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 (\( \sim 10^{39} \, \text{erg s}^{-1} \)), 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. The Eddington limit \( L < 10^{39} \, \text{erg s}^{-1} M/10 \, M_\odot \) gives a lower limit on the mass intermediate between stellar (\( \lesssim 15 \sim 20 \, M_\odot \)) and supermassive (\( \gtrsim 10^4 \, M_\odot \)) black holes. 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 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]; [King 2002]; King, Taam, & Begelman 2000) 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. 2003; 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 (\( \gtrsim 3 \sim 5 \, M_\odot \)), and hence relatively young stellar environments, whereas the second must apply to ULXs in old elliptical galaxies ([Pro & 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 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. 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 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 large 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 phases (§ 3.2). In some cases, the solution for \( \zeta = d \ln R / d \ln M \) 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 \( \zeta \) for a range of \( M \) values. We then identify the solution of \( M \) for which the Roche lobe radius is equal to the stellar radius (predicted from the value of \( \zeta \)). In some cases, the solution for \( M \) is not unique; we then choose the lowest value to avoid large excursions in the rate. As the donor evolves, the response of the stellar radius changes as well, and we recalculate the table of \( \zeta (M) \), if the predicted stellar radius differs from the calculated one by \( \delta \ln R = 10^{-4} \).

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 the mass transfer sequences 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 \( \zeta \) for a range of \( M \) values. We then identify the solution of \( M \) for which the Roche lobe radius is equal to the stellar radius (predicted from the value of \( \zeta \)). In some cases, the solution for \( M \) is not unique; we then choose the lowest value to avoid large excursions in the rate. As the donor evolves, the response of the stellar radius changes as well, and we recalculate the table of \( \zeta (M) \), if the predicted stellar radius differs from the calculated one by \( \delta \ln R = 10^{-4} \).

3.2. Calculations and Results

We consider the most likely stellar donors drawn from young populations. These have \( 5 \sim 25 M_\odot \) (stellar ages up to \( \sim 10^5 \) yr) and transfer mass through Roche-lobe overflow to BHs with an extended range of masses (\( 10 \sim 1000 M_\odot \)). Although we cannot exclude lower-mass donors, the environments where most ULXs are found favor massive companions for a number of reasons: (i) BHs sink by dynamical friction to the center of young star-forming regions, as do massive

\[
M_{\text{crit}} \simeq 6.6 \times 10^{-5} M_\odot \, \text{yr}^{-1} \left( \frac{M_{\text{BH}}}{100 M_\odot} \right)^{0.5} \left( \frac{M_2}{10 M_\odot} \right)^{-0.2} \left( \frac{P}{1 \text{yr}} \right)^{1.4} \quad (1)
\]

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 \( M < M_{\text{crit}} \) 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:

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

Our aim is to examine whether transient behavior favors a distinct black hole mass range. We use mass transfer sequences calculated for a set of initial binary configurations to derive \( M_{\text{crit}} \) for a given donor mass \( M_2 \) and radius \( R_2 \) (i.e., evolutionary state). We then use the dependence of \( M_{\text{crit}} \) on \( M_{\text{BH}} \) and disk radius given in (eq. 30 in Dubus et al. 1999) and solve numerically for \( M_{\text{BH,min}} \) by setting \( M_{\text{crit}} \) 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, \( M \) 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 confine attention to the donor stars likely in young populations for binaries with a wide range of orbital periods and accretor masses (§ 3.2).
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. We also note that such stellar interactions favor a certain range of BH orbital periods, typically just below the limit between hard and soft binaries. For typical velocity dispersions ($\sim 30 \text{ km s}^{-1}$) the hard/soft boundary for 10 $M_\odot$ binaries is $P \approx 10$ yr.

For each donor mass, we evolve single-star models to a range of 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.

Every evolutionary sequence must of course start and end 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. We eliminate these insignificant 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 $M_{\text{BH}} = 1000 M_\odot$ 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.

The discussion of extreme mass transfer (XMT) in intermediate-mass BH binaries. We have calculated mass transfer driven by relatively massive stars ($5 \lesssim 20 M_\odot$) in BH binaries likely in young stellar environments, and derived a minimum BH mass for transient behavior that in most 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 et al. 2001). Hence transient behavior cannot be used as an observational diagnostic in old stellar systems.

So far there appear to be two possible candidate transient ULXs. One ($L_X \sim 1 \times 10^{39}$ erg s$^{-1}$) is in a starburst galaxy NGC 3628 (Strickland et al. 2001). This source 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. The second is in a spiral galaxy (M74, Soria & Kono 2002). The suggestion of transient behavior comes from comparing XMM-Newton and Chandra observations. However its luminosity ($L_X \sim 1.5 \times 10^{39}$ erg s$^{-1}$) is only marginally within the ULX range, and indeed less than some known stellar–mass X–ray binaries.

Current scenarios for IMBH involve formation in young stellar clusters. One possibility invokes repeated black hole mergers (Miller & Hamilton 2002), although gravitational radiation recoil (Redmond & 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 $\sim 10$ Myr), when stars as massive as $\sim 20 M_\odot$ are still present. At that time binary separations would still be wide, favoring the formation of IMBH binaries with orbital periods comparable to, but still below the hard/soft boundary ($< 10$ yr).

It would be useful to calculate the probability of detecting a
transient, if indeed ULXs contain IMBHs. Any such quantitative statement ultimately depends on the duty cycle and the outburst duration. Our current understanding of the disk instability is not developed enough to allow reliable predictions of such quantities as a function of binary parameters, although observations indicate that duty cycles cannot be much larger than \( d \sim 10^{-3} \). Furthermore, a constraint on the detection probability would also require some quantitative knowledge of the probability distributions of BH binaries in clusters that is also unavailable at present. For now it is important to note the significance of a firm observational identification of a transient ULX as repeated Chandra observations of ULXs are made in the next few years. In particular, it is 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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