RADIATIVELY INEFFICIENT ACCRETION IN SHORT-PERIOD BLACK HOLE LOW-MASS X-RAY BINARIES

University of Leicester

University of Amsterdam

Riley Connors Supervisor: Dr. Graham Wynn

Department of Physics and Astronomy, University of Leicester, University Road, Leicester, LE1 7RH

Abstract

I Investigate the switch to inefficient accretion in short-period black hole Low Mass X-ray Binaries (LMXBs) and use this to explain the Galactic population of LMXBs. I analyse the period distributions of LMXBs in the Ritter-Kolb catalogue (Ritter & Kolb 2003) to show that there is statistical evidence for a dearth of short-period (P_{Orb} < 0.1 days) black hole LMXBs in the Galaxy. At short periods accretion onto the central object (be it a black hole) may become inefficient because the cooling timescale of the gas is greater than the accretion timescale, and so energy is lost to the event horizon before it can radiate as X-rays. The nature of the switch to inefficiency may be sharp or smooth with time. I show that the dearth can be explained if this switch to inefficiency occurs sharply at some fraction of the Eddington Luminosity using an analytical model of a Galactic distribution of LMXBs incorporating Monte Carlo techniques. This interpretation for the observed Galactic population of LMXBs can be applied to studies closer to the Galactic Centre to constrain the Luminosity Function (LF), more specifically the low-luminsoity break (see eg. Fabbiano 2010).

1. Introduction

Low-Mass X-ray Binaries (LMXBs) are binary star systems consisting of a low-mass secondary star ($\leq 1M_{\odot}$) and a compact central object (a neutron star or a black hole). Matter is pulled from the secondary star and forms an accretion disk about the primary. The accretion of this matter onto the primary causes the emission of X-ray radiation. LMXBs go through cycles of outburst and quiescence, whereby outbursts are triggered when mass transfer increases the disk density to some maximum limit for thermal stability resulting in increased viscosity. The accretion evolution during outburst is described initially by an exponential decay, and subsequently by a linear one (King & Ritter 1998):

$$\dot{M} \approx R_D \rho \nu \exp\left(-\frac{3\nu t}{{R_D}^2}\right) \quad , \quad t < T, \tag{1}$$

$$\dot{M} = \left[\dot{M}(T) - \left(\frac{3\nu}{B_n}\right)(t-T)\right], \quad T < t < t_{end}, \tag{2}$$

where R_D is the disk radius, ρ is the gas density, ν is the kinematic viscosity and B_n is a constant defined primarily by the temperature of the disk. The subscript n is 1 for neutron stars and 2 for black holes, due to the lack of hard surface in black hole systems. The luminosity is then given by $L \approx \eta \dot{M} c^2$.

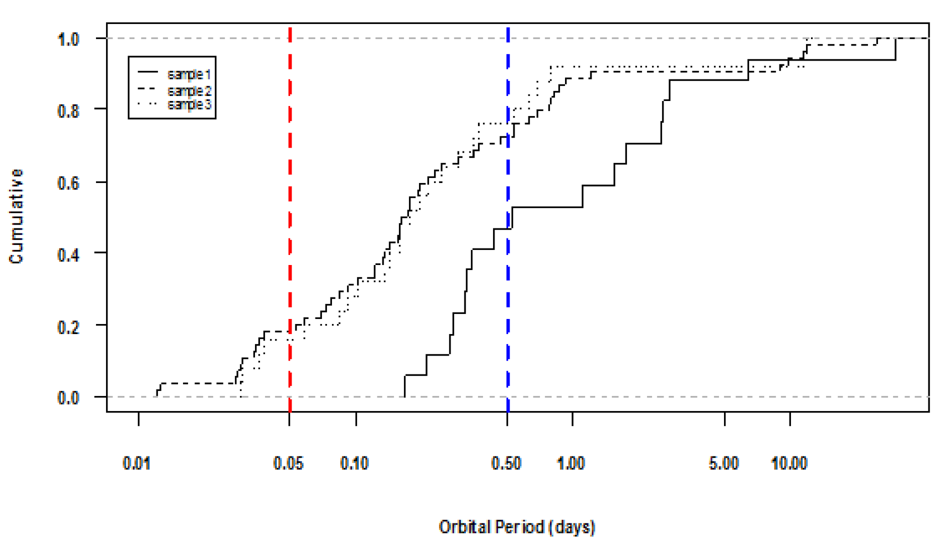
We expect short-period LMXBs to undergo a switch to Advection Dominated Accretion Flow (ADAF) at some fraction of the Eddington luminosity. ADAF occurs in the low density limit of an accretion disk when cooling via Bremsstrahlung becomes inefficient (which we expect at short periods). In this regime the cooling timescale becomes longer than the accretion timescale of the gas. Thus in black hole LMXBs a proportion of the viscous energy built up in the gas is accreted beyond the event horizon rather than radiated as X-rays (see eg. Narayan & Yi 1995). I investigate this switch and whether it can explain Galactic populations of LMXBs.

