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THE BRIGHTEST POINT X-RAY SOURCES IN ELLIPTICAL GALAXIES AND THE MASS SPECTRUM OF ACCRETING BLACK HOLES

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ABSTRACT

We propose that the shape of the upper-end X-ray luminosity function (XLF) observed in elliptical galaxies for point sources carries valuable information about the black-hole (BH) mass spectrum among old X-ray transients formed in the galaxies. Here we present the line of arguments and analysis that support this connection and the methodology for deriving the BH mass spectrum slope from the observed XLF slope. We show that this underlying BH mass spectrum is modified by a weighting factor that is related to the transient duty cycle and it generally depends on the host-galaxy age, the BH mass and XRB donor type (main-sequence, red-giant, or white-dwarf donors). We find that the observed XLF is dominated by transient BH systems in outburst (a prediction possibly testable by future observations), but that the assumption of a constant duty cycle for all systems leads to results inconsistent with current observations. We also find that the derived BH mass slope depends on the strength of angular momentum loss due to magnetic braking for main-sequence donors. More specifically, we find that, for "standard" magnetic braking, BH XRBs with red-giant donors dominate the upper-end XLF; for weaker magnetic braking prescriptions main-sequence donors are found to be dominant. The methodology presented here can be used in the future as our understanding of the transient duty and its dependence on binary and mass-transfer properties improves. Under certain assumptions for this dependence we derive a differential BH mass spectrum slope of $\simeq 2.5$; an upper BH mass cut-off at $\simeq 20\,M_\odot$ is needed to understand the very brightest of the BH XRBs in elliptical galaxies. We also show that our quantitative results are robust against expected variations by factors of a few of the outburst peak X-ray luminosities. We expect that our analysis will eventually help to constrain binary population synthesis models and the adopted relations between black holes and the masses of their progenitors.

Subject headings: galaxies: elliptical – methods: statistical – X-rays: binaries

1. INTRODUCTION

Chandra has revolutionized the study of point X-ray sources in the nearby Universe. The majority of these are interpreted to be X-ray binaries (XRBs; for a general review on *Chandra* performance see Weisskopf et al. 2003, for extragalactic X-ray binaries see, e.g., Kim & Fabbiano 2004; Jordán et al. 2004). Elliptical galaxies out to the Virgo cluster have now been studied and have surprised us with the large number (typically ~ 100 per galaxy) of detectable point X-ray sources down to X-ray luminosities of about $10^{37}\,\mathrm{erg\,s^{-1}}$. Two main population characteristics have attracted considerable attention so far: (i) the X-ray luminosity function (hereafter XLF) that may or may not exhibit a break at about $4-5\times10^{38}\,\mathrm{erg\,s^{-1}}$ (for a recent update see Kim & Fabbiano 2004); (ii) the high fraction of sources coincident with identified globular clusters (GCs) in ellipticals.

The shape of the XLF has been debated since the first observations of ellipticals were reported. Sarazin et al. (2000) identified a shape that required two power laws with a "break" or a "knee" at $\simeq 3.2\times10^{38}\,\mathrm{ergs\,s^{-1}}$. Kim & Fabbiano (2003) argued that the break may result from biases affecting the detection threshold of the data. In the following few years longer exposures became possible and more and more ellipticals were added in the observed sample with low enough sensitivity (see, e.g. Gilfanov 2004). The current situation is probably best summarized in Kim & Fabbiano (2004). They analyzed a large sample of elliptical galaxies with varying sizes of point source samples, and they concluded that: although XLFs of individual galaxies do not require a broken-power-law fit, the combined sample of sources from all the galaxies considered shows a statistically significant requirement for two power laws and a break at $5\pm1.6\times10^{38}$ ergs s^{-1}. They found the best-fit slope of the lower end of the differential XLF to be $\alpha_\mathrm{d}=1.8\pm0.2$ and the best-fit slope of the upper end to be $\alpha_\mathrm{d}=2.8\pm0.6$. It is important to note that the break location is consistent with the Eddington luminosity for a $1.9\pm0.6\,M_\odot$ neutron star (NS) accreting helium-rich material (for hydrogen rich donor this value is as large as $3.2\pm1M_\odot$). In what follows we consider the results of the Kim & Fabbiano (2004) study as representing our current observational understanding of the XLF in ellipticals. We address the question of the interpretation of this understanding and what it implies about the properties of the sources contributing to the observed XLFs.

Large fractions (20% – 70%) of the point sources in ellipticals have been reported to be associated with globular clusters (see, e.g., Sarazin et al. 2003, and references therein). These high fractions have led to the suggestion that *all* point X-ray sources seen currently in ellipticals have been formed through stellar interactions and that sources that are not associated with GCs have originated in GCs and have either been ejected or the parent GCs have been destroyed by the galaxian tidal forces. As

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much interesting as this suggestion is, it raises the question: why would the field stellar population of ellipticals not lead to XRB formation as it has occurred in the Milky Way, for example? One could speculate that the field population is just too old and the XRBs that were formed at some point have completed their X-ray emitting life. However, such a speculation is inconsistent with the expectation that XRBs with low mass donors can live for several Gyrs as the donors lose mass and the binaries enter a transient phase. Such systems would become detectable as bright X-ray sources during the disk outbursts (Piro & Bildsten 2002). Moreover, it has recently been pointed out that the high rate of source coincidence with GCs actually appears consistent with some of the sources having been formed in the field (Juett 2005), although the result may sensitively depend on the definition of GC concentration in ellipticals. Most importantly for the present study, of the bright sources above the XLF break only a very small fraction is associated with GCs (e.g., only one source in the Virgo cluster sample as reported by Jordán et al. 2004).

In a recent *Letter* Bildsten & Deloye (2004, hereafter DB) have suggested an explanation that couples the two population characteristics: the XLF shape and the source coincidence with GCs. They identify the point X-ray sources as ultra-compact binaries (UCBs) that form predominantly in GCs. They are neutron stars accreting from low-mass He or C/O white dwarfs and they contribute to the ellipticals XLF early in their lifetime when they are still bright. Their association with GCs is important in replenishing the population through tidal interactions and allowing a significant number of sources in this bright phase, even though there is no ongoing star formation in ellipticals nor in GCs. DB estimate the rate of ultracompact binary formation to be consistent with the number sources observed and conclude that the model XLF slope is in agreement with the slope *below the break* as derived by Kim & Fabbiano (2004). The association of the XLF break with the NS Eddington limit for He-rich accretion is also consistent with this interpretation. However, the *upper end* of the XLF (at luminosities in excess of the break location) are not easy to interpret. Deloye & Bildsten suggest that some of the NS ultra-compact sources can reach super-Eddington luminosities. However luminosities in excess of $10^{39}\,\mathrm{erg\,s^{-1}}$ are very difficult to explain with NS accretors. Therefore the origin of the upper-end slope is not naturally connected to NS UCBs formed in GCs.

