Echoes in X-ray binaries; mapping the accretion flow

Kieran O’Brien and Keith Horne

University of St Andrews, St Andrews, UK KY16 9SS

Abstract. In X-ray binaries much of the optical/UV emission arises from X-rays reprocessed by material in the accretion disk, stream and the companion star. The resulting reprocessed variability will be delayed in time with respect to the X-ray variability by an amount depending on the position of the reprocessing regions. We can determine a range of time-delays present in the system. This time-delay transfer function can be used to ‘echo-map’ the geometry of the reprocessing regions in the binary system.

We present our modeling of this transfer function and show results from our echo-mapping campaign using X-ray lightcurves from RXTE, simultaneous with HST. In the X-ray transient, GRO j1655-40, shortly after the 1996 outburst, we find evidence for reprocessing in the outer regions of a thick accretion disk.

1 Introduction

X-ray binaries (XRBs) are close binaries that contain a relatively un-evolved donor star and a neutron star or black hole that is thought to be accreting material through Roche-lobe overflow. Material passing through the inner Lagrangian point moves along a ballistic trajectory until impacting onto the outer regions of an accretion disk. This material spirals through the disk, losing angular momentum, until it accretes onto the central compact object, where X-rays are emitted from inner disk regions.

Much of the optical emission in XRBs arises from reprocessing of X-rays by material in regions around the central compact object. Light travel times within the system are of order 10s of seconds. Optical variability may thus be delayed in time relative to the X-ray driving variability by an amount characteristic of the position of the reprocessing region in the binary, which depends in turn on the geometry of the binary. The optical variability may be modelled as a convolution of the X-ray variability with a time-delay transfer function.

This time delay is the basis of an indirect imaging technique, known as echo tomography, to probe the structure of accretion flows on scales that cannot be imaged directly. Echo mapping has already been developed to interpret lightcurves of Active Galactic Nuclei (AGN), where time delays are used to resolve photoionized emission-line regions near the compact variable source of ionizing radiation in the nucleus (Horne, this volume). In AGN the timescale of detectable variations is days to weeks, giving a resolution in the transfer functions of 1-10 light days [1]. In XRBs the binary separation is light seconds rather than light days, requiring high-speed optical/UV and X-ray lightcurves to probe the structure...
of the components of the binary in detail. The detectable X-ray and optical variations in the lightcurves of such systems are also suitably fast.

We present a simple geometric model for the time-delay transfer functions of XRBs, using a synthetic binary code. We analyze correlated X-ray and UV variability in GRO J1655-40, using our computed transfer functions, to constrain the size, thickness and geometric shape of the accretion disk in the system.

2 Reprocessing of X-rays

In the standard model of reprocessing, X-rays are emitted by material in the deep potential well of the compact object. These photoionize and heat the surrounding regions of gas, which later recombine and cool, producing lower energy photons. The optical emission seen by a distant observer is delayed in time of arrival relative to the X-rays by two mechanisms. The first is a finite reprocessing time for the X-ray photons, which for this work is assumed to be negligible [5] and the second is the light travel times between the X-ray source and the reprocessing sites within the binary system.

2.1 light travel times

The light travel times arise from the time of flight differences for photons that are observed directly and those that are reprocessed and re-emitted before travelling to the observer. These delays can be up to twice the binary separation, obtained from Kepler’s third law,

\[
a = \frac{9.76 \text{s}}{c} \left( \frac{M_x + M_d}{M_\odot} \right)^{\frac{1}{3}} \left( \frac{P}{\text{days}} \right)^{\frac{2}{3}} \tag{1}
\]

where \( a \) is the binary separation, \( M_x \) and \( M_d \) are the masses of the compact object and donor star, \( P \) is the orbital period. In LMXBs the binary separation is of the order of several light seconds.

The time delay \( \tau \) at binary phase \( \phi \) for a reprocessing site with cylindrical coordinates \((R, \theta, Z)\) is

\[
\tau(x, \phi) = \frac{\sqrt{R^2 + Z^2}}{c} \left( 1 + \sin i \cos(\phi - \theta) \right) - \frac{Z}{c} \cos i \tag{2}
\]

where \( i \) is the inclination of the system and \( c \) is the speed of light.