2. Period Distribution Analysis

I extract data from Ritter & Kolb (2003) concerning LMXBs, and split the data into three samples:

Sample 1 All black hole LMXBs (17 systems)
Sample 2 All neutron star LMXBs (54 systems)
Sample 3 Transient neutron star LMXBs only (25 systems)

There is statistical evidence for a dearth of short-period black hole LMXBs in the Galaxy.



BHs Compared to:	K-S prob. (all)	Porb < 0.5 days	Porb > 0.5 days
All NS-LMXBs	6.13×10^{-4}	1.18×10^{-3}	0.101
All NS-LMXBs Porb > 80min	8.96×10^{-3}	6.72×10^{-3}	0.101
Transient NS-LMXBs	5×10^{-3}	0.0122	0.176
Transient NS-LMXBs Porb > 80min	0.0287	0.05439	0.176

Figure 1. The cumulative frequency distribution of orbital periods of samples 1, 2 and 3, accompanied by the K-S test statistics. Samples 2 and 3 follow a significantly difference distribution to that of sample 1, with an uncertainty > 2σ according to a K-S test of all the samples. Probabilities are lower in the P_{Orb} < 0.5 days region (shown by the blue line). No black hole LMXBs are seen at P_{Orb} < 0.1 days.

3. Analytical simulations

I explore two possible switches to ADAF (at some fraction of the Eddington luminosity during the accretion flow, fL_{Edd}) for a population of LMXBs following the stellar distribution of the Galaxy, adopting the prescription of James & Wynn 2013;

Case A a sharp switch to $\eta = 0$ at fL_{Edd}.

Case B a smooth switch at fL_{Edd}: $\eta = 0.1\frac{\dot{M}}{f\dot{M}_{Edd}}$.

I put a lower limit on the detection flux of all the LMXBs in the model (based on the minimum detection flux of the Rossi X-ray Timing Explorer (RXTE)), and calculate the probability of detecting these LMXBs at different orbital periods.

The results show that a case A switch to ADAF would significantly reduce the detection probability of short-period (P_{Orb} < 0.1 days) black hole LMXBs relative to neutron star LMXBs, thus explaining the period distribution results shown in fig.1.

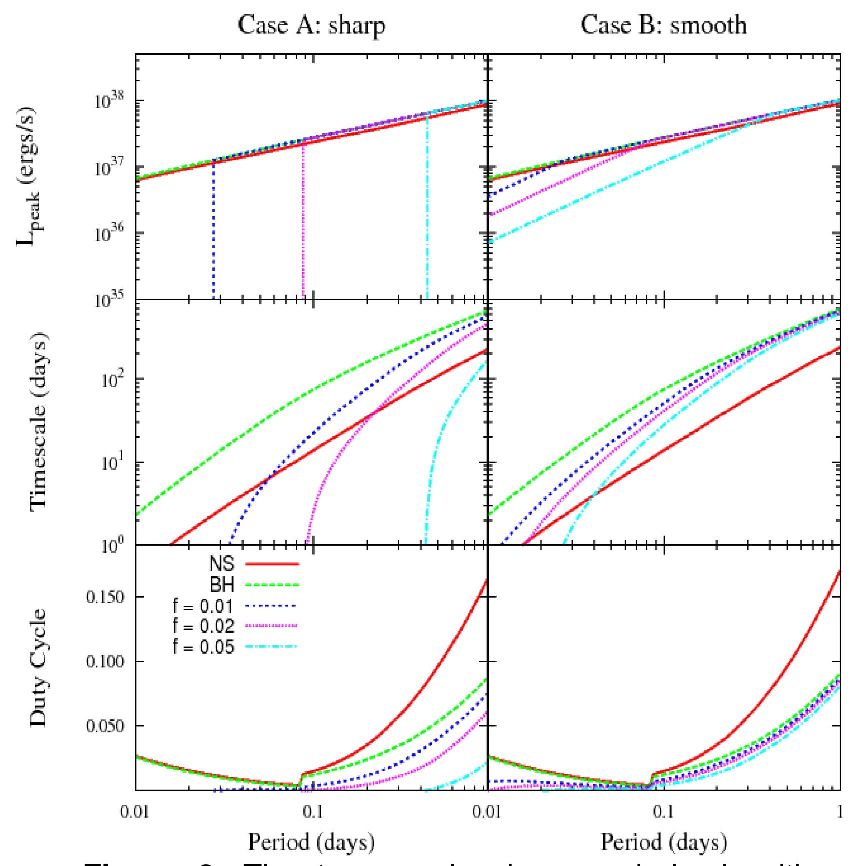


Figure 2. The top panels show peak luminosities, middle panels show outburst timescales, and bottom panels show the X-ray duty cycle. Left panels show these quantities for case A (sharp) switches, right panels for case B (smooth). Each plot shows 5 systems; neutron star LMXBs (red line), black hole ($M = 10M_{\odot}$) LMXBs with no switch (green line), and black holes switching to ADAF at fractions f = 0.01 (dark blue line), 0.02 (purple line), and 0.05 (light blue line) of the Eddington luminosity.

