An observatory for mapping stellar accretion discs

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ABSTRACT

A broad range of physical conditions occur within the atmosphere of any accretion disc. The characteristics of emergent disc spectra are strong functions of local disc physics, and consequently these spectra hold the key to determining physical disc structure. In general however astrophysical discs cannot be resolved spatially because of their small sizes and great distances, therefore our problem is that direct observations provide only a global picture of accretion disc physics. To test disc theory on local scales we require a method to deconvolve global spectra into their local constituents. We discuss one such method, *Echo tomography*, and the relevance of XMM to this field of research.

1. Introduction: resolving accretion discs by astrotomography

Close binary stars provide natural environments for accretion discs to form. In these systems time-dependent variations in the spectral energy distribution from the disc on dynamical timescales are the result of binary rotation. Orbitally-coherent flux and line-profile variations provide enough information to deconvolve the integrated disc light into intensity maps over spatial or velocity coordinates. In response to this, the field of astrotomography has been developed. astrotomography uses the rotational nature of accreting systems and the ensuing brightness variations, combined with a few simple physical assumptions, to reconstruct 2- and 3-dimensional maps from 1- and 2-dimensional data. The non-uniqueness of these problems requires the use of statistical methods such as maximum entropy (Skilling & Bryan 1984) to force solutions towards physically interesting cases. We can, for instance, construct maps of disc-surface brightness using time-resolved photometry of discs as they are occulted by their mass-losing companions (Horne 1985). Kinematic maps are built from orbitally-resolved, doppler-broadened line profile variations (Marsh & Horne 1988). Surface structure is mapped spatially using the doppler method by adopting an appropriate velocity–position transformation (Rutten & Dhillon 1994). Here we discuss a related method which employs light-travel time-delays between directly observed pulses or flares from the region around hot compact sources and reprocessed emission off the colder disc material.

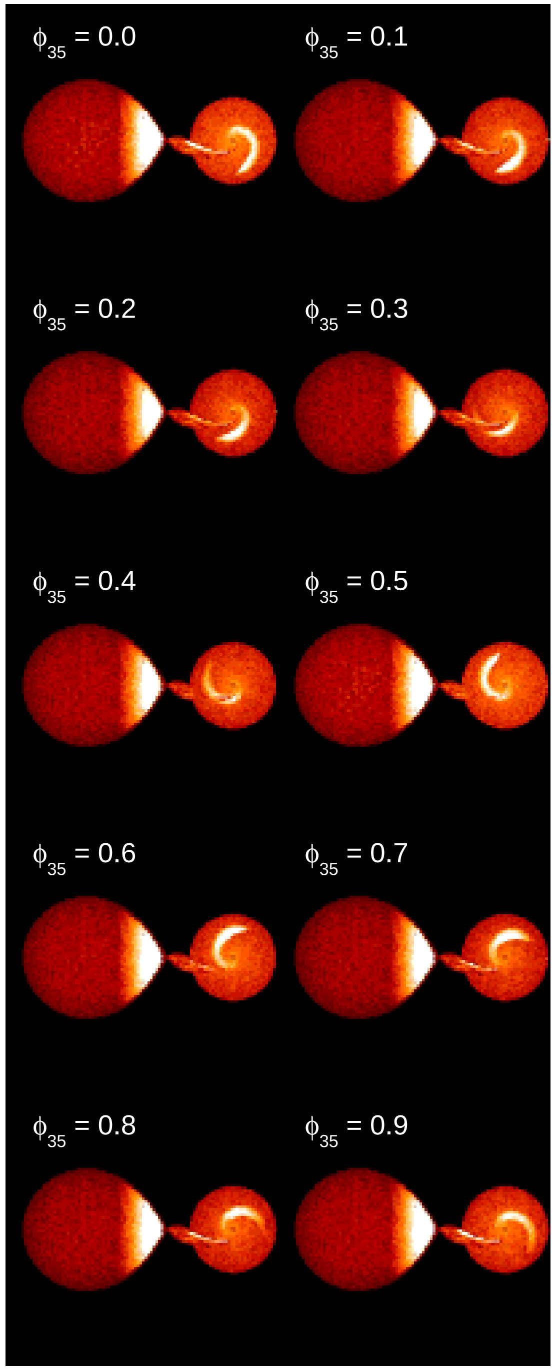

Fig. 1.— A model of the Her X-1 binary system over one 35-d precession cycle. The Earth direction is towards the top of the page and and each snapshot occurs at orbital phase 0.75. The inner faces of the companion star and accretion stream are irradiated by high-energy photons from the accreting neutron star. The atmosphere of the accretion disc heated by the compact object is a small fraction of it's total surface area due to it's warped shape and we see the pattern precessing retrogradely over the cycle. This asymmetric heating pattern both sustains the warp through radiation pressure and provides a unique diagnostic of warp geometry.

