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Are the very faint X-ray transients period gap systems?

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ABSTRACT
We discuss a scenario for the very faint X-ray transients as X-ray binaries fed by winds from detached M dwarf donors in binary systems within the ‘period gap’ – the range of periods where donor stars have become fully convective, and shrunken so that they no longer fill their Roche lobes, but have not yet re-attached due to the systems shrinking through gravitational radiation. This wind-fed detached binary scenario can reproduce the two key properties of the very faint X-ray transients – their faintness, which defines them, and their relatively low duty cycle outbursts which require that they have low mean mass transfer rates. We discuss feasible observational tests of the scenario.

Key words: accretion, accretion discs – binaries: close – stars: late-type – stars: mass-loss – X-rays: binaries.

1 INTRODUCTION
The first observations of transient accretion discs – of the dwarf nova SS Cyg in outburst – were reported more than a century ago (discovered by Louisa Wells, but reported by Pickering & Fleming 1896). The mechanism for the transient behaviour is now believed to be the ionization instability model (Smak 1984). In this model, the transient behaviour is proposed to occur due to the fact that the viscosity of neutral gas is lower than that of ionized gas. Gas is heated during the intervals between transient outbursts, and goes through limit cycles in which it is sometimes hot enough to be ionized, leading to a rapid viscous time-scale, and sometimes cool enough to be neutral, leading to lower accretion rates.

X-ray binaries also show transient behaviour. The standard ionization instability model cannot explain the details of X-ray transient behaviour (see e.g. Lasota 2001, for a review). On the other hand, the effects of irradiation of the outer part of the accretion disc by the inner, brighter part (e.g. Dubus et al. 1999) and incorporating irradiation effects seem to allow the basic picture of the ionization instability to be applied to X-ray binaries with the data matching the model qualitatively. A few key specific predictions of the model are found in the data – nearly all strong black hole candidates in low-mass X-ray binaries (LMXBs) are observed to be transients, and whether a neutron star will be a transient correlates well with the predictions based on observed mean accretion rate and observed orbital period.

In recent years a new class of X-ray transients has been discovered. These systems have low peak X-ray luminosities and short outburst durations (Muno et al. 2005; Sakano et al. 2005; Wijnands et al. 2006), earning them the name ‘very faint X-ray transients’ (VFXTs). The VFXTs are problematic for binary stellar evolution. The implied mean mass accretion rates from these systems are below about $10^{-13}$ $M_\odot$ yr$^{-1}$, a rate which cannot be reached through normal Roche lobe overflow processes from a star unless the accretion rate changes abruptly (King & Wijnands 2006). Note that by ‘mean mass accretion rate’ we are referring to the mean rate at which matter is transferred from the donor star to the outer accretion disc, and that this is best estimated empirically by averaging the source luminosity over several outburst cycles, and then applying a conversion between mass accretion rate and X-ray luminosity.

In fact, for cataclysmic variables, there exists a well-known situation in which the accretion rate does change abruptly – the period gap. Cataclysmic variables with initial orbital periods less than about 10 h are expected to evolve to shorter orbital periods through magnetic braking. When the systems reach an orbital period of about 3 h, the donor stars are expected to become fully convective, provided that it still has some significant hydrogen content (Plyryser & Savonije 1989; Podsiadlowski et al. 2002), at which point the star quickly shrinks in size, becomes detached and the mass transfer rates drop to a sufficiently low level that cataclysmic variables are not expected to be observed (Warner 1976; Rappaport, Verbunt & Joss 1983; Spruit & Ritter 1983; Patterson 1984). Eventually, at periods of about 2 h, gravitational radiation brings the binary back into contact, and accretion begins again, this time with the evolution of the binary driven primarily by gravitational radiation rather than magnetic braking. In this paper, we show that the properties of the very faint transients are well explained if these systems are LMXBs in the period gap, with a low level of accretion from the weak wind of the M dwarf donor star. We discuss possible observational tests of the scenario.

