve in the band 0.7 - 10.0 keV is shown in Fig. 1, in which 4 bursts and 2 eclipses can be seen. It is also evident that the source had decreased by about a factor of 30. The orbital period was obtained by carefully measuring the times of eclipse ingress and egress from the GIS2 light curve with 4 s binning. Differences in time between eclipse centers gave an orbital period $P = 13,762 \pm 6$ s, consistent with the accepted value of $\sim 13766.78$ s.
Fig. 2.— ASCA GIS2 light curves with the 4 bursts removed folded on the orbital period of 13,766.8 s: (a) in the band 1 - 3 keV, (b) in the band 3 - 10 keV and (c) from the total observation at 1- 3 keV. Eclipses are labelled (E).

ever, in producing our folded light curves, we used the more accurate value. The bursts, but not the eclipses, were excluded from the data before folding. Of the 6 orbital cycles observed, only 2 were covered well. When all of the data is included, the folded light curve is distorted from the shape of individual dips; for example, the shape of the dips is affected by the variability in the width of dipping. We therefore show in Fig. 2 folded light curves using orbits 3 and 5 which are not significantly distorted and which can be seen to be significantly different from the folded light curve including all data (lower panel). Note that in this figure, the dip between phases 0.6 and 0.7 is only part of the main dipping activity which in this source generally extends within an envelope between phases 0.5 and 1.1. In the lowest energy band 1 - 3 keV, dipping extends to almost all of the orbital cycle, suggesting the presence of absorber spreading around the outer accretion disk. The dipping at phase 0.6 - 0.7 is 100% deep and relatively steep-sided compared with dipping in the band 3 - 10 keV which is only 80% deep. Thus there is a marked increase in hardness in this source, which contrasts with XB 1916-053 during the ASCA observation, in which the depth of dipping was ~ 100% at all energies in the band 1 - 10 keV (Church et al. 1997). The eclipse in the folded light curve is clear in the center panel in the band 3 – 10 keV, but is less obvious in the band 1 – 3 keV because dipping is in progress when the eclipse starts.

GIS spectra were derived using the complete observation of 6 orbital cycles as there was little evidence for dependence of the results obtained on whether all 6 orbits were used, or the first 3, or the last 3. Firstly, GIS2 spectra were accumulated by removing bursts and eclipses and dividing the data into intensity bins using the ranges: 2.4 - 3.2 c/s (non-dip), 1.8 - 2.4 c/s, 1.2 - 1.8 c/s, 0.6 - 1.2 and 0.0 - 0.6 c/s. A consequence of dipping extending to several parts of the orbital cycle was that little non-dip data was available, and care was necessary to identify the correct intensity band for non-dip to avoid including dip data. The folded light curve in the higher band 3 - 10 keV has a shape more typical of the dipping sources and so was used to determine which data was non-dip. GIS2 and GIS3 data could not be selected in the same intensity bands because of count rate differences due to their different offsets from the bore-sight axis, and so GIS3 data were selected via time filters corresponding to intensity selections in GIS2. The GIS2 and GIS3 spectra were added, systematic errors of 2% were applied conservatively to each channel, and the data regrouped to an appropriate minimum number of counts in each bin. Channels below 0.8 keV and above 10.0 keV were ignored. An average response function was derived from the GIS2 and GIS3 responses appropriate to the source position in each detector. Finally the GIS2 and GIS3 background spectra were added. The non-dip data is of relatively poor quality because of the predominance of dipping during the orbital cycle.

In our work on other dipping sources, it was possible to derive well-constrained values of $kT_{bb}$ and $\Gamma$ for our two-component model from the non-dip data, and to fix these in fitting dip data. In this case, we have carried out simultaneous fitting of non-dip data and the 4 dip spectra. The non-dip spectrum could be fitted by a simple absorbed power law adequately, although this model will not fit the dip spectra because of the absorbed and unabsorbed peaks in the spectrum. Simple thermal models are not capable of fitting the spectra.

Thus we next used the two-component model which we have proposed for the dipping sources in general, consisting of a blackbody component from the neutron star plus Comptonised emission from the ADC with progressive covering of the ADC: $AB_1 \ast BB + AG \ast (AB_2 \ast f + (1-f)) \ast PL$ where BB and PL are
the blackbody and power law terms, AG is a Galactic absorption term, AB are variable absorption terms (including the Galactic term for the blackbody), and $f$ is the covering fraction. The source emission parameters cannot change during dipping and so we require $kT_{bb}$, $\Gamma$ and the two normalisations to remain constant during dipping. Good fits to the 5 spectra simultaneously were obtained, with $\chi^2$ for the simultaneous fitting of 312 for 517 degrees of freedom, suggesting that the systematic errors added were pessimistic.

