

AN OBSERVATIONAL DIAGNOSTIC FOR ULTRALUMINOUS X-RAY SOURCES

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ABSTRACT

We consider observational tests for the nature of Ultraluminous X-ray sources (ULXs). These must distinguish between thermal–timescale mass transfer on to stellar–mass black holes leading to anisotropic X-ray emission, and accretion on to intermediate–mass black holes. We suggest that long–term transient behavior via the thermal–viscous disk instability could discriminate between these two possibilities for ULXs in regions of young stellar populations. Thermal–timescale mass transfer generally produces stable disks and persistent X–ray emission. In contrast, mass transfer from massive stars to black holes produces unstable disks and thus transient behavior, provided that the black hole mass exceeds some minimum value $M_{\text{BH,min}}$. This minimum mass depends primarily on the donor mass and evolutionary state. We show that $M_{\text{BH,min}} \gtrsim 50 M_{\odot}$ for a large fraction ($\gtrsim 90\%$) of the mass–transfer lifetime for the most likely donors in young clusters. Thus if long–term monitoring reveals a large transient fraction among ULXs in a young stellar population, these systems would be good candidates for intermediate–mass black holes in a statistical sense; information about the donor star is needed to make this identification secure in any individual case. A transient ULX population would imply a much larger population of quiescent systems of the same type.

Subject headings: accretion, accretion disks — binaries: close — X-rays: binaries

1. INTRODUCTION

In the past few years high-angular-resolution observations with *Chandra* have revolutionized the study of X–ray binaries in nearby galaxies and have revealed whole populations of sources in a variety of galaxy types (for a recent review see Fabbiano & White 2003). The detected X–ray fluxes have been combined with distance estimates to the host galaxies to infer the *apparent* X–ray luminosities of the sources, *assuming isotropic* emission. The inferred X–ray luminosities reveal a distinct class of sources: non–nuclear point sources with apparent X–ray luminosities above the Eddington limit for a $\sim 10 M_{\odot}$ black hole ($\gtrsim 2 \times 10^{39} \text{ erg s}^{-1}$), often referred to as *ultraluminous X-ray sources* (ULXs). The existence of such sources was first noted in EINSTEIN observations (e.g., Fabbiano 1988). Short-term variability detected in a number of them (see e.g., Fabbiano et al. 2003; Matsumoto et al. 2001) excludes the possibility of source confusion and strongly points towards accretion as the origin of the X-rays. At present the majority of ULXs have been found mainly in young stellar populations and regions of recent star formation, although a few have been identified in elliptical galaxies (e.g., Colbert & Ptak 2002; Sarazin, Irwin, & Bregman 2001) with luminosities close to the lower end of the ULX range.

If the apparent X-ray luminosities are indeed the true luminosities of the sources, their high values have very important implications for their accreting compact objects. For sources with X-ray luminosities comparable or in excess of $10^{40} \text{ erg s}^{-1}$, the Eddington limit gives a lower limit on the mass intermediate between stellar ($\lesssim 50 M_{\odot}$) and supermassive ($\gtrsim 10^6 M_{\odot}$) black holes (BH). ULXs may thus suggest the existence of a new class of compact objects: *intermediate-mass black holes* (IMBH; Colbert & Mushotzky 1999).

On the other hand it is still possible that the accreting compact objects in ULXs are of stellar mass ($\lesssim 20 M_{\odot}$; see Belczynski, Kalogera, & Bulik 2002). The high apparent

X-ray luminosities can be explained in two different ways: (i) either the Eddington limit (rigorously derived for spherical accretion) is not relevant and in fact can be exceeded (see Ruszkowski & Begelman 2003) or (ii) the apparent X-ray luminosities overestimate the true source luminosities because the emission is *anisotropic* (King et al. 2001). Although the theoretical basis for imposing the Eddington limit is somewhat unclear, there is strong support for it partly from observations of X-ray bursts from accreting neutron stars (e.g., Kuulkers et al. 2003; Lewin, van Paradijs, & Taam 1995) and from the current understanding of the evolutionary history of wide binary pulsars (Webbink & Kalogera 1997) and Cygnus X-2 (where the compact object does not seem to have gained any significant amount of mass; King & Ritter 1999; Kolb et al. 2000; Podsiadlowski & Rappaport 2000).

