Disc Instabilities in Soft X–ray Transients

A.R. King

Theoretical Astrophysics Group, University of Leicester, Leicester LE1 7RH, U.K

Abstract. I briefly review the theory of soft X–ray transient systems. Irradiation of the accretion disc faces by the central X–ray source determines both the occurrence and the nature of the outbursts, in particular forcing these to be long viscous events and producing exponential decays at short orbital periods. Soft X–ray transients constitute the majority of LMXBs, persistent systems being largely confined to a subset of neutron–star LMXBs with periods \( P \lesssim 2 \) d. It appears that LMXBs very frequently contain nuclear–evolved companions, even at short orbital periods. In long–period transients \( (P \gtrsim 20 \) d) the outburst recurrence times must become extremely long \( (\gtrsim 1500 \) yr\). The outbursts are highly super–Eddington, markedly reducing the accretion efficiency. Spinup of a neutron–star primary to millisecond periods probably can not occur for orbital periods \( \gtrsim 200 \) d, in agreement with observations of binary pulsars.

1. Introduction

My interest in this subject was kindled by a workshop on Black Holes held in Aspen in early 1996, and transformed by interaction with Jan. I arrived at the meeting after a long snowy drive from Denver, worried about two things. First, my then postdoc Luciano Burderi had persuaded me to try skiing for the first time, at what even I regarded as a perilously advanced age. Second, the meeting organisers had asked me to talk about the evolution of X–ray transients, and I could not make much sense out of this topic. By then the only model seriously considered for the X–ray outbursts involved the thermal–viscous disc instability, resulting from hydrogen ionization. I was puzzled by two aspects of this. I could not see why the outbursts of transients should be so much longer and more infrequent than those of dwarf novae, and I could not understand why some low–mass X–ray binaries (LMXBs) should be transient and others not.

Being asked to talk on the subject made the second of these problems more immediately urgent than the first. My then postdoc Uli Kolb and I had tried to solve it by simply asking when an LMXB accretion disc would have hydrogen ionization zones. The presence of these zones should mean that the disc was unstable, making the system transient. This procedure already worked well for the closely related cataclysmic variables (CVs), in which the accretor is a white dwarf rather than the black hole or neutron star in LMXBs. Given the disc surface temperature distribution \( T_{\text{eff}}(R) \) resulting from viscous dissipation, all one had to do was compare this with some value \( T_{\text{H}} \simeq 6500 \) K typical of
hydrogen ionization. If $T_{\text{eff}}(R)$ was everywhere above $T_H$ the disc should have no ionization zones and be persistent rather than having dwarf nova outbursts. Since $T_{\text{eff}}(R)$ decreases outwards the condition amounted to

$$T_{\text{eff}}(R_d) > T_H$$

(1)

where $R_d$ is the outer disc radius. As $T_{\text{eff}}(R_d)$ could be calculated from the mass transfer rate $-\dot{M}_2$ and orbital period $P$, one could plot a line dividing dwarf novae from persistent (‘novalike’) CVs on the usual $-\dot{M}_2 - P$ relation predicted for CVs, assuming the standard angular momentum loss mechanisms and secondary stars close to the main sequence. Those CVs predicted to have ionization zones, i.e. lie below the line, were indeed dwarf novae. Yet for LMXBs the same method produced the manifestly wrong result that all short-period ($P \lesssim 12$ hr) LMXBs should be transient.

Surviving the first couple of days on the ski slopes without serious injury eased my first set of worries, but I was still fretting over the second set when Jan gave his talk. By immense good fortune this was the evening before I was due to speak. Jan’s talk characteristically combined a powerful insight with a presentation so lucid and simple that the result seemed instantly obvious. He pointed out that LMXB discs differ from CV discs in one vital respect: the optical flux from an LMXB disc is so much higher than expected from the accretion rate revealed by the X–ray flux, that the disc must be heated by some other agency than the viscous dissipation driving the accretion through the disc. The obvious candidate for this is the X–ray emission itself, some of which must fall on the disc faces and heat them. This fact had long been known by observers, but somehow never fully appreciated by theorists, largely I suspect because theoretical calculations predicted (and still predict) that the result of irradiating a disc in this way is to make its central regions swell up and shield most of the rest of it from the X–rays.