We have also carried out spectral fitting of the SIS0 data in the energy band 0.5 - 10.0 keV using the same spectral model. The model fitted the non-dip and dip data well at all energies above 1 keV, but at $\sim$ 0.7 keV, the soft excess reported by Thomas et al. (1997) was seen. First, we added an absorbed Gaussian line to the spectral model above, but found that this could only fit the spectra simultaneously with a decreasing normalisation. This is exactly the behavior in the continuum emission modelled in the absorbed + unabsorbed approach by a decreasing normalisation, but in our fitting by the partial covering term. Consequently we next fitted a model in which a Gaussian line was added to the power law term, thus applying the same partial covering fraction to the line as to the continuum. This model was clearly able to fit the intensity variation of the excess in dipping adequately. We further found that no improvement in the fit was obtained by allowing the line normalisation to vary in addition to the effect of the partial covering term. This strongly suggests that the excess originates in the same region as the Comptonised emission, i.e. in the ADC. The best fit energy from fitting was 0.65 keV, which is the energy of O VIII $\lambda\alpha$, although there are several lines within $\sim$ 0.1 keV of this energy.

Our best fit spectral fitting results from simultaneous fitting the 5 added GIS2 and GIS3 spectra gave $kT_{bb} = 1.99 \pm 0.16$ keV and power law photon index $\Gamma = 1.70 \pm 0.16$. The value of the Galactic column density was $0.16 \pm 0.08 \cdot 10^{22}$ H atom cm$^{-2}$, in reasonable agreement with the Stark et al. value (1992) of $0.1 \cdot 10^{22}$ H atom cm$^{-2}$, and in good agreement with the value of Parmar et al. (1986) of $0.18 \cdot 10^{22}$ H atom cm$^{-2}$. The best fit to non-dip and dip data is show in Fig. 3 and Table 1.

From Table 1 and Fig. 3, it can be seen that the spectral evolution in dipping was fitted by large increases in $N_H$ for the blackbody, together with smaller increases in $N_H$ for the power law as this was progressively covered by absorber. The blackbody is expected to measure $N_H$ along a track across the absorber towards its center where the density is high, whereas the smaller $N_H$ of the power law suggests that $N_H$ is being integrated across the density gradient in the absorber. In deepest dipping for which we have a spectrum, the blackbody is completely absorbed and the partial covering fraction has risen to 95%. However it is clear that the unabsorbed peak is the 5% of incident power law emission not covered by the absorber whereas the higher energy peak is the residual of the power law covered by absorber after photoelectric absorption. It is interesting that the blackbody in the first dip spectrum persistently required an $N_H$ of zero in addition to the Galactic contribution. This
supports the idea that ~ 50% of the extended emission region is covered by absorber before blackbody emission from the neutron star begins to be absorbed, as would be expected.

4. Discussion

The two-component model which we have previously proposed for the dipping sources has been shown to fit the source XBT0748-676. In addition, we have shown that the spectral evolution in dipping can be explained in the same way as we did for XB1916-053, by allowing the extended Comptonised component to be progressively covered by the absorber. In a separate analysis of the PV phase data for XBT0748-676, Thomas et al. (1997) use the absorbed + unabsorbed approach for dip data, and find for non-dip emission that a single component generalised thermal model is ‘preferred from selected models’; however they do not report results using our two-component model, so their results should be seen in this light. Our spectral fitting results give a total absorbed flux of 1.94 · 10^{-10} erg cm^{-2} s^{-1} in the band 1 - 10 keV, of which the blackbody contribution is 29.9%. The luminosity of the blackbody emission calculated from the unabsorbed flux in the band 0.01 to 50 keV, and assuming a distance of 10 kpc (Gottwald et al. 1986) is 9.5 · 10^{35} erg s^{-1}, and from this, we can calculate the height of the emitting region assuming it is an equatorial strip around the star. This is found to be very small: 0.09 km, indicative of a very thin accretion disk, consistent with the fading of the source by a factor of about 30 from the Rosat observation of 1991 Nov 11. In the case that the magnetic field strength of the neutron star were non-zero, the emitting area at the magnetic poles would still be very small: 5.8 km^2.