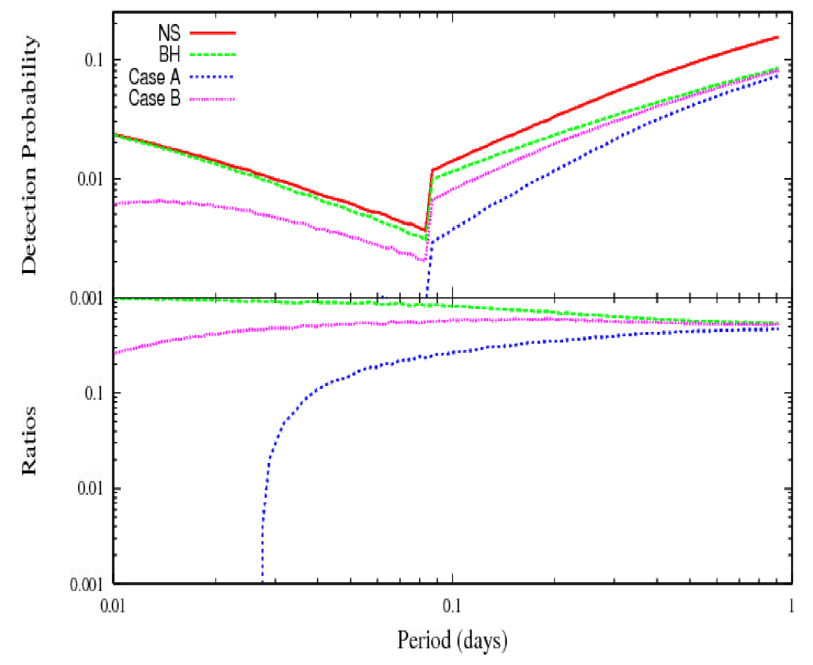


Figure 3. Simulation results: Detection probabilities for neutron star, black hole, black hole with a case A (sharp) switch and black hole with a case B (smooth) switch LMXBs, against orbital period. Also shown are the ratios of black hole detection probabilities with those of neutron stars for further comparison, where f = 0.01.

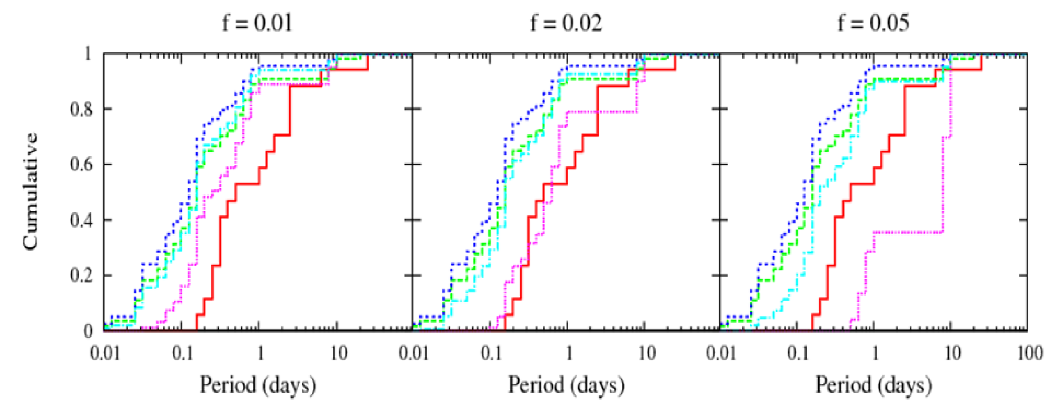


Figure 4. Overplotted predicted histograms. Shown are the original black hole (red) and neutron star (green) period distributions, and then a case A (purple) switch to inefficiency , a case B switch (light blue), and no switch (dark blue).

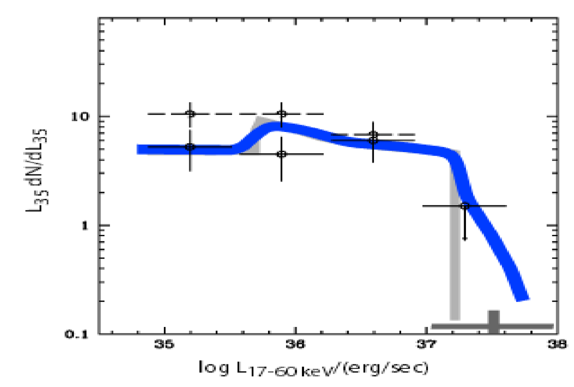


Figure 5. A LMXB LF as detected by INTEGRAL/IBIS in the Galactic bulge region (Revnivtsev et al. 2008). Two breaks can be seen in the slope. The low-luminosity break can be explained either by a state transition (ADAF) or a change in the binary braking mechanism.

Conclusion

The dearth of short-period black hole LMXBs in the galaxy is well explained by a sharp transition to an inefficient accretion state. Fig.4 shows predicted period distributions for LMXBs adopting this inefficient regime; a switch to ADAF at $0.02L_{Edd}$ fits best to the data. A model that focuses on the Galactic centre using empirically determined period distributions could be used to explain the observed LF. Inefficient accretion in short-period LMXBs may be able to explain the apparent low-luminosity break. This may improve our understanding of the low/hard spectral state associated with inefficient accretion.

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