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On the recurrence times of neutron star X-ray binary transients and the nature of the Galactic Centre quiescent X-ray binaries

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ABSTRACT

The presence of some X-ray sources in the Galactic Centre region which show variability, but do not show outbursts in over a decade of monitoring has been used to argue for the presence of a large population of stellar mass black holes in this region. A core element of the arguments that these objects are accreting black holes is the claim that neutron stars (NSs) in low-mass X-ray binaries (LMXBs) do not have long transient recurrence times. We demonstrate in this paper that about half of the known transient LMXBs with clear signatures for NS primaries have recurrence times in excess of a decade for outbursts at the sensitivity of MAXI. We furthermore show that, in order to reconcile the expected total population of NS LMXBs with the observed one and with the millisecond radio pulsar (MSRP) population of the Galaxy, systems with recurrence times well in excess of a century for outbursts detectable by instruments like MAXI must be the dominant population of NS LMXBs, and that few of these systems have yet been discovered.

Key words: accretion, accretion discs – stars:binaries:close – stars: neutron – X-rays: binaries.

1 INTRODUCTION

Low-mass X-ray binaries (LMXBs) are binary systems with low-mass donor stars (i.e. $\lesssim 1\,M_\odot$) and black hole or neutron star (NS) accretors. Most of these systems are susceptible to ionization instability effects that make their accretion discs have transient outbursts, which are quite similar to the dwarf nova instabilities seen in cataclysmic variable stars (Mineshige & Wheeler 1989; Lasota 2001), with modifications to the temperature profiles of the discs being required due to the stronger irradiation of the discs by X-rays from their inner regions in the X-ray binaries (van Paradijs 1996; Dubus, Hameury & Lasota 2001), resulting from to the deeper gravitational potential wells of their accretors. Outbursts may also, in principle, be triggered by variations in the mass transfer rate from the donor star (Bath 1975), and these effects may be responsible for factors of few variability in quiescence in accretion discs around black holes and NSs (Cantrell et al. 2008; Cackett et al. 2010; Bernardini & Cackett 2014) and almost certainly are responsible for some long, weak outbursts in accreting white dwarfs (Rivera Sandoval et al. 2021).

Among the known samples (which are strongly biased towards sources bright enough to trigger all-sky instruments), typical black hole X-ray binaries show peak luminosities in their transient outbursts of $10^{37} - 10^{39}$ erg s^{-1} (Tetarenko et al. 2016a), while typical NS LMXBs show peak luminosities about a factor of 10 fainter (Yan & Yu 2015). The peak luminosities show a clear correlation (with some scatter) with the orbital period of the binary (Wu et al. 2010), another phenomenon analogous to that in the cataclysmic variables (Warner 1987). This is expected if a critical mass density must be reached in the outer accretion disc to trigger an outburst, since the larger discs will then have a greater total amount of mass transported. The quiescent luminosities of these systems also correlate reasonably well (again, with some scatter) with the orbital periods (Garcia et al. 2001; Reynolds et al. 2014), and are typically 3–8 orders of magnitude lower than those in near the peaks of the outbursts. This is expected if the accretion rate in the inner disc scales with the mass transfer rate into the outer disc for all quiescent X-ray binaries, and the mass transfer rate correlates with the orbital period, as expected from binary evolution scenarios (see e.g. King, Kolb & Burderi 1996).

A variety of classes of surveys have the potential for finding X-ray binaries in quiescence – X-ray surveys (Jonker et al. 2011), optical emission line surveys (Casares 2018), flat spectrum radio source surveys (Maccarone 2005; Maccarone et al. 2018), binary wobble (Gould & Salim 2002; Breivik, Chatterjee & Larson 2017; Thompson et al. 2019; Jayasinghe et al. 2021) all hold potential for finding these systems. At the present time, discovery of X-ray binaries in quiescence has been mostly limited to sources in or near globular clusters (e.g. Rutledge et al. 2002; Heinke et al. 2003; Tetarenko et al. 2016b; Bahramian et al. 2020), while X-ray all-sky monitors (ASMs), which have been deployed for most of the past 50 yr, and continuously since the launch of RXTE in late 1995, can detect bright (i.e. $L_X >$ 10^{37} erg s^{-1}) outbursting X-ray binaries over most of the Milky Way.