In this paper we address the question of the *upper-end* XLF slope and its origin. We consider the previously made suggestion (Sarazin et al. 2000) that the XLF above the break at 5×10^{38} erg s^{-1} is populated by XRBs with black hole (BH) accretors. Given that GCs are not expected to harbor a significant number of BH-XRBs (see Kalogera et al. 2004, and references therein), we suggest that the vast majority of these BH-XRBs are part of the galactic-field stellar population in ellipticals. As we will show most of donors in these binaries are of low-enough mass that the XRBs are expected to be transient and therefore they populate the XLF only during disk outbursts when they typically emit at the Eddington luminosity for their BH mass. We further suggest that the slope of the upper XLF is a footprint of the BH mass spectrum in the BH XRBs under consideration. We present analytical derivations that demonstrate this link and we develop a method that allows us to infer the underlying BH mass spectrum consistent with the current upper-end XLF slope (Kim & Fabbiano 2004). We also show that given the current observations it is possible to constrain the strength of magnetic braking acting in these XRBs, the type of BH donors, as well as the transient duty cycle to some extent. We also examine the quantitative robustness of our results against variations of some basic assumptions. This analysis is presented in § 2 and 3. We conclude with a discussion of our results and possible connections to population synthesis calculations (§ 4).

2. BLACK HOLE X-RAY BINARIES IN ELLIPTICALS

We consider XRBs that could possibly populate the part of the observed XLF above the reported break at $4-6\times10^{38}$ erg s^{-1}, and therefore we focus on BH accretors (masses in excess of $2-3\,\mathrm{M_\odot}$). Given the current estimates for the ages of stellar populations in ellipticals (in their majority 8 to 12 Gyr, although some estimates are slightly shorter than 5 Gyr; see Ryden et al. 2001; Temi et al. 2005), we expect that donor masses are lower than $\simeq 1-1.5\,\mathrm{M_\odot}$. Given these mass ratios and the properties of similar observed systems in the Milky Way (i.e., soft X-ray transients), these BH XRBs are expected to be transient X-ray sources (see McClintock & Remillard 2005 for a review of BH X-ray binaries in the Milky Way), where mass transfer is driven by the Roche-lobe filling donor. Given the above upper limit on the donor mass for ellipticals, we expect that there will be three different types of low-mass donors: (i) Main Sequence (MS) stars, (ii) Evolved or Red Giant Branch (RG) stars, and (iii) White Dwarf (WD) donors. Each of these sub-populations of BH XRBs will have different typical mass-transfer rates and binary property distributions, and therefore we examine them separately in our analysis that follows.

2.1. *Transient X-Ray Sources*

We adopt the current understanding for the origin of transient behavior in XRBs (for a recent review, see King 2005). To identify transient systems in our modeling we consider the 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 $\dot M_i < \dot M_{\rm crit}$, then the accretion disk is expected to be thermally unstable and the binary system is assumed to be a transient X-ray source. The value of this critical MT rate for the disk instability is not precisely known and its functional dependence on disk and binary properties are subject to uncertainties associated with our current theoretical understanding of the disk instability. However, both the qualitative concept of the existence of a critical rate for the instability to set in and its quantitative estimates by recent studies appear to be in good agreement with the behavior of Galactic X-ray transients. Therefore, we adopt the current understanding and quantitative estimates. More specifically, for hydrogen-rich donors, we adopt the $\dot M_{\rm crit}$ value derived by Dubus et al. (1999), and for helium or carbon-oxygen donors, we adopt the value derived by Menou et al. (2002). The effects of quantitative deviations from the adopted expressions are discussed in what follows.

To account for the contribution of transient sources in the XLF among any persistent sources, assumptions about the XRB luminosity at outburst and the transient duty cycle need to be made.

When a XRB is identified as transient, we assume that during the disk outburst the X-ray luminosity $L_{\rm X}$ is equal to the Eddington luminosity $L_{\rm Edd}$ associated to the BH accretor:

$$L_{\rm Edd} = \frac{4\pi c G M_{\rm BH}}{\kappa} = 5\times 10^{37}\,\frac{m_{\rm BH}}{\kappa}\quad {\rm ergs\,s^{-1}}\ , \qquad (1)$$

where $m_{\rm BH}$ is the accretor mass in $M_\odot$ and κ is the opacity of the accreting material in ${\rm cm^2\,g^{-1}}$. We adopt electron scattering opacities equal to 0.32 and 0.19 for hydrogen and helium or carbon-oxygen rich material, respectively.

We note that of the 15 confirmed transient BH XRBs in our Galaxy, 3 appear to reach possibly super-Eddington luminosities (McClintock & Remillard 2005) at outburst (although distance estimate uncertainties cannot be ignored). Two of them, V4641 Sgr and 4U 1543-47, have early-type donors. Such donors are not present in elliptical galaxies with population ages of $\sim 5-10$ Gyr. The third one, GRS 1915+105, has a low-mass giant donor and an orbital period of 33 days. However its X-ray luminosity at outburst just barely exceeds its $L_{\rm Edd}$, by 40% only. Given distance uncertainties associated with such an estimate, we conclude that we can neglect the possibility of super-Eddington luminosities during outburst in our XLF modeling. On the other hand outburst peak luminosities cover a significant range at sub-Eddington values. During primary[1] outbursts peak L_X values can be lower than $L_{\rm Edd}$ by factors of a few (McClintock & Remillard 2005, private communication). As part of our analysis we examine the effect of such variations on the methodology and conclusions presented here (see § 3.1.1). From an observationally point of view it has been shown (Zezas et al. 2004 and Zezas 2005, private communication) that variability in X-ray fluxes (and hence luminosities) by factors of a few (typical among accreting sources and detected with *Chandra* observations at different epochs) do not alter the XLF slopes as measured for nearby galaxies within the current errors. Therefore observationally the reported XLF slopes appear to be robust. Consequently we can use them to learn about the underlying XRB population with considerable confidence.

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 % is favored for hydrogen donors (Tanaka & Shibazaki 1996). To our knowledge, there are no data on duty cycles for transients with a WD companion. In what follows we investigate how plausible duty cycle assumptions affect the upper-end XLF shape. In particular, we consider two specific cases: one of constant duty cycle equal to $\eta = 0.01$; another of a variable (dependent on MT rates) duty cycle equal to

$$\eta = 0.1\left(\frac{\dot M_{\rm d}}{\dot M_{\rm crit}}\right)^{\delta} \qquad (2)$$

where $\delta = 1$ is assumed. The first of these two cases corresponds to the standard assumption of a constant duty cycle often made in the literature. The second case is motivated primarily by our plan to examine how one example form of a MT-dependent duty cycle affects our analysis and results. Admittedly the specific choice of the dependence on $\dot M_{\rm crit}$ shown above is not solidly motivated, given all the uncertainties of the outburst mechanism. 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. We stress that in most of our analysis we adopt this form with $\delta = 1$ as a plausible example and throughout the paper we contrast the results to those obtained with a constant duty cycle. Furthermore in § 3.1.1 we examine the sensitivity of our results for main-sequence donors on the choice of the duty-cycle dependence on MT extensively: we adopt $\delta > 1$ in eq.(2) and we also introduce yet one other example of a MT-dependent duty cycle:

$$\eta = 0.1\left(\frac{\dot M_{\rm d}}{\dot M_{\rm EDD}}\right)^{\delta} \qquad (3)$$

for which we examine various values of δ. Once again there is no solid theoretical motivation for this latter functional choice. However, it provides us with a better understanding of how sensitive our results are to the details of the possible duty-cycle dependence on MT properties.

