Doppler Tomography of XTE J2123–058 and Other Neutron Star LMXBs

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Abstract. We describe Doppler tomography obtained in the 1998 outburst of the neutron star low mass X-ray binary (LMXB) XTE J2123–058. This analysis, and other aspects of phase-resolved spectroscopy, indicate similarities to SW Sex systems, except that anomalous emission kinematics are seen in He ii, whilst phase 0.5 absorption is confined to H α. This separation of these effects may provide tighter constraints on models in the LMXB case than is possible for SW Sex systems. We will compare results for other LMXBs which appear to show similar kinematics and discuss how models for the SW Sex phenomenon can be adapted to these systems. Finally we will summarise the limited Doppler tomography performed on the class of neutron star LMXBs as a whole, and discuss whether any common patterns can yet be identified.

1 Introduction

Low mass X-ray binaries (LMXBs) contain a late-type ‘normal’ star of ≤ 1 M⊙ accreting via Roche lobe overflow onto a black hole or neutron star. Black hole systems are mostly only active during transient outbursts, making them difficult targets for techniques requiring phase-resolved spectroscopy such as Doppler tomography. Many neutron star systems are persistently active, but with a few exceptions are sufficiently faint that they are still difficult targets. Amongst the bright exceptions, only Her X-1 has seen extensive application of Doppler tomography.[18,15] This is a very unusual system with a companion star more massive than the neutron star, and not strictly an LMXB at all. We will focus here on the more limited data available on ‘typical’ LMXBs, i.e. those in which the companion star is a late-type dwarf. We begin by summarising our own work on a transient neutron star system, XTE J2123–058 and then compare this with other LMXBs.

2 XTE J2123–058

The transient LMXB XTE J2123–058 was discovered by RXTE on 1998 June 27 [13] and promptly identified with a 17th magnitude blue star with an optical spectrum typical of transients in outburst [2]. Type-I X-ray bursts [14] indicated
Fig. 1. Trailed spectrograms for XTE J2123–058. The left hand panel shows C\textsc{iii}/N\textsc{iii} and He\textsc{ii}; the right H\textsc{a}. In the latter, the transient absorption can be seen as the white region.

the compact object to be a neutron star. A pronounced photometric modulation \cite{2} on the orbital period of 6.0 hr \cite{24,12,10} is due to the changing aspect of the X-ray heated companion indicating a high inclination system. During the outburst we obtained extensive photometry \cite{27} and phase-resolved spectroscopy \cite{11}; this section will focus on the latter.

2.1 The Available Data

We observed XTE J2123–058 using the ISIS dual-beam spectrograph on the 4.2-m William Herschel Telescope (WHT) on the nights of 1998 July 18–20. Full details and discussion of the data analysis are given in \cite{11}. Phase resolved data suitable for Doppler tomography were obtained on July 19–20 (approximately one binary orbit each night) with an unvignetted wavelength range of $\sim$4000–6500 Å and spectral resolution 2.9–4.1 Å.

2.2 Doppler Tomography

The emission lines show significant changes over an orbital cycle (Fig. 1). He\textsc{ii} 4686 Å shows complex changes in line position and structure, with two S-waves apparently interweaving. The light curve reveals a strong peak near phase 0.75 and a weaker one near 0.25.

We have used Doppler tomography \cite{14} to identify He\textsc{ii} 4686 Å emission sites in velocity space (Fig. 2a). One of the fundamental assumptions of Doppler tomography, that we always see all of the line flux at some velocity, is clearly violated, however, as the integrated line flux is not constant. We attempt to account for this by normalising the line profiles. Without normalisation the structure of
The derived tomogram is very similar, so our results do not appear to be sensitive to this difficulty. A better solution would be to use the modulation mapping method [17].

In order to interpret the tomogram quantitatively, we require estimates of system parameters. These were derived from results of fits to outburst light curves [27]. The parameters we assume are $P_{\text{orb}} = 0.24821$ day, $i = 73^\circ$, $M_1 = 1.4 \, M_\odot$, $M_2 = 0.3 \, M_\odot$, $R_{\text{disc}} = 0.75 \, R_{\text{L}}$; see [11] for discussion.

Fig. 2. Doppler tomography of XTE J2123–058. a) From top to bottom, the actual data, the tomogram and the reconstructed data. In the centre panel, the solid line is the ballistic stream trajectory, the dashed line the Keplerian velocity at the stream position and the large circle is the Keplerian velocity at the disc edge. b) Comparison between magnetic propeller trajectories and the tomogram. c) Spatial plot corresponding to (b). Points in region A produce emission with kinematics corresponding to the white hatched region in the tomogram. Points in region B will produce absorption with the phasing and velocities observed in Hα.
The dominant emission site (corresponding to the main S-wave) appears on the opposite side of the neutron star from the companion. For any system parameters, it is inconsistent with the heated face of the companion and the stream/disc impact point. There is a fainter spot near the L\textsubscript{1} point, corresponding to the fainter S-wave, which is possibly associated with the accretion stream. These spots in the tomogram may be joined, although this may be a smoothing artifact of the reconstruction. It is notable that nearly all the emission has a lower velocity than that of Keplerian material at the outer disc edge, and so if associated with the disc requires sub-Keplerian velocities.