1 We note that a different model which also invoked wind accretion was proposed for some of the fainter Galactic Centre region X-ray binaries, by Pfahl, Rappaport & Podsadiowski (2002). That model suggested that the winds were from stars of at least 3 $M_\odot$, and is unlikely to explain transients
2 VFXTs as period gap LMXBs

From the analogy with cataclysmic variables, it is clear that X-ray binaries should have a period gap and that the accretion rates of systems within the period gap should be much lower than those for systems at longer or shorter periods. In fact, Spruit & Ritter (1983) noted that there should be a period gap for LMXBs. The more relevant question, then, is whether one can expect a high enough accretion rate for period gap X-ray binaries that these systems would be seen in appropriate numbers and whether the expected properties of the systems would match well to the observed properties of the systems.

2.1 Expected outburst peak luminosities

We address here the question of whether the expected properties of the systems would match well to the observed properties of the systems. The fundamental property of VFXTs is that they have outbursts with low peak luminosities. The peak outburst luminosities of X-ray binaries have been shown to be well correlated with the X-ray binaries’ orbital periods (e.g. Shahbaz, Charles & King 1998; Portegies Zwart, Dewi & Maccarone 2004; Wu et al. 2010). Since the period gap occurs for periods of $\approx 2$–3 h, these will be at the short-period end of the distribution of orbital periods – these systems should have faint outbursts.

A different relation can be used to estimate the peak luminosity, $L_p$, expected from a transient with an orbital period of 2–3 h. First, we can take a theoretical constraint from King & Ritter (1998). They suggest that $L_p = 2.3 \times 10^{30} R_{11}^2$ erg s$^{-1}$, where $R_{11}$ is the outer disc radius in units of $10^{11}$ cm. The binary separation will be about $7.7 \times 10^{10}$ cm, for an orbital period of 2.5 h, if the accretor mass is $1.4 M_\odot$ and the donor mass is $0.25 M_\odot$. The circularization radius of the accretion disc, under the assumption of Roche lobe overflow, will be about 0.2 times the binary separation (see below), while the tidal radius of the accretion disc will be about 0.9 times the radius of the donor star (Frank, King and Raine 2002, hereafter FKR02). These values are the same to within a few per cent, and as we discuss below, even if the wind speed is large, so that the Roche lobe overflow approximation is a poor one, we can still expect that the matter in the disc will spread out until it reaches the tidal radius. The peak $L_p$ can thus be expected to be about $4 \times 10^{35}$ erg s$^{-1}$ for a typical period gap system, consistent with the observations for many VFXTs.

Alternatively, we can take the empirical relations between $L_p/L_{\text{edd}}$ and orbital period. Sources in the range from 2 to 3 h in orbital period are found to be at a few per cent of the Eddington luminosity, yielding an expected peak luminosity of a few $\times 10^{36}$ erg s$^{-1}$ (Wu et al. 2010). However, it should be noted that the biases in the samples of Wu et al. (2010) are such that they should push up the luminosities of the short-period systems – the systems were necessarily detected as transients in order to have been included in the sample, and current all-sky instruments will not detect VFXTs at Galactic Centre distances.

The outburst durations are more difficult to estimate on theoretical grounds. The observed outburst durations of the VFXTs are often short – days to weeks (Wijnands 2008). This is in line with the statistical study of Portegies Zwart et al. (2004), which found that the decay times of outbursts should be a few days at orbital periods of a few hours. When one looks specifically at the few systems with orbital periods between 1.4 and 4.5 h which have well-understood transient outbursts, some systems (e.g. 1A 1744–361) have frequent short outbursts, consistent with our expectations (e.g. Bhattacharyya et al. 2006), while others have longer outbursts (e.g. EXO 0748–676 – Degenaar et al. 2009). We note, on the other hand, that given that in many cases these systems should have accretion discs which extend to or beyond their tidal radii, they may be susceptible to ‘superoutbursts’ like those seen in the SU Uma class of cataclysmic variables (Osaki 1989) – given observational selection effects that work strongly against detecting faint, short outbursts, the X-ray binary equivalent of superoutbursts may represent the dominant mode of outbursts seen from short-period systems by all-sky instruments. In SU Uma stars, the superoutbursts are both brighter and longer than ‘typical’ dwarf nova outbursts.

