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Neutron Star Radiation Pressure Leading to Jet Formation in the Brightest LMXB

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Abstract. We present an explanation of Z-track behaviour based on spectral fitting of *Rossi-XTE* observations of the sources GX 340+0 and GX 5-1. We show that the soft apex is the quiescent state of the source, and as the source moves away from this point towards the horizontal branch, the large increase in ADC Comptonized emission shows that $\dot{M}$ increases, and leads to a measured rise in neutron star blackbody temperature. This gives a massive rise in radiation pressure and we propose that this disrupts the inner disk and does this most efficiently in the regions high above the orbital plane, the force thus acting close to vertical. We thus propose that this force is directly responsible for the launching of jets observed in radio only at this part of the Z-track. On the flaring branch, we show that $\dot{M}$ is constant such that flaring must be unstable nuclear burning, and the mass accretion rate at the soft apex agrees well with the theoretical critical value at which He burning in a mixed H/He environment becomes unstable. In this explanation, the mass accretion rate does not increase monotonically around the Z as previously thought in the direction horizontal branch to flaring branch.

Key words. accretion: accretion discs – acceleration of particles – binaries: close – stars: neutron – X-rays: binaries – X-rays: individual (GX 5-1, GX 340+0)

1. Introduction

The Z-track sources are the six brightest Low Mass X-ray Binary (LMXB) systems with luminosities consistently at or above the Eddington Limit. The sources were found to trace out a characteristic Z shape on a hardness-intensity diagram (HID) (Hasinger & van der Klis 1989), consisting of three branches: the horizontal branch (HB), normal branch (NB) and flaring branch (FB), showing that the sources undergo strong physical changes between the states. Extensive timing analysis has been carried out on these sources revealing the existence of multiple QPO and showing systematic changes of these along the Z-track. It was proposed that the timing properties depended on a single parameter which changed monotonically round the Z, generally been believed to be mass accretion rate, $\dot{M}$ (Priedhorsky et al. 1986), such that $\dot{M}$ increases in the direction HB-NB-FB. However, observational evidence supporting this hypothesis is very limited. Despite its successes, timing analysis has not revealed the nature of the physical changes taking

Send offprint requests to: N. K. Jackson place between branches. Spectral analysis is more likely to show directly the nature of the changes, but progress has been hindered by disagreement over which spectral model to use. Most of the limited spectral analysis of the Z-track sources has invoked the "Eastern model" (Mitsuda et al. 1989) comprising Comptonization from a small central region plus multi-colour blackbody emission from the inner accretion disk. However, this model has failed to provide a clear physical explanation. For over ten years the Birmingham group working on the dipping class of LMXB found that the spectra of these sources were well-described by a model that may be termed the "Extended ADC model" consisting of blackbody emission from the neutron star and Comptonized emission (represented by a cut-off powerlaw) from an extended ADC (Church & Bałucińska-Church 1995). The extended nature of the ADC had been demonstrated through the technique of dip ingress timing (Church & Bałucińska-Church 2004) and shown to have a typical size of 50000 km, up to 1000 times larger than in the Eastern model.

2. Analysis and results

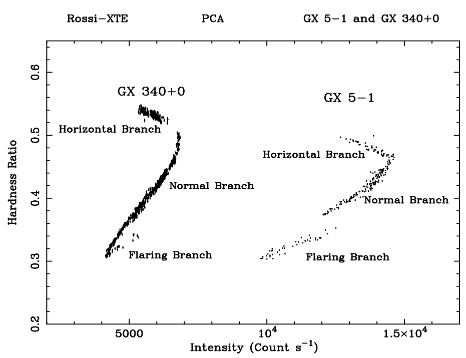

Fig. 1. Z-tracks for the two sources: GX 5-1 and GX 340+0

The current work is based on *Rossi-X-ray Timing Explorer* observations of GX 5-1 and GX 340+0. During the observations, both sources traced out a full Z on the HID (Fig. 1) and the lightcurves displayed strong variability. Spectra were selected in both sources at a sequence of positions along the Z-track, including all 3 branches, and these spectra were then fitted with the Extended ADC model, which provided good fits to all spectra, and demonstrated a clear physical picture of the changes taking place.

