Applications of Indirect Imaging techniques in X-ray binaries

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Abstract. A review is given on aspects of indirect imaging techniques in X-ray binaries which are used as diagnostics tools for probing the X-ray dominated accretion disc physics. These techniques utilize observed properties such as the emission line profile variability, the time delays between simultaneous optical/X-ray light curves, the light curves of eclipsing systems and the pulsed emission from the compact object in order to reconstruct the accretion disc's line emissivity (Doppler tomography), the irradiated disc and heated secondary (echo mapping), the outer disc structure (modified eclipse mapping) and the accreting regions onto the compact object, respectively.

1 Introduction

Low-mass X-ray binaries (LMXBs) involve mass transfer from a main-sequence companion star and accretion onto a neutron star or a black hole via a disc. Their optical and UV emission is dominated by reprocessing of X-rays, mainly in the disc but also on the companion star. The fundamental difference from cataclysmic variable (CV) discs is the amount of X-rays produced close to the accreting region and their irradiating effect on the binary components. The X-ray illumination emanating from the vicinity of the compact object heats up the surrounding disc and the surface of the nearby companion star. The X-ray heating is so intense that it controls the radial and vertical structure of the LMXB discs, thus overtaking viscous heating that controls accretion in CV discs. The study of LMXBs has been difficult since they are faint objects in the optical, and the binary parameters are not well established because there are very few eclipsing systems and irradiation is blurring out any variabilities. The reader who is interested in more details in X-ray binaries can refer to [33] or [59]. Here, we will review a few examples of image reconstruction where an observed property is used in order to gain insight into the state of the companion star, the accretion disc and the compact object of the X-ray binary.

2 The heated companion star

The companion star in X-ray binaries is heated by the hard X-ray radiation, which penetrates the photosphere, and is re-emitted as blackbody flux [15]. As a consequence the light re-emitted by the companion star depends on the X-ray illumination pattern. The occultation by the irradiated disc will become
apparent as a shadow on the companion star. The hard X-ray emission that does not encounter the accretion disc and hits the star directly will heat up its photosphere and cause continuum emission and absorption line production. This orbital heating effect is pronounced in systems like Her X-1 (where the companion star is varying between spectral types ∼O9 at maximum to A7/F0 at minimum [39]) and Cyg X-2 [3]) and can in certain circumstances totally dominate the star’s evolution, as in e.g. the Black Widow pulsar PSR1957+20 [44,50].

That short period LMXBs might exhibit such pronounced heating (of an otherwise cool star) is supported by the discovery of phase-dependent HeI absorption (λ5876) in the secondary of the 5.6 hour eclipsing LMXB X 1822-371 (see Fig. 1), which indicates that the inner face of the star appears to be hotter than its back face by 10000-15000 K [20]. The heating of the photosphere has never been treated correctly and any theoretical progress is expected through observational constraints [8]. Podsiadlowski [45] has shown that X-ray irradiation can drastically change the secondary’s structure (expand atmosphere by a factor of 2-3), and thereby its evolution provided that significant amounts of energy can be transported to the back side [16]. When applying this to outburst radial velocity data of the galactic microquasar Nova Sco 1994 Shahbaz et al. [53] found significant changes to the binary mass solutions. Oroz & Bailyn [41] used a conventional sinusoidal analysis and derived a black hole mass of 7.01±0.22 M⊙ from a K-velocity of 228 km s⁻¹, whereas Shahbaz et al. [53] obtained a much better irradiated fit to the radial velocity curve of K=215 km s⁻¹ and a mass of 5.4±1.3 M⊙. The asymmetric distribution of the absorption line strength around the inner face of the companion star will indicate the X-ray illumination pattern through the disc and Roche tomography may be used to map the enhanced absorption line region onto the companion star Roche-lobe surface (Dhillon and Watson, this Volume).

A new technique which has started producing results, is “Echo” mapping. This method utilizes the time delays between optical and X-ray photons in order to map the irradiated regions in the binary system, assuming that the X-rays are produced at the centre of the disc (O’Brien, this Volume). Here, we present an application of the method on the brightest X-ray object, the 19-hour binary system, Sco X-1, which moves along a Z-shaped curve in the X-ray colour-colour diagrams on a ∼1 day timescale [27]. It is believed that the above behaviour reflects changes in the accretion flow, and therefore changes in the structure of the disc (e.g. thickening of the disc). Petro et al. [43] found fast (<1s) rises in the X-ray flux followed immediately by slower 10-20 second rises in the optical (Fig. 1) at the flaring branch of the Z-curve, a state which is characterized by an enhanced mass transfer rate [25]. The flaring branch is unpredictable and lasts for only a few hours at most [7], and many attempts to obtain simultaneous optical and X-ray light curves during the flaring branch have been unsuccessful so far.

