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Point X-ray Sources in Elliptical Galaxies

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Abstract. We analyze the upper-end X-ray luminosity function (XLF) observed in elliptical galaxies for point sources. We propose that the observed XLF is dominated by transient BH systems in outburst and the XLF shape reflects the black hole (BH) mass spectrum among old X-ray transients. The BH mass spectrum – XLF connection depends on a weighting factor that is related to the transient duty cycle and depends on the host-galaxy age, the BH mass and the donor type (main sequence, red giant, or white dwarf). We argue that the assumption of a constant duty cycle for all systems leads to results inconsistent with current observations. The type of dominant donors in the upper-end XLF depends on what type of magnetic braking operates: in the case of "standard" magnetic braking, BH X-ray binaries with red-giant donors dominate, and in the case of weaker magnetic braking prescriptions main sequence donors dominate.

Keywords. galaxies:elliptical – binaries:close – methods: statistical – X-rays: binaries.

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1. Transient and persistent Black Hole X-Ray Binaries in Ellipticals

With *Chandra* observations, elliptical galaxies out to the Virgo cluster have now been studied. These observations have revealed a large number of point X-ray sources and early on Sarazin *et al.* (2000) identified an XLF shape that required two power laws with a break at $\simeq 3.2 \times 10^{38}\,\mathrm{erg\,s^{-1}}$. Following longer exposures for more ellipticals (Gilfanov 2004, Kim & Fabbiano 2004) have confirmed that the combined sample of sources from all observed galaxies requires two power laws and a break at $5 \pm 1.6 \times 10^{38}$ erg s^{-1} and the best-fit slope of the upper end to be $\alpha_{\rm d} = 2.8 \pm 0.6$.

We analyze the upper-end of XLF assuming: (i) the XLF above the break at 5×10^{38} erg s^{-1} is populated by X-ray binaries (XRBs) with black hole (BH) accretors (Sarazin *et al.* 2000); (ii) the vast majority of these BH-XRBs are part of the galactic-field stellar population in ellipticals; (iii) donor masses are lower than $\simeq$1–1.5 $\mathrm{M_\odot}$ (in accordance to the current estimates for the ages of stellar populations in ellipticals) and (iv) we adopt the current understanding for the origin of transient behavior in XRBs (King 2005). We consider typical mass transfer (MT) rate associated with each type of XRB donor ($\dot{M}_i$) and compare it to the critical MT rates for transient behavior ($\dot{M}_{\rm crit}$): if $\dot{M}_i < \dot{M}_{\rm crit}$, the binary system is assumed to be a transient X-ray source and we assume that during the outburst the X-ray luminosity is equal to the BH accretor Eddington luminosity.

Mass transfer in BH XRBs with low-mass main sequence (MS) donors is driven by angular momentum losses due to magnetic braking (MB) and gravitational radiation (GR). From detailed binary evolutionary calculations using the stellar evolution and MT code (Ivanova & Taam 2004), we find that if MB follows the Skumanich law (taken as in Rappaport *et al.* 1983), then XRBs with BHs $\leqslant 10 M_\odot$ are persistent as long as the donor masses are $>0.3 M_\odot$. The MT rates are about 0.01–0.25 of the BHs' Eddington rate. As a result, the persistent X-ray luminosity for these systems is $\leqslant 10^{38}\,\mathrm{erg\,s^{-1}}$. For $M_{\rm BH} > 10\,M_\odot$, the outburst luminosity is in excess of $\simeq 1.5 \times 10^{39}\,\mathrm{erg\,s^{-1}}$. This limit is comparable to the highest luminosity seen currently in XLFs of ellipticals (Kim & Fabbiano 2004), and therefore these systems cannot contribute significantly to the observed XLFs. Outbursts are possible from transient BH-MS with $M_{\rm BH} < 10\,M_\odot$ and donors less massive than $\simeq 0.3\,M_\odot$; these low mass donors are out of thermal equilibrium. In the case of the MB prescription derived for fast rotating systems, which are BH-MS binaries (Ivanova & Taam 2003, IT), BH-MS systems are transient for all BHs masses $M_{\rm BH} > 3M_\odot$ and for all low-mass MS donors. If a donor is a low-mass subgiant or red giant (RG), it has been shown (King 2005) that such XRBs are transient, regardless of the BH mass. The evolution of mass-transferring BH systems with a white dwarf (WD) very weakly depends on the BH mass. A typical life-time of such a system in the persistent stage is $\sim 10^7$ years and only during 10^6 years a BH-WD will have MT rates in excess of the Eddington limit. We conclude that all BH binaries that contribute to the current upper-end XLFs of ellipticals are expected to be transient sources.

