No magnetars in ULXs

King, A.; Lasota, J.-P.

DOI
10.1093/mnras/stz720

Publication date
2019

Document Version
Final published version

Published in
Monthly Notices of the Royal Astronomical Society

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **485**, 3588–3594 (2019)
Advance Access publication 2019 March 12
doi:10.1093/mnras/stz720

No magnetars in ULXs

Andrew King [1,2,3,4] and Jean-Pierre Lasota [4,5]★
[1] Theoretical Astrophysics Group, Department of Physics & Astronomy, University of Leicester, Leicester LE1 7RH, UK
[2] Astronomical Institute Anton Pannekoek, University of Amsterdam, Science Park 904, NL-1098 XH Amsterdam, the Netherlands
[3] Leiden Observatory, Leiden University, Niels Bohrweg 2, NL-2333 CA Leiden, the Netherlands
[4] Institut d'Astrophysique de Paris, CNRS et Sorbonne Université, UMR 7095, 98bis Bd Arago, F-75014 Paris, France
[5] Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, ul. Bartycka 18, PL-00-716 Warsaw, Poland

Accepted 2019 March 8. Received 2019 March 8; in original form 2018 December 18

ABSTRACT

We consider the current observed ensemble of pulsing ultraluminous X-ray sources (PULXs). We show that all of their observed properties (luminosity, spin period, and spin-up rate) are consistent with emission from magnetic neutron stars with fields in the usual range 10^{11}–10^{13} G, which is collimated ('beamed') by the outflow from an accretion disc supplied with mass at a super-Eddington rate, but ejecting the excess, in the way familiar for other (non-pulsing) ULXs. The observed properties are inconsistent with magnetar-strength fields in all cases. We point out that all proposed pictures of magnetar formation suggest that they are unlikely to be members of binary systems, in agreement with the observation that all confirmed magnetars are single. The presence of magnetars in ULXs is therefore improbable, in line with our conclusions above.

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

1 INTRODUCTION

Ultraluminous X-ray sources (ULXs) are defined by apparent (assumed isotropic) luminosities $L \gtrsim 10^{39}\,\mathrm{erg\,s^{-1}}$, above the usual Eddington value for stellar-mass objects, but which do not contain supermassive black holes. When they were first identified around the turn of the century, the natural assumption was to regard these apparent luminosities as intrinsic, which then required that their accretors should be black holes with masses intermediate between stellar and supermassive (e.g. Colbert & Mushotzky 1999).

But by now it is generally accepted (cf. Kaaret, Feng & Roberts 2017) that most (or possibly all) ULXs are otherwise normal stellar-mass X-ray binaries in an unusual evolutionary state. Their intrinsic luminosities do not significantly exceed Eddington, but appear so when seen in a narrow range of viewing angles: they are not isotropic but collimated (or 'beamed') by some factor $b < 1$. Then (incorrectly) assuming isotropic emission suggests a larger luminosity

$$L_{\rm sph} = \frac{1}{b} L \qquad (1)$$

than the correct value $L \simeq L_{\rm Edd}$, where

$$L_{\rm Edd} = \frac{4\pi c G M}{\kappa} = 2.5 \times 10^{38} (1+X)^{-1} m_1\,\mathrm{erg\,s^{-1}} \qquad (2)$$

is the Eddington luminosity. In equation (2) $\kappa = \sigma_{\rm T}/m_{\rm p}$, where $\sigma_{\rm T}$ is the Thompson scattering cross-section and $m_{\rm p}$ is the proton mass; c is the speed of light; $m_1 \equiv M/\mathrm{M_\odot}$ is the accretor mass in solar units, and X the hydrogen abundance by mass.

Perhaps confusingly, the reason for the beaming is that mass *transfer* rates in ULX binaries are highly super-Eddington (defining the unusual evolutionary state) but mass *accretion* is effectively only Eddington. As envisaged by Shakura & Sunyaev (1973) the excess is ejected in a quasi-spherical outflow whose collimating structure is the cause of the anisotropic luminosity.

Strong support for this picture comes from the fact that at least one neutron star, that in the low-mass X-ray binary Cygnus X-2, has survived being fed $\sim 3\,\mathrm{M_\odot}$ from its (previously more massive) companion star at highly super-Eddington rates ($\sim 10^{-5}\,\mathrm{M_\odot\,yr^{-1}}$), and yet has evidently gained no more than $\sim$few $\times\, 0.2\,\mathrm{M_\odot}$ (King & Ritter 1999), apparently ejecting all the surplus.

This agrees with the reasoning of Shakura & Sunyaev (1973) concerning accretion discs fed at super-Eddington rates. Mass is progressively blown out of the disc near the accretor so that the local Eddington limit is respected at each disc radius R, making the local accretion rate $\dot{M}(R)$ decrease linearly with R. This outflow leaves only narrow channels around the rotational axis of the accretion disc for the accretion luminosity to escape, giving an effective beaming factor $b < 1$ (cf King 2009). The extreme Galactic accreting system SS433 also has this structure, but we do not view it along the beam axis (Begelman, King & Pringle 2006; van den Heuvel, Portegies Zwart & de Mink 2017) so it is a ULX seen 'from the side'. SS433 was found because of its unusual precessing near-relativistic jets, but in general we cannot easily detect ULX

★ E-mail: lasota@iap.fr

systems where we are not on the beam axis (see Middleton et al. 2018).

As King et al. (2001) pointed out, because they result from beaming, ULX luminosities alone do not directly tell us the nature of the accretor. Although the initial tendency was to assume that the accretors were all black holes, they may instead be neutron stars or even white dwarfs, provided that their mass transfer rates are $\gtrsim 10^{-8}$, $10^{-5}\,\mathrm{M_\odot\,yr^{-1}}$, respectively. (In principle rates $\gtrsim 3\times10^{-4}\,\mathrm{M_\odot\,yr^{-1}}$ would make main-sequence accretors super-Eddington, but X-ray production is less likely.) Following this prediction Fabbiano et al. (2003) suggested that one of the ULXs in the Antennae probably involves an accreting white dwarf because of its unusually soft emission.