Armed with clear observational evidence to the contrary, Jan adopted the sensible view that nature knows how to irradiate a disc even if theorists don’t. A simple concave disc model allowed him to calculate the run of disc surface temperature $T_{\text{irr}}(R)$ from the observed X–ray flux and orbital period of a given LMXB. If $T_{\text{irr}}(R)$ was everywhere above $T_H$, Jan assumed that the disc would be stable and the system persistent. Since $T_{\text{irr}}(R)$ decreases outwards this is now equivalent to requiring

$$T_{\text{irr}}(R_d) > T_H$$

(2)

rather than the CV condition (??). Jan showed that indeed the condition (??) correctly divided LMXBs into persistent and transient if he used their observed X–ray luminosities to predict $-\dot{M}_2$ and thus $T_{\text{irr}}$.

Back in my room that evening I spent a lot of time thinking about what Jan had said, and how I should change the talk I was to deliver the next day. It was clear that condition (??) was less restrictive than (??), reflecting the stabilizing effect of irradiation. So the question was what the corresponding line on the $-\dot{M}_2 - P$ plane would give. Fortunately Jan had given enough information for me to add the line to the plots I had prepared for my talk. Sure enough, the new line was at lower $-\dot{M}_2$–values than the old line. But the surprising consequence was that, particularly for neutron–star LMXBs, the standard angular–momentum driven evolution of short–period systems with near–main–sequence secondaries
now predicted that all systems in the observed 3 hr \( \lesssim P \lesssim 10 \) hr period range should be persistent. While this was an advance on the clearly incorrect earlier prediction that all these systems should be transient, I still had to explain the presence of several incontrovertible neutron–star transients at these periods. Given the robust nature of Jan’s condition (??), the only plausible route seemed to lie in dropping one of the assumptions about the evolution of neutron–star LMXBs. By another stroke of good luck, I had brought with me an \(-\dot{M}_2 - P\) plot for an LMXB where the secondary star was somewhat nuclear–evolved at the start of mass transfer, but the system evolved to shorter periods under angular momentum loss. I noticed that the predicted mass transfer rates \(\dot{M}_2\) were significantly lower; this occurred since the somewhat evolved secondary star was slightly larger for its mass than a main–sequence secondary would be. Adding the line corresponding to condition (??) immediately showed that this system would indeed be transient at short periods. In other words, the existence of short–period neutron–star transients is evidence that nuclear evolution can have a significant effect even at such periods.

Jan’s insight (published as van Paradijs, 1996) thus started off an important line of research, which I briefly review in the rest of this article.

2. The Current Situation

2.1. Long–period transients and millisecond pulsars

The consequences of the condition (??) for the long–term evolution of LMXBs have been explored in a number of papers. King, Kolb & Burderi (1996) reinforced the conclusion above that evolved secondaries favour transient behaviour, and noted that all long–period \( (P \gtrsim 2 \) d) LMXBs are likely to be transient because the accretion disc is very large and must have cool edges. Such systems must be the progenitors of long–period \( (P \gtrsim 100 - 200 \) d) millisecond pulsar binaries with circular orbits (e.g. Tauris & Savonije, 1999), yet the longest orbital period seen in a neutron–star LMXB is only 11.8 d (GRO J1744-28, Giles et al., 1996, which is indeed transient). This must mean that outbursts in these long–period transients are so infrequent none has been seen over the \( \sim 30 \) year history of X–ray astronomy. Moreover, these outbursts are likely to be highly super–Eddington (even the mean mass transfer rates are), so very little of the transferred mass will be accreted by the neutron star. As a consequence it is very hard to spin up these stars to millisecond periods, particularly at long orbital periods, explaining an observed trend. In addition, by exploiting these observational constraints, Ritter & King (2001a,b) have shown that the mean recurrence time of outbursts in long–period transients must become extremely long; the current lower limit is about 1500 yr. This is an interesting challenge for accretion disc theory.