2.2 Expected mass transfer rates

In this section, we estimate the range of accretion rates possible for these systems, check whether the systems are likely to be transients and then make estimates of the likely duty cycles. The mass transfer rates we calculate should be $\approx 10^{-14}$ to $10^{-15}$ $M_\odot$ yr$^{-1}$ in order for the model to work effectively. If the mass transfer rates are much larger than $10^{-14}$ $M_\odot$ yr$^{-1}$, then the systems will have duty cycles larger than those observed, and frequent outbursts would be expected for a large fraction of the sources. If, on the other hand, the mass transfer rates are much less than $10^{-15}$ $M_\odot$ yr$^{-1}$, then a very large underlying population of sources would be needed just to produce the observed transient events.

There are multiple possible mechanisms for accretion from M dwarfs by neutron stars. The most likely is that the M dwarfs have weak but non-zero stellar winds which can be captured relatively effectively by their neutron star companions. Such winds probably exist as well for Roche lobe overflowing stars, but, because of their low rates, they can be ignored relative to the much larger mass-loss rates passed from the donor star through Roche lobe overflow. These winds may be important, on the other hand, for the case of at least some of the low accretion rate solar systems, cataclysmic variables which show similarly hard-to-explain low mean accretion rates, one of which is found in the period gap (e.g. Schwope et al. 2002).

The mass-loss rates from M dwarfs are highly uncertain. Debes (2006) find typical values of $M$ of about $10^{-14}$ to $10^{-16}$ $M_\odot$ yr$^{-1}$ by looking at a class of white dwarfs which have detectable metal lines in their atmospheres, and assuming that the metals come from accretion of the white dwarf wind. Models of cataclysmic variable evolution implicitly assume mass-loss rates for M dwarfs similar to the solar mass-loss rate of $2 \times 10^{-14}$ $M_\odot$ yr$^{-1}$ (Sills, Pinsonneault & Terndrup 2000; Schreiber & Gaensicke 2003).

Next we can consider the fraction of the mass we can expect to be accreted by the neutron star companion of an M dwarf which is almost but not quite in Roche lobe contact. Assuming a wind speed of the escape velocity from the donor star, the accretion rate due to wind mass transfer can be found to be

$$\frac{M}{-M_W} = \frac{1}{4} \left( \frac{M_{\text{acc}}}{M_{\text{DON}}} \right)^2 \left( \frac{R_{\text{DON}}}{a} \right)^2,$$

where $M$ is the mass rate on to the compact star, $-M_W$ is the mass-loss rate from the donor star, $M_{\text{acc}}$ is the mass of the accretor, $M_{\text{DON}}$ is the mass of the donor star and $R_{\text{DON}}$ is the radius of the donor star (FKR02). For systems which are nearly Roche lobe overflowing, this number will approach unity. There are some
indications that the Bondi–Hoyle rate may overestimate the real wind mass transfer rates by a factor of about 10, especially in systems where the inferred Bondi rate is a very large fraction of the total mass loss from the donor star. It seems quite reasonable for a substantial fraction of M dwarf/neutron star binaries to have mass transfer rates in the $10^{-14}$ to $10^{-16} \, M_\odot \, yr^{-1}$ range where the VFXTs are most likely to be found. Furthermore, there is some evidence that the wind mass-loss rates of rapidly rotating M dwarfs (for example from looking at the rotation periods of M dwarfs in different Galactic kinematic populations), such as those expected to exist in short-period binaries, may be larger than the typical values for more slowly rotating M dwarfs (e.g. Irwin et al. 2011).

2.3 Should discs form?

To test whether accretion discs should form in these wind-fed systems, one can calculate the circularization radius of an accretion disc in the case of an M dwarf in Roche lobe overflow, with an orbital period of 2.5 h, and an M dwarf with a mass of 0.25 $M_\odot$ and a radius of 0.25 $R_\odot$, and we can compare these circularization radii. We note that we have intentionally chosen the radius we use to be slightly smaller than measured radii of M dwarfs (Fernandez et al. 2009) in order to make conservative assumptions about disc formation. We can compute the circularization radius, $R_{circ}$, in terms of the binary separation, $a$, and the binary mass ratio, $q$, in the Roche lobe overflow case by taking equation (4.20) of FKR02,

$$R_{circ}/a = (1 + q)[0.5 - 0.227 \log q]^{1/4},$$

finding that $R_{circ}/a = 0.24$ for this case. We can then take equation (4.42) of FKR02 and find