The advent of NuSTAR allowed a further confirmation of this prediction, a ULX (M82 X2) with a coherent periodicity P = 1.37 s, naturally interpreted as the spin period of an accreting magnetic neutron star (Bachetti et al. 2014). Its apparent luminosity $L \simeq 1.8\times10^{40}\,\mathrm{erg\,s^{-1}}$ is about 100 times Eddington. Because electron-scattering cross-sections are reduced for some directions and polarizations for very strong-field systems such as magnetars, this raised the possibility that the apparent super-Eddington luminosity might be intrinsic (cf. Tong 2015; Dall'Osso, Perna & Stella 2015; Ekşi et al. 2015). In this sense the idea of magnetar-strength fields for PULXs is a magnetic analogue of the suggestion of intermediate-mass black holes for non-pulsing ULXs. Kluźniak & Lasota (2015) already pointed out that this idea led to problems because the accretion disc would be disrupted very far from the neutron star. This would imply a huge accretion lever-arm and a spin-up rate far larger than observed. Using the observed rate, Kluźniak & Lasota (2015) instead postulated a magnetic field strength typical of a millisecond pulsar.

In line with this, King & Lasota (2016) showed that M82 X-2 fitted naturally into the simple picture of ULXs as beamed X-ray sources, fed at super-Eddington mass transfer rates but accreting only about Eddington, as already established for unpulsed ULXs. It followed that its magnetic field should indeed be weaker ($\simeq 10^{11}$ G) than in a young X-ray pulsar, as expected if the neutron star had gained mass. This unified picture got further impetus from a characteristic property of the beaming formula

$$b \simeq \frac{73}{\dot m^2} \tag{3}$$

suggested by King (2009) on the basis of a combination of theoretical arguments and observations ($\dot m = \dot M/\dot M_{\rm Edd}$ is the accretor's Eddington factor, where $\dot M$ is the mass transfer rate). This implies that for a given $\dot M$, a neutron star accretor has a *higher* apparent luminosity than a more massive black hole. Using $\dot m \propto M^{-1}$ and $L_{\rm Edd} \propto M$, equations (1) and (3) give $L_{\rm sph} \propto M^{-1}$. Accordingly, King, Lasota & Kluźniak (2017, hereafter KLK17) suggested that a significant fraction of non-pulsing ULXs might actually contain neutron stars rather than black holes (see also Koliopanos et al. 2017). KLK17 analysed the three then known pulsing ULXs (PULXs), adopting super-Eddington mass transfer as the defining characteristic of ULXs. They showed that all three systems had magnetospheric radii $R_{\rm M}$ very close to the spherization radii $R_{\rm sph}$ where radiation pressure becomes important and drives mass-loss from the accretion disc. KLK17 argued that the condition

$$R_{\rm M} \sim R_{\rm sph} \tag{4}$$

is very probably necessary for pulsing. $R_{\rm sph}$ is only defined at all if it is larger than $R_{\rm M}$, but if $R_{\rm sph} \gg R_{\rm M}$ the pulse fraction must be small, so the system would probably appear as an unpulsed ULX.

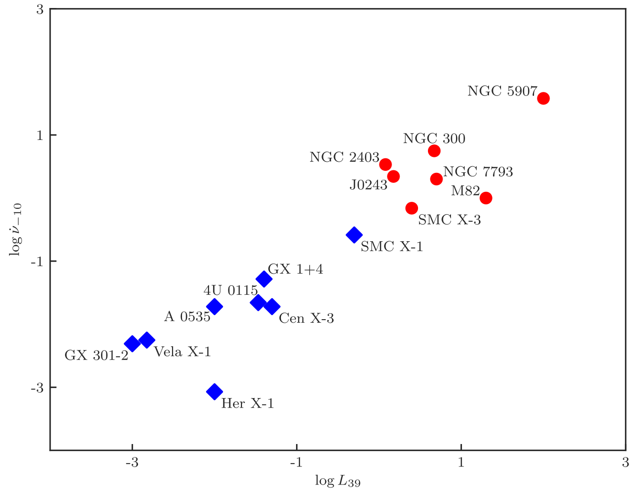

Figure 1. The L_{39}–$\dot\nu_{-10}$ diagram for XRPs and PULXs. Red dots: the seven PULXs with known spin-up rates. Blue diamonds: selected (for comparison) X-ray pulsars (see Table in the Appendix).

KLK17 also showed that (4) requires PULX spin-up rates

$$-\frac{\dot P}{P^2} = \dot\nu > 10^{-10}\,\mathrm{s^{-2}}, \tag{5}$$

more than 10 times larger than any other pulsing neutron star (see Fig. 1). This in turn probably means that, if the system stays at supercritical luminosities, the spin period oscillates very rapidly around its 'equilibrium' value as the accretion rate varies, with spin-up episodes easier to observe than spin-down ones, where presumably accreting matter is centrifugally repelled. Searches for propeller-phase ULXs have not been so far successful (Earnshaw, Roberts & Sathyaprakash 2018). In the three systems analysed by KLK17 the magnetic field is self-consistently in the usual neutron-star range 10^{11}–10^{13} G, again arguing against a magnetar origin for ULX behaviour.

Since pulsing is hard to see if $R_{\rm sph} \gg R_{\rm M}$, KLK17 suggest that the fraction of PULXs observed among ULXs may severely underestimate the true fraction of neutron star ULXs. Recent confirmation of this comes from the discovery that one non-pulsing ULX (Brightman et al. 2018) probably has a magnetized neutron-star accretor, revealed by a cyclotron line in its X-ray spectrum. This was initially identified as a highly unusual *proton* line corresponding to $B \sim 10^{15}$ G (Brightman et al. 2018), but recent reanalysis instead suggests an electron cyclotron line with a more normal (pulsar-like) field of $B \sim 10^{11}$–10^{12} G (Middleton et al. 2019). Another cyclotron line corresponding to a $\sim 10^{12}$ G field is seen in the PULX NGC 300 ULX1 (Walton et al. 2018b, see, however, Koliopanos et al. 2019).

Theoretically the NS/BH fraction in ULXs is uncertain: evolutionary calculations show that it is likely to depend on the star formation history of the host galaxies (Wiktorowicz et al. 2017, 2018). So determining the true fraction could have major implications for understanding this history.