2. Weighting Factor for the BH Mass Spectrum and the Duty Cycle

The transient BH XRBs (those in outburst) contributing to the upper-end XLF is a sub-set of the true population of BH XRBs in ellipticals determined by the duty cycle of BH transient binaries. For the general case of a transient duty cycle that is dependent on the BH accretor mass, the differential XLF $n(L)_{\rm obs}$ and the underlying BH mass distribution in XRBs $n(m_{\rm BH})$ are connected by:

$$n(L_X)_{\rm obs} = n(m_{\rm BH}) \times W(m_{\rm BH}), \tag{2.1}$$

where $W(m_{\rm BH})$ is a weighting factor related to the dependence of the transient duty cycle on $m_{\rm BH}$. The observed slope of the differential upper-end XLF is $\alpha_{\rm d} = 2.8 \pm 0.6$: $n(L_X)_{\rm obs} \propto L_X^{-\alpha_{\rm d}}$. Assuming that $n(m_{\rm BH}) \propto m_{\rm BH}^{-\beta}$ and $W(m_{\rm BH}) \propto m_{\rm BH}^{-\gamma}$, the slope characterizing the underlying BH mass distribution in XRBs is $\beta = \alpha_{\rm d} - \gamma$.

At present there are no strong constraints on the duty cycles either from observations or from theoretical considerations. Among known Galactic X-ray transients, typical duty cycles of a few % are favored for hydrogen donors (Tanaka & Shibazaki 1996) and there are no data on duty cycles for transients with a WD companion. For the standard assumption of a constant duty cycle, $\beta = \alpha_{\rm d} = 2.8 \pm 0.6$. However, according to binary population synthesis models for the Milky Way published so far, the number of formed BH-WD LMXBs exceeds the number of BH-MS LMXBs by a factor of 100 (Hurley *et al.* 2002). If the duty cycle were similar for both types of systems, we would observe a few hundreds BH-WD binaries; however none such binaries have been identified. We therefore investigate how plausible duty cycle assumptions affect the upper-end XLF shape, considering a variable (dependent on MT rates) duty cycle equal to $\eta = 0.1 \times \dot{M}_{\rm d}/\dot{M}_{\rm crit}$. This specific choice of the dependence is not solidly motivated, however, it implies a correlation of the duty cycle with how strong a transient the system is: the further away from the critical MT rate, the smaller the duty cycle.

The expression for η in the case of WD and RG donors can be found analytically. For RG we obtain (using MT rates for RGs from Webbink *et al.* 1983) $\dot{m}_{\rm RG}/\dot{m}_{\rm crit} \simeq 0.2a^{-0.7}m_{\rm d}^{1.5}$. Therefore, for RG donors, $\gamma = 0$. Instead there is a significant dependence on the RG donor mass. Since in ellipticals the typical mass for RG donors is about the same as the mass of the turn-off of MS stars, the duty cycle for RG donors depends on the turn-off mass, and hence on the age T [Gyr] of the elliptical. Assuming a flat in the logarithm distribution of orbital separations before MT starts, we find:

$$W(T) \simeq 0.03 \times T^{-0.5}\,. \tag{2.2}$$

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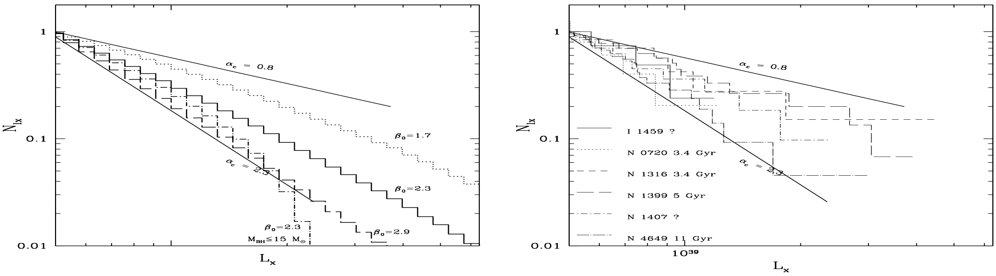

Figure 1. The left panel shows model XLFs for BH-MS binaries. Lines shows results for initial $\beta_0 = 1.7, 2.3, 2.9$ at an age of 10 Gyr (dotted, solid and dashed lines). The dash-dotted line is for a $15\,M_\odot$ BH mass cut-off with $\beta_0 = 2.3$. Thick solid lines corresponds to slopes $\alpha_c = 0.8$ and $\alpha_c = 2.3$. The right panel shows XLFs in observed early type galaxies (data are from Kim & Fabbiano 2004, the ages of the ellipticals are from Ryden *et al.* 2001 and Temi *et al.* 2005).