Anisotropic emission is probably associated with X-ray luminosities comparable to the Eddington limit. Binary systems can reach such high luminosities in two different situations (King 2002): (i) thermal–timescale mass transfer typically occurring when the donor is more massive than the accretor (King et al. 2001). Cygnus X-2 (King & Ritter 1999) and SS433 (King, Taam, & Begelman 2000) may be examples of this phase; (ii) X-ray transient outbursts, where the thermal disk instability governs the accretion behavior. The first possibility obviously requires donors more massive than black holes ($\gtrsim 3\text{--}5 M_{\odot}$), and hence relatively young stellar environments, whereas the second must apply to ULXs in old elliptical galaxies (Piro & Bildsten 2002).

Although population studies suggest that a large fraction of ULXs must be stellar–mass X–ray binaries (Grimm, Gilfanov, & Sunyaev 2003), some may contain IMBH. For the ULX in M82, the very high peak luminosity (Matsumoto et al. 2001), the quasi-periodic oscillations (Strohmayer & Mushotzky 2003), and the detection of an isotropic nebula around it may point away from the anisotropic-emission possibility (although see

King & Pounds 2003). On the other hand, no ULXs are found inside dense clusters, where IMBH are expected not only to form (Miller & Hamilton 2002; Portegies Zwart & McMillan 2000) but also remain, as they are much heavier than the average stellar mass in clusters (fast cluster disruption could help, but this issue is beyond the scope of this paper; Gürkan & Rasio 2003). Thus at present the physical origin of some of these sources is not clear, and there may be ULXs of both stellar and intermediate mass.

In this *Letter* we suggest that long-term transient behavior (not just flux variability by factors of a few to several) due to the thermal-viscous disk instability (King, Kolb, & Burderi 1996; King & Ritter 1998) may distinguish the two possibilities for ULXs in regions of young stellar populations ($\lesssim 10^8$ yr). We show that one can define a minimum BH mass $M_{\text{BH,min}}$ for disk instability and thus transient behavior (§ 2). This minimum mass depends primarily on the mass and evolutionary stage of the donor star. We show that, for donor masses $\gtrsim 5 M_\odot$ (expected to be the most likely donors in young stellar environments), $M_{\text{BH,min}} \gtrsim 50 M_\odot$ for a large fraction of the mass-transfer phase ($\gtrsim 90\%$). (§ 3). By contrast, thermal timescale mass transfer is expected to be persistent (King et al. 2001). Thus if long-term monitoring reveals a significant transient fraction among ULXs in a young stellar population, these systems would be good candidates for IMBH in a statistical sense; information about the donor star is needed to make this identification secure in any individual case. In § 4 we discuss the observational significance of this diagnostic and the connection to IMBH formation scenarios.

2. MINIMUM BLACK HOLE MASS FOR TRANSIENT BEHAVIOR

The thermal-viscous disk instability provides a currently accepted explanation for transient behavior in X-ray binaries. The instability causes the disk to undergo a limit cycle in which the central accretion rate passes through short high states (outbursts) and long low states (quiescence). This picture was originally developed to explain dwarf novae but can be extended to soft X-ray transients by including the effects of disk irradiation (van Paradijs 1996; King, Kolb & Burderi 1996; Dubus et al. 1999; for reviews see Lasota 2001; Frank et al. 2002). The condition for transient behavior is that the disk surface temperature at its outer edge should lie below the hydrogen ionization temperature. This in turn requires the mean mass transfer rate to lie below a critical value $\dot{M}_{\text{crit}}$ (King, Kolb, & Burderi 1996). This depends primarily on the binary component masses M_{BH} , M_2 and orbital period P , and to a lesser degree on the detailed vertical disk structure. The latter is of course uncertain; in this paper we use the form given in (eq. 32 in Dubus et al. 1999):

$$\dot{M}_{\text{crit}} \simeq 6.6 \times 10^{-5} M_\odot \text{yr}^{-1} \left(\frac{M_{\text{BH}}}{100 M_\odot} \right)^{0.5} \times \left(\frac{M_2}{10 M_\odot} \right)^{-0.2} \left(\frac{P}{1 \text{yr}} \right)^{1.4}. \quad (1)$$