Observations relevant to this problem have made rapid progress since the analysis by KLK17. There are now nine identified neutron-star ULXs (NSULXs; see Table 1), of which eight are observed as PULXs. Four of the NSULXs (M82 ULX2, NGC 7793 P13, NGC 5907 ULX1, and M51 ULX8) are 'standard' ULXs, where the mass transfer rate seems to be fairly stably super-Eddington. The observed variability of these bright ULXs might result from precession (e.g. Motch et al. 2014) – for example an accretion disc irradiated by

Table 1. Observed properties of NSULXs.

Name	L_X(max) (erg s^{-1})	P_s (s)	$\dot{\nu}$ (s^{-2})	$P_{\rm orb}$ (d)	M_2 (M$_\odot$)
M82 ULX2[a]	2.0×10^{40}	1.37	10^{-10}	2.51 (?)	$\gtrsim$5.2
NGC 7793 P13[b]	5×10^{39}	0.42	2×10^{-10}	63.9	18–23 (B9I)
NGC 5907 ULX1[c]	$\sim 10^{41}$	1.13	3.8×10^{-9}	5.3(?)	
NGC 300 ULX1[d]	4.7×10^{39}	~31.5	5.6×10^{-10}	>8	40 (Be ?)
SMC X-3[e, f]	2.5×10^{39}	~7.7	6.9×10^{-11}	45.04	>3.7(Be ?)
NGC 2403 ULX[g]	1.2×10^{39}	~18	3.4×10^{-10}	60–100 (?)	(Be ?)
Swift J0243.6+6124[h]	$\gtrsim 1.5 \times 10^{39}$ (?)	9.86	$2.2. \times 10^{-10}$	28.3	(Be ?)
NGC 1313 ULX[i]	1.6×10^{39}	~765.6			(Be ?)
M51 ULX8[j]	2×10^{39}	NO	NO	8–400 (?)	40 (?)

Notes:
[a]Bachetti et al. (2014).
[b]Fürst et al. (2016, 2018); Israel et al. (2017a); Motch et al. (2014).
[c]Israel et al. (2017b).
[d]Carpano et al. (2018).
[e]Tsygankov et al. (2017).
[f]Townsend et al. (2017).
[g]Trudolyubov, Priedhorsky & Córdova (2007).
[h]Doroshenko, Tsygankov & Santangelo (2018).
[i]Trudolyubov (2008).
[j]Brightman et al. (2018).

its central source may warp and precess (Pringle 1996; Ogilvie & Dubus 2001). The correlation between the X-ray luminosity L_X and spectral hardness, as well as changes in low-resolution atomic absorption lines – Middleton et al. (2015) – appears to support this idea.

The five other PULXs (including one in the Galaxy) are transient, and probably Be-X-ray binaries. Here a neutron star is in an eccentric orbit around a Be star, accreting from its circumstellar disc at periastron in a quasi-periodic way. At intervals of ~10 orbits, a much brighter accretion episode occurs, probably because of the Kozai–Lidov effect of the misaligned neutron-star orbit on the Be star disc (Martin et al. 2014). The system becomes a ULX only in these bright outburst phases. The pulsing X-ray sources in Be-ULXs are visible during the sub-Eddington phase. The increase of luminosity by two to four orders of magnitude does not suppress pulsations but does increase $\dot{\nu}$ by at least an order of magnitude. In terms of equation (4), these 'giant outbursts' presumably supply mass at super-Eddington rates, so that $R_{\rm sph}$ is defined but only barely $\gtrsim R_{\rm M}$. All Be-ULXs are relatively faint ($L_X < 4 \times 10^{39}$ erg s^{-1}) compared with other ULXs.

We have three aims in this paper. First, we extend the analysis of KLK17 to the rather larger current sample of ULXs to see if the condition (4) is required for pulsing and (5) holds, and see if the field deduced from the cyclotron line agrees with this analysis. Second, we use this analysis to check whether magnetar-strength fields are required in PULXs, finding that they are not, and indeed are inconsistent with the observations. Finally, considering formation mechanisms for magnetars, we show that their presence in *any binary system* at all appears unlikely.

2 PROPERTIES OF NEUTRON STAR ULXS

2.1 'Standard' NSULXs

2.1.1 M82 ULX2

ULX2 in the galaxy M82, also known as NuSTAR J095551+6940.8, was the first ULX found to be an X-ray pulsar (Bachetti et al. 2014), ending the controversy about the presence of stellar-mass compact objects in ULXs and confirming the predictions of King et al. (2001).

2.1.2 NGC 7793 P13

P13 in the galaxy NGC 7793, also known as XMMU J235751.1−323725, was identified as an X-ray pulsar by Fürst et al. (2016) and Israel et al. (2017a). Motch et al. (2014) had already shown that the compact object in this system has a mass $\lesssim 15\,{\rm M}_\odot$. It is the only ULX with a well-identified companion: a BI9 supergiant (Motch et al. 2011). The 63.9 d binary orbit has eccentricity $e \leq 0.15$ (Fürst et al. 2018).

2.1.3 NGC 5907 ULX1

Israel et al. (2017b) found that ULX1 in the galaxy NGC 5907 (2XMM J151558.6+561810) was a PULX. It is the brightest PULX, with an X-ray luminosity $\sim 10^{41}$ erg s^{-1}, putting it in the category of the so-called hyperluminous sources ($L_X \geq 10^{41}$ erg s^{-1}).

2.1.4 M51 ULX8

The ULX8 in the galaxy M51 was the first ULX system with a probable cyclotron feature: a 3.8σ absorption line at 4.5 keV in its *Chandra* spectrum (Brightman et al. 2018). Since Middleton et al. (2019) rule out the presence of a 10^{15} G dipole magnetic field in the system, it is reasonable to conclude that this line must be produced by electrons gyrating in a field of strength $\lesssim 3 \times 10^{11}$ G.