### 2.3 A Neutron Star SW Sex System?

The phenomenon of emission concentrated in the lower-left hand quadrant of a Doppler tomogram at low velocities is not new; it is one of the distinguishing characteristics of the SW Sex class of cataclysmic variables\cite{22,9,8}. These are all novalike variables, typically seen at a relatively high inclination.

The tomograms are not the only similarity. SW Sex systems exhibit transient absorption lines which are strongest near phase 0.5 or slightly earlier and are moderately blue shifted. Transient absorption near phase 0.5 is seen in H\textalpha in XTE J2123–058 (Fig. 1). It begins slightly redshifted and moves to the blue, and can be clearly seen in a trailed spectrogram. Examination of the average spectrum for phases 0.35–0.55 confirms that this is real absorption below the continuum level.

### 3 Other Candidate SW Sex-like LMXBs

The only other short-period neutron star LMXB with published Doppler tomography is 2A 1822–371\cite{6,7}. This was observed in H\textalpha and exhibited disc emission enhanced towards the stream impact point. Similar behaviour is suggested by a radial velocity analysis of He\textsc{ii}\cite{3}. This is different to what we see in XTE J2123–058. Non-tomographic analysis of other short-period neutron star LMXBs in an active state, however, suggests a similar behaviour to that described for XTE J2123–058 as shown in Fig. 3 where we overplot the He\textsc{ii} radial velocity information for other systems on our He\textsc{ii} Doppler tomogram. 2A 1822–371 is clearly the odd one out, and the other systems (4U 2129+47\cite{21}, EXO 0748–676\cite{4}, 4U 1636–536\cite{1} and 4U 1735–444\cite{1}) all show emission centred in the lower or lower-left part of the tomogram.

### 4 SW Sex Models Applied to Neutron Star LMXBs

Various models have been proposed for the SW Sex phenomenon including bipolar winds, magnetic accretion and variations on a stream overflow theme. Current opinion favours the latter interpretation, with the stream either being accelerated out of the Roche lobe by a magnetic propeller, or re-impacting the disc. Both of these models are discussed in more detail below.
4.1 The magnetic propeller interpretation

It is possible to explain the behaviour of the He\textsuperscript{II} 4686 Å line in terms of the magnetic propeller model. The essence of this model is that in the presence of a rapidly rotating magnetic field, accreting diamagnetic material may be accelerated tangentially, leading to it being ejected from the system. The field might be anchored on the compact object, as in the prototype propeller AE Aqr \cite{26,5} or in the disc itself \cite{9}.

We adopt the parameterisation used by \cite{26} and construct a simple model of a propeller in XTE J2123–058. Full details are given in \cite{11}. We can readily find a trajectory which passes through the central emission on the tomogram. This is shown in Fig. 3b, together with two bracketing trajectories corresponding to more and less acceleration. For a plausible model, we also require an explanation for why one particular place on the trajectory is bright. Such an explanation is offered by \cite{9}: there is a point outside the binary at which trajectories intersect. At this point, faster moving blobs cross the path of slower blobs and enhanced emission might be expected. This can be seen in Fig. 3c. To facilitate a quantitative comparison of our data with the model, the region A in Fig. 3c encloses points with velocities consistent with the bright emission spot. These points are indeed located where the trajectories cross. Our data are therefore consistent with the emission mechanism suggested by \cite{9}. If the region in which accelerated blobs collide is optically thick in the line then emission is expected predominantly
from the inner edge of this region where fast moving blobs impact slow moving blobs. For the geometry we have considered, as can be seen in Fig. 3, this will result in emission predominantly towards the top of the figure. This corresponds to seeing maximum emission near phase 0.75, exactly as is observed in our data. Can we also explain the phase-dependent Balmer absorption? The region B in Fig. 3 encloses points which would absorb disc emission with the phasing and velocities observed in Hα. This region can be attributed to lower-velocity trajectories which fall back towards the disc; thus the transient absorption can be accommodated in this model.

In summary, a magnetic propeller model can account for both HeII emission kinematics and lightcurve and Hα transient absorption. This requires blobs to be ejected with a range of velocities; absorption is caused by low velocity blobs, perhaps because these account for most of the ejected mass. Emission is only seen from higher velocity blobs, which might be expected to exhibit more energetic collisions. The model has some difficulties, however, both for a field anchored on the compact object and for a disc-anchored field.

