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Ultraluminous X-ray sources as super-critical propellers

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ABSTRACT

Ultraluminous X-ray sources (ULX) are generally assumed to host accreting black holes some of which are intermediate mass black holes (IMBH). There is recent understanding that some ULX host accreting neutron stars, i.e. pulsating ultraluminous X-ray sources (PULX). Another subgroup of ULX, ultra-luminous super-soft sources (ULS), have extremely soft X-ray emission ($kT < 0.1$ keV) generally considered as being due to the reprocessing of X-rays in optically thick outflow of matter from the surrounding disc. This motivates a connection between ULSs and the general population of ULXs in terms of viewing angle. Here we propose that the bulk of the ULS/ULX population host rapidly spinning highly magnetized, $B \sim 10^{13}$ G, neutron stars in supercritical propeller stage. The spindown power of the neutron stars dominates luminosity of these sources. We argue that PULXs descend from ULX/ULS' when the neutron star spins-down to a period allowing for accretion to commence. We rekindle the earlier view that the galactic system SS433 is a supercritical propeller and hence is a ULX. We finally speculate that the supernova debris disc detected around the magnetar 4U 0142+61, at its earliest stage, would cause the system to appear as ULS or ULX, depending on the viewing angle, if observed from another nearby galaxy.

Key words: X-rays: binaries, X-rays: ULXs, ULSs, Accretion: discs

1 INTRODUCTION

Ultra-luminous X-ray sources (ULXs) are extragalactic off-nuclear systems hosting compact objects with isotropic equivalent X-ray luminosities well exceeding the Eddington limit for a stellar mass object i.e. $L_{\rm X} \gtrsim 3 \times 10^{39}$ erg s^{-1}, (see Kaaret et al. 2017, for a recent review). Each nearby galaxy, preferentially star-forming ones, host none, one or two ULXs. The compact objects in these systems have been considered as either stellar-mass black holes (see e.g. King et al. 2001a; Poutanen et al. 2007; Gladstone et al. 2009) or intermediate mass black holes (IMBHs; see e.g. Colbert & Mushotzky 1999; Kong et al. 2004; Miller et al. 2004; Liu & Di Stefano 2008). In case of stellar mass black holes the super-Eddington luminosities are addressed by anisotropic (beamed) emission from mildly super-Eddington accretion.

The recent detection of pulsations from three ULXs (Bachetti et al. 2014; Israel et al. 017a,b; Fürst et al. 2016) as well as the super-Eddington outburst from SMC X-3 (Weng et al. 2017; Tsygankov et al. 2017) not only showed that a large fraction of these objects could be hosting neutron stars (Shao & Li 2015) but also that the stellar mass objects could exceed the classical Eddington limit. ULXs are possibly a heterogeneous class and it is likely that pulsating ULXs (PULXs) form a subclass.

Another subclass of ULXs are the ultraluminous super-soft sources (ULS) characterized by very soft X-ray spectra $k_{\rm B}T = 0.05 - 0.2$ keV (Di Stefano & Kong 2003; Fabbiano et al. 2003; Kong & Di Stefano 2003; Di Stefano & Kong 2004) whereas the conventional ULXs have a better part of their luminosity above 1 keV. The soft spectra of ULSs are attributed to the reprocessing of the hard emission from the inner disc in a photosphere of optically thick outflows with velocity $v \sim 0.2c$ (Feng & Soria 2011; Shen et al. 2015; Liu et al. 2015; Pinto et al. 2016; King & Muldrew 2016a; Soria & Kong 2016; Feng et al. 2016; Pinto et al. 2017). There is a correlation between the blackbody temperature and emission radius, $R_{\rm bb} \propto T_{\rm bb}^{-2}$ (Soria & Kong 2016; Urquhart & Soria 2016). ULS', just like conventional ULXs, have been considered as promising hosts of IMBHs (Kong et al. 2004; Liu & Di Stefano 2008).

There is a convergence of opinion that the compact objects in many of the ULXs are stellar mass black holes (Motch et al. 2014; Liu et al. 2013; Pintore et al. 2016) with super-critical accretion evidenced by the presence of radiation driven ultra-fast outflows with velocities $v \sim 0.1 - 0.2c$ (Pinto et al. 2016, 2017; Fiacconi et al. 2017) as would be expected from super-critical accretion discs (Lipunova 1999; King & Pounds 2015; King & Muldrew 2016b). It is further argued that the differences between conventional ULXs and ULS' simply arise from our viewing angle, ULS being ob-

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served at high inclination angles (edge on) so that a thicker layer of material is obscuring the central engine (Kylafis & Xilouris 1993; Poutanen et al. 2007; Feng et al. 2016; Urquhart & Soria 2016; Pinto et al. 2017).