The dynamic response function is found by considering how a change in X-ray flux, \( \Delta f_x(t) \), drives a change in the reprocessed flux. We can define the dynamic time delay transfer function to be

\[
\Psi_{\nu} (\lambda, \tau, \phi) = \int \left[ \frac{\delta I_\nu (\lambda, x, \tau)}{\delta f_x(t - \tau)} \right] d\Omega(x, \phi) \delta(\tau - \tau(x, \phi)) \tag{3},
\]

where \( \tau(x, \phi) \) is the geometric time delay of a reprocessing site at position \( x \), see (3).
3 Model X-ray Binary code

We have developed a code to model time delay transfer functions based on determining the contributions from different regions in the binary. In this section we describe the models used to construct the individual regions of the binary; the donor star, the accretion stream and the accretion disk. The code uses distances scaled to the binary separation in a right-handed cartesian coordinate system corotating with the binary. Each surface panel is a triangle, characterized by its area $dA$, orientation $n$, position $x$ and temperature $T$.

3.1 Donor Star

The donor star is modeled assuming it fills its critical Roche potential, so that mass transfer occurs via Roche lobe overflow through the inner Lagrangian point. Optically thick panels are placed over the surface of the Roche potential. The panels are triangular so that the curved surfaces of the binary are mapped more accurately than is possible using 4-sided shapes [7]. The panels, when unirradiated, are assigned an effective temperature $T_{\text{star}}$ given by the spectral type of the donor star.

3.2 Accretion stream

The accretion stream is modeled by following the ballistic trajectories of 4 test particles. The ‘width’ and the ‘height’ of the stream (its extent in the y- and z-directions respectively) is determined by the initial positions of the test particles. The stream is symmetric about the x-y plane. The unirradiated accretion stream is assumed to have a constant temperature $T_s$ along its length and the effects of irradiation are considered in the same way as those of the donor star.

3.3 Accretion disk

The disk thickness is assumed to increase with radius from 0 at $R = R_{\text{in}}$ to $H_{\text{out}}$ at $R = R_{\text{out}}$, with the form,

$$H = R_{\text{out}} \left( \frac{H}{R} \right)_{\text{out}} \left( \frac{R - R_{\text{in}}}{R_{\text{out}} - R_{\text{in}}} \right)^{\beta},$$

(4)

where the parameters are the inner and outer disk radii, $R_{\text{in}}$ and $R_{\text{out}}$ in units of $R(L_1)$, the half thickness of the outer disk $(H/R)_{\text{out}}$ and the exponent $\beta$ which describes the overall shape of the disk. The temperature structure of the un-irradiated disk is that of a steady state disk, in the absence of irradiation,

$$T_{\text{disk}}(R) = T_{\text{out}} \left( \frac{R}{R_{\text{out}}} \right)^{-\frac{2}{3}},$$

(5)

where $T_{\text{out}}$ and $T_{\text{in}}$ are the temperatures of the outer and inner disk respectively.
The effective temperature of a region at a distance $R$ from the X-ray source, assumed in our model to be a point source located at the centre of the accretion disk, is found from the accretion luminosity for a typical LMXB,

$$T_x^4 = \frac{L_x(1 - A)}{4\pi\sigma R^2},$$

(6)

and

$$L_x = \eta \frac{GM_s \dot{M}}{R_{ns}},$$

(7)

where $T_x$ is the temperature, $A$ the albedo, $\eta$ the efficiency, $M_s$ the mass of the compact object, $\dot{M}$ the accretion rate onto the compact object, $R_{ns}$ is the size of the compact object and $R$ is the distance between the compact object and the irradiated panel. This is normalised using the binary separation, $a$, the distance between the centres of mass of the stars, as is the coordinate system for the binary.

The irradiation of the binary takes place in three stages. The first stage is to calculate the temperature structure of the binary in the absence of any irradiation. This is done with characteristic temperatures for the donor star and the accretion stream and disk. The temperature structure of the disk is assumed to that for an unirradiated disk as given in (5). The surface panels of the binary exposed to X-rays are determined by projecting the binary surfaces onto a spherical polar representation of the sky, as it appears from the X-ray source. Each triangular panel is mapped to the sky starting with the one furthest from the source and ending with the panel closest. Those panels remaining visible and unocculted on the sky map are irradiated. The change in effective temperature of a panel is scaled by the projected area with respect to the X-ray source at a distance $R$ from the source. Hence the temperature after irradiation is given by,

$$T^4 = T_x^4 \cos \theta_x \left(\frac{a}{R}\right)^2 + T_{eff}^4$$

(8)

where $T$ is the temperature of the panel, $\theta_x$ the angle between the line of sight from the central source and the normal to the surface of the panel and $T_{eff}$ is the unirradiated effective temperature of the panel.