If the field is anchored on the compact object then it must rotate very fast, as spin periods of neutron stars are typically of order milliseconds. For such rapid rotation we must consider the light-cylinder, defined by the radius at which the magnetic field must rotate at the speed of light to remain synchronised with the compact object spin. Outside of this radius, $\sim 6 \times 10^{-5} R_{\text{disc}}$ for XTE J2123–058, the magnetic field will be unable to keep up and hence becomes wound up. This will make the propeller less effective, although it may still produce some acceleration (Wynn priv. comm., 2000). The disc-anchored propeller also has problems, in that it should very efficiently remove angular momentum from the disc (Wynn & King priv. comm., 1999), but this could perhaps be overcome if only a small fraction of stream material passes through the propeller. Finally, when a propeller coexists with a disc, there is the added difficulty in explaining how the accelerated material clears the disc rim. In the case of the disc-anchored propeller one can argue that field loops emerging from the disc could accelerate material upwards as well as out; for a propeller anchored on the neutron star some other explanation would be needed.

4.2 The stream overflow and disc re-impact interpretation

The most popular alternative explanation for the SW Sex phenomenon is the accretion stream overflow and re-impact model. This was originally suggested by [10]; for a recent exposition see [8]. This model has the advantage of being physically very plausible. Some stream overflow is implied by the observations of X-ray dips in some LMXBs, and overflowing material should re-impact in the inner disc if not supported in some way. To explain the observations, however, requires a number of additional elements.

In this model the overflowing stream can be thought of in two regions. The initial part of the stream produces the transient absorption when seen against the brighter background of the disc. The latter part, where the overflow re-impacts the disc, is seen in emission giving rise to the high velocity component. In the
Doppler Tomography of Neutron Star LMXBs

Table 1. Doppler tomography of neutron star LMXBs. Bowen refers to the C\text{III}/N\text{III} blend near 4640 Å. Cen X-4 was observed in quiescence; the others in an X-ray active state. Private communications are (a) M. Torres, 2000, (b) Steeghs & Casares, 2000.

| P\text{orb} (hr) | Companion | Disc | Stream/Hotspot | Other | Source |
|-----------------|-----------|------|----------------|-------|--------|
| 2A 1822–371     | 5.6       | H\text{I} | H\text{I} |       |        |
| XTE J2123–058   | 6.0       | H\text{I} | He\text{II}? | He\text{II} |        |
| Cen X-4         | 15        | H\text{I} | H\text{I}? |       | a      |
| AC211           | 17        |       | He\text{II}? | He\text{II}? | a      |
| Sco X-1         | 19 Bowen  | He\text{II}, Bowen |       |       | b      |
| GX 349+2        | 22        | H\text{I} |       |       |        |
| Her X-1         | 41 Bowen  | H\text{I}, He\text{I}, Bowen | He\text{II} |        |        |

simplest form of the model, the overflow stream should produce absorption at all phases; it always obscures some of the disc. This problem is overcome by invoking a strongly flared disc so that the overflow stream is only visible near phase 0.5. In XTE J2123–058, however, the neutron star is directly visible, so the disc area that can be obscured by a flare is limited and it is harder to reproduce the depth and transience of the absorption. A further difficulty is that to produce emission at the low velocities observed requires disc emission which is sub-Keplerian by a significant amount. This problem is not peculiar to XTE J2123–058 but common to the SW Sex class in general.

5 Conclusions

We have demonstrated that XTE J2123–058 at least, and likely some other short-period neutron star LMXBs, show observational similarities to SW Sex cataclysmic variables. These include a Doppler tomogram with emission concentrated at low velocities in the lower left quadrant and transient absorption around phase 0.5. We have discussed the application of two current SW Sex models to LMXBs. The stream overflow and re-impact model is theoretically plausible, but does not readily account for observations. The magnetic propeller model can easily explain the main observations, at least in XTE J2123–058, but has yet to overcome several theoretical objections. Whatever the correct interpretation, it is clear that the LMXB–SW Sex connection is an intriguing and fruitful one that may enhance our understanding of both types of systems.

So far we have concentrated on short-period ‘normal’ LMXBs; systems similar to XTE J2123–058. In Table 1 we summarise all the Doppler tomography of neutron star LMXBs known to us. The sample is clearly small and we include this as much to highlight the lack of data compared to cataclysmic variables as to draw strong conclusions. One can perhaps suggest that the companion star mainly tends to be prominent only in the longer period systems, and that
‘unusual’ tomograms (the other category) are most often seen in He II, but both of these conclusions require a larger sample for confirmation. It can be hoped that increasing availability of large telescope time will make such observations possible.

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