$$R_{circ}/a = \frac{M_N^2(M_N + M_E)}{16 \pi^2 M_E} \left( \frac{R_E}{a} \right)^4,$$

where $M_N$ is the mass of the neutron star accretor, $M_E$ is the mass of the star emitting a wind and $\lambda$ is the ratio of the wind speed to the escape velocity from the wind emitter. Evaluating with the values given above, and $\lambda = 1$, we find that $R_{circ}/a = 0.20$. This value is about the same as that for standard Roche lobe overflow, so the disc properties should be essentially the same for such a system as for a Roche lobe overflow of the same orbital period. If the wind speed is larger than the escape velocity from the donor star, then the circularization radius will decrease. This effect is potentially quite substantial, even for small changes in the wind speed, given the $\lambda^{-4}$ dependence of the circularization radius. However, it is not clear that a decrease in the circularization radius will have a major effect on the observed properties of the outbursts from these objects, since viscous spreading should cause the disc to spread outwards until it reaches the tidal truncation radius regardless of the circularization radius; as long as the disc circularizes before the gas reaches the accretor, the properties of the disc should be largely unaffected by the circularization radius. Essentially, the systems should have slightly lower peak luminosities and shorter outbursts than systems at orbital periods just longer than systems just above the maximum period for the period gap, and slightly longer, brighter outbursts than those of systems with periods just shorter than the period at which systems leave the period gap.

2.4 Should the systems be transient?

We can now verify that the observed systems should, in fact, be transients. The mean accretion rate needed to sustain a persistent accretion disc with an outer radius of $2 \times 10^{10}$ cm is about $2 \times 10^{15}$ g s$^{-1}$ (Dubus et al. 1999), a factor of about 300 higher than the $10^{-13} \, M_\odot \, yr^{-1}$ which represents the maximum value that could be expected from period gap systems. Even the highest accretion rate systems should be below the accretion rate where discs are stably ionized. We can also check the converse, whether the systems might be stably neutral (see e.g. Menou et al. 1999). To avoid the stable ‘cold branch’ solution, the disc truncation radius must be less than $5 \times 10^8$ cm for a mass transfer rate of $10^{15}$ g s$^{-1}$. The Alfvén radius for a neutron star with a magnetic field of $10^9$ G will be about $6 \times 10^8$ cm for this accretion rate, so the disc can be reasonably expected to extend inwards far enough to allow for a hot state to develop.

2.5 Expected versus observed number of sources

The next issue is the detected number of VFXTs. While we can make a clear case that period gap binaries would make a plausible argument for producing VFXTs, the argument is rather uninteresting if the expected number of objects is so low that only a tiny fraction of the VFXTs could be produced through this mechanism. The bulk of the known VFXTs is found in monitoring observations of the Galactic Centre region, where mass segregation may lead to heavy stars settling into the central parsec (e.g. Muno et al. 2005; Freitag, Amaro-Seoane & Kalogera 2006; Alexander & Hopman 2009), and dynamical formation of X-ray binaries may take place (Voss & Gilfanov 2007). In this region, one might expect to see an excess of X-ray binaries in general, but especially of the classes of X-ray binaries which are oldest (and hence have had the longest amount of time to segregate inwards). Perhaps most importantly, at least in the very centre of the Galaxy, dynamical interactions may form substantial numbers of X-ray binaries; furthermore, it has been suggested that the dynamically formed binaries may preferentially be formed by tidal capture of low-mass ($M \lesssim 0.3 \, M_\odot$) donor stars (Voss & Gilfanov 2007). The dynamical effects and other uncertainties in binary stellar evolution will allow us only to make very crude estimates of the number of VFXTs expected from this scenario. At the same time, the observational constraints on the number of such systems are also not yet very well defined. Still, we can ensure that all the assumptions needed to get the numbers of predicted and observed sources to match are plausible.