2. Irradiated accretion disc atmospheres

A central irradiating source heats an accretion disc atmosphere and structural instabilities rapidly result in irradiation-driven warping and precession (Wijers & Pringle 1999). Warps have been found in both AGN and planetary discs but the most classic examples are found in the X-ray binary stars. In this paper we will discuss the obvious example of disc warp the eclipsing X-ray binary Hercules X-1 (e.g. Gerend & Boynton 1976), a 1.24-s pulsar orbiting an Avii star on a 1.7-d period. The precessing disc in this object provides an occulting body for the central X-ray source of variable column density on a quasi-period of 20 orbital cycles and a shadow over the X-ray heated face of the companion star which varies on the same timescale. Disc models recreate these observations easily, but the problem of fitting a three-dimensional disc geometry to a one-dimensional X-ray or optical light curve is poorly constrained. In order to put useful constraints on the disc shape we require a more robust diagnostic than simple photon collecting. We have developed Echo tomography to solve this problem.

3. Echo tomography

This technique is a derivative of the reverberation mapping method commonly used in time-tagged studies of AGN (e.g. Horne 1997a). Echo tomography employs the X-ray pulses from the central object as it spins on its 1.24-s period. A large fraction of the discs atmosphere is self-shielded from the central source because of its warped shape. The X-rays reprocess off exposed regions of the disc atmosphere but there is a time delay due to the light-travel time between the X-ray source and the reprocessing site. The range of time delays between X-ray and UV/optical pulsations is a transfer function which defines a set of iso-delay curves over the surface of the disc. A sample of transfer functions measured over a full precession cycle allow a spatial map of the irradiated regions of the disc to be constructed, as Figs. 2 and 3 illustrate; see also Horne (1997b), Hynes et al. (1998).

The UV/optical/IR pulsation amplitude as a function of wavelength yields a temperature map of the disc. Furthermore gas reprocessing times provide a time-independent component to the time delay transfer functions which yields the gas density of the disc, where

$$\frac{\tau}{\text{1-s}} \sim \frac{n_e}{10^{13}\text{cm}^3}. \qquad (1)$$

τ is the reprocessing timescale and n_e the electron density. Consequently echo tomography provides maps of both spatial structure and the fundamental physical properties of the irradiated disc atmosphere.