2.2. *Main Sequence Donors*

Mass transfer in BH XRBs with hydrogen-rich, low-mass MS donors is expected to be driven by angular momentum losses due to magnetic braking (MB) and gravitational radiation (GR). In the case of conservative mass transfer (Verbunt 1993) the angular momentum loss rate are connected to the MT rate as follows:

$$\frac{\dot J_{\rm gr}}{J_{\rm orb}} + \frac{\dot J_{\rm mb}}{J_{\rm orb}} = \frac{\dot M_{\rm d}}{M_{\rm d}}\left(\frac{5}{6} + \frac{n}{2} - \frac{M_{\rm d}}{M_{\rm BH}}\right), \qquad (4)$$

where n is the radius-mass exponent for the donor. For a low-mass MS star:

$$r_{\rm d} \simeq m_{\rm d}, \qquad (5)$$

where $r_{\rm d} = R_{\rm d}/R_\odot$ and $m_{\rm d} = M_{\rm d}/M_\odot$ are the donor stellar radius and mass in solar units. Therefore $n \equiv d\,lnR_{\rm d}/d\,lnM_{\rm d}$ is equal to $\simeq 1$ for MS donors.

According to general relativity the rate of angular momentum loss due to GR is given by:

$$\frac{\dot J_{\rm gr}}{J_{\rm orb}} = -\frac{32G^3}{5c^5}\,\frac{M_{\rm BH}M_{\rm d}(M_{\rm BH}+M_{\rm d})}{A^4}$$
$$= -2.6\times 10^{-17}\,\frac{m_{\rm BH}m_{\rm d}(m_{\rm BH}+m_{\rm d})}{a^4}\ {\rm s^{-1}}, \qquad (6)$$

where a is the orbital semi-major axis in units of solar radius. For a mass ratio $q \equiv M_d/M_{\rm BH} < 0.8$ (Paczyński 1971) and using the mass-radius relation eq. (5):

$$a = \frac{1}{0.46} m_{\rm d}^{2/3}(m_{\rm BH}+m_{\rm d})^{1/3}. \qquad (7)$$

[1] We use the term "primary" to distinguish from "follow-up" outbursts that are occasionally observed very soon after primary ones with peak luminosities orders of magnitude below the Eddington limit (Remillard & McClintock 2005, private communication). Such small outbursts do not reflect an extremely short duty cycle and do not contribute to the high-end XLF of interest here.

We consider two derivations of the angular momentum loss rate due to magnetic braking: (i) the Skumanich law based on the empirical relation for slowly rotating stars adopted from (Rappaport et al. 1983) (RVJ), and (ii) the revised law based on X-ray observations of faster rotating dwarfs adopted from (Ivanova & Taam 2003) (IT):

$$\dot{J}_{\rm mb}^{\rm RVJ} = -3.8\times10^{-30} M_{\rm d} R_\odot^4 (R_{\rm d}/R_\odot)^2 \Omega^3 \ {\rm dyn\,cm} \quad (8)$$

$$\dot{J}_{\rm mb}^{\rm IT} = -6\times10^{30} (R_{\rm d}/R_\odot)^4 \left(\frac{\Omega^{1.3}\Omega_{\rm x}^{1.7}}{\Omega_\odot^3}\right) \ {\rm dyn\,cm}, \quad (9)$$

where Ω [$\rm s^{-1}$] is the stellar angular velocity which is equal to the binary orbital velocity assuming the star is in full synchronization with the binary orbit, $\Omega_\odot = 5\times10^{-6}$ $\rm s^{-1}$ is the Sun's angular velocity, and $\Omega_{\rm x} = 10\Omega_\odot$. Using Kepler's law the above are re-written as:

$$\frac{\dot{J}_{\rm mb}^{\rm RVJ}}{J_{\rm orb}} = -7.2\times10^{-15}\,\frac{m_{\rm d}^2(m_{\rm BH}+m_{\rm d})^2}{m_{\rm BH}a^5}\,{\rm s}^{-1}\ , \quad (10)$$

$$\frac{\dot{J}_{\rm mb}^{\rm IT}}{J_{\rm orb}} = -2.7\times10^{-17}\,\frac{m_{\rm d}^3(m_{\rm BH}+m_{\rm d})^{1.15}}{m_{\rm BH}a^{2.45}}\,{\rm s}^{-1}\ . \quad (11)$$

In XRBs with BH masses $\geq 3M_\odot$ and MS donor masses $\leq 1.0M_\odot$, it is $J_{\rm gr} \ll J_{\rm mb}^{\rm RVJ}$ and $J_{\rm gr} \gtrsim J_{\rm mb}^{\rm IT}$. The lifetime of the MS-BH XRBs is much longer in the latter case.

As mentioned earlier in this study we adopt the derivation of the critical MT rate below which the accretion disk becomes unstable for irradiated disks presented by Dubus et al. 1999:

$$\dot{M}_{\rm crit} = -1.5\times10^{15} m_{\rm BH}^{-0.4}\left(\frac{R_{\rm disk}}{10^{10}{\rm cm}}\right)^{2.1} {\rm g\,s^{-1}}\ . \quad (12)$$

Here $R_{\rm disk}$ is the radius of the accretion disk. We note that the exact value of this critical rate is subject to uncertainties associated with our limited understanding of the disk instability, but we adopt the above expression as indicative of the process and we continue with our analysis.

From eq.(4), (10) and (12) it can be shown numerically, that for the RVJ MB law and for low-mass donors, there is a BH mass $M_{\rm PT}$ of $\sim 5\,M_\odot$ that separates BH-MS systems into persistent ($M_{\rm BH} < M_{\rm PT}$), and transient ($M_{\rm BH} > M_{\rm PT}$). From more detailed binary evolutionary calculations using the stellar evolution and MT code described in (Ivanova & Taam 2004), we find that this boundary is about $10\,M_\odot$ (see Fig. 1 for details). For BHs less massive than this critical mass, the XRBs are persistent as long as the donor masses are higher than about $0.3\,M_\odot$. In these persistent sources the MT rates driven by the RVJ type of MB turn out to be $0.01-0.25$ of the black holes's Eddington rate. As a result, the persistent X-ray luminosity for these systems is $\lesssim 10^{38}\,{\rm erg\,s^{-1}}$, i.e., below the bright L_X range we consider here. Therefore we conclude that the persistent BH-MS binaries driven by the RVJ type of MB cannot contribute significantly to the upper-end XLFs of ellipticals.