Although the precise conditions assumed by Dubus et al. (1999) (in particular the central mass and vertical structure) probably cannot be extrapolated to all of the cases we shall consider, this equation gives an adequate idea of when transient behavior is likely. Using a somewhat simpler expression King, Kolb, & Burderi (1996) first showed that the condition $\dot{M} < \dot{M}_{\text{crit}}$ translates into a *minimum BH mass* $M_{\text{BH,min}}$ required for the development of transient behavior. Similarly,

equation (1) can be used to derive this minimum:

$$M_{\text{BH}} \gtrsim 230 M_\odot \left(\frac{\dot{M}}{10^{-4} M_\odot \text{yr}^{-1}} \right)^2 \times \left(\frac{M_2}{10 M_\odot} \right)^{0.4} \left(\frac{P}{1 \text{yr}} \right)^{-2.8}. \quad (2)$$

Our aim is to examine whether transient behavior favors a distinct BH mass range. We use mass transfer sequences calculated for a set of initial binary configurations (of varying orbital periods, black hole and donor masses) and we derive $\dot{M}_{\text{crit}}$ for a given donor mass M_2 and radius R_2 (i.e., evolutionary state). We then use the dependence of $\dot{M}_{\text{crit}}$ on M_{BH} and disk radius given in (eq. 30 in Dubus et al. 1999) and solve numerically for $M_{\text{BH,min}}$ by setting $\dot{M}_{\text{crit}}$ equal to the mass transfer rate found from our mass transfer sequences, for given (M_2, R_2) . If the BH mass used in the mass transfer calculations exceeds this minimum the system will be transient. (Note that for a given sequence, $\dot{M}$ depends most sensitively on the donor mass and evolutionary stage at the onset of mass transfer and not so much on the accretor mass.) We examine the range of values for $M_{\text{BH,min}}$ and whether transient behavior can be associated with certain types of BH accretors (§ 3.2).

3. MASS TRANSFER SEQUENCES

3.1. Stellar Evolution Code

We calculate stellar models and mass-transfer sequences with an updated stellar evolution code described in detail in (Ivanova et al. 2003; Podsiadlowski, Rappaport, & Pfahl 2002). The current version has been modified to minimize numerical noise in the mass transfer calculations and ensure that the stellar and Roche lobe radii track one another during mass transfer. We use mixing length and overshooting parameters of 2 and 0.25 pressure scale heights respectively. Since we are dealing with massive stars, we account for mass loss due to stellar winds (rates adopted from Hurley et al. 2000). In calculating orbital changes we take account of both mass transfer and wind mass loss with the specific angular momentum of the mass-losing donor. We assume that any mass transfer above the Eddington rate is lost from the binary with the specific angular momentum of the accretor.

We model mass transfer self-consistently following the donor response to the appropriate rate of mass loss. The mass-transfer rate $\dot{M}$ is calculated in an *implicit* manner, so that the donor radius R remains equal to the Roche lobe radius R_L (using Eggleton's approximation; Eggleton 1983). We consider the radius-mass exponents of the Roche lobe $\zeta_L = d \ln R_L / d \ln M$ and of the star itself $\zeta = d \ln R / d \ln M$ in our solution method. The response of the Roche lobe to the mass transfer is solely a function of the mass ratio, whereas the response of the stellar radius depends on the mass transfer rate. For a given model, we tabulate values of ζ for a range of $\dot{M}$ values. We then identify the value of $\dot{M}$ for which the Roche lobe radius is equal to the stellar radius (predicted from the value of ζ). In some cases, the solution for $\dot{M}$ is not unique; we then choose the lowest value to avoid large excursions in the rate. As the donor evolves, the stellar-radius response changes, so we recalculate the table of $\zeta(\dot{M})$, if the predicted stellar radius differs from the calculated one by $\delta \ln R = 10^{-4}$.