2.2 Transient PULXs

2.2.1 NGC 300 ULX1

This system in the galaxy NGC 300 became active in X-rays and optical in 2010 and was initially classified as the supernova SN 2010da. After its unmasking as a supernova impostor, it was initially thought to be a BeX system in a giant outburst. But its luminosity seems not to have varied by more than a factor 2 or 3 between

2010 and 2018 (Vasilopoulos et al. 2018), making this classification dubious. The nature of the companion is unclear (see Vasilopoulos et al. 2018, and references therein). Carpano et al. (2018) found a strong modulation in the 2016 X-ray data with a pulse period of 31.6 s. The X-ray signal shows spin-down glitches (also called 'antiglitches'; Ray et al. 2018). If, as speculated by Binder et al. (2016), NGC 300 ULX1 were the first massive progenitor binary ever observed to evolve into an HMXB, this system would have to be moved into the standard NSULX category.

2.2.2 *SMC X-3*

The Small Magellanic Cloud contains 121 high-mass X-ray binaries (HMXBs) of which 64 contain pulsars (see Townsend et al. 2017, and references therein). SMC X-3 is a well-known ∼7.8 s X-ray pulsar in a near-circular orbit with a Be star. In 2016 this system was observed to undergo a five month super-Eddington outburst (Weng et al. 2017; Koliopanos & Vasilopoulos 2018) during which the previously slowing pulsar was discovered to be rapidly spinning up. The observed spin-up was 500 times larger than the previous spin-down. The angular momentum transferred by matter accreted during the five months giant outburst was greater than that lost by magnetic braking over the preceding 18 yr (Townsend et al. 2017). SMC X-3 is the only PULX where we clearly see the transition from an X-ray pulsar to a PULX and back, when first, on MJD 5168, it switched from spin-down mode to an extremely rapid spin-up coincident with super-Eddington luminosity, returning to the previous mode after five months (Townsend et al. 2017).

2.2.3 *NGC 2403 ULX*

This transient X-ray pulsar in the nearby spiral galaxy NGC 2403, known as 2XMM J073709.1+653544 (or CXOU J073709.1+653544), has a peak luminosity just above the 10^{39} erg s^{-1} 'limit', but its spin-up rate $>10^{-10}$ s^{-2} (Trudolyubov et al. 2007) definitely puts it in the PULX category.

2.2.4 *NGC 1313 ULX*

This transient PULX XMMU J031747.5−663010 in the isolated galaxy NGC 1313 was observed once in 2004 by Trudolyubov (2008). Its pulse period is much longer than observed in other PULX and the pulse time-derivative has not been measured. This object should not be confused with sources NGC 1313 X-1 or X-2 that are also ULXs (Pintore & Zampieri 2012).

2.2.5 *Swift J0243.6+6124*

The first ULX candidate observed in the Galaxy, details of this presumed Be-X system depend on its uncertain distance (van den Eijnden et al. 2018). However, its high spin-up rate (Doroshenko et al. 2018) supports ULX membership. It is the first known highly magnetized neutron-star jet emitter (van den Eijnden et al. 2018).

3 THE PULX MODEL OF KLK17

The only observables directly relating to PULX properties are the pulse period P, spin-up $\dot{\nu}$, and luminosity L. In one other case a magnetic field is measured directly through a CRSF. No direct mass measurement exists, but for neutron stars the likely mass range is limited.

PULXs are sharply distinct from other pulsing X-ray sources in their luminosities (by definition $L > 10^{39}$ erg s^{-1}) and their spin-up rates ($\dot{\nu} > 10^{-10}$ s^{-2}), which are tightly correlated (Fig. 1). This correlation argues strongly that accretion provides the dominating torque in the system as assumed in e.g. KLK17 and Vasilopoulos et al. (2018), since

$$\dot{\nu} = \frac{\dot{J}(R_{\rm M})}{2\pi I} = \frac{\dot{M}(GMR_{\rm M})^{1/2}}{2\pi I} \propto \dot{M}^{6/7}, \qquad (6)$$

where $R_{\rm M} \propto \dot{M}^{-2/7}$ (e.g. Frank et al. 2002) is the magnetospheric radius and I the neutron star's moment of inertia.

KLK17 used this fact to set up a model describing super-Eddington accretion on to a magnetized neutron star. To describe the mass inflow they used the supercritical solution described in Section IV of Shakura & Sunyaev (1973) (not the celebrated thin-disc solution). In this picture, most of the super-Eddington mass supply is eventually expelled as a wind, which provides the beaming making ULXs appear super-Eddington. The accretor gains mass only at about its Eddington rate. As mentioned in the Introduction, systems such as Cyg X-2 give strong support to this picture.

Within the *spherization radius*, where the height of the radiation-pressure-dominated accretion disc becomes comparable to the distance to the centre, the local disc luminosity is Eddington-limited, generating a strong outflow. Using $\dot{m} = \dot{M}/\dot{M}_{\rm Edd}$, where

$$\dot{M}_{\rm Edd} \equiv \frac{L_{\rm Edd}}{0.1c^2} = 1.6 \times 10^{18} m_1\,{\rm g\,s^{-1}}$$
$$= 2.5 \times 10^{-8} m_1\,{\rm M_\odot\,yr^{-1}}, \qquad (7)$$

the spherization radius is defined through the equation

$$R_{\rm sph} \simeq 1 \times 10^6 \dot{m}_0 m_1\,{\rm cm}, \qquad (8)$$

where $\dot{M}_0 = \dot{m}_0\,\dot{M}_{\rm Edd}$ is the accretion rate at $R_{\rm sph}$, assumed equal to the mass transfer rate. To keep the local energy release $GM\dot{M}(R)/R$ below $L_{\rm Edd}$ for $R < R_{\rm sph}$ we therefore have

$$\dot{M}(R) \simeq \dot{m}_0 \dot{M}_{\rm Edd} \frac{R}{R_{\rm sph}}. \qquad (9)$$

KLK17 assume that the Shakura & Sunyaev (1973) model describes the accretion flow between $R_{\rm sph}$ and the magnetospheric radius $R_{\rm M}$ defined by the equations (Frank, King & Raine 2002)

$$R_{\rm M} = 1.2 \times 10^8 q\,\dot{m}^{-2/7} m_1^{-3/7} \mu_{30}^{4/7}\,{\rm cm}, \qquad (10)$$

where q is a factor taking into account the geometry of the accretion flow at the magnetosphere. Then from equation (9)

$$\dot{M}(R_{\rm M}) \simeq \dot{M}_0 \frac{R_{\rm M}}{R_{\rm sph}}. \qquad (11)$$

(see the unnumbered equation placed 22 lines from the top of p.353 of Shakura & Sunyaev 1973).