Next we examine whether the transient phases associated with BH-MS binaries and the RVJ MB law are important when they reach X-ray luminosities comparable to the Eddington limit. For $M_{\rm BH} > 10\,M_\odot$, the outburst luminosity is expected to be in excess of $\simeq 1.5\times10^{39}\,{\rm erg\,s^{-1}}$. However, this lower 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. The last possibility is outbursts from transient BH-MS with $M_{\rm BH} < 10\,M_\odot$ and donors less massive than $\simeq 0.3\,{\rm M}_\odot$. Such low mass donors are out of thermal equilibrium and significantly expanded ($\simeq 3\times$) compared to an undisturbed MS star of the same mass. In the case of the MT dependent duty-cycle η is about a few %. We note, however, that applicability of MB for these stars is very questionable, as it is generally accepted

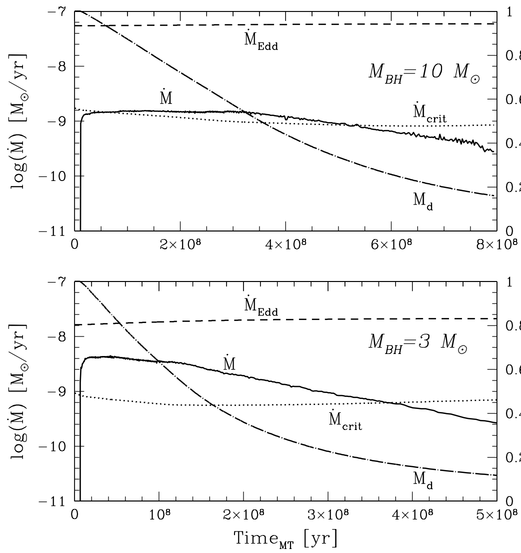

Fig. 1.— Evolution of BH-MS binaries with the RVJ magnetic braking prescription, for BHs of 3 and 10 $M_\odot$; the initial MS companion mass is 1 $M_\odot$. Shown are the MT rate $\dot{M}$ (solid line), the critical MT rate $\dot{M}_{\rm crit}$ (dotted line) and the Eddington MT rate $\dot{M}_{\rm Edd}$ (dashed line), all rates are in $M_\odot$ per yr. The dash-dotted line shows the donor mass evolution.

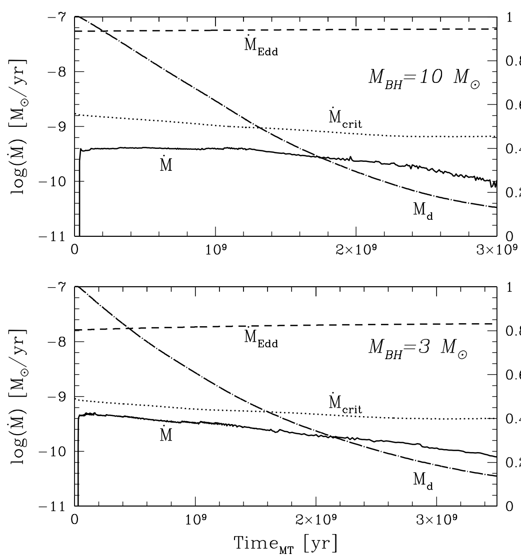

Fig. 2.— Evolution of BH-MS binaries with the IT magnetic braking prescription, for BHs of 3 and 10 $M_\odot$; the initial MS companion mass is 1 $M_\odot$. Shown are the MT rate $\dot{M}$ (solid line), the critical MT rate $\dot{M}_{\rm crit}$ (dotted line) and the Eddington MT rate $\dot{M}_{\rm Edd}$ (dashed line), all rates are in $M_\odot$ per yr. The dash-dotted line shows the donor mass evolution.

that MB does not operate in fully convective stars, which are found to be less massive than $0.35\,M_\odot$ for undisturbed stars. In principle, however, "eroded", out-of-thermal-equilibrium low-mass MS donors like the ones in XRBs do not necessarily become fully convective at the same critical mass as stars with no prior MT evolution. For this reason we have used detailed MT calculations (Fig. 1) with a stellar-evolution code to examine this behavior further. We find that in the donor-mass range $0.15-0.3M_\odot$ the radiative core is extremely small, even for these "eroded" stars, and therefore applying angular momentum loss due to MB is not reasonable. Instead MB activity and hence mass transfer is expected to be interrupted until eventually GR drives Roche-lobe overflow much later.

Based on the above line of arguments we conclude that BH-MS binaries evolving according to the RVJ MB law are not expected to contribute significantly to the high-end XLFs of ellipticals.

In the case of the IT MB prescription, BH-MS systems are transient for all BHs masses $M_{\rm BH} > 3M_\odot$ and for all low-mass MS donors. The reason is that the IT MB is weaker; consequently the donors are mildly out of thermal equilibrium and the mass transfer rates are lower compared to the RVJ MB case. Using again detailed MT evolutionary simulations we find that $\dot{M}/\dot{M}_{\rm crit} \simeq 0.25 \pm 0.15$ (see Fig. 2). Therefore, in the case of the MT dependent duty-cycle η is again about a few %. In both cases (RVJ MB and IT MB), the value of the duty cycle is consistent with observations for BHs of different masses, though the transiency occurs at very different donor masses.

We conclude that, regardless of the specific MB law, it is rather unlikely that persistent sources with a BH accretor and a hydrogen-rich, low-mass MS donor populate at any significant fraction the upper-end XLF of ellipticals; only transient BH-MS sources driven by the IT MB law can populate this X-ray luminosity range.

2.3. *Red Giant Donors*

For orbital periods more than about a day, MT occurs when the low-mass donor is a subgiant or a giant. The driving force is the nuclear expansion of the donor, and a simple analytic prescription for the MT is (Webbink, Rappaport, Savonije 1983; Ritter 1999; see also King 2005):

$$\dot{M}{\rm rg} = -3.4\times 10^{15} a^{1.4}\frac{m_{\rm d}^{1.47}}{(m_{\rm BH}+m_{\rm d})^{0.465}}\ {\rm g\,s^{-1}}\ . \quad (13)$$

It has been shown (by King et al. 1997; King 2000) that such wider XRBs are transient, regardless of the BH mass (original derivations were based on a somewhat different expression for the critical MT rate for transient behavior, but still quite similar to eq. [12].

2.4. *White Dwarf Donors*

A typical WD mass-radius relation is (see, e.g., Rappaport et al. 1987):

$$r_{\rm d} = 0.0128 m_{\rm d}^{-1/3} \quad (14)$$

Using an approximation for the Roche Lobe radius (from Paczyński 1971) and assuming that the mass of WD is much smaller than a BH mass, we can show that

$$a = 0.0278\, m_{\rm d}^{-1/3}\left(\frac{m_{\rm d}}{m_{\rm BH}}\right)^{-1/3} \quad (15)$$

We consider again conservative mass transfer (4) but without any MB losses, adopting $n=-1/3$ and assuming that $m_{\rm d} \ll m_{\rm BH}$. Then

$$\dot{M}_{\rm d} \simeq -\frac{32G^3}{3.3c^5}\frac{M_{\rm BH}^2 M_{\rm d}^2}{A^4} = -7.9\times 10^{16}\frac{m_{\rm BH}^2 m_{\rm d}^2}{a^4}\ {\rm g\,s^{-1}} \quad (16)$$

We substitute here eq. (15) and then have

$$\dot{m}_{\rm d} = -2\times 10^{-3}\, m_{\rm d}^{4\frac{2}{3}} m_{\rm BH}^{\frac{2}{3}}\ \ M_\odot{\rm yr}^{-1} \quad (17)$$

In what follows we adopt the critical MT rate for He-rich donors from Menou et al. (2002), but we note that the expression is subject to quantitative uncertainties associated with the current understanding of the disk instability:

$$\dot{M}_{\rm crit} = -5.9\times 10^{16} m_{\rm BH}^{-0.87}\left(\frac{R_{\rm disk}}{10^{10}}\right)^{2.62}\ {\rm g\,s^{-1}} \quad (18)$$

For a large mass ratio $q_{\rm BH} = m_{\rm BH}/m_{\rm d}$ the Roche lobe of the accretor is $r_{\rm RL} \simeq 0.7a$ and

$$r_{\rm disk} \simeq 2/3 r_{\rm RL} = 0.013 m_{\rm d}^{-2/3} m_{\rm BH}^{1/3} \quad (19)$$

$$\dot{m}_{\rm crit} = -1.7\times 10^{-12} m_{\rm d}^{-1.74}\ M_\odot{\rm yr}^{-1} \quad (20)$$