A substantial number of low-luminosity outbursting and quiescent X-ray sources have been identified near the Galactic Centre (Muno et al. 2003, 2005; Degenaar & Wijnands 2009; Degenaar et al. 2012), which is one of the regions with sufficiently deep X-ray data in which to detect quiescent X-ray binaries and with sufficient monitoring by

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pointed instruments to detect faint ($\sim 10^{35}$ erg s^{-1}) outbursts. Sixteen of the quiescent objects in this data set have been argued to be quiescent stellar mass black holes (Hailey et al. 2018; Mori et al. 2021) and it is further argued that these represent a set of gas-capture binaries, with ∼300 such black hole binaries in the nuclear star cluster (Tagawa, Haiman & Kocsis 2020). These objects have X-ray spectra inconsistent with magnetic cataclysmic variable stars, which show strong iron emission lines (Hailey et al. 2018). They are brighter than most, but not all, non-magnetic CVs, and while the non-magnetic CVs have weaker emission lines than the magnetic ones, even the non-magnetic CVs would have stronger iron emission than these systems (Mori et al. 2021). None has shown an X-ray outburst (although most do show substantial non-outburst variability). A core argument of Hailey et al. (2018) is that the lack of bright outbursts from these systems demonstrates that they are extremely likely to have black hole accretors. Specifically, Hailey et al. (2018) argue that they rule out neutron-star, LMXB as candidates for these objects because the large outbursts of accreting NSs have recurrence times of about 5–10 yr. That statement is the only argument made by Hailey et al. (2018) that the systems they identify as black hole accretors cannot be NSs. The same arguments are repeated in Mori et al. (2021), with the latter paper acknowledging that not all NSs which have large outbursts recur on time-scales less than 10 yr, but treating the more infrequently recurrent systems as irrelevant outliers.

In this Letter, we show that multiple lines of evidence indicate that the lack of outbursts over 2–3 decades cannot be used as reliable evidence that these sources are black holes. We show by reference to the literature that (1) a large fraction of known NS LMXBs shows outbursts with long recurrence times, and that (2) the sample of known NS LMXBs is much smaller than predicted by binary evolution models and much smaller than the size of the population needed to produce the observed population of millisecond radio pulsars (MSRPs). In neither of the papers claiming a population of quiescent black hole X-ray binaries in the Galactic Centre region (Hailey et al. 2018; Mori et al. 2021) do they define a 'large' outburst quantitatively, but from context, it is clear that they are referring to the kinds of outbursts that can trigger all-sky instruments. For the purposes of this paper, we take that to be a luminosity of 2×10^{36} erg s^{-1} or more, which would trigger typical ASMs at Galactic Centre distances. We define long recurrence times to be recurrence times of at least 10 yr, again based on the claim by Hailey et al. 2018 that recurrence times longer than 10 yr are indicative of black holes, rather than NS accretors. Within the context of the above definitions, we show that NS accretors frequently have long recurrence times for their large outbursts.

2 TRANSIENT PROPERTIES OF OUTBURSTING SYSTEMS

When looking at the sample of transients seen with the RXTE ASM above 100 mCrab,[1] Yan & Yu (2015) find that 14 different NS accretor objects had a total of 68 transient outbursts. About 72 per cent of the outbursts came from three sources, Aql X-1, 4U 1608-52, and MXB 1730-33 (the Rapid Burster). The former two objects can both be inferred to have subgiant donor stars based on their orbital periods of 18.9 and 12.9 h, respectively. This leads to mass transfer driven by the expansion of the donor star, which gives a higher mass transfer rate than is possible in most shorter period systems (King et al. 1996); at the same time, the accretion disc radii are not dramatically bigger than for main sequence donor systems, so the ratio of the accretion rate to the critical accretion rate for stability (Lasota 2001) is higher, and the duty cycle of the outbursts is higher as well. Due to the Rapid Burster's location in Liller 1, a highly reddened globular cluster, its donor star cannot be studied.

