

## TRANSIENT X-RAY BINARIES IN ELLIPTICAL GALAXIES

ANTHONY L. PIRO<sup>1</sup> AND LARS BILDSTEN<sup>1,2</sup>

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### ABSTRACT

*Chandra* observations of elliptical galaxies have revealed large numbers of low-mass X-ray binaries (LMXBs) accreting at rates greater than  $10^{-9} M_{\odot} \text{ yr}^{-1}$ . One scenario that generates this  $\dot{M}$  from an old stellar population is nuclear-driven mass transfer onto a neutron star or black hole from a Roche lobe–filling red giant. However, in our Galaxy, most of these systems accrete sporadically as transients because of a thermal instability in the accretion disk. Using the common criterion for disk instability (including irradiation), we find that this mode of mass transfer leads to transient accretion for at least 75% of the binary’s life. Repeated *Chandra* observations of elliptical galaxies should reveal this population. The recurrence times might be very long ( $\sim 100$ – $10,000$  yr depending on the orbital period at the onset of mass transfer), and outbursts might last for 1–100 yr. Mass transferring binaries can also be formed in old populations via interactions in dense stellar environments, such as globular clusters. These tend to have shorter orbital periods and are more likely stable accretors, making them apparently a large fraction of an elliptical galaxy’s LMXB population.

*Subject headings:* accretion, accretion disks — binaries: close — galaxies: elliptical and lenticular, cD — pulsars: individual (GRO J1744–28) — stars: neutron — X-rays: binaries

### 1. INTRODUCTION

*Chandra* observations of nearby elliptical and S0 galaxies (e.g., Sarazin, Irwin, & Bregman 2000, 2001; Blanton, Sarazin, & Irwin 2001; Finoguenov & Jones 2001; Angelini, Loewenstein, & Mushotzky 2001; Kraft et al. 2001) often find  $\approx 20$  X-ray sources with luminosities greater than  $10^{38}$  ergs  $\text{s}^{-1}$  and even more with luminosities greater than  $10^{37}$  ergs  $\text{s}^{-1}$ . For a neutron star (NS) accretor, this corresponds to accretion rates as large as  $10^{-8} M_{\odot} \text{ yr}^{-1}$ , implying a short lifetime compared with the age of the stellar population. One way to generate such rapid accretion rates in an old stellar population (neglecting the formation of tight binaries in dense environments, such as globular clusters) is to have a Roche lobe–filling binary driven by the nuclear expansion of a low-mass star on the red giant branch (orbital periods are days or longer). Ritter (1999) has shown an analytic solution for such a low-mass X-ray binary (LMXB), which is further simplified in elliptical galaxies where the initial companion masses should all be  $\approx 0.9 M_{\odot}$  for an old population.

However, such wide binaries are subject to thermal instabilities in the accretion disk (King, Kolb, & Burderi 1996; see Dubus, Hameury, & Lasota 2001 for an up-to-date discussion) that cause transient accretion. Using the current instability criterion, we follow the evolution of such an LMXB and find that over 75% of its life is spent as a transient. We thus expect that a large fraction of the field LMXBs in elliptical galaxies are long-term transients. Our ability to detect them with repeated *Chandra* observations depends on their outburst durations, which can be as long as years.

We present an overview of the binary evolution scenario in § 2 and summarize the challenge of finding the bright, blue optical counterparts to these LMXBs in elliptical galaxies. In § 3, we apply the current understanding of accretion disk instabilities in X-ray sources and estimate the outburst recurrence times. In § 4, we compare our work with Galactic systems, noting

that the recently discovered Galactic transients with outburst durations in excess of 10 yr (e.g., Wijnands 2002) might well be wide binaries. We close in § 5 with our conclusions and a discussion of alternative binary scenarios that lead to more stable mass transfer, especially relevant for those LMXBs found in globular clusters (Sarazin et al. 2001; Angelini et al. 2001).

### 2. BINARY EVOLUTION WITH RED GIANT DONORS

We only consider binaries with initial orbital periods  $\geq 1$  day. If the binary is tighter ( $P_{\text{orb}} < 1$  day), rapid accretion may be initiated as a result of orbital angular momentum loss from magnetic braking, resulting in mass transfer while a low-mass star is still on the main sequence (see Tauris & Savonije 1999). Whenever there are multiple parameters to choose, we always take the value that maximizes the stability of the accretion disk. This assures that our calculated fraction of the evolutionary lifetime spent as a transient is a firm lower limit.