The assumption that the stellar mass compact objects in ULX are black holes likely is possibly an imprint of persisting black hole paradigm though the existence of a black hole as the accreting object in some ULXs can not be rejected in some cases (Liu et al. 2013) given the lower bound of $5\mathrm{M}_{\odot}$ on the mass of the accretor. After the discovery of PULXs in the ULX population it is more likely that the compact objects in most of ULXs are neutron stars (see e.g. King et al. 2017; Wiktorowicz et al. 2017). Given the lack of pulsations in most systems and the presence of outflows and winds from the discs we advance the view that the bulk of both ULX population are strongly magnetized $B \sim 10^{13}$ G neutron stars in super-critical propeller stage (Mineshige et al. 1991). In this picture the spin-down energy transferred to the disc is the main source of energy at the initial episodes. It has already been shown by Medvedev & Poutanen (2013) that *isolated* pulsars could address some fraction of the ULX population i.e. that some ULX are spin-down powered. The proposal here employs the same energy source, but for considers systems with discs. It is likely that more of these objects, given the evidence for the presence of discs and optically thick outflows, are more likely spinning down under propeller torques from a quasi-spherical disc. In our picture ULX/ULS systems (depending on the viewing angle) are progenitors of PULXs i.e. they would become PULX when the neutron star slows down sufficiently. This view is consistent with the recent understanding that any ULX system represents a short-lived phase in the life of a binary system (King et al. 2001b; Wiktorowicz et al. 2015).

The structure of this *letter* is as follows: In the next section we introduce some properties of the super-critical propellers and in the final section we discuss the astrophysical implications of ULXs being super-critical propellers.

2 SUPER-CRITICAL PROPELLER

2.1 Basic concepts

Propeller stage was first considered for isolated pulsars interacting with the interstellar medium (Shvartsman 1970). In binary systems with mass transfer from the companion the propeller stage is realized when the neutron star rotates so fast that mass can not be accreted due to the centrifugal barrier (Illarionov & Sunyaev 1975). This condition is satisfied when the inner radius of the disc, $R_{\rm in}$, is greater than the corotation radius, $R_{\rm co} = (GM/\Omega_*^2)^{1/3}$ where M is the mass and Ω_* is the angular rotation frequency of the neutron star (Davies et al. 1979; Davies & Pringle 1981; Wang & Robertson 1985; Stella et al. 1986; Lovelace et al. 1999).

The mass donor may transfer matter at a super-Eddington rate, $\dot{M}_0 > \dot{M}_{\rm E} \equiv L_{\rm E}/c^2$, where $L_{\rm E} = 4\pi GMm_{\rm p}c/\sigma_{\rm T}$ is the Eddington luminosity. Here $m_{\rm p}$ is the proton mass, c is the speed of light and $\sigma_{\rm T}$ is the Thomson cross-section of the electron.

The super-critical mass transfer within the disc leads to the spherization of the disc within a critical radius determined by $L(R > R_{\rm sp}) = GM\dot{M}_0/2R_{\rm sp} = L_{\rm E}$

$$R_{\rm sp} = \frac{\sigma_{\rm T}\dot{M}_0}{8\pi m_{\rm p}c} \simeq 0.53 \times 10^8 \ \mathrm{cm} \left(\frac{\dot{M}_0}{10^{20}\,\mathrm{g\,s^{-1}}}\right) \tag{1}$$

(Shakura & Sunyaev 1973). The **flow** regulates itself so that some of the matter within the spherization radius is ejected from the system with a radiation dominated outflow

$$\dot{M} = \begin{cases} \dot{M}_0(R/R_{\rm sp}), & \text{for } R < R_{\rm sp}; \\ \dot{M}_0, & \text{for } R > R_{\rm sp}. \end{cases} \tag{2}$$

(Shakura & Sunyaev 1973). Accordingly, the mass flux within the disc is regulated not to exceed the Eddington limit too much, but only logarithmically

$$L \simeq L_{\rm E}[1 + \ln(\dot{M}_0/\dot{M}_{\rm E})] \tag{3}$$

(Shakura & Sunyaev 1973).