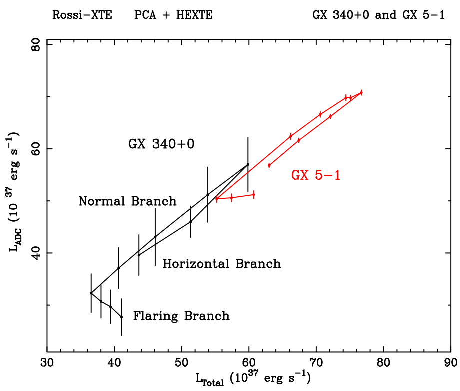

Fig. 2. Variation of the ADC luminosity as a function of position on the Z-track showing a striking rise on the Normal Branch.

In Fig. 2 we show the strong variation of the luminosity of the dominant emission component: the Comptonized emission of the ADC, as a function of the total luminosity. It can be seen that there is a strong increase of L_{ADC} as the source moves from the soft apex (SA) to the hard apex (HA). It is most unlikely that this increase can take place without $\dot{M}$ increasing, and so our result (in both sources) is strong evidence contrary to the generally-accepted view that $\dot{M}$ increases in the direction HB-NB-FB.

In Fig. 3 we show the neutron star blackbody temperature kT and blackbody radius $R_{\rm BB}$. At the soft apex, the temperature is minimum and $R_{\rm BB}$ close to 10 km, implying that the whole neutron star is emitting, and we propose that this is the quiescent state of each source. As the source moves away from this quiescent state towards the HA, kT rises as expected for an increasing $\dot{M}$, and $R_{\rm BB}$ decreases.

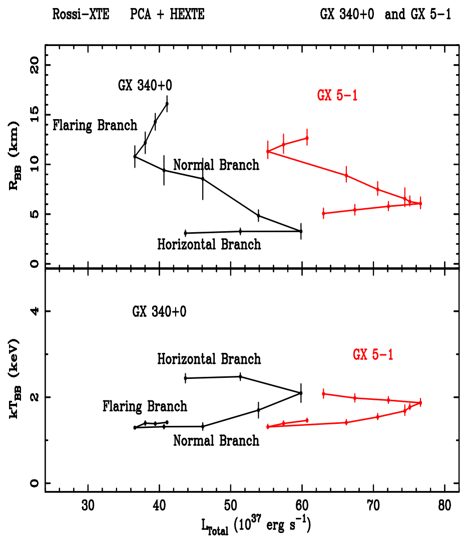

Fig. 3. Variation of neutron star blackbody temperature and blackbody radius along the Z-track.

The factor of two rise in temperature means that the radiation pressure close to the narrow equatorial emitting band on the neuron star increases by more than 10 times. Comparing the emitted flux of the band with the Eddington value ($L_{\rm Edd}/4\,\pi\,R^2$, where R is the radius of the neutron star), we find that the flux rises from $0.3\,f_{\rm Edd}$ to $3\,f_{\rm Edd}$ at the HA and on the horizontal branch. We thus propose that this very strong radiation pressure disrupts the inner disk and launches jets accounting for the radio emission seen on these parts of the Z-track. For an explanation of the decrease in $R_{\rm BB}$, see Church et al. (2007).

The nature of the flaring branch has itself been controversial, with the opposing views that the flaring is due to $\dot{M}$ being maximum here, or alternatively that it is unstable nuclear burning. Fig. 2 shows the striking result that $L_{\rm ADC}$ is constant on the FB, strongly indicating that $\dot{M}$ does not change, so that flaring *must* consist of unstable nuclear burning on the surface of the neutron star.

3. Discussion

We present evidence for the very strong radiation pressure on the upper parts of the Z-track. In these sources, the inner disk is thickened to a height of ~ 50 km due to the radiation pressure of the disk itself. The high radiation pressure of the equatorial emitter on the neutron star is likely to be able to blow away the high regions of the inner disk efficiently and in a direction close to vertical. We propose that this is the major requirement for the launching of jets in these systems.

Secondly, the constancy of $\dot{M}$ on the FB proves that flaring can not be caused by an increase of $\dot{M}$ and must be caused by unstable thermonuclear burning. Detailed calculations from our spectral fitting results (e.g. Church et al. (2007)) show that the mass accretion rate per unit area of the neutron star $\dot{m}$ evaluated at the soft apex is close to the theoretical critical $\dot{m}$ at which unstable He burning in a mixed H/He atmosphere becomes stable (Bildsten 1998). Thus unstable burning is not possible on the HB and NB, but as $\dot{M}$ falls, unstable burning becomes possible at the SA and is seen as the strong flaring on the flaring branch.

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