

The faintest accretors

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ABSTRACT

Recent X-ray observations have detected a class of very faint X-ray transients in the Galaxy which probably reveal a previously unrecognized type of accretion on to neutron stars or black holes. We show that these systems cannot have descended from binaries with stellar-mass components of normal composition. Accretion of hydrogen-depleted matter on to stellar-mass black holes can account for individual systems, but requires that these transients should be observed to repeat within a few years, and does not explain why the class is distinctly faint.

Two other explanations appear to be quite natural. One invokes accretion by neutron stars or stellar-mass black holes from companions that were already brown dwarfs or planets when the systems formed, i.e. which did not descend from low-mass stars. The other possibility is that these systems are the endpoints of primordial (zero-metallicity) binaries in which the primary was extremely massive, and collapsed to a black hole of mass $\gtrsim 1000 M_{\odot}$. The (primordial) companion must by now have reached an extremely low mass ($\lesssim 0.01 M_{\odot}$) and be transferring mass at a very low rate to the black hole. This picture avoids the main difficulty encountered by models invoking intermediate-mass black hole formation at non-primordial metallicities, and is a natural consequence of some current ideas about Population III star formation.

Key words: accretion, accretion discs – black hole physics – binaries: close – X-rays: binaries.

1 INTRODUCTION

Recent sensitive X-ray observations of Galactic fields (e.g. Sakano et al. 2005; Munro et al. 2005a) have revealed the existence of a class of very faint X-ray transients (henceforth VFXTs) with peak outburst luminosities between 10^{34} and 10^{36} erg s⁻¹, and quiescent states at least a factor of 10 below their peak values. A large number of them are found very close (within 10 arcmin: e.g. Munro et al. 2005a) to Sgr A* although several are found at larger distances [see e.g. Hands et al. (2004) who reported on a VFXT about 20° away from Sgr A*]. Accretion on to a black hole or neutron star is the most likely origin of this luminosity, as only one white dwarf accretor (GK Per: Watson, King & Osborne 1985) is observed to have X-ray outbursts as bright. The outburst peak luminosities of the VFXTs are several orders of magnitude lower than the peak luminosities observed for the classic X-ray transients in our Galaxy (e.g. Chen, Shrader & Livio 1997). Observational limitations mean that our knowledge of the duty cycle of the VFXTs is sketchy at best (Munro et al. 2005a). However, if this is $\lesssim 10$ per cent, as is common for the brighter X-ray transients, typical accretion efficiencies of 10^{20} erg g⁻¹ imply that the mean accretion rates on to these black holes or neutron stars in VFXTs must be extraordinarily low, i.e. $\lesssim 10^{-13} M_{\odot}$ yr⁻¹. These correspond to mean luminosities $\lesssim 10^{33}$ erg s⁻¹ and thus very cool accretion discs. This means that

the thermal–viscous disc instability can operate, switching the accretion discs between high- and low-viscosity states, and thus making the systems transient (King, Kolb & Burderi 1996; cf. King 2000). Hence, despite their very low mean luminosities, these systems are potentially detectable when using sensitive X-ray instruments (e.g. *Chandra* or *XMM-Newton*) because they save up their accretion energy for release in short outbursts.

The mass transfer rates of the VFXTs are a factor of 10–100 less than the mean rates in the *BeppoSAX* transients reported by Heise et al. (1999). King (2000) suggested that these *BeppoSAX* transients might be low-mass X-ray binaries (LMXBs) which had passed the minimum orbital period, and are currently accreting from very low-mass ($\lesssim 0.1 M_{\odot}$) companions which are largely degenerate. Detailed calculations by Bildsten & Chakrabarty (2001) tend to support this picture. The fainter VFXTs reported above clearly present a challenge to theory, which this Letter takes up.