Lipunova (1999) constructed a more detailed supercritical disc model taking account of advection as well as mass loss through the accretion disc. For $3R_g \ll R \leq R_{\rm sp}$ the outflow model of Lipunova (1999) reduces to the original simple scaling of Shakura & Sunyaev (1973) given above. The model of Lipunova (1999) was applied to SS 433 and the ULXs (Okuda et al. 2009; Poutanen et al. 2007) assuming these systems host black holes. Supercritical accretion onto neutron stars is considered by Lipunov (1982), and more recently by Chashkina et al. (2017) in the context of ULXs (thus for accretion stage rather than the propeller stage). Super-critical propeller regime of spherical flow was considered by Mineshige et al. (1991) who briefly mentioned "SS433 may be such an object." This work (see also Begelman & Rees 1983, 1984) introduces many relevant concepts suitable for application to ULS' (such as optically thick envelope "where any outgoing radiation is thermalized" and friction luminosity) yet the authors assumed that the inner radius of the accretion flow will adjust so that the luminosity does not exceed the Eddington limit. For allowing different viewing angles to have different observational manifestations we prefer a disc-like (quasi-spherical) propeller system.

If matter is transferred from the donor at a super-critical rate ($\dot{M}_0 > \dot{M}_{\rm E}$) while the corotation radius is greater than the inner radius of the disc the system is in the super-critical propeller stage (Lipunov 1987; Lipunov et al. 1992). We propose here that ULS' are in such a state ($R_{\rm co} < R_{\rm in} < R_{\rm sp}$) and later evolve into PULXs when the neutron star is sufficiently slowed down that accretion can commence ($R_{\rm in} < R_{\rm co} < R_{\rm sp}$). Propeller regime with super-critical mass inflow has been studied .

The luminosity given in Equation 3 does not include the spin-down power contributed by the neutron star in the propeller stage. A distinguishing feature of discs in the propeller stage is the spin-down energy of the star added to the disc luminosity (Priedhorsky 1986; Treves & Bocci 1987; Mineshige et al. 1991; Ekşi et al. 2005; Yan et al. 2012; Özsükan et al. 2014). In what follows we adopt these previous works for supercritical propellers.

2.2 Angular momentum loss from the system

A young strongly magnetized neutron star enshrouded in super-critical flow would spin-down at a very high rate. We assume that the angular momentum also is lost with the outflows. For consistency with Equation 2 we write

$$\dot{J} = \begin{cases} \dot{J}_0 (R/R_{\rm sp})^{3/2}, & \text{for } R < R_{\rm sp}; \\ \dot{J}_0, & \text{for } R > R_{\rm sp}. \end{cases} \quad (4)$$

where $\dot{J}_0 = \sqrt{GMR_0}\dot{M}_0$ is the angular momentum flux at the outer rim of the disc and R_0 is the size of the disc. Accordingly, the mass loss rate into the wind is $\dot{M}_{\rm w} \sim \dot{M}_0(1 - \dot{M}_{\rm E}/\dot{M}_0)$ and angular momentum loss rate due to wind is $\dot{J}_{\rm w} \sim \dot{J}_0(1 - \dot{M}_{\rm E}/\dot{M}_0)$.

2.3 Inner radius of the disc

The inner radius of a disc is determined by the balance of magnetic and material stresses (Ghosh & Lamb 1979a,b). In the quiescent disc solution (Sunyaev & Shakura 1977), sometimes employed for describing the propeller regime (D'Angelo & Spruit 2010; Özsükan et al. 2014), the mass flux in the disc is zero so that the material torque $\dot{M}R^2\Omega$ vanishes and the viscous stress is alone to balance the magnetic stress. For the supercritical propellers, the mass flux is not totally zero throughout the disc, but still it is reduced heavily at the inner rim so that the inner radius of the disc is to be found by the balance of viscous and magnetic stresses

$$2\pi R^3 \eta \left.\frac{d\Omega}{dR}\right|_{R_{\rm in}} = -\int_{R_{\rm in}-\Delta R}^{R_{\rm in}} B_\phi^+ B_z R^2 dR \quad (5)$$

(see e.g. D'Angelo & Spruit 2010, 2011, 2012; Özsükan et al. 2014) where $B_z \simeq -\mu/R^3$ is the poloidal magnetic field, $B_\phi^+ = \gamma B_z$ is the toroidal magnetic field above the disc and γ is the pitch factor of order unity. The right hand side of this equation is of the form $\epsilon\mu^2/R_{\rm in}^3$ where $\epsilon = \Delta R/R_{\rm in}$ is the relative width of the coupled domain (boundary region) between the disc and the magnetosphere. The left hand-side of Equation 5, the viscous stress, is radially constant for the case with no mass loss (Özsükan et al. 2014). For the case with mass loss we assume it is given by Equation 4 so that we obtain