2.2. The evolution of short–period transients

Clearly the conclusion that nuclear evolution is significant even in short–period systems implies interesting constraints on the pre–contact evolution. King & Kolb (1997) and Kalogera, Kolb & King (1998) showed that the existence of a sufficient number of such systems to account for short–period neutron–star
transients is plausible, even without extreme assumptions: the formation of a neutron–star binary is such a rare event that rather unusual companions are not uncommon. King, Kolb & Szuszkiewicz (1997) noted that the formation constraints for black–hole binaries were considerably weaker, chiefly because any supernova explosion in the latter does not come perilously close to unbinding the binary, as is inevitable in neutron–star systems. With standard assumptions about common–envelope evolution (CE) and magnetic braking (MB) there is little to prevent the formation of large numbers of black–hole binaries with unevolved low–mass companions. These systems would be persistent, in conflict with the observation that most persistent short–period LMXBs show Type I X–ray bursts and therefore contain neutron stars. Without modifying CE and MB, the most likely escape seems to be an effect noted by Shakura & Sunyaev (1973) in their original paper on accretion discs. This involves the lack of a hard surface for black holes: this may inhibit the formation of a central point irradiating source. The accretion disc will still be irradiated, but now only by the inner accretion disc rather than a quasi–spherical object, weakening the irradiation effect by the aspect ratio \( H/R \) of the disc (\( H = \) disc scaleheight). Taking account of this factor in the irradiation formula does indeed make such BH + main sequence binaries transient. However recently there has emerged evidence that many if not most short–period black–hole transients have significantly nuclear–evolved companions: HST spectra of XTE J1118+480 show clear signs of CNO processing for example. This in turn must mean that the formation constraints for LMXBs differ from those resulting from the standard assumptions about MB and particularly CE. This may remove the motivation for including the \( H/R \) factor in the irradiation formula. The conclusion about CE may have important consequences for general close binary evolution, including CVs (King & Schenker, 2001). In particular nuclear evolution and finite age effects may be far more significant that hitherto thought.

### 2.3. Soft X–ray transient outbursts

None of the work referred to above deals with the crucial question raised in the Introduction of why transient outbursts have much longer timescales than dwarf novae. Here too disc irradiation provides an insight. Once an outburst starts, the central regions of the disc will find it impossible to return to the cool state until the central X–ray source turns off. But this turnover itself cannot occur while these central regions contain significant mass: observation is unambiguous in showing that the disc remains strongly irradiated throughout the outburst. Clearly the outburst must last until most of this mass is removed by accretion, which occurs on the hot–state viscous timescale. King & Ritter (1998) constructed a simple analytical model of this process, incorporating the assumption that the disc was irradiated by the central source in the way indicated by the earlier evolutionary studies and Jan’s original paper. King & Ritter’s paper showed that in short–period systems, where the whole of the disc faces could be effectively illuminated, there was a strong tendency to produce an exponential X–ray decay, while in longer period systems only the centre of the disc could be kept in the hot state, producing a linear decay. This is supported by observation (Giles et al., 1996; Shahbaz et al., 1998). More elaborate numerical calculations confirm this (cf Lasota, 2001, and references therein), although the theoretical problem of why
the central disc does not puff up and shield the outer parts from the irradiation is still not understood. Recently, Truss et al. (2001) have suggested that the secondary maximum seen in exponential decays may result from the standard unirradiated ionization instability operating on matter at the edge of a small disc, which is shielded from the central X–rays simply because there is inevitably a shadowing effect at the outer disc edge.

3. Conclusions

Jan’s insight that disc irradiation could have important effects has been amply justified. He would have been pleased by this, but even happier to realise that we are only at the beginning of understanding all its consequences.

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