BH-WD binaries will be transient if

$$\frac{\dot{m}_{\rm d}}{\dot{m}_{\rm crit}} = 1.2\times 10^{9} m_{\rm d}^{6.4} m_{\rm BH}^{\frac{2}{3}} \le 1 \quad (21)$$

Therefore the maximum donor mass that leads to transient behavior in BH-WD binaries is:

$$m_{\rm tr} = 0.038\, m_{\rm BH}^{-0.1} \quad (22)$$

The time interval in Gyr needed for the WD donor mass to evolve from $m_d^{-11/3}(T_1)$ to $m_d^{-11/3}(T_2)$ is (using eq. 17):

$$T_2 - T_1 = \frac{3}{22}\times 10^{-6} m_{\rm BH}^{-2/3}\times \Big(m_d(T_2)^{-11/3} - m_d(T_1)^{-11/3}\Big) \quad (23)$$

Here we assume that the mass of the BH is constant, since $m_{\rm BH} \gg m_d$. Consequently and using eq. (22) we can find that the time a BH-WD system spends in the persistent state is $t_{\rm pers} \simeq 20\times 10^6\, m_{\rm BH}^{-0.3}$ yr, i.e., it very weakly depends on the accretor mass (the dependence on the initial donor mass is negligible, below that 1%). We note that through this persistent phase the MT rate will be comparable or higher to the Eddington limit only for a very short time, $t_{\rm Edd} \simeq 2\times 10^6\, m_{\rm BH}^{-0.9}$ yr [2].

The evolution of BH-WD systems with C/O WD companions is rather similar. The critical MT rate (using Menou et al. 2002) is

$$\dot{m}_{\rm crit} = -9.4\times 10^{-13} m_{\rm d}^{-1.47}\ M_\odot{\rm yr}^{-1} \quad (24)$$

[2] Although MT is non-conservative during the super-Eddington accretion, and eq. (4) formally should not be applied, this result is well consistent with the detailed calculations that take into account non-conservative MT

and

$$m_{\rm tr} = 0.03\ m_{\rm BH}^{-0.1}\ . \tag{25}$$

The time that a BH-WD system with a C/O rich donor spends in the persistent state is also not very long, $t_{\rm pers} \simeq 50 \times 10^6\, m_{\rm BH}^{-0.3}$ yr.

We conclude that BH-WD binaries that contribute to the current upper-end XLFs of ellipticals are expected to be transient sources[3]

3. MASS SPECTRUM WEIGHTING FACTOR AND TRANSIENT DUTY CYCLE

In the previous section we have shown that the upper-end XLF of ellipticals is dominated by transient BH XRBs possibly with a variety of donors: MS (for the case of the IT MB prescription) and RG stars, and WD donors with masses lower than $\sim 0.035\,{\rm M}_\odot$. All these systems contribute to the XLF only when in outburst, when their $L_X \simeq L_{\rm Edd} \propto M_{\rm BH}$. Consequently the slope of the upper-end XLF can serve as a footprint of the BH mass distribution of accretors in the contributing BH XRBs. These contributing BH XRBs are just a sub-set (those in outburst) of the true population of BH XRBs in ellipticals determined by the duty cycle of BH transients binaries. For the general case of a transient duty cycle that is dependent on the BH accretor mass (and possibly other quantities), the differential XLF $n(L)_{\rm obs}$ and the underlying BH mass distribution in XRBs $n(m)_{\rm BH}$ are connected by:

$$n(L_X)_{\rm obs} = n(m_{\rm BH}) \times W(m_{\rm BH}), \tag{26}$$

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 $\alpha_{\rm d} = 2.8 \pm 0.6$: $n(L_X)_{\rm obs} \propto L_X^{-\alpha_{\rm d}}$ (the slope of the cumulative upper-end XLF reported by Kim & Fabbiano 2004 is $\alpha_{\rm c} = 1.8 \pm 0.6$). 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:

$$\beta = \alpha_{\rm d} - \gamma. \tag{27}$$

For the standard assumption of a constant duty cycle, $\beta = \alpha_{\rm d} = 2.8 \pm 0.6$. In the following subsections we derive $W(m_{\rm BH})$ and γ for all three types of donors in one example case of a duty cycle dependent on the binary and MT properties (see, e.g., eq.2).

3.1. *Main Sequence Donors*

In what follows we estimate the typical duty cycle for BH-MS transients averaged over the possible distribution of donor masses. In the case of the IT MB perscription, the angular momentum loss rate due to GR is comparable or even more important than MB for all BH masses above 3 $M_\odot$ and donor masses $\lesssim 1.0 - 1.2 M_\odot$. The MT timescale during the transient phase is longer than the donor's thermal timescale when the donor is $\gtrsim 0.25\,{\rm M}_\odot$. For this range the donor is in thermal equilibrium and the approximation for the mass-radius dependence eq. (5) can be used. Using eq. (4), (6) and (12), and the fitting formula for the Roche lobe radius from Eggleton (1983), we find:

$$\frac{\dot m}{\dot m_{\rm crit}} \simeq 0.054 \frac{m_{\rm BH}^{0.4}(q_{\rm BH}^{-2/3}\log(1+q_{\rm BH}^{1/3})+0.6)^{2.1}}{m_{\rm d}^2(1+q_{\rm BH})(4/3-1/q_{\rm BH})}\ , \tag{28}$$

where $q_{\rm BH} = m_{\rm BH}/m_{\rm d}$ is the mass ratio. For $q_{\rm BH} \gg 1$ we have

$$\frac{\dot m}{\dot m_{\rm crit}} \simeq 0.014 m_{\rm BH}^{0.4} m_{\rm d}^{-2} \tag{29}$$

At donor masses smaller than $0.25\,{\rm M}_\odot$, the donor is out of the thermal equlibirum and its radius is about twice bigger than predicted by eq. (5). We then find:

$$\frac{\dot m}{\dot m_{\rm crit}} \simeq 0.0004 m_{\rm BH}^{0.4} m_{\rm d}^{-2} \tag{30}$$

We note that the split into the two expressions above is a rough, but useful approximation.

As discussed in § 2.2, for IT MB, a BH-MS system is transient throughout the MT phase. The MT rates are well below the Eddington limit for the BH mass and therefore we assumed that MT is fully conservative; i.e., $M_{\rm d} + M_{\rm BH} = M_{\rm tot}$ is constant with time. In what follows we assume a *flat* current mass distribution for donors ($\partial N/\partial m_{\rm d} = const$). We are guided in this choice by results from binary population synthesis calculations (with the StarTrack code; Belczynski et al. 2002 and 2005; Belczynski 2005, private communication). We integrate eq. 29 for $m_{\rm d}$ from $\simeq 0.25$ to $1\,{\rm M}_\odot$ and using eq. (2), we find that at present the probability that a system with a BH accretor of $m_{\rm BH}$ is in outburst and therefore contributes to the upper-end XLF is:

$$W(m_{\rm BH}) = \frac{\int_{0.25}^{m_{\rm TO}} \eta \frac{\partial N}{\partial m_{\rm d}}\, dm_{\rm d}}{\int_{0.25}^{m_{\rm TO}} \frac{\partial N}{\partial m_{\rm d}}\, dm_{\rm d}} \simeq 0.05 m_{\rm BH}^{0.4}, \tag{31}$$

where $m_{\rm TO}$ is the turn-off MS mass for the elliptical galaxy in solar units. We note that this result is valid only for large mass ratios $q_{\rm BH} >> 1$. The contribution of BH-MS system when donors have masses $\lesssim 0.25 M_\odot$ (systems where the donor is out of the thermal equilibrium) is less significant.