It is, thus, clear that the number of *outbursts* seen from NS LMXBs is dominated by the systems with a short recurrence time, even if the number of known *outbursting objects* is not. It is likely because of these systems that a point of astronomical lore has developed that the NS LMXBs are predominantly systems with short recurrence times. It is also true that there are many LMXBs with NS accretors that appear to be persistent accretors.[2] The frequently recurrent transients and the persistent sources generally dominate the total number of publications in the literature, because the amount of useful data for these sources is so much greater than for the long recurrence time transients.

It is clearly *not* the case that the number of *systems* is dominated by short recurrence time transients. Even in the Yan & Yu (2015) study, which considered data only from RXTE, 5 of the 14 studied systems show only a single outburst, and 4 more objects show only two outbursts. Therefore, given the 16-yr long mission lifetime for RXTE, the majority of the NS X-ray binary transients that reached 100 mCrab in the RXTE era were systems with recurrence times of at least 5 yr, and more than 1/3 of the systems have recurrence times of at least 8 yr. *By number of sources*, rather than by number of outbursts, the relatively long recurrence time transients are quite common. When attempting to interpret quiescent systems, it is the number of sources that must be considered, rather than the number of outbursts. In fact, if there is a substantial number of single outburst transients in the sample, then they should be assumed to represent a much larger underlying population of transients that have recurrence times longer than the duration of existing surveys. Similarly, the classical novae are generally believed to have typical recurrence times of thousands to tens of thousands of years based in part on models and in part on the fact that so few of them recur, meaning that the typical recurrence time-scale must be significantly longer than the roughly one century duration over which optical monitoring programmes have been able to identify them. Also similarly, there is a small subset of 'recurrent novae' which can recur as quickly as yearly (Bode 2011).

We can further examine the known transient population to illustrate the need for a large population of long recurrence time transients. We start from the Liu, van Paradijs & van den Heuvel (2007) catalogue of X-ray binaries, and add to it, in Table 1, a set of NS LMXBs that showed their first transient outbursts after that catalogue was finalized. We limit the Liu et al. (2007) sources to those which are identified as transients, and which show evidence for either bursts, pulsations, or quiescent soft thermal emission that can be used to classify them clearly as NS LMXBs. We furthermore exclude sources which are in sufficiently crowded regions that either outbursts from them can be missed (e.g. 1M 0836–425, which is very close to a bright accreting pulsar) or where the poor positional accuracy of some early all-sky missions means that there may be several sources with individual outbursts or a recurrent transient (e.g. sources in the Galactic Centre region that do not have sub-arcminute follow-up). We also exclude sources for which the peak fluxes were less than 30 mCrab, since those could not be discovered with the RXTE ASM. Within the excluded sample are likely to be several additional NS

[1] This corresponds to 1.5×10^{37} erg s^{-1} at 8 kpc.

[2] It is likely that most are persistent, but a small fraction of these objects may be systems with outburst durations that exceed duration of the history of X-ray astronomy.

Table 1. LMXBs with NS accretors that have shown outbursts separated by at least 10 yr in time, or single outbursts bright enough that they would have triggered ASMs over the period in which ASMs existed (i.e. since 1996). Objects above the horizontal line are in the Liu et al. (2007) catalogue, while objects below the line were discovered since its publication. All the objects below the line show Type I X-ray bursts (Galloway et al. 2020).