3.2. Calculations and Results

To investigate the systematics of mass transfer and disk (in)stability we consider a large set of mass-transfer sequences driven by Roche-lobe overflow: binaries with BH masses in the range $10 - 1000 M_{\odot}$, donor masses in the range $1 - 25 M_{\odot}$. For each donor mass, we evolve single-star models to different evolutionary stages that cover most of the stellar lifetime: from the Zero-Age to the End of the Main Sequence (ZAMS and EMS), the Hertzsprung gap (HG), and through core helium burning. We consider the possibility of multiple mass-transfer episodes in the evolutionary history of each binary and we evolve each of our models up to carbon ignition.

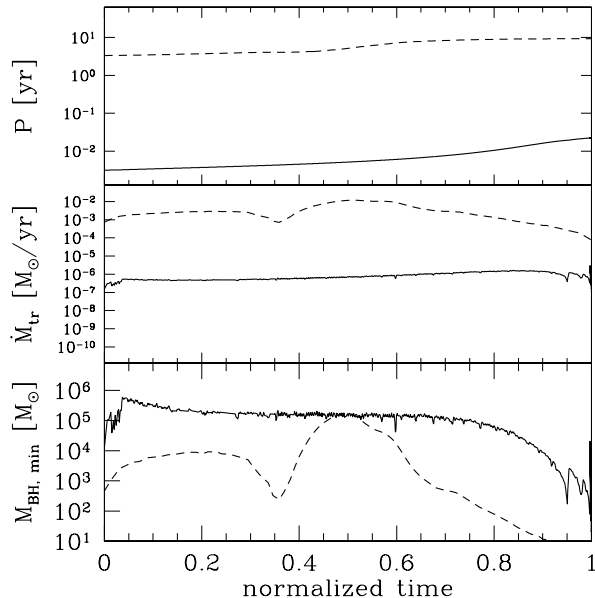


FIG. 1.— Two examples of mass-transfer sequences for a $1000 M_{\odot}$ BH with a $20 M_{\odot}$ donor. Mass transfer starts on the Zero-Age Main Sequence (solid) and the Base of the Giant Branch (dotted). The orbital period (top), mass transfer rate (middle), and derived minimum BH mass for transient behavior (bottom) are shown as functions of time normalized to the total duration of each mass transfer episode.

Every evolutionary sequence of course starts and ends with transient behavior as the mass transfer rate rises from and returns to zero. For episodes of otherwise persistent mass transfer these transient windows form a very small fraction of the total mass transfer lifetime and have very low discovery probability. In terms of the solutions for $M_{\text{BH,min}}$, this means that at the start and end of every mass-transfer episode the minimum BH mass for transient behavior is very low and certainly enters the stellar-mass range. We eliminate these insignificant (due to their low discovery probability) transient epochs by excluding the first and last 5% of the mass-transfer lifetime.

The behavior of two example mass-transfer sequences is shown in Figure 1. These have been calculated for $M_{\text{BH}} = 1000 M_{\odot}$ and donors of $20 M_{\odot}$ at two evolutionary stages: unevolved (ZAMS) and at the base of the Giant Branch. Our results for the binary orbital period, mass transfer rate, and minimum BH mass for transient behavior are shown as a function of time normalized to the total duration of each mass-transfer episode ($\simeq 10^7$ yr and $\simeq 2 \times 10^3$ yr, respectively). Evidently, for most of these episodes (90%-100% of their duration), transient behavior requires BHs in the intermediate-mass range $M_{\text{BH,min}} > 50 M_{\odot}$ and *not* the stellar-mass range.