It is also important to note here that for MS donors the factor W does not appear to depend on time (i.e., the age of the elliptical galaxy). Such a time dependence would enter in relation to the value of the maximum donor mass (turn-off mass for the host galaxy). However we find that $W(m_{\rm BH})$ is a very weak function of $m_{\rm TO}$, and therefore it is not sensitive to the elliptical age.

3.1.1. *Monte Carlo Simulations*

In principle, prolonged mass accretion onto the BHs can affect 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 $q_{\rm BH}$. Donor masses at birth were varied in from $0.1\,M_\odot$ to the current $m_{\rm TO}$ at an elliptical age of 10 Gyr, assumed as a standard value. Each BH-MS binary was evolved to the current elliptical age

[3] This would not be true if BH-WD binaries continuously formed, but this is not possible in the galactic field of ellipticals and is not even expected in globular clusters, since BHs tend to dynamically separate from the rest of the cluster and eject one another (Kulkarni et al. 1993; Sigurdsson & Hernquist 1993; Watters et al. 2000).

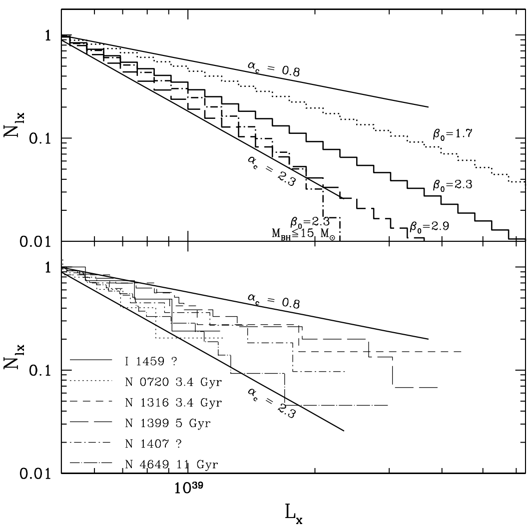

FIG. 3.— The upper panel shows model XLFs for BH-MS binaries. Lines shows results for initial $\beta_0 = 1.7, 2.3, 2.9$ at an age of 10 Gyr (dotted, solid and dashed lines; respectively). The dash-dotted line is for a $15\,M_\odot$ BH mass cut-off with $\beta_0 = 2.3$. Thick solid lines corresponds to slopes $\alpha_c = 0.8$ and $\alpha_c = 2.3$. The lower panel shows XLFs in observed early type galaxies, where it is shown that the observed range of slopes is also within the range $\alpha_c = 0.8 - 2.3$. Data are taken from Kim & Fabbiano (2004) and the ages of the ellipticals are from Ryden et al. (2001) and Temi et al. (2005).

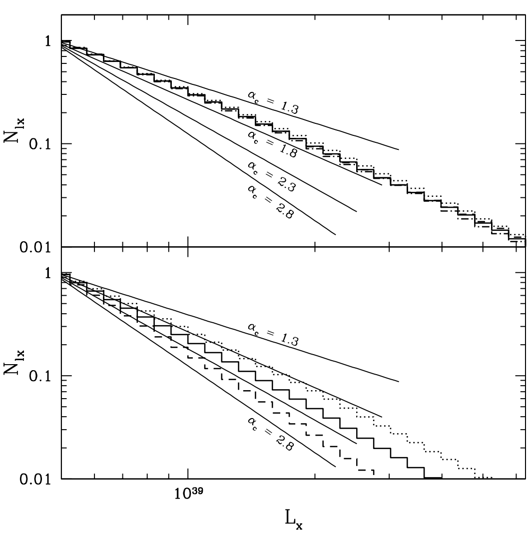

FIG. 4.— Model XLFs for BH-MS binaries for initial $\beta_0 = 2.3$ at an age of 10 Gyr. The upper panel includes results for η given by eq. (2) for $\delta = 1$ and outburst peak luminosity deviating by a factor of 2 from the Eddington luminosities (the dash-dotted line), and for $\delta = 0.5, 1, 2$ without any luminosity variation (dotted, solid, and dashed lines, respectively). The bottom panel includes results for η given by eq. (3) for $\delta = 0.5, 1, 2$ without any luminosity variation (dotted, solid, and dashed lines, respectively). Straight lines with various α_c slopes are also shown.

using equations shown in the § 2.2. For the MT evolution we took into account both IT MB and GR, and for the Roche lobe radius we adopted the approximation by Eggleton (1983). A binary is removed from the MT population if the donor mass falls below $0.05\,\mathrm{M}_\odot$. 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 $t_{\rm TH}$. Evolution of the transient systems follows the adopted duty cycle (eq.[2] with $\delta = 1$).

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. 3). We also find that the relation between β and β_0 is not sensitive to the age of the elliptical (as long as it is in the range of a few to several Gyr).

Next we examine how the results in this section are affected by plausible variations of a number of possibly oversimplifying assumptions made so far. Although it is possible to re-derive the analytical expressions with different assumptions, it requires repeating essentially the same analysis multiple times, something inappropriate for presentation here. Instead it is more efficient to examine these effects using the Monte Carlo simulations for XLF slopes.

For the tests that follow we adopt $\beta = 2.3$ and examine how the cumulative XLF slopes α_c are affected.

We first examine the effect of random variations by a factor of 2 of outburst peak X-ray luminosities of individual transient systems. The results are shown in Fig. 4 (top panel): the solid line is our standard model where peak L_X are set equal to $L_{\rm Edd}$ (same as the solid curve in Fig. 3 top panel) and the dash-dotted line is the result we obtain when random L_X variations are introduced. They are essentially indistinguishable, and therefore the derivation of a BH mass spectrum slope from the observed XLF slope appears highly robust. This is consistent with the findings of observational studies of such variations (Zezas et al. 2004).

Next we examine the effect of δ values in the case of the MT-dependent duty cycle in eq. 2 other than 0 or 1. A set of curves for δ =0.5, 1, and 2 are shown in Fig. 4 (top panel). Once again we conclude that the variations are essentially negligible to such quantitative changes. Instead the slope behavior seems to be dominated by the qualitative character of η in eq. 2: the stronger the transient character, the smaller the duty cycle.

Last we examine the effect of changing the functional dependence of the duty cycle normalizing it to the Eddington MT rate instead of the critical rate for transient behavior (eq. [3]). The results are shown in Fig. 4 (bottom panel) for δ =0.5, 1, and 2 and they are compared to the our standard case of η (from eq. [2] with $\delta = 1$). This is the only case where significant variations are evident. More specifically, the resultant XLFs are steeper (absolute α_c values are higher) and they are more dependent on the choice of δ. Given that the results are shown for a fixed β value, it means that, for a specific observed XLF slope, this different form of the MT-dependent duty cycle would lead to the derivation of a flatter BH mass spectrum compared to that derived using eq. (3). We conclude that better understanding of the transient duty cycle and its dependence on binary or MT properties is important for obtaining reliable quantitative results in the future.