Name	RA	Dec.	Comments	References
EXO 0748–676	07 48 33.300	−67 45 00.00	Single long outburst	(1)
XTE J0929–314	09 29 20.190	−31 23 03.20	Single outburst in 2002	(2,3)
4U 1456–32	14 58 22.000	−31 40 08.00	Cen X-4, outbursts 1969 & 1979, none since	(4)
MXB 1659–298	17 02 06.500	−29 56 44.10	Three outbursts in Lin et al. (2019), ∼1 per 14 years	(1)
XTE J1701–462	17 00 58.450	−46 11 08.60	Single outburst, very bright and long duration	(5)
XTE J1723–376	17 23 38.700	−37 39 42.00	Single outburst with RXTE, not seen with MAXI	(6)
4U 1730–220	17 33 57.000	−22 02 07.00	Outbursts in 1972 and 2021	(7,8)
KS 1731–260	17 34 13.470	−26 05 18.80	Single outburst from 1989-2001	(9,10)
EXO 1747–214	17 50 24.520	−21 25 19.90	Single outburst	(11)
2S 1803–245	18 06 50.720	−24 35 28.60	Outbursts in 1976 and 1998	(12)
XTE J1807–294	18 06 59.800	−29 24 30.00	Two outbursts during RXTE mission, so $\lesssim 0.1$/yr	(1)
GS 1826–238	18 29 28.200	−23 47 49.12	Single very long outburst with reflaring	(13)
HETE J1900.1–2455	19 00 08.650	−24 55 13.70	Single outburst	(1)
4U 1905+000	19 08 26.970	+ 00 10 07.70	Off since at least 1990	
			Not clear if one long outburst or	
			Some clustering of outbursts	(14)
XTE J2123–058	21 23 14.540	−05 47 53.20	Single outburst	(1)
MAXI J1647–227	16 48 12.32	−23 00 55.2	Single outburst	(15)
MAXI J1421–613	14 21 37.2	−61 36 25.4	Possible outburst in 1970s, outburst in 2014	(16,17)
Swift J185003.2–005627	18 50 03.2	-00 56 27	Single outburst	(19)
MAXI J1621–501	16 20 22.01	−50 01 11.6	Single outburst	(20,21)
Swift J181723.1–164300	18 17 23.1	−16 43 00	Single outburst	(22)

Notes. References: (1) Lin et al. (2019); (2) Galloway et al. (2002); (3) Cartwright et al. (2013); (4) Chen et al. (1997); (5) Homan et al. (2007); (6) Yan & Yu (2015); (7) Cominsky et al. (1978); (8) Iwakiri et al. (2021); (9) Sunyaev & Kwant Team (1989); (10) Wijnands et al. (2001); (11) Parmar et al. (1985); (12) Cornelisse, Wijnands & Homan (2007); (13) Ji et al. (2018); (14) Jonker et al. (2006); (15) Negoro et al. (2012); (16) Morooka et al. (2014); (17) Serino et al. (2015); (18) Falanga, Belloni & Campana (2006); (19) Beardmore et al. (2011); (20) Hashimoto et al. (2017); (21) Bahramian et al. (2017); (22) Barthelmy et al. (2017).

X-ray binaries with long recurrence times, but our goal in this Letter is simply to illustrate that a large population of long recurrence time transients exists. Where necessary to establish the long recurrence times for a source, we supplement literature data (mostly from Yan & Yu 2015; Lin et al. 2019) with data from the Monitor of All-sky X-ray Image (MAXI; Matsuoka et al. 2009).

Then, using these literature compilations, and MAXI data, we assess the recurrence times of the transient systems. The MAXI data reach a detection limit of 1 mCrab in one week (Isobe et al. 2007). Most of the other all-sky instruments are somewhat less sensitive than MAXI, but if the source was detected before MAXI's launch, then MAXI extends the baseline over which its outbursts have been studied to at least 10 yr, so the poorer sensitivity of some of the earlier monitors is not a concern for the purposes of establishing that recurrence times for bright outbursts are long.

