A new ranking scheme for neutron-star low-mass X-ray binaries

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NS LMXBs: sub-classes

Two patterns of correlated X-ray timing and spectral behaviour in low-mass X-ray binaries

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• Evolution from Eddington to quiescence

• $\dot{M}$-ranked sequence of CD/HID tracks (Lin et al. 2009)
  • No B-field, no viewing angle involved

• Can it be used to get a relative ranking for other NS LMXBs?
• Can we find similar behavior in other sources?
• At low luminosities: yes, atoll transients
• At high luminosities: unsure
  • Investigate sources with strong secular changes:
    • Cyg X-2, Cir X-1, and GX 13+1
Figure 8. CDs and HIDs showing more complete tracks for Cyg X-2. These were made by combining data from various times throughout the RXTE mission. The dashed and solid lines are the lower and upper vertex lines shown in Figure 7. See text for further details.

very sensitive to these ambiguities in the combining process. In Figure 8 we show 12 examples of these more complete combined tracks. We note that small secular shifts do occur in some of these tracks; some of the individual segments used have a broad appearance, which may in some cases be due to secular motion, and in some instances we match up segments despite their not lining up perfectly if the overall appearance of the track is only minimally affected by this. In the tracks shown, the number of individual segments used (widely separated in time) ranges from 1 to 10. For many of these tracks, it would have been possible to combine many more segments with them and thereby make use of a larger portion of the data set; in many cases this would have resulted in somewhat broader tracks. In general, for the purposes of this plot we tried to create tracks that are as complete as possible while minimizing any guesswork. Still, many of the tracks we show are likely not perfectly complete, either because data segments that would serve to complete them are simply not available in the data set, or we felt that there was too much ambiguity in whether a candidate segment actually belonged to a given track. Overall, we opted to rather err on the side of caution and leave a given track with some incompleteness than engage in what we felt was too much guesswork; this applies in particular to the HB upturn segments of the tracks. Nevertheless, there is inevitably some uncertainty regarding how close some of our combined tracks are to “actual” tracks the source traces out at a given point in its secular progression (or would trace out in the absence of secular shifts). The 12 particular tracks we show were chosen from the larger set we constructed to illustrate as clearly as possible the overall evolution of the tracks—both of the individual branches and the overall locations of the tracks—as they move through the CD/HID. As before, we order the panels based on the vertex locations of the tracks, and show the same vertex lines as in Figure 7. We now discuss individual tracks in Figure 8 in more detail.

Panel A shows a track consisting of a single data subset (as defined in Section 4.1) taken over a period of \( \pm 28 \) hours. This track is intermediate between those shown in panels A and B in Figure 7. The broad appearance of the NB is likely due to mild secular motion, and this obscures the appearance of the FB in the CD, which extends horizontally to the left, as it does in panels A and B in Figure 7 (with perhaps a slight upward bend in panel B). Missing from this track is the upper vertex and presumably most of the HB upturn. The track in panel B is based on the one in panel B of Figure 7. This track shows an HB upturn and the FB seems to show a slight upward bend in both the CD and HID. In the track in panel C, the FB has rotated slightly further clockwise in the HID but has jumped rather abruptly in the CD to pointing up and to the right, parallel to and overlapping with the NB, thus making it difficult to discern. The track in panel D consists of the subset shown in panel D of Figure 7 in addition to another subset showing an FB and a lower NB. The FB in the CD is oriented in
Cyg X-2

Diagram showing the correlation between hard color and soft color, as well as intensity in counts per second per unit (counts s\(^{-1}\) PCU\(^{-1}\)) for Cyg X-2 and XTE J1701-462.
Cir X-1 & GX 13+1

Cyg-like Z ↔ atoll

Cyg-like Z ↔ Sco-like Z
NS LMXBs

• **Conclusion:** XTE J1701-462 is not alone. Behavior might be representative of NS-LMXBs

• **Next step:** rank 40+ NS-LMXBs based on CD/HID morphology (150+ ks, no dipping/eclipsing sources)

• **Ranking criteria:** presence & orientation of Z/atoll states/branches

• **Assumption:** luminosity (mass accretion rate) determines CD/HID morphology
the ranking
the ranking
• Radiative stresses may play an important role:
  • Increasingly violent intensity swing at high $L_x$ (up to factors of $\sim 8$ in 30 minutes).
  • Systematic shift in kHz QPO frequency ranges
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  • Increasingly violent intensity swing at high \( L_x \) (up to factors of \(~8\) in 30 minutes).
  • Systematic shift in kHz QPO frequency ranges
What’s next?