In reality, for stellar-mass binaries the orbital separation is small enough that the radiation field of the O,B donor is able to keep the disk ionized, and therefore stable. This effect is negligible for the much wider separations of IMBH binaries.

For sequences with donors down to $10 M_{\odot}$ and $7 M_{\odot}$ results are very similar to the $20 M_{\odot}$ sequences, with $M_{\text{BH,min}} > 50 M_{\odot}$ for more than 90% of their duration. We note that ULX luminosities would be reached in outbursts and would then probably reflect the Eddington luminosity rather than the mass-transfer rates shown in Figure 1.

For binaries with more evolved donors (during most of the short phase of core-helium burning when orbital periods are $\simeq 10$ yr), $M_{\text{BH,min}}$ values can be $\lesssim 10 M_{\odot}$. In these cases accretion disks are so large that their edges are cool and allow the disk instability to develop. However, such binaries are expected to be uncommon in young clusters for two reasons. First, they are too wide to survive stellar interactions; typical interaction timescales are 10^5 yr for stellar densities of 10^5 pc^{-3} (typical of young stellar clusters in star-forming regions; see § 8.4 in Binney & Tremaine 1987). Second, our numerical calculations show that their mass-transfer episodes are much shorter ($\lesssim 10^4$ yr) than for MS donors ($10^5 - 10^7$ yr). Therefore for the same formation probability, it is more difficult to detect such short-lived X-ray phases.

Sequences with $5 M_{\odot}$ donors at different evolutionary stages show a qualitative change in behavior. They straddle along the dividing line between $M_{\text{BH,min}}$ values in the intermediate-mass and the stellar-mass range because of a close balance between two effects on $M_{\text{BH,min}}$ (eq. [2]): the orbital period and the mass transfer rate at Roche-lobe overflow. As a result a $5 M_{\odot}$ donor at the ZAMS and beyond the MS gives $M_{\text{BH,min}}$ values in the stellar-mass, whereas the same donor filling its Roche-lobe close to the end of the MS leads to $M_{\text{BH,min}}$ values in the intermediate-mass range. Sequences with less massive donors always have $M_{\text{BH,min}}$ values in the stellar-mass range, i.e., $< 50 M_{\odot}$.

Before drawing firm conclusions from our results, we examine whether the derived $M_{\text{BH,min}}$ values are affected by the fact that we have used an IMBH for the calculations. We have repeated our sequences for a stellar-mass BH ($10 M_{\odot}$) and found no qualitative or significant quantitative differences, as is evident in Figure 2 for two example sequences with a $10 M_{\odot}$ donor. These deviations occur because the mass ratio is close to unity in one case, and lead to *higher* values of $M_{\text{BH,min}}$ for BH masses comparable to the donor masses.

Given the qualitatively different results for donors more or less massive than $\simeq 5 M_{\odot}$, we consider their relative probabilities as *Roche-lobe filling BH binary companions* in young star-forming regions where most ULXs are found. From basic results of stellar dynamics and preliminary calculations of our own (Ivanova, Kalogera, & Belczynski, in preparation) we find that relatively massive companions are favored for a number of reasons: (i) BHs sink by dynamical friction to the center of young star-forming regions, as do massive stars, and therefore there is more of them in the BH's vicinity; (ii) massive stars have a higher cross section for capture by a BH and, if exchange into binaries is relevant, lower-mass objects are generally ejected in the interaction; (iii) such stellar interactions strongly favor orbital periods in excess of ~ 100 d, so even, if a low-mass companion were present at some point in the BH dynamical lifetime, it would not fill its Roche lobe in young clusters (requires orbital periods shorter than $\simeq 1$ d).