Therefore, the only data of Sco X-1 where a correlation between optical and X-ray photons is seen during the flaring branch is the data from [43]. Fig. 2 shows
Fig. 1. The trailed spectra of HeI λ5876 from the binary X 1822-371. The line is in absorption and moves from red-to-blue at phase 0.5 which is the signature of the companion’s star motion. There is also an unidentified component at phase 0.9. Reproduction from [20].

the simultaneous X-ray and optical light curves of Sco X-1. The transfer function between the light curves (small upper panel in Fig. 2) shows a distribution of time-delays which peak at ∼13 seconds which corresponds to the light-travel distance of the neutron star to the inner face of the donor star [40]. A model diagram showing the time-delay versus binary phase is presented in Fig. 3. The constant time-delay with phase is due to irradiation in the disc and the cut-off at 6.5 seconds signifies the outer edge of the disc. The sinusoidal-like time delays with phase are due to the irradiated donor star and is minimum at the back face but maximum at the inner face of the star. The spread of time-delays at binary phase 0.5 should eventually constrain the total area of the heated surface with regard to the Roche lobe. The model of the irradiated regions in the binary system of Sco X-1 is given in Fig. 4.

3 The accretion disc

3.1 Doppler tomography

Doppler tomography has shown its great diagnostic value with the discovery of spiral shocks in accretion discs (Steeghs, this Volume). Application of the
Fig. 2. Simultaneous optical and X-ray light curves of Sco X-1 [43]. A re-analysis of the data, using a maximum-entropy technique (echo mapping) gives a transfer function (top-left panel) which shows a time delay of $\sim 13$ seconds, consistent with reprocessing off the inner face of the donor star [40].

The technique in X-ray binaries has been proved much more difficult, mainly due to the fact that X-ray binaries are optically fainter than cataclysmic variables.

For example, in persistent X-ray sources, such as X 1822-371, the Balmer emission profiles are not clearly double-peaked due to effects which are most likely related to the irradiated, extended discs observed edge-on. The trailed spectra look more like a blurred version of typical trailed spectra in dwarf novae (e.g. OY Car [18]). The projected outer rim of the disc is quite likely the source of the “blurred” trailed spectra. Thereafter, reconstruction of the emission line distribution reveals a blurred ring-like structure with no other clearly defined structure. Fig. 5 presents such a Doppler map of the X-ray persistent source X 1822-371, one of the accretion disc corona (ADC) sources in which X-rays from the compact object are not viewed directly, but are scattered into our line-of-sight by an extended corona above the disc (and which explains its unusually low $L_X/L_{opt}$ ratio). Furthermore, the discovery of spiral shocks in the accretion disc of the cataclysmic variable IP Peg [54], which occurred at a time of a high mass transfer rate similar to that in LMXBs, raises the question of detecting them in X1822-371. Clearly, any hint of disc structure will be easier to reveal...
Fig. 3. The echo-phase diagram, based on the Sco X-1 parameters, which shows the time delay versus orbital phase. At orbital phase 0.5, the range of time delays is maximal (10-15 seconds) [40].

with observations of the high-ionisation line He II $\lambda$4686 which should provide maps with better clarity than Hα. However, He II Doppler maps of other neutron star X-ray binaries show complex line distributions, such as that of XTE J2123-058 (Hynes et al., this Volume; see also there a list of Doppler maps of neutron star LMXBs). The latter Doppler map shows a low-velocity emission at the backside of the disc which is difficult to interpret. A magnetic propeller scenario is favoured by Hynes et al. (this Volume) as the origin of the low-velocity emission. Alternatively, it may be that this emission is produced by the gas stream overflow crashing back on the disc, thus the gas velocities would be shocked from around 1200 km s$^{-1}$ to 300 km s$^{-1}$ [22].

