Echo Tomography of Sco X-1 using Bowen Fluorescence Lines

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Abstract. We present preliminary results of a simultaneous X-ray/optical campaign of the prototypical LMXB Sco X-1 at 1-10 Hz time resolution. Lightcurves of the high excitation Bowen/HeII emission lines were obtained through narrow interference filters with ULTRACAM, and these were cross-correlated with X-ray lightcurves. We find evidence for correlated variability, in particular when Sco X-1 enters the Flaring Branch. The Bowen/HeII lightcurves lag the X-ray lightcurves with a light travel time which is consistent with reprocessing in the companion star.

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INTRODUCTION:IRRADIATION IN LMXBS

Optical emission in persistent low mass X-ray binaries (hereafter LMXBs) is triggered by reprocessing of the powerful, almost Eddington limited, X-ray luminosity ($L_{\rm x} \simeq 10^{38}$ erg s^{-1}) in the gas around the compact object. This is supported by independent arguments such as (i) the statistical distribution of dereddened $(U-B)$, $(B-V)$ colours (or $F_\nu \sim$ const., see [20]) which can be accounted for by redistribution of high energies into UV+optical through irradiation models (e.g. [21]); (ii) the detection of optical counterparts of Type I X-ray bursts, with delay times consistent with binary separations (e.g. [7]); (iii) the presence of the broad emission feature at $\lambda\lambda$4640-50 associated with a blend of CIII/NIII/OII powered by X-ray photoionization and Bowen fluorescence emission (hence refered to as *the Bowen blend*; [12], [17]); (iv) suppression of outburst cycles caused by irradiation-induced heating of the outer disc [19], [11].

The accretion disc subtends the largest solid angle as viewed by the X-ray source, and is therefore responsible for the majority of the irradiation component. The spectroscopic features of the weak companion star, on the other hand, are completely swamped by the disc's reprocessed light, with the exception of a few long-period LMXBs with evolved companions such as Cyg X-2 ([1]). Therefore, dynamical studies have classically been restricted to the analysis of X-ray transients during quiescence (e.g. see [4]).

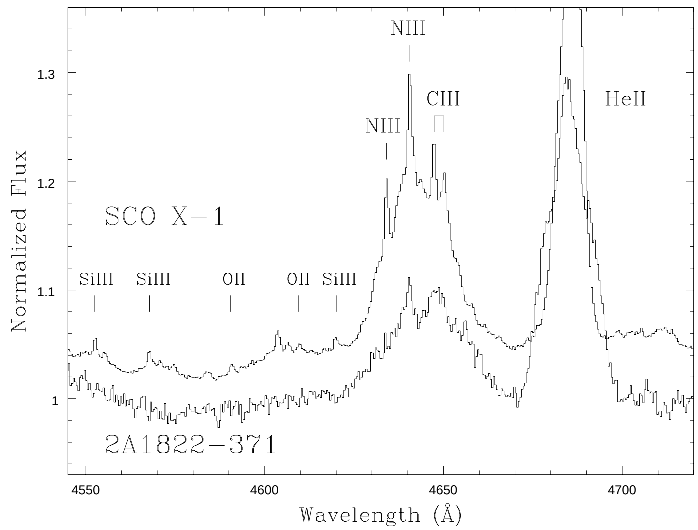

FIGURE 1. Summed spectra of Sco X-1 (top) and 2A1822-371 (bottom) in the rest frame of the companion star. Adapted from [18] and [2].

Fluorescence Emission from Donor Stars

However, this situation has changed recently thanks to the discovery of narrow emission components arising from the donor star in Sco X-1 [18]. High resolution spectroscopy, obtained with ISIS at the WHT, revealed many narrow high-excitation emission lines, the most prominent associated with NIII $\lambda\lambda$4634-41 and CIII $\lambda\lambda$4647-50 at the core of the broad Bowen blend (Fig. 1). The NIII lines are powered by fluorescence resonance through cascade recombination which initially requires seed photons of HeII Lyα. These narrow components are not resolved (i.e. their FWHM is the instrumental resolution) and they move in antiphase with respect to the wings of the HeII λ4686 line, which approximately trace the motion of the compact star. Both properties (narrowness and phase offset) imply that these components originate in the irradiated face of the donor star. This work represents the first detection of the companion star in Sco X-1 and opens a new window for extracting dynamical information and thereby deriving mass functions in a population of $\sim$ 20 LMXBs with established optical counterparts.

