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Predicting ultraluminous X-ray source demographics from geometrical beaming

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ABSTRACT

The ultraluminous X-ray source (ULX) population is known to contain neutron stars (NS), but the relative number of these compared to black hole (BH) primaries is unknown. Assuming classical supercritical accretion and resultant geometrical beaming, we show that the observed population ratio can be predicted from the mean masses of each family of compact objects and the relative spatial density of NSs to BHs. Conversely – and perhaps more importantly – given even a crude estimate for the spatial densities, an estimate of the fraction of the population containing NSs will begin to constrain the mean mass of BHs in ultraluminous X-ray sources.

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

1 INTRODUCTION

To first order, supercritical disc accretion is expected to obey classical theory (Shakura & Sunyaev 1973) with a critical radius at which the mass accretion rate equals the local Eddington limit and the disc inflates towards an aspect ratio of unity due to radiation pressure. The combined loss of material into a wind (see Poutanen et al. 2007; King & Muldrew 2016) and inward radial advection (e.g. Abramowicz et al. 1988) can cool the flow, thereby keeping it locally Eddington limited and yielding a total radiative luminosity of $\sim L_{\rm Edd}(1 + \ln \dot{m}_0)$ (Poutanen et al. 2007). By itself, this allows even very low mass compact objects such as white dwarfs to appear at luminosities well in excess of $\sim 10^{39}$ erg s^{-1} and appear as ultraluminous X-ray sources (ULXs), provided the mass transfer rate $\dot{m}_0$ (usually quoted in units of Eddington accretion rate, i.e. $\dot{m}_0 \propto \dot{m}/M$, where M is the compact object mass) is sufficiently high. In the case of high-mass X-ray binary (HMXB) systems (with $q > 1$), mass transfer eventually shrinks the Roche lobe of the donor star below the radius of thermal equilibrium such that the donor must expand against the contraction of the Roche lobe (and thereby return to equilibrium). This expansion drives a period of intense mass transfer on the thermal time-scale of the donor (King & Begelman 1999; King & Ritter 1999; King, Taam & Begelman 2000; Podsiadlowski & Rappaport 2000) where $\dot{m} \approx \frac{M_*}{t_{\rm KH}}$ (Kolb 1998) (M_* is the secondary mass and $t_{\rm KH}$ is the associated Kelvin–Helmholtz time). It is therefore very likely that most HMXB systems will experience periods of supercritical accretion at some stage of their lives.

The high *intrinsic* luminosities in supercritical systems are further amplified as a consequence of the geometry of the flow; the wind launched from the inflated disc is expected to be highly optically thick (Poutanen et al. 2007), leading to an evacuated wind-cone from which the majority of the radiation escapes (Ohsuga et al. 2005; Jiang, Stone & Davis 2014; Sądowski et al. 2014). The result is *highly* anisotropic emission with the radiation scattered and beamed towards a favourably inclined observer (King 2009) or de-boosted at higher inclinations (Dauser, Middleton & Wilms 2017). Naturally, for smaller wind-cone opening angles, the emission becomes increasingly anisotropic and the beaming amplification factor will increase. Geometrical beaming is often cited as an explanation for the most extreme end of the ULX population (above $\approx 1 \times 10^{40}$ erg s^{-1}), and observations charting the evolution in the X-ray spectra and coupled variability appear to match predictions (Middleton et al. 2015). There is additional evidence in favour of geometrical beaming from the apparent lack of eclipses (Middleton & King 2016) and ULX X-ray luminosity functions in the Local Group (e.g. Mainieri et al. 2010), the latter arguing for beaming factors scaling as $\sim \dot{m}_0^2$ (King 2009).