$$R_{\rm in} = \begin{cases} \left(\epsilon\mu^2/\dot{J}_0\right)^{1/3}, & \text{for } R_{\rm sp} < R_{\rm co} < R_{\rm in} \\ \left(\epsilon\mu^2 R_{\rm sp}^{3/2}/\dot{J}_0\right)^{2/9}, & \text{for } R_{\rm co} < R_{\rm in} < R_{\rm sp} \end{cases} \quad (6)$$

for sub-critical Özsükan et al. (2014) and super-critical propellers. The latter case can be parametrized as

$$R_{\rm in} = 2.1 \times 10^7 \text{ cm} \left(\frac{\epsilon}{0.01}\right)^{2/9} \mu_{31}^{4/9} \dot{M}_{20}^{1/9} R_{11}^{-1/9} \quad (7)$$

where $\mu_{31} = \mu/10^{31}$ G cm^3, $\dot{M}_{20} = \dot{M}_0/10^{20}$ g s^{-1} and $R_{11} = R_0/10^{11}$ cm.

2.4 Spin-down rate of the star

The nominal value of the spin-down torque, $N_0 = \epsilon\mu^2/R_{\rm in}^3$ is

$$N_0 = 1.1 \times 10^{38} \,{\rm dyn\,cm}\, \mu_{31}^{2/3} \left(\frac{\epsilon}{0.01}\right)^{1/3} \dot{M}_{20}^{-1/3} R_{11}^{1/3}. \quad (8)$$

The torque acting on the neutron star is of the form $N \equiv nN_0$ where $n = n(\omega_*)$ is the dimensionless torque and $\omega_* \equiv \Omega_*/\Omega_{\rm K}(R_{\rm in})$ is the fastness parameter. The spin evolution of the neutron star is then found by solving $I\dot{\Omega}_* = nN_0$ where I is the moment of inertia. Accordingly, the characteristic spin-down rate of the star, $\dot{P}_{\rm c} = N_0 P^2/2\pi I$ where $P = 2\pi/\Omega_*$ and $\dot{P} = -2\pi\dot{\Omega}_*/\Omega_*^2$, is

$$\dot{P}_{\rm c} = 1.7 \times 10^{-12} \mu_{31}^{2/3} \left(\frac{\epsilon}{0.01}\right)^{1/3} \dot{M}_{20}^{-1/3} R_{11}^{1/3} P_{10}^2 I_{45}^{-1} \quad (9)$$

Here $P_{10} = P/10\,{\rm ms}$ and $I_{45} = I/10^{45}\,{\rm g\,cm^2}$. Accordingly, the characteristic spin-down time scale $\tau_{\rm c} \equiv P/\dot{P}$ is

$$\tau_{\rm c} = 185 \,{\rm years}\, \mu_{31}^{-2/3} \dot{M}_{20}^{1/3} R_{11}^{-1/3} P_{10}^{-1} I_{45} \quad (10)$$

This increases to 1000 yrs for $\mu = 10^{30}$ G cm^3, but luminosity decreases. Note that $L_{\rm sd}\tau_{\rm c} = 4\pi^2 I/P^2$ and are so for a certain luminosity one finds

$$\tau_{\rm c} = 1.25 \times 10^3 \,{\rm yr}\, I_{45} L_{40}^{-1} P_{10}^{-2} \quad (11)$$

where $L_{40} = L_{\rm sd}/10^{40}\,{\rm erg\,s^{-1}}$.

2.5 Luminosity of the disc

The energy budget of propeller systems involve the gravitational potential energy released, spin-down energy of the neutron star and the kinetic energy taken away with the out-flowing matter (see e.g. Ekşi et al. 2005)

$$L = \frac{GM_*\dot{M}}{R_{\rm in}} - I\Omega_*\dot{\Omega}_* - \frac{1}{2}\dot{M}_{\rm out}v_{\rm out}^2. \quad (12)$$

By employing a dimensionless torque of the form $n = 1 - \omega_*$, Ekşi et al. (2005) found

$$L = \frac{GM\dot{M}}{2R_{\rm in}}\left[1 + (\omega_* - 1)^2\right]. \quad (13)$$

The first term $GM\dot{M}/2R_{\rm in}$ is the disc luminosity, and the second term is the boundary layer luminosity mostly contributed by the spin-down energy. In case of beaming $b < 1$ the luminosity would appear even larger $L_{\rm obs} = L/b$. This expression above, as it is, applies for sub-critical propellers. Super-critical propellers need further care as gravitational energy released outside and inside the spherization radius requires separate treatment. Moreover, the luminosity above assumes matter is ejected only from the inner rim of the disc with velocity $R_m\Omega_*$ though the matter in the super-critical propeller is ejected at a wide range of radii ($R_{\rm in}$ to $R_{\rm sp}$) with a correspondingly wide range of velocities. This is left for a later work. Here we estimate the characteristic spin-down power, $N_0\Omega$,

$$L_{\rm sd} = 6.7 \times 10^{40} \mu_{31}^{2/3} \left(\frac{\epsilon}{0.01}\right)^{1/3} \dot{M}_{20}^{-1/3} R_{11}^{1/3} P_{10}^{-1} \quad (14)$$

which is sufficient for powering even the most luminous ULX when a moderate beaming is employed.