The second stage is to irradiate the binary with the constant component of the X-ray flux. This component of the X-ray flux is equated to the mean effective temperature of the X-ray source, as given in (3), where $T_x \equiv T_x$. The third and final stage is to repeat stage two with $T_x \equiv T(t)_{x}$, which represents irradiating the binary with a time varying component. The difference between stages two and three represents the temperature change of the panels due to the time varying component of the X-ray flux alone, $\Delta f(t)$.

The irradiated regions of the binary can be clearly seen in Fig. 1, where the left hand panels show a typical X-ray binary, using binary parameters based on those of Scorpius X-1, viewed from an inclination of 60°.
The response of a panel to the variable component of the irradiating X-ray flux is given by,

$$I_x(\lambda, x, \Delta f_x(t)) = \int \left[B_x(\lambda, T_x(t)) - B_x(\lambda, T_x)\right] P(\lambda, u, \alpha) d\Omega(x, \phi) d\lambda. \quad (9)$$

This response is substituted into the expression for the dynamic response given in (3). The resulting time delays are mapped onto a time delay grid to produce our time-delay transfer function. Examples of this transfer function can be seen in the right-hand panels of Fig. 1. The time delay of donor star can be
seen to change with binary phase in the individual images, whereas the accretion disk remains constant throughout the binary orbit. This effect can be seen more clearly in Fig. 2, where the individual transfer functions have been trailed in orbital phase to create an echo-phase diagram, showing clearly how the time delays of the individual components change with binary phase.

![Fig. 2. A plot of time-delay transfer functions as a function of binary phase, based on the binary parameters of Scorpius X-1. The accretion disk has constant time delays in the region 0-8 seconds, whereas the time delays from the companion star are seen to vary sinusoidally with binary phase between 0-20 seconds.](image)

### 4 Results for GRO J1655-40

We have used these model transfer functions to constrain the geometric parameters for the soft X-ray transient GRO J1655-40. The X-ray data was taken with the PCA onboard RXTE on June 8 1996, simultaneous with the HST data. These lightcurves are shown in the top and middle panels of Fig. 3 respectively. The data were previously fitted with causal and acausal Gaussian transfer functions and found to have a mean \(14.6 \pm 1.4\) seconds, with a RMS of \(10.5 \pm 1.9\) seconds. We have used our model X-ray binary code to predict transfer functions, using the known binary parameters for GRO J1655-40. The trial transfer functions are convolved with the X-ray lightcurve to create a synthetic reprocessed lightcurve. The badness of fit is found between the synthetic and observed reprocessed lightcurves and minimized to find the best-fit values for the size, thickness and shape of the accretion disk. The synthetic lightcurve from
the best-fit transfer function is shown by the thick line in the middle panel of Fig. 3 while the bottom panel shows the residuals of the fit. The best-fit model is shown in Fig. 4, together with the best-fit Gaussian transfer function from [2].

We find that the disk extends to 67% of the way to the inner Lagrangian point, is geometrically thick, with an opening angle $\sim 14^\circ$ and is somewhat flared. This has the effect of shadowing the donor star from much of the irradiation.

5 Discussion

We have used the time delays observed between the X-ray and optical/UV variability in X-ray binaries to echo-map the irradiated regions. We have developed a code to simulate the time-delay transfer functions for such systems and find that, in the case of the SXT, GRO J1655-40, there is evidence for a geometrically thick outer accretion disk that shields the innerface of the donor star from irradiation.

While the method of echo-tomography of X-ray binaries is still in its infancy, we have shown that with just a small amount of data, from co-ordinated observing campaigns using ground-based and satellite observatories, this technique can reveal interesting insights into the geometry of X-ray binaries. Furthermore this
Fig. 4. A comparison of the best fit transfer functions for GRO J1655-40 from our two modeling methods. On the left is the synthetic X-ray binary model transfer function and on the right is the acausal Gaussian transfer function.

The technique has the promise of probing the structure and geometry of such systems on scales unobtainable with any other current technique.

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