2 MODELS FOR VERY FAINT X-RAY TRANSIENTS

The source properties (e.g. spectral behaviour: Sakano et al. 2005; temporal behaviour: Munro et al. 2005a,b) indicate that the VFXTs are probably not a homogeneous set of sources and several models may be needed to explain all of them. One possibility is that these transients are wind-fed X-ray transients: the accretor (apparently always a strongly magnetic neutron star) accretes from the equatorial

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disc of a Be star companion. The outbursts can be arbitrarily faint. However no optical/infrared companions of VFXTs have so far been detected, suggesting that most VFXTs harbour companions fainter than B2 IV stars (e.g. Munro et al. 2005a). This in turn suggests that at least a sizable fraction of these systems accrete from relatively low-mass companions. Moreover, two VFXTs (GRS 1741.9–2853: Cocchi et al. 1999;¹ SAX J1828.5–1037: Cornelisse et al. 2002; Hands et al. 2004) have shown type I X-ray bursts. Only neutron stars accreting from low-mass companions have so far been observed to show such bursts, providing additional evidence that a significant fraction of the VFXTs might be LMXBs. However, as we shall see, the requirement that mass transfer from a Roche-lobe-filling companion should drop to values $\lesssim 10^{-13} M_{\odot} \text{ yr}^{-1}$ within a Hubble time poses extremely tight constraints on the nature of these systems. Accordingly, we briefly consider other types of explanations for the VFXTs.

A number of known LMXBs appear fainter than their true luminosities because we view them at unfavourable angles (e.g. White & Holt 1982), and at least one VFXT appears fainter than its intrinsic luminosity because of inclination effects (Munro et al. 2005b). One might ask if the VFXT class are the ‘accretion disc corona’, and ‘dipping’ sources belonging to an intrinsically faint population of LMXBs. However, the range of inclination angles over which accretion disc corona and dipping behaviour can be seen is quite small. If we generously allow a range from $i = 60^{\circ}$ to 90° for this behaviour, a random distribution of orbital inclinations should give roughly equal numbers of brighter LMXBs mixed in with the VFXTs (solid angle $\propto \cos i$). This is quite contrary to the observed distribution around the Galactic Centre, where observations go deepest, which is dominated by VFXTs (e.g. Munro et al. 2005a; Wijnands et al. 2005).

Another idea invoking orthodox LMXB evolution is that of long-term variability. Binaries transferring mass via Roche-lobe overflow can deviate significantly from the evolutionary mean mass transfer rate for a time-scale of the order of $(H/R_2)t_M$, where $H/R_2 \simeq 10^{-4}$ (Ritter 1988) is the ratio of atmospheric scaleheight H to radius R_2 for the mass-losing star, and $t_M = -M_2/\dot{M}_2$ is the mass transfer time-scale ($M_2 =$ companion mass, $-\dot{M}_2 =$ mass transfer rate). This can happen for a variety of reasons, e.g. the motion of starspots under the L_1 point (cf. King & Cannizzo 1998; King 2006), or through irradiation-driven cycles (cf. King et al. 1995).

For the VFXTs the mass transfer rate can thus depart from the mean for a time-scale $\sim 10^9 m_2 \text{ yr}$, where $m_2 = M_2/M_{\odot} \lesssim 1$ for an LMXB. This is significantly less than the age of the Galaxy and (by construction) significantly less than the lifetime of the LMXB. Thus again the VFXTs should be accompanied by a set of much brighter systems at or above the evolutionary mean mass transfer rate, and indeed at intermediate luminosities. While it is impossible to rule this possibility out completely, one would need a candidate mechanism (say of radius variations of the companion) which would cause the transfer rate to decrease by very large factors. Precisely the same argument applies to systems just beginning Roche lobe overflow.

As explained above, no early-type companion has so far been detected for any VFXTs, suggesting that most are not wind-accreting systems. One might seek to evade this difficulty by invoking accre-

tion from the wind of a fainter low-mass star. However, the system must eventually evolve into a state where the companion fills its Roche lobe, giving a brighter and probably longer-lasting system. Again the lack of brighter systems mixed in with the VFXTs makes this idea implausible.

INTEGRAL has detected a class of X-ray binaries with such high intrinsic absorption (equivalent hydrogen columns $\gtrsim 10^{23-24} \text{ cm}^{-2}$) that much of the primary X-ray emission is absorbed and reradiated at longer wavelengths (Walter et al. 2003). However, most of these systems appear to be high-mass systems, with the wind of the companion providing the absorption. As discussed above, such systems are not good models for VFXTs.

We conclude that none of these alternative ideas provides a tenable picture of the VFXTs. However, all of the arguments against them invoke the properties of the whole population, rather than individual source characteristics. This means that we cannot rule out the possibility that *some* of the VFXTs belong to one or other of these classes. Indeed, this is extremely likely.

