Fundamental Parameters of Low Mass X-ray Binaries II: X-Ray Persistent Systems

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Abstract

The determination of fundamental parameters in X-ray luminous (persistent) X-ray binaries has been classically hampered by the large optical luminosity of the accretion disc. New methods, based on irradiation of the donor star and burst oscillations, provide the opportunity to derive dynamical information and mass constraints in many persistent systems for the first time. These techniques are here reviewed and the latest results presented.

Key words: binaries: close - X-rays: binaries,- stars: neutron

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1 Introduction

Sco X-1 was the first Galactic X-ray source discovered by X-ray satellites and its powerful X-ray luminosity explained through mass accretion into a degenerate star [25]. Sco X-1 became the prototype of a new class of objects, the low mass X-ray binaries (hereafter LMXBs), where late-type, Roche lobe-filling stars transfer matter onto compact objects [35]. Their orbital periods are very compact, clustering at 3-6hr, and they mostly contain accreting neutron stars [14]. This is demonstrated by the exhibition of Type I X-ray bursts ([27]) and, in a few exceptional cases (X1822-371 [11], X1626-67 [18]) X-ray pulses. There are about 150 X-ray luminous or 'persistent' LMXBs in the Galaxy, 30 of which with confirmed optical counterparts [14]. For comparison, it is estimated that the Galaxy contains a population of \( \sim 10^3 \) 'transient' LMXBs which only show X-ray activity sporadically and mostly harbour black holes (see accompanying review by Charles & Casares).

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The reason for the different luminosity behaviour stems from the interplay between the mass transfer rate from the donor star $\dot{M}_2$ and irradiation effects. $\dot{M}_2$ determines the temperature structure of the accretion flow and, if it is somewhere below a critical temperature, $T_{\text{crit}}$ (that of H ionisation), then instability cycles (outbursts) can be triggered (see [13]). However, in persistent LMXBs, irradiation can keep the outer disc hotter than $T_{\text{crit}}$ (even for low $\dot{M}_2 \leq 10^{-9} \, M_\odot \, \text{yr}^{-1}$), so that outburst cycles are suppressed and discs appear persistently bright ([36], [12]). They display a large $L_X/L_{\text{opt}}$ and the optical and X-ray fluxes are correlated, a strong indication that optical emission is caused by reprocessing of higher energy photons by material in the vicinity of the X-ray source. Further evidence for X-ray reprocessing includes:

- Statistical properties: dereddened optical colours follow the distribution $(B-V)_0 = -0.09 \pm 0.17$, $(U-B)_0 = -0.97 \pm 0.17$ [32]. This is consistent with $F_\nu \sim$ constant as expected for the reprocessing of high energy photons.
- Correlated X-ray/optical Type I bursts: the optical lags by a few seconds, consistent with light travel times within the binary. Optical profiles are smeared versions of the X-ray profiles, indicating an extended reprocessing site (e.g. [31]).
- Presence of high excitation lines: e.g. HeII $\lambda 4686$, CIII/NIII $\lambda\lambda 4640-50$, and their flux is well correlated with $L_X$. Bowen fluorescence was proposed to explain the enhanced NIII emission [17], a mechanism subsequently confirmed by the detection of OIII cascades in Her X-1 [15] and Sco X-1 [30] (Fig. 1).

However, X-ray irradiation has systematically plagued attempts to determine system parameters in persistent LMXBs. These rely on dynamical information from the companion star, which is typically $> 10^3$ times fainter than the X-ray heated accretion disc at optical-IR wavelengths. Fortunately, there are...
methods which can exploit the effects of irradiation and X-ray variability. Here we provide an overview of these recent advances in the determination of fundamental parameters of persistent LMXBS.

2 Optical light curves

Soon after the discovery of the first optical counterparts it was clear that constraining binary parameters in X-ray bright LMXBs was a difficult challenge [35]. Even the determination of the most fundamental binary parameter, $P_{orb}$, proved elusive due to the lack of obvious photometric variability. This led Milgrom [19] to propose a scenario where the companion star was effectively shadowed from the central X-ray source by a flared accretion disc. The absence of eclipsing systems was hence a pure selection effect. Since then, the gain in X-ray sensitivity and deeper surveys has presented several examples of eclipsing LMXBs and others with regular optical/X-ray modulations and dips which indicate the binary periods [14].