Regardless, we can estimate the number of outbursting sources that would be expected by looking at the duty cycles, recurrence time-scales and numbers of the sources. The lifetime of cataclysmic variables in the period gap is about 200 Myr (Spruit & Ritter 1983), and a similar duration should be expected for neutron star LMXBs in the period gap (Podsiadlowski et al. 2002). This duration is comparable to that of the bright phase of LMXB evolution which can be estimated simply by dividing the mass of a typical donor star by the mass accretion rate needed to sustain a bright LMXB, assuming that most neutron stars accrete their entire $\sim 1 \, M_\odot$ companions, and evolve through the period gap. By taking this approach, we can circumvent many of the uncertainties in binary population synthesis modelling.

Therefore, the number of active ($L_X \gtrsim 3 \times 10^{37}$ erg s$^{-1}$) neutron star X-ray binaries in the Galaxy should be roughly equal to the total number of neutron star X-ray binaries in the period gap, since a donor star of $1 \, M_\odot$ will be entirely accreted in 200 Myr to produce that luminosity. If LMXBs with small initial masses (e.g. of $\sim 0.4 \, M_\odot$) are relatively common, or if non-conservative mass transfer dominates for bright neutron star X-ray binaries, or if the masses of the companions to neutron stars are still a substantial fraction of the initial masses at the time accretion stops, then
total number of period gap systems could actually dominate by number over the bright systems observed in any one epoch. For the Milky Way, Grimm et al. (2002) estimate that there are typically about 30 active LMXBs with luminosities of at least 10^{37} erg s^{-1}, so one can safely assume that the Galaxy has at least 20 period gap X-ray binaries. We emphasize again that this number could increase by a factor of a few if the typical amounts of mass accreted over the lifetimes of bright X-ray binaries are significantly less than 1 M_{\odot}. Since 1 M_{\odot} is the upper bound for the mass of the donor stars for LMXBs with neutron star accretors, and many of the LMXBs are even a bit brighter than 3 \times 10^{36} erg s^{-1}, and hence have lifetimes shorter than 200 Myr, this number is thus a conservative lower limit.

The ratio of the number of VFXTs to bright LMXBs could also rise if mass transfer is non-conservative in the LMXB phase. Strong disc winds driven by irradiation and/or magnetic fields have been seen when the accretion discs are bright and in soft states (e.g. Neilsen & Lee 2009; Ponti et al. 2012). In the black hole system A0620-00, a mismatch between the brightness of the hotspot, which indicates the mass transfer rate, and the mean integrated X-ray luminosity has also been noted as tentative evidence that a substantial fraction of the mass is lost due to disc winds (Froning et al. 2011); it also suggested that these winds could be driven in quiescence (e.g. Blandford & Begelman 1999). It would not be unreasonable for the ‘effective lifetime’ of bright LMXBs to drop by a factor of a few due to mass loss from disc winds in outburst, and for this mass loss to have important implications both for the millisecond pulsar birth rate problem (e.g. Kulkarni & Narayan 1988) and for the fact that the typical millisecond pulsar seems to have accreted only \sim 0.2 M_{\odot} (e.g. Zhang et al. 2011), but clearly more work is needed before this can be stated definitively. All these concerns taken together, it seems reasonable that the number of period gap X-binary systems in the Galaxy at the present time should not be less than \sim 30. At the same time, the number can reasonably be expected to exceed a few hundred only if the rate of LMXB formation was considerably larger in the past than it is now.

If the typical outburst exponential decay time-scale for the VFXTs is about one week, and the peak luminosity is typically about 10^{35} erg s^{-1}, then with radiatively efficient accretion, one can estimate that about 10^{-13} M_{\odot} is accreted per outburst. For objects at the high end of the range of wind mass transfer rates given above (i.e. M \sim few \times 10^{-14} M_{\odot} yr^{-1}), the outburst recurrence time-scale should be every few years, consistent with what is seen from the most frequently recurring VFXTs (e.g. Degenaar et al. 2012).

Next, we can use the variability survey of Degenaar et al. (2012) to make a rough estimate of the number of VFXTs in the Galaxy. This survey covered the central 1.2 deg^{2} of the Galaxy with 10 epochs of data obtained over the course of 4 years. Each epoch reached a flux level corresponding to a luminosity of 5 \times 10^{36} erg s^{-1} if at the Galactic Centre. If we assume that the typical VFXT will have a peak luminosity of 10^{35} erg s^{-1}, and an exponential decay with a time-scale of a few weeks, then these systems should remain detectable for a few weeks, and most sources which undergo outbursts should have been detected in the 10 epochs spread over 4 years. Degenaar et al. (2012) reported the detection of 10 VFXTs in their survey, so the total number in the central 1.2 deg^{2} of the Galaxy is unlikely to be significantly more than about 20 – Degenaar et al. (2012) reached similar conclusions on the basis of the fact that no new transients were detected during this survey (most of the region had already been surveyed e.g. by Munu et al. 2006), and many had been seen as recurring transients.