KLK17 found that for the first three PULXs known, $R_{\rm M} \approx R_{\rm sph}$, implying that the accretion flow inside the magnetosphere is highly super-Eddington when $\dot{m}_0 \gg 1$. As it is hypersonic but forced to follow fieldlines it is highly dissipative, and one expects it to generate an outflow similar to that of Shakura & Sunyaev (1973), limiting the local luminosity to its Eddington value.

The total luminosity is then given by the unnumbered equation (11) lines from the top of p. 353 of Shakura & Sunyaev (1973), which is equivalent to

$$L \simeq L_{\rm Edd}\,[1 + \ln \dot{m}_0]\,. \qquad (12)$$

Table 2. Derived properties of PULXs.

Name	$\dot{m}_0$	$\mu\, q^{7/4} m_1^{-1/2} I_{45}^{-3/2}$ (Gcm^3)	$R_{\rm sph} m_1^{-1}$ (cm)	$R_M m_1^{-1/3} I_{45}^{-2/3}$ (cm)	$R_{\rm co} m_1^{-1/3}$(cm)	$P_{\rm eq} q^{-7/6} m_1^{1/3}$ (s)	$t_{\rm eq}$ (yr)^a
M82 ULX2	36	9.0×10^{28}	3.6×10^7	1.0×10^7	1.9×10^8	0.02	15600
NGC 7793 P13	20	2.5×10^{29}	2.1×10^7	1.6×10^7	8.4×10^8	0.09	1386
NGC 5907 ULX1	91	2.1×10^{31}	9.1×10^7	1.1×10^8	1.6×10^8	1.86	0
NGC 300 ULX1	20	1.2×10^{30b}	2.1×10^7	3.2×10^7	1.5×10^9	0.19	297
SMC X-3	18	2.3×10^{28}	1.8×10^7	7.1×10^6	5.9×10^8	0.006	76621
NGC 2403 ULX	11	5.6×10^{29}	1.1×10^7	2.3×10^7	1.1×10^9	0.16	578
Swift J0243.6+6124	14	1.6×10^{29}	1.4×10^7	1.7×10^7	6.9×10^8	0.07	2047
NGC 1313 ULX	14		2.8×10^7		8.8×10^{13}		
M51 ULX8	16	$\sim 3 \times 10^{29c}$	1.6×10^7	2.7×10^{7d}	?	?	

Notes: ^{a} calculated using the value of $P_{\rm eq} q^{-7/6} m_1^{1/3}$ from the previous column.
^{b} close to $B \sim 10^{12}$G as measured by Walton et al. (2018b).
^{c} from observations (Brightman et al. 2018; Middleton et al. 2019).
^{d}from equation (10) for a 10^{11-12} G magnetic field.

In Section 5 we discuss further the problems of modelling magnetospheric accretion flows in NSULXs[1] .The luminosity from both parts of the super-Eddington outflow is expected to be beamed (see e.g. King et al. 2001; King 2009; King & Lasota 2016; Middleton & King 2017, and KLK17). Outside the magnetosphere the beaming factor is taken to be

$$b \simeq \frac{73}{\dot{m}^2} \quad (13)$$

for the total beam solid angle $4\pi b$, valid for $\dot{m}_0 > 8.5$. King (2009) deduced equation (13) from the $L_{\rm soft} \propto T^{-4}$ dependence observed in a sample of ULXs by Kajava & Poutanen (2009). Although some ULXs obey $L_{\rm soft} \propto T^4$ (Miller et al. 2013), these are probably black-hole systems with masses large enough to make their luminosities sub-Eddington.

Mainieri et al. (2010) found that the Local Group ULX luminosity function favours $b \sim \dot{m}^{-2}$. Also, as shown in King & Lasota (2016) and KLK17 and confirmed in this paper, the approximate formula (13) gives reasonable results when applied to PULXs, and its main conclusion that these systems have $R_{\rm M} \approx R_{\rm sph}$ is supported by observations (see e.g. Walton et al. 2018a).

For accretion rates such that radiation is geometrically beamed as described by equations (1) and (13) one can deduce $\dot{m}_0$ from the observed X-ray luminosity $L = L_{\rm X}$ by combining these two equations into

$$L_{\rm X} \simeq 2.0 \times 10^{36} \dot{m}_0^2 \left[1 + \ln \dot{m}_0\right] m_1. \quad (14)$$

Having $\dot{m}_0$ we obtain $R_{\rm sph}$ from equation (8).

Then the second observed quantity, the observed spin-up

$$\dot{\nu} = 3.3 \times 10^{-11} q^{1/2} \dot{m}^{6/7} m_1^{6/7} \mu_{30}^{2/7} I_{45}^{-1}\, {\rm s}^{-2}, \quad (15)$$

provides the values of the magnetic moment μ, which in turn allows us to calculate the values of $R_{\rm M}$ and $\dot{m}(R_{\rm M})$ from equations (10) and (11):[2]

$$\mu_{30} = 0.04\, q^{-7/4} \dot{\nu}_{-10}^{3/2} m_1^{1/2} I_{45}^{3/2}\, {\rm G\, cm}^3 \quad (16)$$

$$R_{\rm M} = 1.0 \times 10^7 \dot{\nu}_{-10}^{2/3} m_1^{1/3} I_{45}^{2/3}\, {\rm cm} \quad (17)$$

$$\dot{m}(R_{\rm M}) = 9.9\, \dot{\nu}_{-10}^{2/3} m_1^{-2/3} I_{45}^{2/3}, \quad (18)$$

where $10^{-10}\dot{\nu}_{-10} = \dot{\nu}$.