Optical lightcurves are quasi-sinusoidal with superposed erratic variations and flickering, probably in response to variable X-ray illumination. It is widely assumed that optical maxima are associated with the irradiated inner face of the companion i.e. orbital phase $\phi = 0$. This is supported by the relative phasing of X-ray eclipses ($\phi = 0$) and dips ($\phi = 0.8$) (e.g. [20]). Interestingly, the amplitude $A$ seems to be correlated with inclination [33], from which LMXBs can be placed into three broad categories: (i) eclipsing, with $A \sim 0.5$-1.5 mag and $i \geq 80^\circ$ (e.g. X1822-371, X0748-636, X2129+47) (ii) dippers, with $A \sim$0.5 mag and $i \simeq 70-80^\circ$ (e.g. X1254-690, X1755-338, X1916-05) and (iii) low $i$, with $A \leq$0.5 mag and $i \leq 70^\circ$ (e.g. X1636-536, X1735-444, Sco X-1).

Tighter constraints on $i$ can be set by detailed modelling of optical/X-ray eclipses and light curves of accretion disc coronae (ADC) sources [37]. In particular, simultaneous fits to EXOSAT X-ray/optical light curves in X1822-371 have led to the most accurate determination of the disc geometry and $i$ ($83^\circ \pm 2^\circ$) in an LMXB [8], [7]. The model includes irradiation, shadowing and obscuration by the disc, donor star, bulge and ADC structures (see Fig. 2).

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1 However, lightcurves of the transient LMXB XTE J2123-058, obtained throughout the outburst cycle, show a factor of 2 increase in optical amplitude when $L_X$ drops by one order of magnitude (see [38], [23]). Therefore, a straight correlation between $A$ and $i$ should be treated with caution.
3 Dynamical Information

With the exception of a few long period \((P > 1 \text{ d})\) systems with evolved donors (e.g. Cyg X-2 [3], X0921-630 [24]), spectroscopic features of companion stars in persistent LMXBs are totally veiled by the accretion disc continuum. Attempts to derive dynamical information of the compact star using emission lines (mainly Balmer or HeII \(\lambda 4686\)) have proven unreliable because the emission lines are very broad and show a complex, variable, multi-component structure. The bulk of the emission tends to be dominated by the disc bulge with superior conjunction at orbital phase \(\sim 0.75^2\) e.g. X1636-536, X1735-444 [1].

3.1 Fluorescent emission from the companion

New prospects for dynamical studies have been opened by the discovery of high-excitation emission lines arising from the donor star in Sco X-1 [26]. The most prominent are in the core of the Bowen blend, namely the triplets NIII \(\lambda 4634-40\) and CIII \(\lambda 4647-50\). In particular, the NIII lines are powered by fluorescence resonance which requires seed photons of HeII Ly-\(\alpha\). These narrow components move in phase with each other and are not resolved (i.e. their FWHM is the instrumental resolution, 50 km s\(^{-1}\)), an indication that the reprocessing region is very localized (Fig. 3). The extreme narrowness rules out the accretion flow or the hot spot and points to the companion star as the reprocessing site.

The radial velocity curve of the Bowen lines (Fig.3) is in antiphase with the HeII \(\lambda 4686\) wings, which approximately trace the motion of the compact star. Furthermore, they are also in phase with the maximum of the photometric

\(^2\) As determined by photometric ephemerides from eclipses or lightcurve minima.
light curve, ascribed to the irradiated face of the donor star [2]. This work represents the first detection of the companion star in Sco X-1 and has opened a new avenue for dynamical studies of luminous LMXBs.