3 ACCRETION FROM VERY LOW-MASS COMPANIONS

Here we test whether Roche lobe overflow from a low-mass degenerate companion offers a viable explanation for VFXTs. For a simple picture we model the companion as an $n = 3/2$ polytrope with radius

$$R_2 \simeq 10^9 (1 + X)^{5/3} m_2^{-1/3} \text{ cm}, \quad (1)$$

where m_2 is the companion mass in M_{\odot} . This permits an analytic description of the evolution and thus makes the dependences on various parameters transparent. Specifically we use the formulae from King (1988), but retain explicitly the dependences on primary mass m_1 (in M_{\odot}) and fractional hydrogen content by mass X . We consider the effect of relaxing these assumptions at the end of this section.

Gravitational radiation drives a mass transfer rate

$$-\dot{m}_2 = 1.3 \times 10^{-3} (1 + X)^{-20/3} m_1^{2/3} m_2^{14/3} \text{ yr}^{-1}. \quad (2)$$

Integrating this gives

$$m_2 = m_0 \left[1 + 4.8 \times 10^{-3} (1 + X)^{-20/3} m_1^{2/3} m_0^{11/3} t \right]^{-3/11}, \quad (3)$$

where m_0 (in M_{\odot}) is the companion mass at time $t = 0$. Then (2) gives the transfer rate as an explicit function of time:

$$-\dot{m}_2 = \frac{1.3 \times 10^{-3} (1 + X)^{-20/3} m_1^{2/3} m_0^{14/3}}{[1 + 4.8 \times 10^{-3} (1 + X)^{-20/3} m_1^{2/3} m_0^{11/3} t]^{14/11}}. \quad (4)$$

We see from (2) that to ensure the required transfer rates $\lesssim 10^{-13} M_{\odot} \text{ yr}^{-1}$ to explain the VFXTs, current masses $m_2 \lesssim 0.014 m_1^{-1/7}$ are needed for hydrogen-rich companions, and still smaller ones ($m_2 \lesssim 0.0068 m_1^{-1/7}$) for hydrogen-poor companions. Clearly one way of ensuring these would be to postulate that the companions came into contact with masses of these orders. This would require brown dwarf or planetary companions. If we assume instead that the companion came into contact with a normal stellar mass, but has been whittled down to the required low current mass through mass transfer in the past, we must take $m_0 \gtrsim 0.1$. Then for times $t \gg t_0 = 200(1 + X)^{20/3} m_1^{-2/3} m_0^{-11/3}$ the constant 1 in the denominator is negligible: since $t_0 \lesssim 2 \times 10^8 \text{ yr}$ (even taking $X = 1$, $m_0 = 0.1$) this is essentially all of the evolution. Then we get the simplified formula

$$-\dot{m}_2 = 2 \times 10^{-13} (1 + X)^{20/11} m_1^{-2/11} (t/t_0)^{-14/11} M_{\odot} \text{ yr}^{-1}, \quad (5)$$

¹ We note that GRS 1741.9–2853 has shown peak outburst X-ray luminosities of a few $\times 10^{36} \text{ erg s}^{-1}$, which would place it just outside our maximum X-ray luminosity of $10^{36} \text{ erg s}^{-1}$ for classification as VFXTs.

where $t_{10} = t/10^{10}$ yr: we note that estimates of the Hubble time require $t_{10} \lesssim 1.37$.

The result (5) shows that with normal primary masses ($m_1 \lesssim 10$), hydrogen-rich companions are ruled out, and even hydrogen-poor companions ($X = 0$) are not promising candidates for explaining VFXTs. The general problem is that the predicted mass transfer rates are too low to reduce the companion from a normal stellar mass to the very small values $\lesssim 0.01 M_{\odot}$ needed to explain the VFXTs within the age of the Galaxy. This problem is exacerbated if we consider more detailed models for the binary evolution. Bildsten & Chakrabarty (2001) show that the companion is likely to evolve at constant radius rather than the $R_2 \propto m_2^{-1/3}$ polytrope considered above. This makes the time to reach the required low masses still longer. We conclude that stretching ‘standard’ LMXB evolution to its limits does not explain the VFXTs.