3.2. *Red Giant Donors*

In principle we should repeat the above estimate for BH-RG transients. However, from eq. (12), (13) and (19) we obtain:

$$\frac{\dot m_{\rm RG}}{\dot m_{\rm crit}} \simeq 0.2 a^{-0.7} m_{\rm d}^{1.5}, \qquad (32)$$

and it is evident that, in this case, the MT-dependent duty cycle η (see eq. 2) is independent of the BH mass. Therefore, for RG donors, $\gamma = 0$. Instead it is significantly dependent 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. For a solar metallicity and stars of $1\,{\rm M}_\odot \lesssim M \lesssim 1.5\,{\rm M}_\odot$, the approximate dependence of the turn-off mass with the age is $m_{\rm d} \sim m_{\rm TO} \sim 2\,T^{-1/3}$ (here we used the simplified evolutionary code from Hurley et al. 2000). Using eq. (2), and integrating eq. (32) over binary separations (similar to our integrations for MS donors; see eq. 31), we find:

$$W(T) \simeq 0.03\,T^{-0.5}, \qquad (33)$$

Here we assume a distribution of orbital separations for BH-RG binaries before MT starts that is flat in the logarithm. The reason for this choice is that this is appropriate for the distribution of zero-age binaries and the shape is actually preserved through wind mass loss, common-envelope evolution, and asymmetric explosions with small kicks appropriate for black holes (Kalogera & Webbink 1998).

It is interesting to note that for RG donors W is dependent on the galaxy age whereas for MS donors the dependence on the BH mass dominates.

3.3. *White Dwarf Donors*

During the transient stage, the WD mass can be written as a function of time T in Gyr (using eq. 23):

$$m_{\rm d}(T) = 0.0134 T^{-3/11} m_{\rm BH}^{-2/11} \qquad (34)$$

We can then calculate the probability for a BH-WD system to contribute to the upper-end XLF at an elliptical age T. We assume that (i) all accreting BH-WD systems were formed within a short interval of elliptical ages $T_{\rm start}$ to $T_{\rm fin}$ (in Gyrs) several Gyrs ago when star formation was still occurring in the elliptical; and (ii) $T - T_{\rm fin} > t_{\rm pers}$,i.e., the binary is a transient at time T. The latter assumption is well justified given the short duration of the persistent phase (see § 2.4). We further adopt a constant BH-WD formation rate between $T_{\rm start}$ and $T_{\rm fin}$, i.e., $\frac{\partial N}{\partial t} = const.$ The probability then is expressed by the duty-cycle weighting factor at T for a given BH mass:

$$W(T;m_{\rm BH}) = \frac{\int_{m_{\rm d1}}^{m_{\rm d2}} \eta \frac{\partial N}{\partial m_{\rm d}}\, dm_{\rm d}}{\int_{m_{\rm d1}}^{m_{\rm d2}} \frac{\partial N}{\partial m_{\rm d}}\, dm_{\rm d}}$$

$$= 0.1 \frac{\int_{m_{\rm d1}}^{m_{\rm d2}} \frac{\dot m_{\rm d}}{\dot m_{\rm crit}} \frac{\partial N}{\partial t} \frac{\partial t}{\partial m_{\rm d}}\, dm_{\rm d}}{\int_{m_{\rm d1}}^{m_{\rm d2}} \frac{\partial N}{\partial t} \frac{\partial t}{\partial m_{\rm d}}\, dm_{\rm d}}$$

$$= 0.1 \frac{\int_{m_{\rm d1}}^{m_{\rm d2}} \dot m_{\rm crit}^{-1}\, dm_{\rm d}}{\int_{m_{\rm d1}}^{m_{\rm d2}} \dot m_{\rm d}^{-1}\, dm_{\rm d}} \qquad (35)$$

Here $m_{\rm d1} = m_{\rm d}(T - T_{\rm start}; m_{\rm BH}) = m_{\rm d}(t_1; m_{\rm BH})$ and $m_{\rm d2} = m_{\rm d}(T - T_{\rm fin}; m_{\rm BH}) = m_{\rm d}(t_2, m_{\rm BH})$; $m_{\rm d2} > m_{\rm d1}$. Then, using eq. (17), (20) and (34), we obtain:

$$W(T;m_{\rm BH}) = 1.6\times 10^{-4} m_{\rm BH}^{-0.5} t_1^{-7/4} \times \frac{1-(t_2/t_1)^{-3/4}}{1-(t_2/t_1)} \qquad (36)$$

Therefore for WD donors $\gamma = 0.5$ and W depends on both the BH mass and the galaxy age.

4. ACCRETING BLACK HOLE MASS SPECTRUM

So far we have derived the dependence of the duty-cycle weighting factor W (eq.26) on the accreting BH mass and the age of the host elliptical galaxy, for the different types of BH donors. In order to make progress and develop a method for deriving constraints on the slope β of the underlying accreting BH mass spectrum we need to examine which of the possible donor populations dominate the observed upper-end XLF under what conditions. The answer to this question requires large-scale population synthesis models that are not part of the scope of this paper. However, as is shown below, we can use a number of different arguments and pieces of evidence to derive tentative constraints. The primary purpose of our analysis is not to derive an unambiguous constraint at present, but instead to develop a methodology for how to derive the most reliable constraints, given the current uncertainties associated with our current understanding of these X-ray binaries.

For RG donors we find that in the case of a MT-dependent duty cycle η is about an order of magnitude smaller than for MS donors: by comparing eq. (31) and eq. (33), using an elliptical-galaxy age of at least a few Gyr (more typical is 12 Gyr) and a BH mass of at least $3\,{\rm M}_\odot$ the difference with the η value for MS donors is a factor of 15. We also note that among known BH X-ray transients in our Galaxy, the ratio of transient BH-RG systems to transient BH-MS systems is about 1:2 (see Table 4.1 in McClintock & Remillard 2005). Consequently we conclude that BH-RG transients cannot be important contributors to the upper-end XLF of elliptical galaxies for the example case of the MT-dependent duty cycle as defined by η. *Only* in the case of the constant, MT-independent (and therefore donor and BH-mass independent) duty cycle we expect BH-RG transients to be a significant population of the observed upper-end XLF.

Let us consider the case when the number of transient BH-RG systems exceeds the number of transient BH-MS system in a way that the contributions of the two populations become comparable at some age of the elliptical. We also assume that β_0 should be the same for both populations. In this case, the resultant combined XLF will be flatter than the XLF provided by only BH-MS contributors. Secondly, as the contribution of BH-RG system decreases with elliptical age (see eq. 33), the XLF becomes steeper, evolving towards the slope characteristic for BH-MS binaries. It is possible that this is the kind of behavior that we observe in XLFs of ellipticals (see Fig. 3): we note that younger ellipticals appear to have flatter XLFs, although uncertainties are significant.