The results are presented in Table 2, with the values of the corotation radius $R_{\rm co} \equiv \left(GMP_s^2/4\pi^2\right)^{1/3}$cm, the equilibrium period $P_{\rm eq} = 0.23 q^{7/6} m_1^{-1/3} \mu_{30}^{2/3}$ s, and the lower limit on the time to reach equilibrium at the present spin-up rate

$$t_{\rm eq} \equiv \frac{1}{\dot{\nu}} \left(\frac{1}{P_{\rm eq}} - \frac{1}{P}\right). \quad (19)$$

It is encouraging that for NGC 300 ULX-1 the KLK17 model predicts a neutron-star magnetic field $B \approx 10^{12}$ G, as the same value is deduced by Walton et al. (2018b) from the CRSF observed in the X-ray spectrum of the PULX. According to the KKL17 model all seven PULXs have magnetic fields in the range $10^{11} - 10^{13}$ G, i.e. below the value defining magnetars.

The predicted values of the beaming factor b are in the range ∼0.06–0.6, except for the hyperluminous source in NGC 5709, for which $b \approx 0.009$ (similar to the values deduced by King & Lasota 2014 and Lasota, King & Dubus 2015, for HLX1 in ESO 243-49.) For ULX1 in NGC 300 we get $b \approx 0.18$, while Binder, Levesque & Dorn-Wallenstein (2018) using our model obtain $b \approx 0.25$, because to deduce $\dot{m}_0$ they use the average instead of the maximum luminosity. The beaming factor $b \approx 0.2$ for P13 in NGC 7793 is consistent with observations of the X-ray irradiation of neutron-star companion (Motch 2018).

We see that, as found by KLK17 for the three 'standard' PULXs, all seven PULXs with known values of spin-up rates $\dot{\nu}$ give $R_{\rm M} \sim R_{\rm sph}$, which as explained in the Introduction is probably the condition for observing pulses at all if mass transfer is super-Eddington.

Parametrizing $R_{\rm M} = fR_{\rm sph}$, with $f \approx 0.3$–1, then from equation (11) $m(R_{\rm M}) = f\dot{m}_0$ (KLK17) and from equations (15) and (18)

[1]An equation deceptively formally similar to equation (12) holds in the physically completely distinct case of an advection-dominated accretion flow (see e.g. Poutanen et al. 2007; Lasota 2016). But here $\dot{M}(R) = {\rm const}$ (*not* $\propto R$), and the binding energy which has not been radiated away would be still contained in the matter landing on the accretor's surface. For a black hole accretor, equation (12) would correspond to the actual luminosity, but when the accretor is neutron star this is obviously not true, and equation (12) might not be a good approximation. We stress that, *by construction*, outflows from advection-dominated flows must be weak. They cannot represent ULXs, where strong outflows are observed (Pinto, Middleton & Fabian 2016). Mushtukov et al. (2019) propose a model with a mixture of outflow and advection but do not test it against the observed values of $\dot{\nu}$.

[2]Here and elsewhere small numerical errors and inconsistencies in KLK17 have been corrected.

one finds

$$\dot{\nu} = 7.8 \times 10^{-10} f^{7/6} q^{7/6} \mu_{30}^{2/3} m_1^{-1/7} I_{45}^{-1}, \quad (20)$$

in agreement with the observed spin-up values of PULXs.

For M51 ULX8 – not a PULX – we know the value of the magnetic field. Assuming its X-ray radiation is beamed we deduce $\dot{m}_0$ and so both $R_{\rm M}$ and $R_{\rm sph}$. In this case $R_{\rm M}$ is slightly larger than $R_{\rm sph}$ (see Table 2) but no more than in some PULXs. In view of the model uncertainties (see Section 5) we speculate that M51 ULX8 might be a PULX and suggest that pulsations may be seen in future observations of this system. As pointed out by Brightman et al. (2018), longer *XMM–Newton* observations would be needed to detect ∼1s pulsations if the pulsed fraction is $\lesssim$45 per cent, as in most PULXs. (Interestingly the only exception is NGC 300 ULX1, in which a CRSF has been found by Walton et al. 2018b).

4 NO MAGNETARS IN BINARY SYSTEMS

We have shown that the properties of PULXs are explicable with standard magnetic fields – there is no need to invoke the presence of magnetars in them, and indeed the presence of magnetars is incompatible with the observations.

Our no-magnetar result is consistent with the fact that no observed magnetar is a member of a binary system. We suggest here that there are good reasons for this absence.

All observed magnetic field strengths of neutron stars in X-ray binaries are in the range 10^8–10^{13} G (see e.g. Revnivtsev & Mereghetti 2016). In contrast, *all* ∼30 known magnetars (or 'candidate' magnetars) are isolated neutron stars (Olausen & Kaspi 2014).

There is strong evidence that magnetars are (or even must be) *formed* in binary systems, but that the formation process usually leads to the destruction of the binary (Popov 2016). Magnetar formation through neutron star mergers (e.g. Giacomazzo & Perna 2013; Piro, Giacomazzo & Perna 2017) obviously produces a single object. Magnetars may be also produced in type Ibc supernova outbursts in massive binaries, as demonstrated by the magnetar CXOU J1647−45 in the young massive cluster Westerlund 1 (Clark et al. 2014). Such superluminous supernovae disrupt the binary and produce isolated magnetars. In principle, a small fraction of binaries could survive the catastrophe: for example the very slow (pulse period ∼2.6 h) X-ray pulsar in the high-mass X-ray binary 4U 0114+65 could have a magnetar-strength magnetic field (Sanjurjo-Ferrrín et al. 2017, and references therein). The problem with this channel as a model for PULX formation is that strong neutron-star fields $\sim10^{15}$ G decay quickly ($\lesssim$a few Myr) by several orders of magnitude (Mereghetti, Pons & Melatos 2015). Igoshev & Popov (2018) find that the age of 4U 0114+65 is 2.4–5 Myr since the formation of the neutron star, and discuss the conditions for long survival (up to 10 Myr) of a magnetar-strength field. One of these conditions is rapid cooling of the crust below $T \approx 3 \times 10^7$ K. This is probably satisfied for slowly accreting neutron stars, but doubtful for fast-rotating, Eddington-accreting NSULXs. One might try to escape these restrictions by postulating magnetar formation in hierarchical triple systems, but it is then hard to overcome the twin problems that magnetar formation may well unbind the resulting loosely bound daughter binary system, or that this system is too wide to come into contact within the field decay time ∼ few Myr. It appears very unlikely that any, let alone *all* NSULXs are survivors of binaries experiencing powerful type Ibc supernova explosions. Accordingly it is unsurprising that our analysis does not suggest any candidate for a magnetar-strength field in NSULXs.