4 DISCUSSION

We have seen above that standard LMXB evolution is too slow for initially stellar-mass companions to reach the very low masses that the VFXTs probably have. There are evidently three ways out of this impasse:

- (a) VFXT companions are hydrogen-poor, or
- (b) VFXTs are born with very low companion masses, or
- (c) VFXTs evolve more quickly than assumed above, i.e. they have larger accretor masses m_1 than assumed there.

4.1 (a) Hydrogen-poor companions

From (5) we see that transfer rates $\sim 10^{-13} M_{\odot} \text{ yr}^{-1}$ are just possible if $X = 0$, $t_{10} = 1.37$ and $m_1 > 5$. Thus VFXTs would have to be extremely old black hole LMXBs with hydrogen-poor companions. This explanation requires that the transfer rates are not significantly lower than the $10^{-13} M_{\odot} \text{ yr}^{-1}$ inferred by assuming a 10 per cent duty cycle for the transient outbursts, and hence that VFXT outbursts are seen to repeat in a few years. In addition, any optical identifications should show an absence of hydrogen.

Before accepting this idea as a viable model for VFXTs, it is clear that more elaborate evolutionary calculations with full stellar models for the companion are needed. In any case, the main weakness of this fairly conservative explanation is that it gives no reason for the defining feature of the VFXT class, namely that their inferred luminosities are distinctly lower than for other accreting systems.

4.2 (b) Low initial companion masses

LMXBs with very low-mass companions are known, e.g. HETE J1900.1–2455 (Kaaret et al. 2005). Here the reported companion mass could be as low as $0.016 M_{\odot}$, i.e. almost down at the value inferred above for most VFXTs. Unless HETE J1900.1–2455 is in an unusual short-lived stage, however, the work of this Letter shows that the companion mass must have been similarly low at formation, and not the result of mass transfer from an initially stellar-mass companion. The same conclusion holds if we want to explain a significant fraction of the VFXT population in this way. Evidently the companion must start life as a brown dwarf, or possibly a planet, and somehow survive the eventful evolution of its stellar companion (expansion, and possible supernova). A further constraint is that this object must eventually fill its Roche lobe, despite having little orbital energy to contribute to any common-envelope ejection. Despite these difficulties, the mere existence of HETE J1900.1–2455

shows that this type of model for the VFXTs is clearly possible. To see if this model explains why VFXTs have distinctly low luminosities probably requires one to understand the initial masses of brown dwarfs.

4.3 (c) Larger mass accretor

Equation (5) shows that hydrogen-rich systems which initially have stellar-mass companions require accretor masses

$$m_1 \gtrsim 5(1 + X)^{10} \simeq 1000. \quad (6)$$

Hence this type of explanation requires VFXTs to contain intermediate-mass black holes (IMBHs). There are claims that such black holes may form by rapid dynamical processes in dense clusters (e.g. Portegies Zwart et al. 2004; Gürkan, Freitag & Rasio 2004) or through capture of the nuclei of small satellite galaxies (e.g. King & Dehnen 2005). However, the fact that the VFXTs are evidently extremely old systems offers an attractive alternative.

Namely, this kind of VFXT is the natural endpoint for a *primordial* (Population III) binary containing a very massive star with a normal-mass companion. At primordial metallicities (say $Z < 10^{-4}$) the formation of very high-mass stars is quite possible: moreover, the lack of metals means that they retain most of their mass on collapsing to form a black hole, i.e. they form an IMBH (cf. Madau & Rees 2001). (IMBH formation scenarios invoking formation in clusters fail this test, as at non-primordial metallicities massive stars lose almost all their mass via metal-driven winds and ultimately form only stellar-mass black holes.) As we have seen, the evolution of such binaries effectively grinds to a halt once the companion has reached masses $m_2 \sim 10^{-2}$. Such systems would appear as VFXTs. A second potentially attractive feature also appears naturally. Such systems would probably spiral toward the Galactic Centre by dynamical friction. This offers a possible explanation if the reported excess of VFXTs near the Galactic Centre is confirmed (Muno et al. 2005a).

Observing programmes to monitor the VFXTs in the Galactic Centre region are continuing (see Wijnands et al. 2005 for details). We have seen that extremely low mass transfer rates in X-ray sources can pose very tight constraints and suggest far-reaching conclusions. So for once it may be that *non-detections* in repeated observations, which drive down the mean luminosities of these objects, could be as interesting as detections.

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