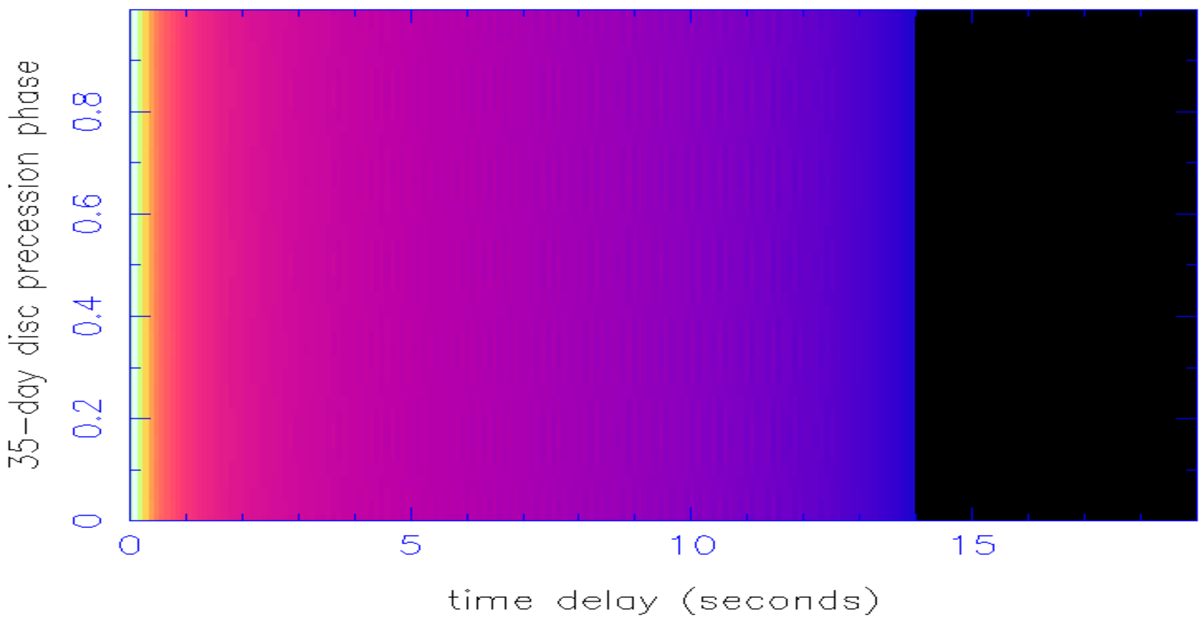

Fig. 2.— A sample of time-delay transfer functions over one precession cycle of the Her X-1 model from an axisymmetric, thin accretion disc. Although time-independent, the function provides constraints on the size of the disc and it's inclination and opening angles (O'Brien et al. 1999).

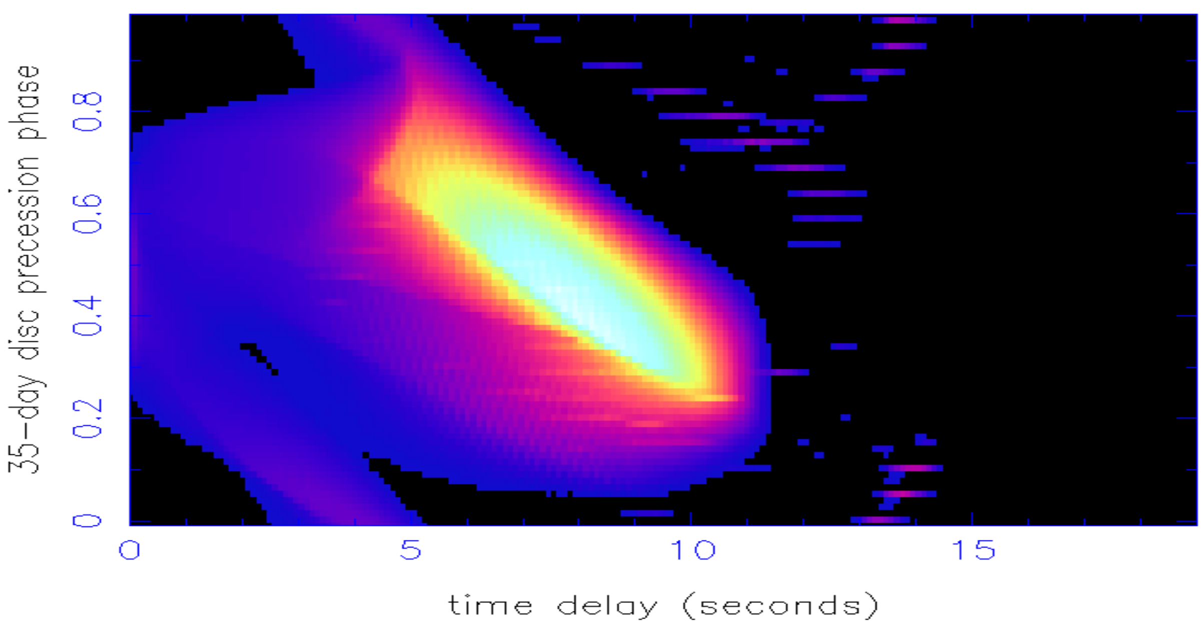

Fig. 3.— A sample of time-delay transfer functions over one precession cycle of the Her X-1 model from the thin accretion disc of Wijers & Pringle (1999). The variations across the transfer function during the 35-d cycle provide a direct method of constraining the warp geometry.

4. Echo tomography with XMM

This type of experiment requires a multiwavelength observing campaign consisting of X-ray observatories to monitor X-ray pulses and flares in conjunction with UV satellites and large optical telescopes in order to record the reprocessed pulses and flares. Securing this amount of hardware time is time-consuming and the inability of these instruments to provide totally simultaneous data due to SAA passages, Earth occultations and daylight hours is inefficient.

XMM is a facility which provides broad energy coverage between the X-ray and optical bands and allows complete simultaneity between instruments. These are both suitably sensitive and fast to record pulsar flashes, bursts and flares from both the X-ray source and the sites of reprocessing, while the high-Earth orbit provides a long continuous base-line of data unobtainable from low-Earth satellites. Consequently XMM is the ideal instrument for echo mapping the hot, irradiated atmospheres of accretion discs, companions, accretion streams, disc winds and jets of the accreting binary stars.

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