In Table 1, we present a list of 21 long recurrence time transients that have survived our cuts. The Liu et al. (2007) catalogue from which we started had 45 LMXBs that showed clear evidence for NS primaries, and then we have added six more sources discovered after the production of that catalogue. From this analysis, we can say that *at bare minimum* 40 per cent of the transient LMXBs have long (>10 yr) recurrence times. The number *must* be much larger due to the need for ultralong (>50 yr) recurrence time systems which have not yet been discovered to match the population synthesis numbers and long period MSRP numbers, and also to explain the presence of so many systems with only a single known outburst, as well as the continued discoveries of new NS LMXBs making their first outbursts.

There is considerable and clear evidence that some X-ray binaries and cataclysmic variables show clustering in the times of their outbursts. Thus, beyond the clear evidence for long recurrence times among known transients, there is good reason to believe that some of the known transients with short recurrence time-scale may alternate between epochs of longer and shorter recurrence times, with selection biases obviously favouring them being in the short recurrence time phases of their lifetimes when we detect them. Among NS X-ray binaries, Cen X-4, which showed extremely bright outbursts in 1969 and 1979 (Chen, Shrader & Livio 1997), but has been quiescent since 1979, provides a good example. Among the black hole X-ray binaries, there are several objects which were undiscovered until the 1990s, and have shown several outbursts since then that were sufficiently bright and sufficiently long duration that they would have been seen with earlier monitors (e.g. XTE J1550-564 and GRO J1655–50; Corral-Santana et al. 2016; Tetarenko et al. 2016a). In cataclysmic variables, the clustering of outbursts has been seen in a few cases (Bianchini 1990; Wenzel & Splittgerber 1990; Kato et al. 2002) as well, with some work arguing that magnetic activity cycles in the donor stars are the likely cause (Bianchini 1990). Clustered outbursts can lead to objects alternating between epochs of shorter and longer recurrence times. Given observational biases towards systems which do outburst, it is likely, then, that this leads to an underestimate in the typical recurrence times based on empirical data. The observed clustering of the outbursts is likely to be due to short time-scale effects in either the donor star or the accretion disc; on longer time-scales, of tens to hundreds of Myr, the outburst recurrence times may also change due to more fundamental, secular changes in the mass transfer rates.

An essential point here is that what matters for using long recurrence times to infer the nature of a compact object is what fraction of the *underlying population* of sources have long recurrence times. It does not matter whether the fraction of the transient NS LMXBs observed in a single snapshot, or even over the ∼60 yr history of X-ray astronomy is dominated by a particular class of objects. The sources observed in single snapshots are very strongly biased towards high duty cycle transients.

Given the presence of a substantial population of NS LMXBs with only a single observed outburst, the underlying population's size cannot be directly assessed from the data, without some modelling assumptions. Still a bit more than half of known NS transients have shown only a single outburst, and the vast majority of the expected population remains quiescent and undiscovered unless the total NS LMXB population is a few hundred objects.

3 WHAT THE OVERALL GALACTIC POPULATION OF NS LMXBS TELLS US

Not only does the population of known NS LMXBs includes a substantial contribution from systems with long recurrence times, it is furthermore likely that this population is the dominant population of NS LMXBs. Numerous population synthesis works find that 2000–10 000 NS LMXBs should exist in the Milky Way (Kalogera & Webbink 1998; Kiel & Hurley 2006; van Haaften et al. 2015). The range of estimates from first principles binary population synthesis depends largely on treatment of natal kicks of the NS and on the common envelope phase of binary evolution, both of which are relatively poorly constrained from the existing data, and are extremely challenging problems to approach using theoretical methods. If, on the other hand, it were assumed that there were no long recurrence time NS X-ray binaries (and hence that the known sample of about 80 objects represents the whole Milky Way sample), then the total number of NS X-ray binaries would be underpredicted by a factor of ∼50.