Next we must extrapolate the number of VFXTs seen in the central region of the Galaxy to the Galaxy as a whole. We can take the bulge model of Kent (1992), and integrate out the bulge luminosity to a projected radius of 40 pc, getting a total luminosity of about 4 \times 10^{4} L_{\odot}, which is about 2 per cent of the total luminosity of the Milky Way. We can thus expect that there should be \sim 500 VFXTs in the Galaxy. This number is a factor of only a few larger than the crude population estimate above. Furthermore, the observations suggest that there must really be some dynamical enhancement of the VFXT numbers; four of the 10 VFXTs in the sample of Degenaar et al. (2012) are located within the central 25 arcsec of the Galaxy, which contains only about one region. One of those objects is likely an edge-on system with a 7.9-h period (see below for more discussion), but the other three may very well be dynamically formed systems as in the scenario presented by Voss & Gillanov (2007). Ignoring the central 2 pc of the Galaxy yields excellent agreement between predicted and observed numbers of systems. It does require that the accretion rates be near the upper end of the possible range of accretion rates – but the fact that many of the systems are observed to be recurrent transients already requires that; and it does require that the typical neutron star in an LMXB accretes no more than about 0.2 M_{\odot} – but there are indications for this already from the estimated masses of neutron stars and the millisecond pulsar birth rates, and mechanisms for explaining this in terms of disc winds, and both the alternative evidence for low total amount of accretion and mechanisms for reducing this amount from the total masses of the typical donor stars are independent of the motivations of this paper.

3 THE EFFECT OF BLACK HOLE ACCRETORS

The shortest period dynamically confirmed black hole system known, XTE J1118+480, shows a peak X-ray luminosity of about 1.5 \times 10^{36} erg s^{-1}, just above the luminosities of the VFXTs, and has an orbital period of about 4.1 h, just longer than the period in the period gap. Given that this source remained in a low/hard state for its entire outburst, its low peak luminosity may be partly due to its low radiative efficiency, if, for example, the hard state is well described by an advection-dominated accretion flow (e.g. Narayan & Yi 1994) – black hole systems with such short orbital periods should all be expected to be below the 2 per cent of the Eddington luminosity where systems are generally found in low hard states (Maccarone 2003), and said radiative inefficiency should set in.

One can then assume that \sim L_{X} \propto \dot{m} (m/0.02 m_{\text{edd}}), where m_{\text{edd}} is the mass accretion rate needed to get a source up to the Eddington luminosity for radiatively efficient accretion. The critical accretion rate for triggering an outburst scales as R_{o} or as \dot{P}_{\text{crit}}^{3/4}, assuming that the ratio of the circularization radius to the orbital separation is a weak function of the orbital period (e.g. FKR92). The critical X-ray luminosity will then scale as \dot{P}_{\text{crit}}^{3/4}. We then can take XTE J1118+480 as a typical example, and find that black hole X-ray binaries with orbital periods less than 3.6 h will peak at X-ray luminosities below 10^{36} erg s^{-1}, making them VFXTs. The duty cycles of the outbursts of such systems will also be lower than inferred from assumed that the systems are radiatively efficient by factors of a few, meaning that the inferred mass transfer rates become possible in the context of normal binary evolution. On the other hand, black hole X-ray binaries cannot explain VFXTs with Type I bursts (e.g. Del Santo et al. 2007), so one cannot explain the whole VFXT population as black hole X-ray binaries in radiatively inefficient spectral states.
4 POSSIBLE TESTS OF THE SCENARIO