The duration of eclipse or dip ingress and egress can in principle be used to derive the size of the extended source region, ie the ADC. However, in the present observation the source was faint, much fainter than during the Exosat observations, and we have only two dips that are well covered and 2 eclipses, compared with the 9 eclipses used by Parmar et al. (1986) to obtain the duration of eclipse ingress. The count rate of the source in RXTE was also much higher than in ASCA (Hertz et al. 1997). In these circumstances we can only estimate the size of the ADC. Using individual dips, we get an approximate duration of ingress ∆t of about 110 s. In the present case, the angular size of the absorber is known to be greater than that of the source because dipping is 100% deep and so the duration of dip ingress is the time taken for the bulge in the outer disk to cross the diameter of the ADC. We estimate the radius of the disk as 3.4 · 10^{10} cm, and the velocity of the bulge is 2πrdisk/P, where P is the orbital period. From these we derive the radius of the ADC to be 8.5 · 10^{8} cm. From the 2 eclipses, we find that the duration of ingress is between 16 s and 64 s. Combining these with a binary separation of the stars of 1 · 10^{11} cm, we get a radius of the ADC of between 3.9 · 10^{8} cm and 1.5 · 10^{9} cm. This can be compared with the results from Exosat as follows. Fig. 3 of Parmar et al. (1986) shows the profile of 9 eclipses added by folding on the orbital period, having a steep transition to eclipse and also shoulders to the transition. The total duration of ingress can be seen to be about 30 s, equivalent to a r_{ADC} of 7.2 · 10^{8} cm. Our eclipse ingress times are consistent with their value. Thus our dip and eclipse data suggest a value of r_{ADC} between 3.9 · 10^{8} cm and 1.5 · 10^{9} cm, consistent with an extended region above the inner part of the accretion disk.

The spectrum of XBT0748-676 is clearly dominated by non-thermal emission which is identified with Comptonised emission of the ADC, and we can derive some information about the ADC from our results. Firstly, the value of the Comptonisation y-parameter is found to be ~ 1.5 from our power law index of 1.7 (eg Rybicki and Lightman 1979). There is no evidence (or expectation) for the Comptonisation break being less than 10 keV; however we can assume that the break energy is similar to that we have determined for the related source XB1916-053 using the very broad band of 0.1 - 300 keV of BeppoSAX (Church et al. 1998), ie ~ 80 keV. From this value, the electron temperature ke is ~ 30 keV, from which we derive values in XBT0748-676 of the average optical depth and column density in the ADC of 2.5 and 4 · 10^{24} cm^{-2}. We have also shown that the low en-

| Table 1: Best fit spectral fitting results. |
|--------------------------------------------|
| I^a | N_H(BB)^b | N_H(PL)^b | f |
|--------------------------------------------|
| 2.4 - 3.2 | ~ 0.2 | 0.16±0.08 | 0.0 |
| 1.8 - 2.4 | ~ 0.2 | 1.6±0.5 | 0.57±0.08 |
| 1.2 - 1.8 | 4.8±1.5 | 2.1±0.2 | 0.84±0.03 |
| 0.6 - 1.2 | 17.7±2.7 | 4.7±0.2 | 0.93±0.07 |
| 0.0 - 0.6 | 79±16 | 12.3±0.8 | 0.95±0.07 |

^a intensity in c/s; ^b in units of 10^{22} H atom cm^{-2}
ergy feature can be fitted by a Gaussian line at 0.65 keV in non-dip and dip spectra, and in addition have shown that it originates in the ADC, since it can be fitted by the same progressive factor as the extended continuum emission. Future identification of this line, perhaps as O VIII L\(\alpha\) will, of course, provide direct information on conditions in the ADC. High energy data is clearly required for XBT 0748-676, together with higher resolution data below 1 keV to reveal the nature of the line emission.

The explanation of spectral evolution in XBT 0748-676 is radically different from previously modelling of the source using the absorbed + unabsorbed approach. Previously partial covering has not explicitly been used in modelling, and fitting our two-component model including partial covering of the extended component shows that the unabsorbed emission can be identified with uncovered non-dip emission. Gradual covering is represented in absorbed + unabsorbed modelling by the decreasing normalisation often attributed to electron scattering. We do not need to invoke electron scattering in the absorber, so that dipping can be explained by photoelectric absorption alone. In the case of XB 1916-053 we presented calculations showing that electron scattering is not expected to be important in the bulge in the outer disk at energies below 10 keV (Church et al. 1997). In XBT 0748-676, the density increase in dipping is less, and so the effects of scattering will be even smaller.

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