• Study variability/spectral properties across entire range of mass accretion rate

• Type I X-ray bursts

• Add more sources (<150 ks, dipping/eclipsing NS LMXBs)

• Test the ranking scheme - obtain luminosities
  • distance estimates (VLBA)

• Try something similar for black holes?
Figure 2.32. CDs for 24 of the 41 sources in our sample, all shown on the same scale.
Figure 2.33. CDs for the remaining 17 sources in our sample shown on the same fixed scale as in Figure 2.32.
X-ray variability: kHz QPOs

Maximum upper kHz QPO frequencies

Lower mass accretion rates → higher kHz QPO frequencies

\[ \nu_{K,\text{rad}} = \nu_K (1 - \text{const} \times \frac{L}{L_E})^{1/2} \]
Many short (few ks) observations spread over 15 years
Figure 2.13.

CD and HID representing the entire RXTE PCA data set of Cir X-1.

Other systems. Soleri et al. (2009a) analyzed a series of simultaneous RXTE PCA and radio observations from 2000 and 2002 and identified various Z branches in several observations. In other observations, they claimed that the source showed behavior that was either atoll-like or consistent with neither atoll nor Z sources; however, from inspection of the data it is clear that those observations were heavily influenced by absorption dips whose 

effects Soleri et al. (2009a) did not recognize.

2.5.1 Dipping

We processed the RXTE PCA data of Cir X-1 as described in Section 2.2. A CD/HID using the entire data set is shown in Fig. 2.13. The diagrams are heavily affected by both the effects of absorption and secular shifts and shape changes in the source tracks. As mentioned above, most of the dipping occurs close to the time of presumed periastron passage, which is often associated with flaring in the X-ray and radio bands. Stewart et al. (1991) give a quadratic radio ephemeris based on measurements of radio flares between 1978 and 1988; phase 0 corresponds to the onset of radio flaring. Clarkson et al. (2004) fit a quadratic ephemeris to dips in RXTE ASM data from 1996–2003, and find that it provides a better predictor of the X-ray light curve than ephemerides based on the radio flares or the full X-ray light curve (Saz Parkinson et al. 2003). The strongest dipping typically occurs in the last half a day before the onset of X-ray flaring and often produces a characteristic track in the CD and HID; this track goes up to high color values and has two sharp bends in the CD. This can be seen in Figs. 2.13 and 2.14; in the latter we show various diagrams for 7 days of observations in June 1997, which we discuss further below (these constitute the bulk of the "complete Z track" observations analyzed by Shirey et al. 1999a). The shape of these tracks can be understood if the X-ray emission is composed of two components: a bright component that is subject to heavy absorption and a faint component that is unaffected by the absorption (the latter perhaps due to X-rays from the central source scattered into our line of sight by surrounding material). Shirey et al. (1999b) 90

Figure 2.15.

CD and HID for Cir X-1 after the removal of data affected by absorption. Note the changes in scale compared to Fig. 2.13.