An approach which is more robust to model assumptions, but also rougher, is the comparison of the populations of MSRPs with the populations of NS LMXBs. The MSRPs must be spun up in LMXB evolutionary phases. From this approach, if the population level of the LMXBs is in steady state (which is likely, given that the Milky Way's star formation rate is roughly constant over the past 8 Gyr; Snaith et al. 2015). The total MSRP population is about 40 000 (Lorimer 2008), and these systems are expected to live for a Hubble time, so that the typical age is about 5×10^9 yr. Then, the number of NS LMXBs, $N_{\rm NS\text{-}LMXB}$, can be expected to be 40 000 ($\tau_{\rm LMXB}/5 \times 10^9$ yr). Then, to have ∼200 LMXBs, so that only a small fraction have been discovered, requires that the LMXBs have characteristic lifetimes of 2×10^7 yr over which they show phases of bright X-ray emission. Such short lifetimes are at odds with binary evolution calculations that show that LMXB lifetimes as sources which are at least sporadically bright are typically at least $\sim 10^8$ yr (Podsiadlowski, Rappaport & Pfahl 2002).

For relatively short period NS X-ray binary transients, Lin et al. (2019) showed, using the orbital period-peak luminosity relations from Wu et al. (2010), that all-sky surveys with 50-mCrab sensitivity should be complete within about 3 kpc. The very faint X-ray transients (VFXTs) do have peak luminosities about 10 times fainter than this value, but MAXI's sensitivity is also about 1 mCrab, so MAXI should be complete to VFXTs within 3 kpc. Thus, within 3 kpc, we have completeness to a luminosity limit well below that of 'large outbursts'. Next, we determine by integrating the local stellar density, that about 5 per cent of the stellar mass of the Milky Way disc is within 3 kpc, if one assumes a Galactic scale length of 2.1 kpc, meaning that there should be 100–500 NS LMXBs within 3 kpc if the population synthesis estimates are correct.

Only ∼5 of the sources with known distance estimates are found at distances closer than 3 kpc (Jonker & Nelemans 2004; Arnason et al. 2021).[3] Therefore, to be compatible with the theory derived both from the best estimates and from expected ratios of MSRPs to LMXBs, there should be ∼20−100 undiscovered NS LMXBs for every one that is known. The most likely manner in which to explain the lack of known nearby NS LMXBs is if there is a large population of transients which have yet to be discovered. Nearby undiscovered transients which are not VFXTs must have recurrence times longer than the 25 yr over which continuous all-sky monitoring has been available, and nearby VFXTs must have recurrence times longer than the 12 yr over which MAXI has been operating.

Additionally, binary MSRPs predominantly have orbital periods of at least 1 day (Lorimer 2008), and often have much longer orbital periods. These long period binary pulsars are explained as arising from the X-ray binaries that evolve from shorter to longer periods via the expansion of their donor stars (e.g. Podsiadlowski et al. 2002). These systems are likely to appear either as persistent X-ray binaries (like Sco X-1 or Cyg X-2) or as transients with long durations, long outbursts and very long recurrence times (like KS 1731-260 and XTE J1701-462, both of which have shown outbursts of several years, and either of which has yet recurred).[4] These objects, thus, likely exist in fairly large numbers, as transients with approximately decade outburst durations and approximately millennium or longer recurrence time-scales (e.g. Piro & Bildsten 2002); even if they recurred as frequently as once a century, then we would already have found approximately half of them, given the ∼60 yr history of X-ray astronomy.

4 QUIESCENT NS LMXBS IN GLOBULAR CLUSTERS

At low foreground extinction, NS LMXBs in quiescence show a signature of thermal cooling. Their X-ray spectra are well-fitted by a NS atmosphere model with a characteristic radius of about 10 km (Rutledge et al. 1999). Many of these thermal emitters[5] have been found in globular clusters (Heinke et al. 2003), where the extinction is low, and dynamical interactions lead to the formation of new close binaries, a process which might also be relevant in the innermost part of the Galactic Bulge (Voss & Gilfanov 2007). The cluster 47 Tucanae, in particular, is both nearby, and sufficiently far from the ecliptic plane that it is continuously observable for most all sky monitors. It has two quiescent LMXBs with clear spectroscopic evidence for being NS, but has never shown an X-ray outburst (Heinke et al. 2003; Bahramian et al. 2014), and the cluster has also even been the subject of past *Swift* monitoring to search for VFXTs, which also have not yet been found.[6] M62 has five of these objects, and has never shown an X-ray outburst (Heinke et al. 2003; Bahramian et al. 2014), and given the large number of candidates from which to have outbursts, even if a few outbursts were lost due to taking place while the cluster was close to the Sun, that would leave some objects which had not shown outbursts. In the region near the Galactic Centre, these soft components are typically not detectable with *Chandra*, because of the very high foreground absorption (i.e. $\sim 4 \times 10^{22}$ cm^{-2}).