In X-ray transient sources it has been difficult to derive Doppler maps, since they are very faint at quiescence, and when they are at outburst the binary period is not accurately known in order to tailor phase-resolved observations. The disc outshines the star and it is very difficult to derive a spectroscopic period, and thus a reliable ephemeris. This becomes apparent with the Doppler tomogram of GRO J0422+32 [2], presented in Fig. 6, where two solutions were possible at the time given the uncertainty in the definition of absolute phase zero (inferior conjunction of the companion star). However, the He II emission spot is most
likely caused by the impact of the gas stream onto the disc in GRO J0422+32. When at quiescence, the object faintness prohibits any phase-resolved studies. However, the advent of a wealth of X-ray satellites in the 90’s and the advent of the new generation of telescopes has enabled the first Doppler tomograms of the accretion discs around black holes. The line emissivity of such discs follows a $R^{-b}$ law with $b = 1.5 - 2.2$ [23]. The Doppler map of GS2000+25 in quiescence clearly shows that there is on-going mass transfer onto the disc from the presence of the bright spot along the ballistic trajectory of the gas stream in Fig. 7 [19]. However, there is no detectable emission in the X-rays or UV suggesting that the inner disc may be empty or frozen (Mukai, private communication). The same behaviour has also been observed in A0620-00, i.e. a bright spot in the outer disc but no activity from the inner disc [34,36], a behaviour consistent with advection dominated accretion flow models [9]. A Doppler map of Nova Oph 1977 in quiescence - with a hint of some secondary star emission (for further
details see [21]) - is also shown in order to demonstrate the difficulty in building Doppler maps of X-ray transients in quiescence even with 10m class telescopes.

Fig. 5. The Hα Doppler map of X1822-371 shows the emission-line distribution as the typical ring-like structure with possibly enhanced emissivity at phases 0.2 and 0.8. Reproduction from [20].

3.2 The vertical structure of the accretion disc

Although many measurements of the radial disc structure exist, mainly from eclipse mapping studies of the temperature-radius relationship (e.g. [51]), very little is known about the vertical stratification of accretion discs. The vertical structure of the disc would require a temperature inversion to explain, for example, the emission lines from discs. Indeed, Hubeny [29] finds that the emergent spectrum depends on the vertical structure model and constraints on the value of the disc viscosity could be imposed from measurements of the optical thickness of the disc lines. In irradiated discs, the vertical height goes like
Fig. 6. Doppler images of He II, Hα and Hβ of the X-ray transient GRO J0422+32 during a mini-outburst. Two models were used to fit the He II bright-spot with most likely the one that shows the gas stream passing through the bright-spot (the latter one has a phase offset and arbitrary parameters of $K_c = 375$ km s$^{-1}$ and $K_x = 75$ km s$^{-1}$; Harlaftis et al. [22] estimate $K_c = 372$ km s$^{-1}$ and $K_x = 43$ km s$^{-1}$). Reproduction from [2].

$H/R \sim (R^{-1/8} - R^{-2/7})$ which results in a concave disc at large distances from the compact object rather than a dependence like $H/R \sim R^{-1/8}$ in a viscously-heated disc. Analysis of existing X-ray and UV light curves of X 1822-371 (Fig. 9) requires a $H/R$ ratio for the disc that is rather large ($\sim 0.2$; [46]). The question that arises is how one can utilize the vertically-extended accretion discs in order to derive constraints of the accretion disc properties. One (new) way is to observe simultaneous optical and X-ray light curves and analyse them using echo mapping. The analysis should reveal X-ray reprocessing regions in the disc, as in the case of GRO J1655-40 ([30] and O’Brien in this Volume). In principle, these regions should eventually constrain the vertical structure with azimuth. The other way is to infer the outer disc thickness from the X-ray shadow cast on the companion star. The 1.24 seconds pulsar Her X-1 irradiates the accretion disc around the neutron star and gives rise to a precessing and warped accretion disc. The shadow of the accretion disc onto the inner face of the companion star
Fig. 7. The Hα Doppler image (top-right panel) of the accretion disc surrounding the black hole GS 2000+25 (bottom-right panel for Nova Oph 1977), as reconstructed from 13 Keck-I/LRIS spectra which are also presented (top-left panel; bottom-left panel for the 12 spectra of Nova Oph 1977). By projecting the image in a particular direction, one obtains the Hα emission-line profile as a function of velocity; for example, projecting toward the top results in the profile at orbital phase 0.0, which has a blueshifted peak. The path in velocity coordinates of gas streaming from the dwarf K5 secondary star is illustrated. The GS 2000+25 Doppler map shows a bright spot, at the upper left quadrant, which results from collision of the gas stream with the accretion disc around the black hole. The Nova Oph 1977 map also shows a trace of an “S”-wave component which, however, is not resolved with clarity. The image was reconstructed by applying Doppler tomography, a maximum entropy technique, to the phase-resolved spectra, as described in [19,20].

provides a diagnostic of the vertical structure of the disc (see Fig. 8; also see [24]).