Before proceeding with our analysis of the Cir X-1 data set, we removed—to the extent possible—data points affected by absorption dips. We illustrate how this was done in Fig. 2.14, where we show removed data points in red. As can be seen in the figure, during these observations the source showed intense dipping shortly before phase 0 in the radio ephemeris, producing a CD/HID track of the sort described above. This was followed by strong X-ray flaring along with some shallower dips. We note that the periodic flaring during an orbital cycle is not exclusively associated with motion along the FB (which often, as in this case, is mostly a dipping FB); it would perhaps be more appropriate to refer to this as "strong intensity swings," although in the literature they are usually simply called flares. As is apparent from the figure, it is almost impossible to identify dips on the basis of the light curve alone during periods of flaring. However, tracking the behavior of the soft color (and, although less helpful, the hard color as well), both as a function of time and in the CD and HID, greatly aids in identifying dipping. In addition, we took into account the dipping ephemeris of Clarkson et al. (2004) when performing the removal, since the vast majority of dipping events take place in the last day before and the \( \tau \) days after phase 0. However, we note that (shallow) dips are sometimes seen later in an orbital cycle; one example can be seen in Fig. 2.14. In this manner, we manually removed data points affected by dipping from all observations; the resulting "cleaned" CD/HID is shown in Fig. 2.15. It was of course unavoidable that some minor effects of dipping remain, and that a small amount of unaffected data be removed; however, we expect that the effects of this on the conclusions we draw from the data are negligible.
Figure 2.25. CDs and HIDs of six Z sources. Red data points show data taken from narrower time intervals, ranging from \( \sim 3 \) to \( \sim 34 \) days in length. The diagrams for Sco X-1 only contain data obtained with a pointing set of 0.34. As we have seen for the previous sources discussed, the secular shifts are more pronounced in the HID than the CD, and the strongest shifts for these two sources are on the NB and around the upper vertex.

Panels C–F in Fig. 2.25 show the Sco-like Z sources GX 17+2, Sco X-1, GX 349+2, and LMC X-2. These four sources show very similarly shaped tracks, although there are some noticeable differences between them. They also show mild secular shifts, and as for the two Cyg-like Z sources discussed above we color data from narrower time intervals (\( \sim 9, \sim 8, \sim 14, \) and \( \sim 3 \) days for GX 17+2, Sco X-1, GX 349+2, and LMC X-2, respectively) within which there are minimal shifts. GX 17+2 shows what seems to be the fullest and clearest track. The position of the NB/HB vertex in the CD is quite clear (see Fig. 1.12 for a labeling of the branches), with the HB bending to the left as the hard color increases. Further up there is a bend to the right in the HB; this is probably analogous to the HB upturn in the Cyg-like Z sources. Sco X-1 and especially GX 349+2 show shorter HBs than GX 17+2; the NB in GX 349+2 also curves in the opposite way to the NBs in GX 17+2 and Sco X-1 (also note that the uppermost part of the red track for GX 349+2 clearly shows a...
transitional state than the other three sources, as the banana branch in the CD curves up and to the left at the lowest soft color. GX 3+1 and GX 9+1 show hints of similar behavior, but no indication of that can be seen for GX 9+9. Yet another atoll source that has never been observed in the hard state is 4U 1735–44 (panel E); however, this source shows a much fuller lower banana branch than the other four soft-state atoll sources, and has on one occasion been seen to make a slight excursion into the IS (data points with intensities $200 \text{ counts s}^{-1} \text{ PCU}^{-1}$). The CD/HID of 4U 1735–44 shows a strong similarity to the combined atoll diagram for XTE J1701–462 in Fig. 2.7 (which also includes a full transition to the hard state); however, we note that the individual flaring tracks of 4U 1735–44 show somewhat more curvature than those of XTE J1701–462, and the source is in that respect more akin to GX 9+1 than GX 9+9.

2.7.3 Transitional Atoll Sources

Figs. 2.28 and 2.29 show the 17 atoll sources in our sample that have been observed in both the hard and soft states. In many cases, these sources span a large dynamic range in intensity, particularly in the soft state (some are transients that spend a large portion of their time in quiescence), and features in the transitional and hard states can be hard to make out in the HID when plotted on a linear intensity scale. We therefore also show HIDs...
Figure 2.28. CDs and HIDs of ten atoll sources that display states ranging from extreme island to upper banana.
Figure 2.29. CDs and HIDs of seven transitional atoll sources that show no upturn on the banana branch in the CD (i.e., no proper upper banana) and no soft-state flaring.
Figure 2.31. CDs and HIDs of nine hard-state atoll sources.