The numbers of these quiescent NS LMXBs scale with stellar encounter rate (Heinke et al. 2003; Pooley et al. 2003), so we can use the stellar encounter rate calculations of Bahramian et al. (2013) to estimate the number of quiescent NS LMXBs in the full system of Milky Way globular clusters, based on published observations

[3] The number is approximate because there are many sources with distance uncertainties that allow them to be closer to or further than 3 kpc.

[4] The system MXB 1629–298 has similar outburst properties, but with an orbital period of 7.1 h, it is an unlikely progenitor of a millisecond pulsar with a long orbital period, as it should be evolving to shorter period.

[5] These systems also often show power-law tails to their spectra.

[6] See http://research.iac.es/proyecto/SwiftGloClu

of globular clusters. Twenty-four clusters with published *Chandra* observations are deep enough to identify most quiescent NS LMXBs (reaching 10^{32} erg s^{-1}). These clusters contain 50 quiescent NS LMXBs and about 38 per cent of the dynamical interactions in Milky Way globular clusters occur in this set of objects, assuming that the interaction rate follows the formulation of Verbunt & Hut (1987).

Thus, we can estimate that there should be roughly 130 quiescent NS LMXBs within the Galactic globular cluster system. (Note that not all quiescent NS LMXBs would be detected by this method; Heinke, Grindlay & Edmonds 2005 estimate that at least half of quiescent NS LMXBs would likely be missed by this method, as half show relatively hard quiescent spectra, and/or are significantly fainter). On the other hand, all-sky monitoring of globular clusters has only detected 8 persistent and 13 transient X-ray binaries in globular clusters to date (Bahramian et al. 2014; Sanna et al. 2017, 2018). Thus, we conclude that we have seen outbursts from less than 16 per cent of the quiescent NS LMXB population. For the clusters which have the largest numbers of known quiescent NS LMXBs (NGC 6440, Ter 5, and NGC 6266), as well as many of the other such clusters, the distances are small enough that outbursts above 3×10^{34} erg s^{-1} would have been detected with MAXI, for these systems to be explained as VFXTs, they would need to be at the faint end of the distribution of VFXTs.

5 FUTURE PROSPECTS

The discussion above indicates that observational work has found only a small fraction of the NS LMXBs in the Galaxy. This is likely to change in the near future, due to the combination of eROSITA (Predehl et al. 2021) and the Legacy Survey of Space and Time (LSST) of the Vera Rubin Observatory (Ivezic et al. 2008), which will be able to detect the thermal emission from a substantial subset of quiescent NS LMXBs, and the ellipsoidal modulations from their donor stars, respectively (Maccarone et al. 2019). While these two projects will not produce a complete sample of all the NS LMXBs in the Galaxy, they should be very effective at detecting these systems over the whole Galactic bulge, and much of the foreground of the Galactic disc, so that the full population can be modelled.