We now know that this property is not peculiar to Sco X-1 but is a feature of persistent LMXBs, as demonstrated by the following examples:

(i) Radial velocities of narrow Bowen lines in the black hole candidate GX339-4, detected during the 2002 outburst, led to a mass function in excess of 5.8 $M_{\odot}$ and hence provided the first dynamical proof for a black hole [10].

(ii) Velocity information from the Bowen NIII λ4640 line in the eclipsing ADC (*accretion disc corona*) pulsar 2A 1822-371, established a lower limit to the neutron star's mass of 1.14 $M_{\odot}$. Moreover, the radial velocity curve of the NIII emission is perfectly consistent with the donor's phase, as expected from the pulse time delay of the 0.59s spin period of the neutron star [2].

(iii) Sharp NIII λ4640 Bowen emission has been detected in 4U 1636-536, 4U 1735-444 and the transient millisecond pulsar XTE J1814-338, which lead to donor velocity semi-amplitudes in the range 200-300 km s^{-1} [3].

Echo-Tomography

One of the most exciting prospects for this new technique is the possibility to perform echo-tomography using the Bowen lines. Echo-tomography is an indirect imaging technique which uses time delays between X-ray and UV/optical lightcurves as a function of orbital phase in order to map the reprocessing sites in a binary [16]. The optical lightcurve can be simulated by the convolution of the (source) X-ray lightcurve with a transfer function which encodes information about the geometry and visibility of the reprocessing regions. The transfer function quantifies the binary response to the irradiated flux as a function of the lag time and it has two main components, the accretion disc and the donor star. The latter is strongly dependent on the inclination angle, binary separation and mass ratio and, therefore, can be used to set tight contraints on these fundamental parameters. Successful echo-tomography experiments have been performed on several X-ray active LMXBs using X-ray and broad-band UV/optical lightcurves. The results indicate that the reprocessing flux is mostly dominated by the large contribution of the accretion disc (e.g. [9], [15], [8]).

Exploiting emission-line reprocessing rather than broad-band photometry has two potential benefits: a) it amplifies the response of the donor's contribution by suppressing most of the background continuum light (which is associated with the disc); b) since the reprocessing time in the lines is instantaneous, the response is sharper (i.e. only smeared by geometry) and also the transfer function is easier to compute (see [13]). Therefore, we decided to undertake a simultaneous X-ray/optical campaign on the prototypical LMXB Sco X-1 with the aim of performing echo-tomography so as to search for the reprocessed signatures of the donor using Bowen/HeII lines. As a first step, here we present our preliminary cross-correlation analysis which provides evidence for delayed echoes consistent with reprocessing in the companion star.

OBSERVATIONS

Simultaneous X-ray and optical data of Sco X-1 were obtained on the nights of 17-19 May 2004. The full 18.9 hr orbital period was covered in 12 snapshots, yielding 20.1 ks of X-ray data with the RXTE PCA. Only 2 PCA detectors (2 and 5) were used and the pointing offset was set to $0^{\circ}.71$ due to the brightness of Sco X-1. The data were analysed using the FTOOLS software and the times corrected to the solar barycenter. The STANDARD-2 mode data, with a time resolution of 16s, were used to produce a colour-colour diagram which showed that Sco X-1 was in the Normal Branch on 17 and 19 May and in the Flaring Branch on 18 May. The STANDARD-1 mode, with a time resolution of 0.125s, was used for the variability analysis.