5 DISCUSSION AND CONCLUSIONS

We have extended the analysis of KLK17 to the current sample of PULXs and found that the condition $R_M \sim R_{\rm sph}$ for observable pulsing still holds [in the language of Middleton et al. (2019, see their fig. 4) this corresponds to a 'critical' disc geometry]. As in KLK17, we showed that this implies values of the spin-up rate $\dot{\nu} > 10^{-10}\ {\rm s}^{-2}$, fully consistent with the observed PULX properties, and correlating strongly with their luminosities (see Fig. 1).

Models invoking magnetar-strength magnetic fields (e.g. Mushtukov et al. 2015) do not address the observed PULXs spin-up rates but as we have shown above, these spin-up rates imply normal-strength ($\sim10^{11}$–10^{13} G) fields.

Our calculations, like all other attempts to describe super-Eddington accretion flows, are based on a simple approximate model, and minor discrepancies (in a few cases $R_{\rm M}$ slightly exceeds $R_{\rm sph}$) are to be expected. The magnetospheric radius is calculated from formulae appropriate to thin-disc accretion, whereas we assume that the disc interacting with the magnetosphere is thick. The formula for the spherization radius derived by Shakura & Sunyaev (1973) corresponds to the ring where the disc height is equal to its radius, which might not be exact in reality (see e.g. Poutanen et al. 2007). Numerical simulations, although very impressive, cannot be of much help (even if they discuss the 'spherization radius'). Instead of an external thin disc, they have a torus (Takahashi & Ohsuga 2017; Abarca, Kluźniak & Sądowski 2018; Takahashi, Mineshige & Ohsuga 2018). The critical radii are uncertain by no more than factors ∼1, so we expect (as here) the results of KLK17 will remain robust in comparison with both observations and future numerical simulations.

We conclude that magnetar field strengths are not required to describe PULXs. This is reassuring because the presence of magnetars in binary systems, especially ultraluminous accreting systems, appears extremely unlikely.

ACKNOWLEDGEMENTS

We are grateful to the anonymous referee for a very detailed and helpful report. We thank Matt Middleton for useful advice and help. This research was supported by the Polish National Science Centre grant No. 2015/19/B/ST9/01099. ARK acknowledges partial support by the LABEX 'Institut Lagrange de Paris'. The Theoretical Astrophysics Group at the University of Leicester is supported by an STFC Consolidated Grant. JPL acknowledges support from the French Space Agency CNES.

REFERENCES

Abarca D., Kluźniak W., Sądowski A., 2018, MNRAS, 479, 3936
Bachetti M. et al., 2014, Nature, 514, 202
Begelman M. C., King A. R., Pringle J. E., 2006, MNRAS, 370, 399
Binder B., Williams B. F., Kong A. K. H., Gaetz T. J., Plucinsky P. P., Skillman E. D., Dolphin A., 2016, MNRAS, 457, 1636
Binder B., Levesque E. M., Dorn-Wallenstein T., 2018, ApJ, 863, 141
Brightman M. et al., 2018, Nat. Astron., 2, 312
Carpano S., Haberl F., Maitra C., Vasilopoulos G., 2018, MNRAS, 476, L45
Clark J. S., Ritchie B. W., Najarro F., Langer N., Negueruela I., 2014, A&A, 565, A90
Colbert E. J. M., Mushotzky R. F., 1999, ApJ, 519, 89
Dall'Osso S., Perna R., Stella L., 2015, MNRAS, 449, 2144
Doroshenko V., Tsygankov S., Santangelo A., 2018, A&A, 613, A19
Earnshaw H. P., Roberts T. P., Sathyaprakash R., 2018, MNRAS, 476, 4272
Ekşi K. Y., Andaç I. C., Çıkıntoğlu S., Gençali A. A., Güngör C., Öztekin F., 2015, MNRAS, 448, L40