Another way is to extend the traditional eclipse mapping technique (see Baptista, this Volume) in the steps of Rutten [52] in order to fit the full orbital light curve of a prototype vertically-extended disc. Indeed, Billington et al. [1] explained the UV dips seen in the light curves of OY Car during superoutburst as outer rim structure where UV light is reprocessed into optical, using the
Due to the large twist gradient in the accretion disc, the disc shadow does not display great variability over the orbital cycle [48,56].

The reconstructed rim structure dependence with binary phase is presented in the following figure (Fig. 11). The rim arises at the outer disc, and in particular from radii larger than 0.55 $R_{L1}$. This is reflected in Fig. 12 where the rim at 0.5 $R_{L1}$ has a different structure than the other outer rims. This is because the rim structure is too far inside the disc and this forces the re-distribution of the flux to an artificially asymmetric flux map. A map which is not consistent with the
observed axisymmetric discs in the UV. The variation of the mean rim height with azimuth in Fig. 11 matches the wavelength dependence of the absorption coefficient of a hot disc atmosphere of 10,000 K (except for the shorter wavelengths where the line emission is not dominated anymore by the disc but by a wind). The success of this model in explaining the UV dips which appear simultaneous to the superhump maximum during superoutburst of OY Car (outer disc structure where UV light is reprocessed into the optical) points now to a revision of the technique and application to the complex light curves of the prototype of vertically-extended discs, X 1822-371, as the next step.
Fig. 9. The “dipping” X-ray source X 1822-371 is the prototype X-ray binary for large vertical structure, as implicated from the X-ray light curve (X-ray “dips” at binary phase 0.2 and 0.8 and eclipse). Simultaneous fits of a disc model to X-ray, UV and optical light curves. The UV-HST data have been separated into three bands. The contribution of each model component (companion star, disc, outer and inner disc wall) to each curve is shown separately [46].
Fig. 10. The model for fitting the UV dips in the superoutburst light curves of OY Car is triggering structure in the outer disc which evolves with time on a dynamical timescale. The areas of the disc surface obscured by the rim and the secondary star are illustrated. The rim rotates in the binary frame and each rim element starts to flare up at the same position relative to the secondary star. The centre of the disc is eclipsed by the secondary star at phase 0.0 and by the rim between phase 0.05 and 0.15 causing the UV dip [1].
Fig. 11. The average rim height as a function of wavelength. The lower dashed line and the right-hand scale show the theoretical opacity of an accretion disc atmosphere at 10,000 K for the same wavelength band.

Fig. 12. The reconstructed rims at radii 0.6 $R_{L1}$, 0.7 $R_{L1}$, and 0.8 $R_{L1}$. The rim at 0.5 $R_{L1}$ is not well reconstructed as is evidenced by the different shape of the rim at this radius. The discrepancy on the left side of the curves is due to non-disc line emission.
4 The compact object