For WD donors we find $W(m) \propto t_1^{-7/4}$ (see eq. 36), implying that the probability of each BH-WD transient contributing to the observed XLF decreases with the age of the elliptical galaxy (similar to the case of RG donors, but unlike the case of MS donors). Let us consider an elliptical where the formation of BH-WD systems has ended at least a few Gyr ago. We also consider that BH-MS systems are transient and have $W(M)$ according eq. (31). In order for BH-WD binaries to contribute significantly to the observed XLF they must form at a rate such that more than $\sim 8,000$ BH-WDs form for each BH-MS. This ratio is calculated adopting a value for the age of the elliptical of $\simeq 3.5\,$Gyr (among the lowest reported in the literature) and for a choice of BH masses in binaries with WD and MS donors, so that their Eddington X-ray luminosities are comparable, and therefore they contribute to the same X-ray luminosity bin ($3\,M_\odot$ for WD and $5\,M_\odot$ for MS donors). For more typical, older ellipticals with ages closer to 10 Gyr the required ratio becomes even higher than $8,000$. 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 at most a factor of 100 (Hurley et al. 2002). Furthermore, the lifetime of BH-MS binaries is of order 1 Gyr (or a few Gyr; see also Fig. 1), whereas the lifetime BH-WD binaries is longer, but cannot exceed the age of the elliptical galaxy ($\sim 10\,$Gyr). We conclude that the number of BH-WD LMXBs could be at most about a factor of 1000 higher than the number of BH-MS LMXBs, but this ratio is still below what is required for BH-WD to become an important contributor. So, if the ratio of BH-MS binaries to BH-RG binaries in ellipticals is similar to that in the Milky Way, BH-WD XRBs will not be a significant contributor to the XLF. Based again on the discrepancy between the duty cycles for WD and RG donors (smaller for WDs by a factor of ~ 800), expect that BH-RG transients dominate over BH-WD transients too.

For the case of an example MT-dependent duty cycle (expressed by η in eq. 2) we conclude that: (i) if IT MB describes the angular momentum loss best, then only BH-MS transients significantly contribute to the XLFs of elliptical galaxies; consequently $\beta = 2.5 \pm 0.6$; (ii) if instead RVJ MB is a better prescription, then the XLF is dominated by BH-RG binaries and $\beta = 2.8 \pm 0.6$.

For the case of a constant duty cycle independent of the donor type, it is clear that the XRB type with the highest formation rate should dominate the XLF. According to formation rates calculated by Hurley et al. (2002), BH-WD binaries form at a rate about 100 times higher than BH-MS and BH-RG binaries. Consequently, WDs would be expected to dominate the transient population and this is certainly not true for the Milky Way. Therefore we conclude that the assumption of a constant, MT-independent duty cycle is most probably not realistic.

Overall, we conclude that MS or RG donors dominate, depending on whether the IT or RVJ MB prescription is more realistic. Consequently, the slope of the accreting BH mass spectrum is $\beta = 2.5 \pm 0.6$ ($\beta_0 = 2.3 \pm 0.6$) or $\beta = 2.8 \pm 0.6$, respectively. These quantitative results are of course dependent on the adopted example form of the MT-dependent duty cycle (eq. [2]). As shown in § 3.1.1 a possible different form (e.g., eq. [3]) could lead to somewhat flatter values for β.

Next we consider the fact that the upper-end XLF of ellipticals is not a perfect power-law up to arbitrarily high L_X values; instead there is a usually smooth cut-off behavior that limits the maximum L_X observed at $\simeq 2 \times 10^{39}\,\mathrm{erg\,s^{-1}}$. In Fig. 3 we show the *cumulative* XLF associated with a model population of BH-MS binaries with a BH mass spectrum with a *differential* slope of $\beta = 2.3$ and with an imposed upper limit of $15\,M_\odot$ on the maximum BH mass present in the XRB population. We obtain a model XLF that behaves very similarly to observed XLFs (dash-dotted line). Clearly this is just to show the importance of the qualitative effect of a BH mass cut-off on the cumulative XLF.

5. DISCUSSION

We consider the upper-end XLF of ellipticals (above the reported break at $\simeq 4-6 \times 10^{38}\,\mathrm{erg\,s^{-1}}$) and suggest that it is populated by BH X-ray transients at outburst emitting approximately at the Eddington limit. We argue that the upper-end XLF slope is a footprint of the underlying accreting BH mass spectrum modified by a weighting function related to the transient duty cycle. We show that this weighting factor is generally dependent on the BH mass and/or the age of the host galaxy and the derived power-law dependence is different for each of the possible BH donor types: MS, RG, and WD. Our predicted dominance of X-ray transients at outburst contributing to the upper-end XLF could possibly be tested by future high-resolution X-ray observations designed to achieve long-term monitoring probably at time scales of years or longer. Unfortunately, given the uncertainties in the theory of the thermal disk instability, it is not possible to make any predictions about the expected duration of these outbursts.

Based on our analysis and prior population synthesis results we conclude that a constant transient duty cycle independent of the donor type can be excluded. Instead a duty cycle dependent on the binary and MT properties seems to be required. Given the uncertainties associated with transient duty cycles at present, we adopt a couple of different formulations of such a dependence (eqs. [2,3]), as reasonable examples, which in no way exhaust the possibilities. In the specific case of a duty cycle that depends on the ratio of the binary mass transfer rate to the critical rate for transient behavior (see eq. 2) we conclude find that the BH X-ray transients forming the upper-end XLF in ellipticals have a dominant donor type and an accreting BH mass spectrum slope β that depend on the strength of MB angular momentum loss: (i) for the IT MB prescription, only BH-MS transients significantly contribute to the upper-end XLF and $\beta = 2.5 \pm 0.6$ ($\beta_0 = 2.3 \pm 0.6$); (ii) for the RVJ MB prescription, the XLF is dominated by BH-RG binaries and $\beta = 2.8 \pm 0.6$. We note that these quantitative results do depend on our conclusions about which donor-type population dominates based on currently published population synthesis models (Hurley et al. 2002) and on available observations of BH X-ray systems in our Galaxy. If, e.g., the relative fraction of BH-RG transients in ellipticals is larger than the observed relative fraction in our Galaxy, we expect that 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 slop predicted for BH-MS binaries.

The primary goals of this study are to present (i) the line of arguments that connects the upper-end XLF of ellipticals to BH XRBs formed in the galactic field and (ii) the methodology for how to extract information about the accreting BH mass spectrum from the observed XLF slopes. We have further obtained quantitative results on the BH mass spectrum slope under certain reasonable assumptions, some of which (e.g., the functional form of the MT-dependent duty cycle) represent mere examples. A careful examination of the robustness of these quantitative results has been for the case of MS donors. It has been found that the derived slopes are robust against (i) random variations by factors of a few of the outburst peak luminosity of individual sources, and against (ii) variations of the possible duty-cycle dependence on the critical MT rate for outburst behavior. However, completely difference duty-cycle dependencies cannot be excluded. An improved understanding of this issue would be required to derive reliable quantitative conclusions about the value of the BH mass spectrum slope in transient XRBs in ellipticals.

We expect that our analysis and methods can be used to reveal more information about the formation of BH XRBs in elliptical galaxies. More specifically they could eventually be used to constrain the physical connection between massive stars in XRB progenitors and the resultant BH masses. Current simulations assume either an artificially constant mass for BHs formed (usually at $\sim 10\,M_\odot$), or a constant mass fraction of the progenitor leading to the remnant objects, or a remnant mass relation consistent with core-collapse simulations. Constraints on the accreting BH mass spectrum as those discussed here could contribute to our understanding of core collapse, and the connection of BH masses to their progenitor masses.

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