It is also of value to identify further tests of the nature of the Galactic Centre sources, since, while we have invalidated the evidence favouring that they are black holes, we have not proved that they must be NSs. With current instrumentation, the strongest tool in the arsenal for identifying the nature of the compact objects in these systems is radio emission. The ratio of radio-to-X-ray flux for black hole X-ray binaries is considerably higher than for NS LMXBs (Fender & Kuulkers 2001). Radio measurements can, thus, help break the degeneracies between the classes of X-ray binaries in the Galactic Centre (Maccarone 2005). While some outliers to this correlation might exist, it remains the most straightforward manner in which to approach this problem at the present time, and one on which the ngVLA should be able to improve further (Maccarone et al. 2018).[7]

In the future, X-ray astronomy may also benefit from higher duty cycles of sensitive observations, which may open up the possibility of detecting fainter outbursts than have been seen to date with wide-field instruments. Such outbursts are likely to be qualitatively different in nature than standard outbursts due to the ionization instability, because a minimum amount of mass needs to be involved to trigger the ionization instability. In recent years, a few accreting white dwarfs *have* shown long, faint outbursts in which the optically thick components of their accretion discs never reached high enough temperatures for the disc to become ionized (Rivera Sandoval, Maccarone & Pichardo Marcano 2020; Rivera Sandoval et al. 2021; Sunny Wong et al. 2021), and these are likely due to changes in the mass transfer rate from the donor stars, rather than due to disc processes (Rivera Sandoval et al. 2021). This is likely to happen in X-ray binaries as well, and such long term, low amplitude variability is already well-noted in the optical bands in one black hole X-ray binary (Cantrell et al. 2008), and in the X-ray band in at least one accreting NS (Cackett et al. 2010) and one black hole (Bernardini & Cackett 2014). This high amplitude variability in quiescence, thus, does not offer any more diagnostic power of whether the accretor is a black hole or a NS than the *bona fide* outbursts. It *is*, on the other hand, reasonably likely that if high duty cycle monitoring were available of the whole sky down to the quiescent X-ray fluxes of typical LMXBs that some variability pattern could emerge that might be useful for distinguishing between black holes and NSs, but it is unlikely that this would be a mere reduction in the recurrence times only for the NS X-ray binaries.

[7]The Square Kilometre Array can do this type of work further out from the Galactic Centre (Corbel et al. 2015), but given its lack of high-frequency coverage, it is likely to be far more challenging for SKA than ngVLA in the innermost parts of the Galaxy.

6 SUMMARY

Our primary goal in this paper is to establish that the absence of large outbursts from a quiescent X-ray binary in a 10 yr timespan is not evidence for the object being a black hole. Rather, such objects may be black holes or NSs, and the lack of outbursts provides no evidence about the nature of the compact accretor.

First, in Section 2, we have shown that even from the known transient NS X-ray binaries, at least 40 per cent of the objects have recurrence times longer than 10 yr, and about 1/4 of the objects have shown only a single outburst in the 60 yr history of X-ray astronomy. This point alone shows that the lack of outbursts from an object over a 5–10 yr timespan cannot be used as evidence that the object must be a black hole.

Secondly, in Section 3, we have shown that reconciling the populations of MSRPs with their NS low mass X-ray binary progenitors requires that the underlying population of NS LMXB which at least occasionally have large outbursts (as required to have enough accretion to spin-up the pulsars) is at least five times as large as the known population of NS LMXB. These systems, thus, must be undiscovered transients. Furthermore, given the orbital period distribution mismatch between the observed NS X-ray binaries and the observed millisecond pulsars, a substantial fraction of the missing NS X-ray binaries must be systems with orbital periods of several days or more, a class of system which generically has shown single outbursts among the known transients, and which is expected to show recurrence times of millenia from theory (Piro & Bildsten 2002). Notably, these long period, long duration, long recurrence time outbursts are expected to be especially bright in quiescence as well, making this class' properties a good match to the observed properties of the Galactic Centre quiescent X-ray binaries.

Finally, in Section 4, we have shown that the Milky Way's globular cluster system has about 50 known quiescent NS LMXBs, and is expected to have about 130 of these objects. Only 10 per cent of these have shown outbursts during the history of X-ray astronomy, indicating again that there must be a large underlying population of rare outbursters.

DATA AVAILABILITY

This paper presents re-analysis of existing data which can be obtained from published papers, the Vizier service, or NASA archives for Swift and RXTE or JAXA archives for MAXI.

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