The compact object hidden in the luminous X-ray binary can be inferred by using various techniques (except for the classical radial velocity study of the wings of the emission lines [14]). The most interesting are based on the observed coherent pulses which must arise either from the surface of the compact object or from the coupling region between the accretion disc and the magnetosphere. Indeed, the UV continuum double pulse profile observed at the 33-sec spinning period of the compact object in the cataclysmic variable AE Aqr was successfully modeled as the accreting spots on the surface of the compact object (Fig. 13 [10]; but see also work by [6] who mapped the accreting regions onto the magnetic white dwarf of ST LMi). This is also the system where the magnetic propeller model has found substantial support from emission line observations (see Wynn, this Volume). According to the magnetic propeller model, the compact object rotates so fast that the gas cannot accrete on it but rather is propelled away. This concept, first proposed for neutron star X-ray binaries in the 70’s [32], has recently returned as a potential model for neutron star X-ray binaries (Hynes et al., this Volume), after it found sound support in the AE Aqr case.
Fig. 13. Maximum entropy maps of the white dwarf surface brightness distribution reconstructed from the observed UV pulse profile showing the emission spots on the surface of the rapidly rotating white dwarf at an inclination of 60°, limb darkening coefficient of one and background light of zero [10].
**Fig. 14.** The He II Doppler map of Her X-1 showing a spot of emission close to the neutron star at velocities associated to the gas stream. The parameters used were \( q = 1.67 \) (mass of donor/accretor) and \( M = 1.3 \) for the neutron star [47].
Perhaps, the magnetic propeller model is the likely interpretation of the He II Doppler map of Her X-1 where a low-velocity emission spot close to the neutron star is revealed (Fig. 14). Alternatively, the 1.24 sec searchlight beam from the neutron star illuminates the truncated inner disc. Gas from the inner edge of the disc is then funneled along the magnetic field lines onto the poles of the neutron star (for a review see [42] and references therein). In this case, there is current consensus that the disc feeds gas to the compact object through an ‘accretion curtain’ model [13,49] which produces a dipole pattern in both emission and absorption as the searchlight beam from each pole passes through the accretion curtain to the line of sight [22]. For example, the double-pulse He II emission profile coming from the 545-sec spinning compact object in the intermediate polar RX J0558+53 is mapped as such a dipole pattern in both emission and absorption centred on the white dwarf (Fig. 15).

The illuminating effects of the compact object’s beams on the surrounding supersonic gas can provide insight in the inner disc of X-ray binaries through periodogram analysis of the line profiles. For example, harmonics of the beat frequency between the \( \omega \) spin frequency and the \( \Omega \) orbital frequency as well as different combinations of these frequencies are then suggestive of specific illuminating patterns. For example, a simple, disc-fed emission has most power in the \( 2\omega \) frequency. Such a periodogram analysis of power spectra of line profiles against frequency and velocity is shown in Fig. 16 where prevalence of the \( 2(\omega - \Omega) \) and \( 2\omega \) frequencies indicate both disc- and stream-fed emission from two diametrically-opposed poles with similar emission properties a truncated disc is implied in RX J0558+53 [22]. This analysis provides a powerful probing tool in the coupling region between the supersonic gas in the inner disc and the magnetosphere of the compact object and perhaps this will be undertaken soon for the He II line of Her X-1.
Fig. 15. The Doppler map of the double-pulse He II emission profile with spin period (545 seconds) of the intermediate polar RX J0558, as viewed from the compact object (0,0). Back projection of the He II pulsed emission profiles produces a quadrapole-like velocity distribution, consisting of the minima ('dark' shade) and the maxima ('bright' shade) of the two pulses. The spin phases where the above are more pronounced are also marked. The emission line pulse lags behind the continuum pulse by 0.12 spin cycles giving a powerful insight into the coupling region between the Kepler-orbiting gas and the magnetosphere [22].
Fig. 16. The Fourier periodogram per velocity bin in the continuum and the emission lines. See text. The spin frequency is only evident in Hβ whereas the first harmonic is dominant in all power spectra except that of Hα. An orbital side-band at 2(ω − Ω) is also clearly present.
5 Future prospects

Indirect imaging techniques, utilizing optical spectroscopy, can now probe X-ray binary physics with sufficient signal to noise ratio and start distinguishing accretion details comparable to those observed in the brighter cataclysmic variables. Moreover, the quality of X-ray observations is such now that applications in this domain is the next step forward. The behaviour of the hard X-rays with respect to the soft X-rays (time lags and spectra) can probe the size of the Compton scattering region and infer radial density profiles [28]. Image reconstruction of the hot electron plasma may result in defining better properties of the hot accretion disc and clarify its relation to advection dominated accretion flows. The spectral resolution of iron profiles has considerably increased with the advent of the ASCA satellite and has revealed in many interactive binary systems three peaks in the iron profile, namely thermal emission at 6.7 and 7.0 KeV, and fluorescent emission at 6.4 KeV [11]. Doppler tomography and echo tomography using X-ray iron line profiles and continuum, and even eclipse maps of the accretion disc from X-ray light curves [37], may become possible with the new X-ray satellites.

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