On the other hand, such relatively massive donors to stellar-mass BH could drive thermal-timescale mass transfer and

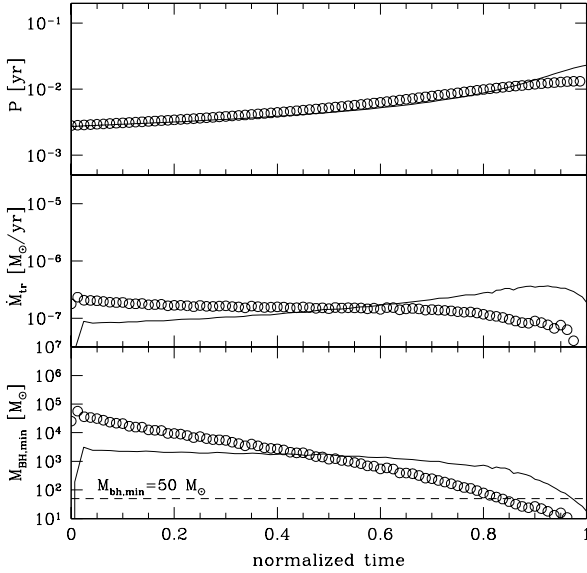


FIG. 2.— Comparison of orbital period (top), mass transfer rate (middle), and derived minimum BH mass for transient behavior (bottom), for mass-transfer sequences with $10 M_{\odot}$ donors at ZAMS for a $1000 M_{\odot}$ BH (solid) and a $10 M_{\odot}$ BH (open circles with reduced time resolution for best clarity of the figure). It is evident that results are insensitive to the BH mass used in the mass-transfer calculations.

therefore produce *persistent* X-ray sources (King et al. 2001). Thus we conclude that, if a substantial fraction of ULXs prove to be transient, then IMBH accretors could be favored.

4. DISCUSSION

We have calculated mass transfer driven by relatively massive stars ($5 - 20 M_{\odot}$) in BH binaries likely in young stellar environments, and derived a minimum BH mass for transient behavior that in the majority of relevant cases is in excess of $50 M_{\odot}$. This provides an observational diagnostic that could allow us to distinguish between stellar-mass ($\lesssim 20 M_{\odot}$) and intermediate-mass BH binary models for ULXs. We note that in old populations of ellipticals both classes of sources are expected to be transient (King 2002; Piro & Bildsten 2002).

Hence transient behavior cannot be used as an observational diagnostic in old stellar systems (ages in excess of 10^8 yr).

So far there is only one candidate for a transient ULX. One ($L_X \simeq 1.1 \times 10^{40} \text{ erg s}^{-1}$) is in a starburst galaxy NGC 3628 (Strickland et al. 2001). It may be associated with a ROSAT X-ray source (so the position is not well constrained) that faded below the sensitivity limit by a factor of more than 27 and reappeared in *Chandra* observations.

Current scenarios for IMBH involve formation in young stellar clusters. One possibility invokes repeated black hole mergers (Miller & Hamilton 2002), although gravitational radiation recoil (Redmount & Rees 1989) could prevent this by ejecting merger products from the cluster. Another idea invokes runaway collisions of massive stars and eventual collapse of the massive remnant (provided that stellar winds do not decrease the mass of the collision product; see Portegies Zwart & McMillan 2000). Then an IMBH may form within the lifetime of the most massive stars (3 Myr), and it may acquire a binary companion within a cluster relaxation time after BH formation (at $\lesssim 10$ Myr), when stars as massive as $\simeq 20 M_{\odot}$ are still present. At that time binary separations would still be wide, favoring the formation of IMBH binaries with orbital periods longer than about 100 d. We are currently studying the dynamical evolution of an IMBH in young clusters and the characteristics of IMBH binaries and we expect to present our results in the near future (Ivanova, Kalogera, Belczynski 2003, in preparation).

It is important to realize that the transient behavior we discuss must occur on timescales far longer than an observer's lifetime. Therefore tests for transient behavior must be carried out in a statistical sense. Any quantitative statement ultimately depends on the duty cycle and the outburst duration. It is also important to remember that such a detection would imply a much larger number $\sim 1/d \gtrsim 100 - 1000$ of quiescent systems of the same type.

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