Fabbiano G., King A. R., Zezas A., Ponman T. J., Rots A., Schweizer F., 2003, ApJ, 591, 843
Frank J., King A., Raine D. J., 2002, Accretion Power in Astrophysics. Cambridge Univ. Press, Cambridge, UK
Fürst F. et al., 2016, ApJ, 831, L14
Fürst F. et al., 2018, A&A, 616, A186
Giacomazzo B., Perna R., 2013, ApJ, 771, L26
Igoshev A. P., Popov S. B., 2018, MNRAS, 473, 3204
Israel G. L. et al., 2017a, MNRAS, 466, 48
Israel G. L. et al., 2017b, Science, 355, 817
Kaaret P., Feng H., Roberts T. P., 2017, ARA&A, 55, 303
Kajava J. J. E., Poutanen J., 2009, MNRAS, 398, 1450
King A., Lasota J.-P., 2014, MNRAS, 444, L30
King A., Lasota J.-P., 2016, MNRAS, 458, L10 (KL16)
King A., Lasota J.-P., Kluźniak W., 2017, MNRAS, 468, L59
King A. R., 2009, MNRAS, 393, L41
King A. R., Ritter H., 1999, MNRAS, 309, 253
King A. R., Davies M. B., Ward M. J., Fabbiano G., Elvis M., 2001, ApJ, 552, L109
Kluzniak W., Lasota J.-P., 2015, MNRAS, 448, L43
Koliopanos F., Vasilopoulos G., 2018, A&A, 614, A23
Koliopanos F., Vasilopoulos G., Godet O., Bachetti M., Webb N. A., Barret D., 2017, A&A, 608, A47
Koliopanos F., Vasilopoulos G., Buchner J., Maitra C., Haberl F., 2019, A&A, 621, A118
Lasota J.-P., 2016, Black Hole Accretion Discs. Astrophysics of Black Holes: From Fundamental Aspects to Latest Developments. Springer-Verlag Berlin Heidelberg, Germany, p. 1
Lasota J.-P., King A. R., Dubus G., 2015, ApJ, 801, L4
Mainieri V. et al., 2010, A&A, 514, A85
Martin R. G., Nixon C., Armitage P. J., Lubow S. H., Price D. J., 2014, ApJ, 790, L34
Mereghetti S., Pons J. A., Melatos A., 2015, Space Sci. Rev., 191, 315
Middleton M. J., Brightman M., Pintore F., Bachetti M., Fabian A. C., Fürst F., Walton D. J., 2019, MNRAS, 468
Middleton M. J. et al., 2018, preprint (arXiv:1810.10518)
Middleton M. J., King A., 2017, MNRAS, 470, L69
Middleton M. J., Walton D. J., Fabian A., Roberts T. P., Heil L., Pinto C., Anderson G., Sutton A., 2015, MNRAS, 454, 3134
Miller J. M., Walton D. J., King A. L., Reynolds M. T., Fabian A. C., Miller M. C., Reis R. C., 2013, ApJ, 776, L36
Motch C., 2018, Optical Observations of Ultra-luminous X-ray Pulsars, presentation at Ultra-luminous X-ray Pulsars. European Space Astronomy Centre (ESAC), Villafranca del Castillo, Madrid, Spain
Motch C., Pakull M. W., Grisé F., Soria R., 2011, Astron. Nachr., 332, 367
Motch C., Pakull M. W., Soria R., Grisé F., Pietrzyński G., 2014, Nature, 514, 198
Mushtukov A. A., Suleimanov V. F., Tsygankov S. S., Poutanen J., 2015, MNRAS, 454, 2539
Mushtukov A. A., Ingram A., Middleton M., Nagirner D. I., van der Klis M., 2019, MNRAS, 484, 687
Ogilvie G. I., Dubus G., 2001, MNRAS, 320, 485
Olausen S. A., Kaspi V. M., 2014, ApJS, 212, 6
Pinto C., Middleton M. J., Fabian A. C., 2016, Nature, 533, 64
Pintore F., Zampieri L., 2012, MNRAS, 420, 1107
Piro A. L., Giacomazzo B., Perna R., 2017, ApJ, 844, L19
Popov S. B., 2016, Astron. Astrophys. Trans., 29, 183
Poutanen J., Lipunova G., Fabrika S., Butkevich A. G., Abolmasov P., 2007, MNRAS, 377, 1187
Pringle J. E., 1996, MNRAS, 281, 357
Ray P. S. et al., 2018, preprint (arXiv:1811.09218)
Revnivtsev M., Mereghetti S., 2016, The Strongest Magnetic Fields in the Universe: Space Sciences Series of ISSI. Springer Science + Business Media, New York, p. 299
Sanjurjo-Ferrrín G., Torrejón J. M., Postnov K., Oskinova L., Rodes-Roca J. J., Bernabeu G., 2017, A&A, 606, A145
Shakura N. I., Sunyaev R. A., 1973, A&A, 24, 337
Takahashi H. R., Ohsuga K., 2017, ApJ, 845, L9
Takahashi H. R., Mineshige S., Ohsuga K., 2018, ApJ, 853, 45
Tong H., 2015, Res. Astron. Astrophys., 15, 517
Townsend L. J., Kennea J. A., Coe M. J., McBride V. A., Buckley D. A. H., Evans P. A., Udalski A., 2017, MNRAS, 471, 3878
Trudolyubov S. P., 2008, MNRAS, 387, L36
Trudolyubov S. P., Priedhorsky W. C., Córdova F. A., 2007, ApJ, 663, 487
Tsygankov S. S., Doroshenko V., Lutovinov A. A., Mushtukov A. A., Poutanen J., 2017, A&A, 605, A39
van den Eijnden J., Degenaar N., Russell T. D., Wijnands R., Miller-Jones J. C. A., Sivakoff G. R., Hernández Santisteban J. V., 2018, Nature, 562, 233
van den Heuvel E. P. J., Portegies Zwart S. F., de Mink S. E., 2017, MNRAS, 471, 4256
Vasilopoulos G., Haberl F., Carpano S., Maitra C., 2018, A&A, 620, L12
Walton D. J. et al., 2018, ApJ, 856, 128
Walton D. J. et al., 2018, ApJ, 857, L3
Weng S.-S., Ge M.-Y., Zhao H.-H., Wang W., Zhang S.-N., Bian W.-H., Yuan Q.-R., 2017, ApJ, 843, 69
Wiktorowicz G., Sobolewska M., Lasota J.-P., Belczynski K., 2017, ApJ, 846, 17
Wiktorowicz G., Lasota J.-P., Middleton M., Belczyński K., 2018, ApJ, accepted, preprint (arXiv:1811.08998)
Ziolkowski J., 1985, Acta Astron., 35, 185

APPENDIX A: X-RAY PULSARS

To illustrate the fact that PULX differ from standard X-ray pulsars not only by the luminosity $>10^{39}\,\mathrm{erg\,s^{-1}}$ but also by their very large spin-up rate $\dot{\nu} > 10^{-10}\,\mathrm{s^{-2}}$, we used the XRP sample with known luminosities and spin-up rates (Table A1) as compiled by Ziolkowski (1985).

Table A1. Observed properties of 'classical' X-ray pulsars[a].

Name	L_X(max) (erg s^{-1})	P_s (s)	$\dot{\nu}$ (s^{-2})
SMC X-1	5.0×10^{38}	0.71	2.6×10^{-11}
Cen X-3	5.0×10^{37}	4.84	1.9×10^{-12}
GX 1+4	4.0×10^{37}	122	5.2×10^{-12}
4U 0115+63	3.4×10^{37}	3.61	2.2×10^{-12}
A 0535+26	1.0×10^{37}	104	1.9×10^{-12}
Her X-1	1.0×10^{37}	1.24	8.5×10^{-14}
Vela X-1	1.5×10^{36}	283	5.6×10^{-13}
GX 301-2	1.0×10^{36}	696	4.9×10^{-13}

Note:
[a]From Ziolkowski (1985).

This paper has been typeset from a TEX/LATEX file prepared by the author.