In order to find the probability that a BH-WD contributes to the upper-end XLF at an elliptical age, we assume that (i) all accreting BH-WD systems were formed within a short interval of elliptical ages several Gyrs ago; and (ii) the binary is a transient at time T. We further adopt a constant BH-WD formation rate during this interval. We obtain:

$$W(T; m_{\rm BH}) = 1.6 \times 10^{-4} m_{\rm BH}^{-0.5} t_1^{-7/4} \frac{1-(t_2/t_1)^{-3/4}}{1-(t_2/t_1)} \tag{2.3}$$

Here t_1 and t_2 are the time in Gyrs from the current moment to the start and the end of BH-WD binaries formation. Therefore for WD donors $\gamma = 0.5$ and W depends on both the BH mass and the galaxy age.

As discussed previously, for IT MB, a BH-MS system is transient throughout the MT phase. It also can be seen that the MT dependent duty cycle is about few %, consistent with the observations. Prolonged mass accretion onto the BHs affects their mass spectrum. Since this effect cannot be included analytically, we have examined it quantitatively using simple Monte Carlo simulations. We set up the simulations assuming a flat BH-MS birth (MT onset) rate and a flat mass distribution for donors at the onset of the MT phase, without any restrictions on the mass ratio $q_{\rm BH}$. For the MT evolution we took into account both IT MB and GR, and if the MT timescale is longer than the thermal timescale of the donor, the donor radius evolution is simply proportional to the mass lost due to MT. On the other hand, if the MT timescale is shorter than the donor's thermal timescale, the donor is out of the thermal equilibrium. In this case we modify the evolution of the donor radius using a prescription that is in acceptable agreement with our results from detailed MT calculations with the stellar evolution: $\delta r \sim \delta m \sqrt{\dot m_{\rm TH}/\dot m}$, where $\dot m_{\rm TH} = m_{\rm d}/t_{\rm TH}$ is the MT rate driven on the donor's thermal timescale $t_{\rm TH}$.

Based on the results of our Monte Carlo simulations we find that: (i) due to accretion the BH mass spectrum slope increases by about 0.2, i.e., $\beta = \beta_0 + 0.2$, where β_0 is the BH mass slope at MT onset; (ii) the slope of the BH mass spectrum at the beginning of mass transfer best reproduces the observations with $\beta_0 = 2.3 \pm 0.6$ (see Fig. 1). We also find that the relation between β and β_0 is not sensitive to the age of the elliptical.

3. Conclusions

We conclude that all BH binaries contributing to the upper-end XLF of ellipticals are transient. A constant transient duty cycle independent of the donor type can be excluded unless BH-WD transients have very weak outbursts and can not be detected. The upper-end XLF is formed by an underlying mass spectrum of accreting BHs. The BH X-ray

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transients have a dominant donor type and an accreting BH mass spectrum slope β that depends on the strength of MB angular momentum loss. In particular, in the case of Skumanich-type MB, the XLF is dominated by BH-RG binaries and $\beta = 2.8 \pm 0.6$. In the case of MB for fast-rotators, only BH-MS transients significantly contribute to the upper-end XLF and $\beta = 2.5 \pm 0.6 \ \ (\beta_0 = 2.3 \pm 0.6)$. If the relative fraction of BH-RG transients in ellipticals is larger than the observed relative fraction in our Galaxy, we expect that the BH-RG binaries contribution will lead to a time-dependence of XLF slopes, where younger ellipticals will have a slope predicted for BH-RG binaries, and older ellipticals a steeper slope predicted for BH-MS binaries.

Acknowledgements

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Discussion

Lipunov: The initial mass function can not be described as simple power law.

Ivanova: It is not assumed or insisted. This is what the XLFs tell us about how the BHs mass spectrum looks like, for a specific type of donors. It does not represent the whole spectrum of all ever formed BHs, only for selected type of donors. We hope that this result will provide additional constrains for these scientific teams who work on the connection between pre-collapse stars and the resulting masses of formed compact objects.

Kim: Can you constrain the minimum mass of BH?

Ivanova: No, we can not make it directly. We can only give constrains on the BH mass spectrum given by our understanding of their donors is correct. E.g., we can not rule out BH less massive than $3M_\odot$ as the possible lack of BH-MS binaries with BHs of such masses in XLFs can be the result of different selection effects originating in the binaries evolution, but not in BHs formation.

Sivakoff: You predict that all XRB in the high end of the XLF are transient. Can you comment on the time-scales expected for this transience? In particularly, are the time-scales observable on our life-times?

Ivanova: We can only give estimates for the duty cycles, but not for the outbursts durations. The latter will have to come from observations.