3 DISCUSSION AND CONCLUSION

We have proposed that most ULX and ULS sources host neutron stars in super-critical propeller stage. This leads to a natural mechanism for the optically thick winds with velocity $v \sim 0.2c$ launched by radiative and centrifugal processes. The X-ray emission is then processed in this optically thick medium and be observed as soft emission at large viewing angles. The spin-down energy released by the slowing down neutron star is the main source of the extreme luminosity of these objects. We have estimated, from the balance of magnetic and material stresses, the inner radius of the disc in super-critical propeller regime. We assumed that the magnetic field of ULX's are of order $B \sim 10^{13}$ G as appropriate for very young pulsars. This value is the logarithmic center of the values estimated by Bachetti et al. (2014) (as $\sim 10^{12}$ G) and Ekşi et al. (2015) (as $\sim 10^{14}$ G) for the neutron star in PULX source M82 X–2. We have estimated the the spin-down torque and shown that the spin-down power is sufficient to power the ULX and ULS systems.

Given the abundance of neutron stars over black holes as the outcome of stellar evolution it is more likely that the bulk of the ULS/ULX population consists of young neutron stars in binary systems at the *super-critical propeller stage* rather than accreting stellar mass black holes. A similar argument is given by King et al. (2017) and Wiktorowicz et al. (2017) who argue that the the bulk of the ULX population consists of *accreting* neutron stars.

It may not be possible to easily discriminate between black hole models with the super-critical propeller model we propose here as these systems are not expected to show pulsations. Yet some systems may show outbursts where a short episode of accretion occurs such that pulsations are observed from a favourable viewing angle where the optical thickness of the envelope is reduced.

The first discovered PULX M82 X-2 is known to show propeller episodes in the archival data (Tsygankov et al. 2016). We find it necessary to emphasize that this is not exactly what we consider in this work, as the neutron star in this system has already slowed down and the spin-down power is no longer significant. Thus the object in its propeller stage, which is 40 times less luminous, does not appear to be an ULX.

There are arguments that the galactic source SS 433 is a misaligned ULX (Khabibullin & Sazonov 2016). If this indeed is the case, then our argument would favour super-critical propeller models for this source as suggested by Mineshige et al. (1991) though with spherical flow rather than quasi-spherical (Begelman & Rees 1983, 1984, see also). The recent photometric measurements indeed indicate to a mass consistent with the presence of neutron star in this system (Goranskij 2011, 2013).

A final note is about 4U 0142+61 which is identified as an anomalous X-ray pulsar (AXP) and hence is a magnetar. A supernova debris disc is detected in this system by Wang et al. (2006) and likely around 1E 2259+586 (Kaplan et al. 2009) which also is an AXP. Such discs were proposed to exist around young pulsars (Michel & Dessler 1981) at a time AXPs had not been identified. Later on they were proposed as an alternative to the magnetar picture (Chatterjee et al. 2000; Alpar 2001) and as an ingredient of magnetars with strong magnetic fields in quadrupole (Ekşi & Alpar 2003; Ertan & Alpar 2003). Whether the debris disc is now passive (Wang et al. 2006) or active (Ertan et al. 2007) at the present time, it must have been highly active at its earliest stages with super-critical mass infall (Chatterjee et al. 2000) passing through a super-critical propeller stage (Ekşi & Alpar 2003; Yan et al. 2012). This implies that some fraction of ULX or ULS systems though not in binary systems could form super-critical propeller systems with the supernova fallback matter and form the progenitors of young enigmatic neutron stars. In fact a fallback disc model for ULX sources, assuming the accreting object is a black hole, was proposed by Li (2003). Though our argument does not exclude some ULX being stellar mass black holes accreting from fallback discs at a super-critical rate, very young neutron stars with fallback discs would be more common among the ULX/ULS population. If correct, than the heterogeneous class of ULXs may also involve a small fraction of super-critical propellers without a binary companion, propellering a one-time disc.

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