In light of the above, the discovery of neutron star (NS) primaries in three ultraluminous pulsars (ULPs; Bachetti et al. 2014; Fürst et al. 2016; Israel et al. 2017a,b) is unsurprising (cf. the prediction of King et al. 2001). However, the interpretation of the brightness of these ULPs is still contentious as the nature of the accretion flow will depend heavily on the surface dipole magnetic field strength (see e.g. Mushtukov et al. 2017) and whether this has been effectively diluted by the high $\dot{m}_0$ (which itself is not in question). For field strengths $<10^{12}$ G, it is probable that most ULPs will be geometrically beamed as the discs reach the Eddington limit before

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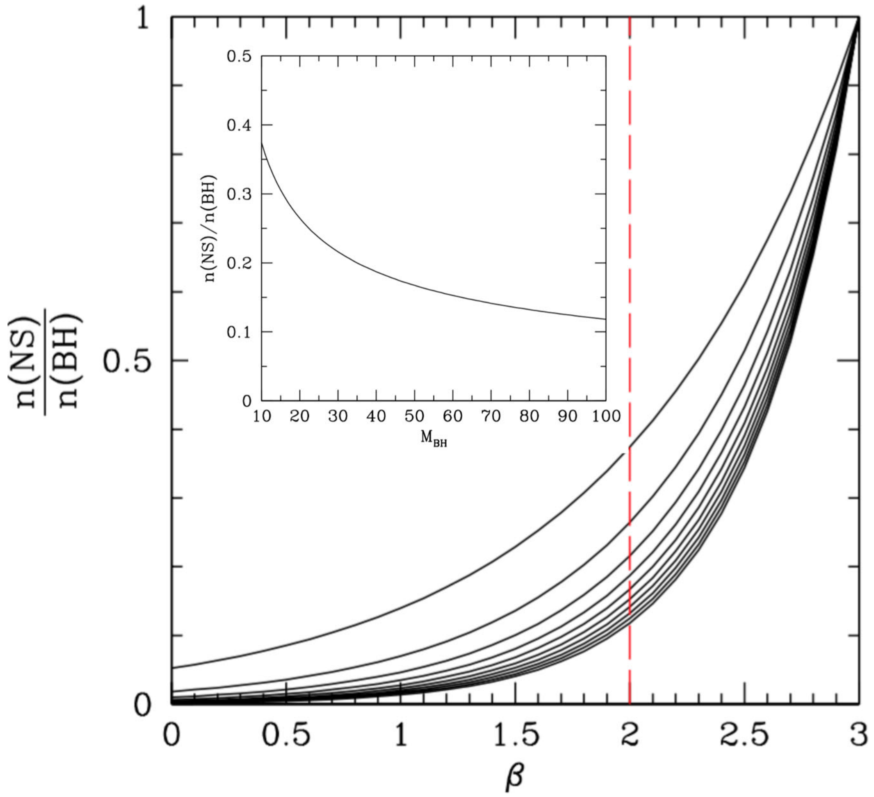

Figure 1. Main panel: observed population ratio (NS/BH) in a flux-limited survey versus beaming index (β) for a range in BH mass (10–100 $M_\odot$ from the top to bottom curve) assuming a ratio of NS to BH spatial density of unity, and $M_{NS} = 1.4\,M_\odot$. Whilst the spatial density almost certainly deviates from unity, this is only a multiplicative scaling factor and the overall trend remains unchanged. This demonstrates that the observed population ratio is a relatively steep function of BH mass (as highlighted in the inset for $\beta = 2$ – the vertical red dashed line in the main panel); as a consequence, even a rough estimate of the spatial density and observed population will constrain the mean BH mass in ULXs.

being magnetically truncated (e.g. King & Lasota 2016). Assuming that this is the case, then such beaming must undoubtedly aid in our ability to detect ULXs with either black hole (BH) or NS primaries out to significantly larger distances than if isotropic emitters. Conversely, as the beaming factor must be tied to the opening angle of the wind-cone, for an isotropic distribution of beam directions, an observer detects a smaller fraction of more tightly beamed sources because of their smaller solid angles on the sky.

In this Letter, we obtain a simple analytical relationship for the *observed* population demographic of NSs and BHs in ULXs based on the beaming factor, and which relies on only the mass ratio and the spatial density as free parameters. Note that we do *not* assume that all NS ULXs show pulsing; as we shall see, most do not.