We currently know that fluorescence is not peculiar to Sco X-1, but is a general signature of active LMXBs. This is exemplified by recent work on X1822-371, the archetypal eclipsing ADC which also contains a 0.59s pulsar [11]. Both \(i\) and the pulsar orbit are extremely well constrained and hence only the radial velocity curve of the companion star is needed for a full determination of the system parameters. The faintness of X1822-371, coupled with the high spectral resolution \((\leq 70 \text{ km s}^{-1})\) required to resolve the Bowen lines, prevents detection in individual spectra. However, exploiting Doppler Tomography [16] we can combine all the information contained in individually phase-resolved spectra to reconstruct the emissivity distribution. Fig. 4 shows the Doppler maps of HeII \(\lambda 4686\) and NIII \(\lambda 4640\) in velocity space. Unlike HeII \(\lambda 4686\) (which shows the classic accretion disc ring) the NIII map displays a compact spot located at the expected velocity and phasing of the donor star, as predicted from the pulsar ephemeris. The centroid of the spot lies at 300 km s\(^{-1}\) and establishes a lower limit to the velocity of the companion because it arises from the irradiated inner face. In order to derive the true velocity (and then accurate masses) one needs to model the displacement between the reprocessing site and the donor’s center of mass as a function of the mass ratio \(q\). The so-called \(K\)-correction depends on details of reprocessing physics and irradiation geometry, such as shielding effects by the disc (see [21]).

Follow-up campaigns, using 8m-class telescopes (e.g. VLT), has enabled us to extend this analysis to fainter LMXBs. This has led to the first detection of the donors in X1636-536, X1735-444 and GX 9+9 and the determination of their orbital velocities, which lie in the range 200-300 km s\(^{-1}\) ([4], [5]). In addition, this technique has been applied to transient LMXBs in outburst,
such as the millisecond pulsar XTE J1814-338, Aql X-1 and the black hole candidate GX339-4 [9]. In the latter case, the observations provided the first dynamical proof that it is a black hole.

3.2 Burst Oscillations

Despite LMXBs having long been considered the progenitors of millisecond pulsars, such pulsations have escaped detection until recently. This changed thanks to RXTE with the discovery of: (i) persistent pulses in 5 transient LMXBs with $P_{\text{spin}}$ in the range 185-435 Hz, and (ii) nearly coherent oscillations during X-ray bursts in 13 luminous LMXBs. In SAX J1808-3658 [6] and XTE J1814-338 [29] both burst oscillations and persistent pulses were detected and with identical frequencies, confirming that burst oscillations are indeed modulated with the neutron star spin. Furthermore, a smooth frequency drift in the oscillation could be observed during a superburst in X1636-536, caused by the doppler motion of the neutron star [28]. Burst oscillations can therefore be used to trace the neutron star orbit in persistent LMXBs and, in combination with Bowen fluorescence, these luminous LMXBs can become double-lined spectroscopic binaries.

4 Echo-tomography

Echo Tomography is a powerful technique which employs time delay between X-ray and UV/optical variability to map the reprocessing sites in a binary [22]. The optical lightcurve results from the convolution of the X-ray lightcurve with a transfer function representing the binary response to the illuminating flux. The transfer function contains a phase-dependent component, associ-
ated with the donor, which encodes information on the most fundamental parameters, namely $i$, $a$ and $q$. Successful Echo-tomography experiments have been performed in several X-ray active LMXBs using X-ray and broad-band UV/optical lightcurves. However, the results indicate that the reprocessing flux is mostly dominated by the accretion disc with no orbital phase dependency (e.g. [34], [10]). 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 (dominated by the disc); b) since the emission line reprocessing time is instantaneous, the response is sharper (i.e. only smeared by geometry). Recent results on Sco X-1, using narrow-band filters centered on the Bowen blend $+ \text{HeII} \lambda 4686$ region, simultaneously with RXTE, have shown evidence for delayed echoes associated with the donor (see Muñoz-Darias et al., these proceedings).

5 Conclusions

The study of Bowen fluorescence in X-ray active LMXBs is producing significant progress in the determination of fundamental system parameters. This is possible because of: i) dynamical information obtained by detecting the donors through high-resolution spectroscopy of the Bowen blend; ii) echo-mapping reprocessing sites through simultaneous Bowen-line/X-ray lightcurves. These techniques, together with results from burst oscillations, will likely provide the first accurate neutron star masses in luminous LMXBs in the near future. High-speed and high-resolution instruments in new generation large telescopes (such as OSIRIS at GTC and PFIS at SALT) will play a crucial role in this goal.

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