The most obvious test of this mechanism obviously comes from measuring the orbital periods of the systems and seeing that they are in the period gap. The observed period gap is from 2.1 to 3.1 h for cataclysmic variables (Knigge 2006). Such measurements can be made in the optical or infrared (IR) from ellipsoidal modulations, but the volume out to which they are feasible is rather small, given the faintness of the donor stars. It would not be surprising if a substantial fraction of the period gap accretors turn out to be accreting millisecond X-ray pulsars. Indeed, of the two known X-ray binaries that have been measured to fall into this range of periods, one is IGR J00291+5934 (Galloway et al. 2005), an accreting millisecond pulsar. Galloway et al. (2005) argue that that object is likely to be fed from a substellar mass donor in Roche lobe contact, in part on the basis of the requirement of a very low inclination angle needed to allow a main-sequence hydrogen-rich donor star. The other is a black hole system, MAXI J1659−152, which has been suggested to have a donor star made mostly of helium, which would allow the star to maintain Roche lobe contact even at a short orbital period (Kuulkers et al. 2012).

It should be noted that both of these systems have periods within the empirical period gap found for cataclysmic variables. They are at shorter periods than those expected in the calculations of Podsiadlowski et al. (2002) for X-ray binaries which are not binoculated at the start of mass transfer, but in the period gap for some ranges of systems which are partially evolved at the start of mass transfer.

One VFXT has been reported to show suggestive evidence of an orbital period of 7.9 h (Muno et al. 2005). This system does not refute the scenario for producing VFXTs we present here. First, Muno et al. (2005) note that the integration time on this object is only 14 h, less than two cycles of the putative orbital period, and thus they urge caution in interpreting the data. Secondly, they note that if the periodicity is real, it is likely to come from an eclipse. Eclipsing X-ray binaries are usually ‘accretion disc corona’ (ADC) sources, where the observed X-ray luminosity is only 1–10 per cent of the intrinsic luminosity (e.g. Bayless et al. 2010). Transient ADC sources may represent a fraction of the VFXTs, but are unlikely to represent the bulk of them – since geometric considerations indicate that there should be several transients observed at lower inclinations angles for every transient ADC source.

4.1 Optical peak brightness of VFXTs

An additional test is that the outbursts of the VFXTs should be faint in the optical and near-IR bands (with the near-IR likely being more important observationally because searches for these objects are dominated by monitoring campaigns on heavily extinct regions near the Galactic Centre). Taking the V-band luminosity to be \( L_V \), one expects that \( L_V \propto L_X^{1/2}R \) if the optical flux is dominated by reprocessing of X-rays which illuminate the outer accretion disc, and it has been shown that this relation holds up well when compared with real data (van Paradijs & McClintock 1994; Russell et al. 2006). This method provides only crude orbital period estimates, especially when combined with uncertainties in source distance and whether the accretor is a black hole or a neutron star. The one VFXT for which good simultaneous optical and X-ray data have been obtained, XTE J1119−291, has X-ray and optical luminosities consistent with those seen from the 2-h period system SAX J1808−365, provided the source is at a distance of 8 kpc (Armas-Padilla et al. 2011). This test is only a weak one, since the differences between black holes and neutron stars can lead to large differences in the inferred orbital period for a system, and differences in inclination angle can lead to substantial uncertainties, since at low luminosities, the X-rays are likely to come from relatively large scale height regions, while the optical emission necessarily comes from a thin disc. At low luminosities, the donor star’s optical emission and jet emission can also become important. None the less, any VFXTs which can be confirmed (e.g. by bursting) to be neutron stars should have relatively faint peak outburst fluxes in the optical and IR.

4.2 Superhumps

In the context of this model, the VFXTs should all be good candidates to show superhumps in outburst. Superhumps are periodic variations with time-scales a few per cent longer than the orbital period of the binary system, and are seen in binaries with mass ratios less than about 0.35 (Patterson et al. 2005). The origin of the periodicity is thought to be due to the growth of an eccentricity in the outer accretion disc (e.g. Whitehurst 1988). Since period gap systems with neutron star accretors will always have mass ratios less than about 0.18, they are comfortably within the range of mass ratios where superhumps should be seen. It may thus be that the regular dwarf nova type outbursts produce VFXT-like outbursts, and the superoutbursts, which show superhump behaviour, produce the brighter outbursts from systems with similar orbital periods which have already been seen with all-sky instruments.

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