2 ANALYTICAL ESTIMATE FROM BEAMING

We can safely assume that the area of the flux sphere not subtended by the wind (A) is inversely related to the level of geometrical beaming, i.e. $b \propto A$ (following the convention laid down in King 2009). The chance probability of detecting a source out to a distance D is therefore given simply by $P \propto nbD^3$, where n is the spatial number density of sources with a given primary. Assuming supercritical accretion (and, where the primary is an NS, a low surface dipole field strength), source luminosity is given by

$$L \propto \frac{L_{\rm Edd}}{b}(1 + \ln \dot{m}_0). \tag{1}$$

We can reasonably assume that the beaming factor is related to the mass transfer rate such that $1/b \propto \dot{m}_0^\beta \propto (\dot{m}/M)^\beta$, where β is some positive valued beaming index. This allows us to write

$$L \propto (\dot{m}/M)^\beta M(1 + \ln \dot{m}_0), \tag{2}$$

where L is the *beamed* luminosity of the source such that in a flux-limited survey (limited to some flux, f), $D^3 \propto (L/f)^{3/2}$. We then observe that

$$P \propto n(M/\dot{m})^\beta \left(\frac{\left[(\dot{m}/M)^\beta M(1 + \ln \dot{m}_0)\right]}{f}\right)^{3/2}. \tag{3}$$

The ratio of P_{NS}/P_{BH} is the relative fraction of those ULX primaries found in a flux-limited survey. Assuming that the absolute mass transfer rate is the same for both 'species' of ULX, we then find

$$\frac{P_{\rm NS}}{P_{\rm BH}} = \frac{n({\rm NS})}{n({\rm BH})}\left(\frac{M_{\rm NS}}{M_{\rm BH}}\right)^{(3-\beta)/2}\left(\frac{1 + \ln \dot{m}_{0,{\rm NS}}}{1 + \ln \dot{m}_{0,{\rm BH}}}\right), \tag{4}$$

where the trailing term is of order unity. This leaves us with

$$\frac{P_{\rm NS}}{P_{\rm BH}} \approx \frac{n({\rm NS})}{n({\rm BH})}\left(\frac{M_{\rm NS}}{M_{\rm BH}}\right)^{(3-\beta)/2}. \tag{5}$$

Various observational findings (see King 2009) may motivate us to expect $b \propto \dot{m}_0^{-2}$ such that

$$\frac{P_{\rm NS}}{P_{\rm BH}} \approx \frac{n({\rm NS})}{n({\rm BH})}\sqrt{\frac{M_{\rm NS}}{M_{\rm BH}}}, \tag{6}$$

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which depends only on the relative spatial densities (also a function of the mass ratio), mean mass of the NSs (which covers only a very small range) and the mean mass of the BHs in the ULX sample (assuming Gaussian statistics).

3 DISCUSSION AND CONCLUSION

We have demonstrated a simple means of predicting the relative observable population of NSs and BHs in ULXs from simple beaming arguments that depend on the beaming index (β), ratio of masses and spatial densities. Although we have a reason to believe $\beta \approx 2$ (King 2009), in Fig. 1, we also show the range in observed population ratio (n(NS)/n(BH)) for a range in beaming index and a range in mean BH mass (from 10–100 $M_{\odot}$) assuming an equal spatial density of NSs and BHs, and a canonical NS mass (1.4 $M_{\odot}$).

Based on the relative numbers of HMXBs containing NSs and BHs (see Casares, Jonker & Israelian 2017, and references therein), the true ratio of spatial densities is probably skewed in favour of NSs by a factor of $\geq$2. Equation (6) then shows that there must be a substantial number of NS ULXs even if we do not observe their pulsations (see also the arguments in King, Lasota & Kluźniak 2017). It is also clear that, unless the true spatial density is *heavily* skewed in favour of NSs, BH ULXs still provide a significant (if not dominant) component of the population. This reinforces the argument that the NSs in ULXs probably have low to moderate dipole field strengths such that the X-ray spectra do not deviate massively from the remainder of the population (Kluźniak & Lasota 2015).

The ratio of spatial densities is still somewhat unclear (and will probably require detailed population synthesis). However, this adds only a multiplicative scaling factor, so it is immediately clear that for moderate beaming indices, the observed population ratio must be a relatively steep function of BH mass (see the inset to Fig. 1). This opens up the distinct possibility of using flux-limited surveys to determine the maximum (mean) mass of BHs in ULXs quite independently of other techniques.

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