The optical data were obtained with ULTRACAM on the 4.2m WHT at La Palma. ULTRACAM is a triple-beam CCD camera which uses two dichroics to split the light

TABLE 1. Observing log

Date	Exp. time (secs)	Seeing	Orbital Phases*	Number of XTE windows	X-ray State
17 May 2004	0.1	< 1"	0.07-0.35	4	Normal Branch
18 May 2004	0.25-1	1"-5"	0.34-0.73	5	Flaring Branch
19 May 2004	0.3	1"-2"	0.55-0.95	5	Normal Branch

* Computed using ephemeris from [18]

into 3 spectral ranges: Blue (<λ3900), Green($\lambda\lambda$3900-5400) and Red (>λ5400). It uses frame transfer 1024x1024 Marconi CCDs which are continuously read out, and are capable of time resolution down to 500 Hz by reading only small selected windows (see [5] for details). ULTRACAM is equipped with a standard set of *ugriz* Sloan filters. However, since we want to amplify the reprocessed signal from the companion, we decided to use two narrow (FWHM =100 Å) interference filters in the Green and Red channels, centered at $\lambda_{\rm eff}$=4660Å and $\lambda_{\rm eff}$=6000Å. These will block out most of the continuum light and allow us to integrate two selected spectral regions: the Bowen/HeII blend and a featureless continuum, from which continuum-subtracted lightcurves of the high excitation lines can be derived. The images were reduced in the standard way with bias subtraction and flatfielding. Star counts were extracted using an optimal extraction algorithm [14] and lightcurves were obtained relative to a comparison star which is 96 arcsecs NW of Sco X-1. Lightcurves of the Bowen/HeII lines were computed by subtracting the Red (continuum) and Green channel lightcurves. The seeing was 1-1.5 arcsecs most of the time, except for the first two RXTE windows of the second night when it rose to over 3 arcsecs. Optical observations during the first 3 RXTE visits on 19 May were not possible because of clouds. The exposure time was initially set to 0.1s but was increased to 0.25s, because of weather conditions. Integrations of 1s were used for the first window on 18 May, when the seeing was worst. An observing log is presented in Table 1.

RESULTS

Figure 2 presents the X-ray and Bowen/HeII lightcurves corresponding to the nights of 17 and 18 May. Sco X-1 was at the bottom of the Normal Branch during most of the first night but moved towards the Flaring Branch in the last RXTE visit, showing a 50 percent increase in flux. The amplitude of the X-ray variability is less than 1% for the first three windows and no clear correlation with Bowen/HeII is evident on long timescales. On 18 May Sco X-1 was in the Flaring Branch and exhibited large amplitude variability, with large flares similar to that seen during the third RXTE visit. The left panel in Fig. 3 presents a 10 min segment of the third RXTE window, with each tickmark corresponding to 43s. We note significant X-ray variability, at the 10 percent level, and some correlated structures can be identified in the Bowen/HeII lightcurve towards the end of this interval. This window is centered at orbital phase 0.53 i.e. near the superior conjunction of the donor star, when the irradiated face of the donor presents the largest visibility and the

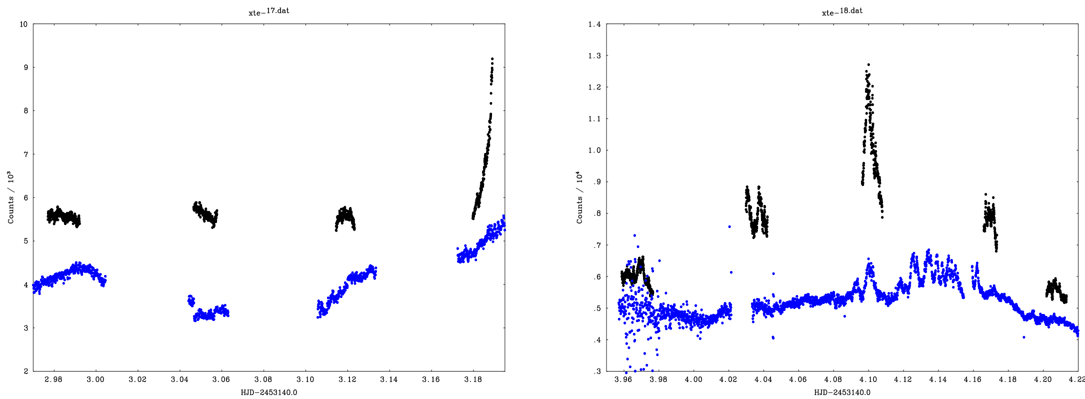

FIGURE 2. X-ray and Bowen/HeII lightcurves for the nights of 17 May (left panel) and 18 May (right panel). The top lightcurves correspond to the RXTE data and have been averaged in 4s bins. The bottom lightcurves represent the (continuum-subtracted) Bowen/HeII emission lightcurves and have been averaged in 8s bins. The Bowen/HeII counts are relative to the comparison star and have been multiplied by a factor 23500 for display clarity.

light-travel delay is expected to be at a maximum (around 12s for the binary parameters in [18]). We have calculated cross-correlation functions [6] for several time intervals within this window, after subtracting a low-order polynomial fit to the lightcurves in order to remove low-frequency variations. The right panel in Fig. 3 presents one of the cross-correlation functions, and shows a clear peak centered at a lag of $\sim$ 10-15s. This is in good agreement with the expected delay time for reprocessing in the companion star at this particular orbital phase. We have also detected correlated variability in other windows and we expect to be able to combine this information in order to set constraints on the binary parameters of Sco X-1.

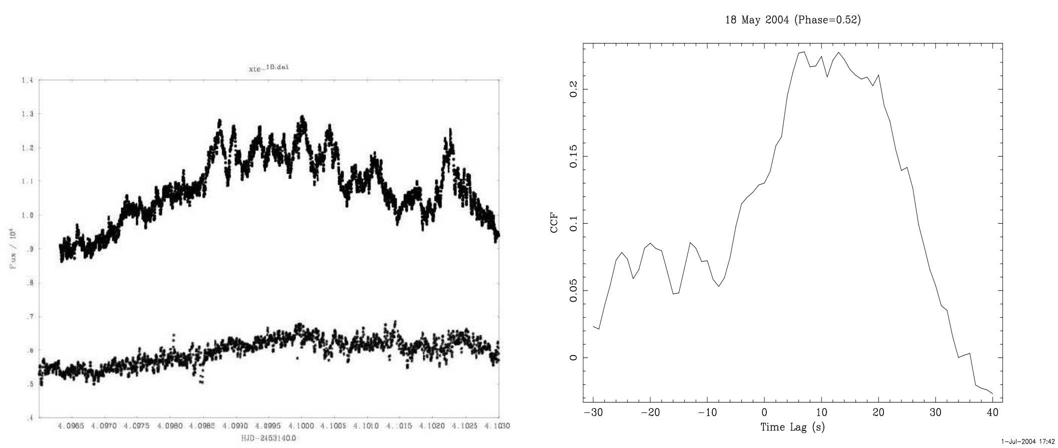

FIGURE 3. Left panel: 10 min detail from the third RXTE visit during 18 May. Top lightcurve represents the RXTE data whereas the bottom lightcurve is the Bowen/HeII data. Right panel: Cross-correlation function of the two lightcurves for the last 3 min interval.

SUMMARY

We have obtained simultaneous X-ray/optical photometry of Sco X-1 at 1-10 Hz time resolution using RXTE and WHT+ULTRACAM. The use of narrow interference filters in ULTRACAM has provided us with lightcurves of the Bowen blend + HeII λ4686 emission lines. Our preliminary analysis shows evidence for correlated variability, with the Bowen/HeII lightcurves lagging the X-rays. The observed time delays are consistent with reprocessing in the companion star and the correlations are most evident when Sco X-1 is in the Flaring Branch.

Future work requires a systematic search for correlated variability at different orbital phases and as a function of X-ray energy, and to use the information in order to constrain the binary parameters (mainly inclination, binary separation and mass ratio) using appropriate synthetic transfer functions [13].

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