We use Ritter’s (1999) analytical solution for the LMXB evolution, which assumes that the donor star is Roche lobe–filling on the red giant branch and expanding because of an increasing luminosity. The mass transfer is slow enough that the donor star always remains close to thermal equilibrium; thus,  $R_2 = R_{2,R}$ , where  $R_2$  is the radius of the donor star and  $R_{2,R}$  is the radius of its Roche lobe. For simplicity, we assume that the mass and angular momentum are conserved, which implies that at the end of the LMXB’s evolution, the NS (of mass  $M_1$ ) will have a mass of 1.7–2.1  $M_{\odot}$ . We assume that the initial donor mass is 0.9  $M_{\odot}$  with a Population I metallicity, consistent with recent determinations of the age and metallicity of the predominant stellar populations in these elliptical galaxies (Trager et al. 2000).

Once the evolution is solved, all parameters of the binary can be found in terms of the orbital period at the onset of mass transfer,  $P_i$ , which is measured in days, and the donor’s mass,  $M_2$ , which is measured in units of solar mass. The mass transfer

<sup>1</sup> Department of Physics, Broida Hall, University of California at Santa Barbara, Santa Barbara, CA 93106-9530; piro@physics.ucsb.edu.

<sup>2</sup> Institute for Theoretical Physics, Kohn Hall, University of California at Santa Barbara, Santa Barbara, CA 93106-4030; bildsten@itp.ucsb.edu.

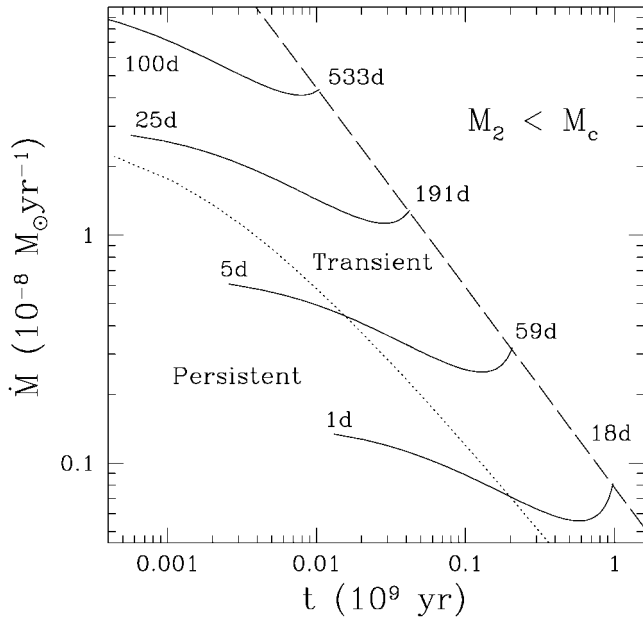


FIG. 1.—Mass transfer rate as a function of time for LMXBs with red giant donors. The solid lines represent the evolutionary path of the binary given an initial orbital period when Roche lobe overfilling begins (evolution is from left to right). The dashed line is the boundary where the hydrogen envelope of the donor has vanished, thus halting the evolution. The dotted line is the boundary at which the accretion disk instability begins.

rate within the binary is

$$\begin{aligned} -\dot{M}_2 = & 6.4 \times 10^{-10} M_{\odot} \text{ yr}^{-1} P_i^{14/15} \left(\frac{M_2}{0.9}\right)^{-7/3} \\ & \times \left(\frac{2.3 - M_2}{1.4}\right)^{-14/5} \left(\frac{5}{3} \frac{1}{M_2} - \frac{2}{2.3 - M_2}\right)^{-1}, \quad (1) \end{aligned}$$

where  $1.4 M_{\odot}$  is the initial NS mass and  $2.3 M_{\odot}$  is the total mass of the binary. Since we will show in § 3 that the disk is likely unstable, we will not concern ourselves here with the implied super-Eddington accretion rates at large  $P_i$  should this mass transfer rate proceed onto the NS. Using equation (1), the evolution of the binary system is shown for varying  $P_i$  by the solid lines in Figure 1. The dashed line is the boundary where the hydrogen envelope of the donor has vanished, halting the evolution at the ending orbital period noted. The evolving orbital period is

$$P_{\text{orb}} = P_i \left(\frac{M_2}{0.9}\right)^{-3} \left(\frac{2.3 - M_2}{1.4}\right)^{-3}, \quad (2)$$

shown in Figure 2 by the solid lines.

For such an LMXB in an elliptical galaxy, we expect that (1) the orbit must be wide in order to reach such high  $\dot{M}$ 's and (2) the reprocessing of the X-rays by the large accretion disk should make it a bright, very blue object. At the Eddington luminosity, an X-ray binary with  $P_{\text{orb}} = 10$  days (much like Cygnus X-2) has  $M_v = -2$  (van Paradijs & McClintock 1994) and is blue ( $B - V \approx 0$ ,  $U - B \approx -1$ ; van Paradijs & McClintock 1995). For NGC 4697 (at a distance modulus of  $\approx 30.35$ ; Tonry et al. 2001), this corresponds to an apparent  $V$  magnitude of 28.4.

Assuming that the LMXB is not associated with a globular cluster, the brightest star that could confuse a search for the

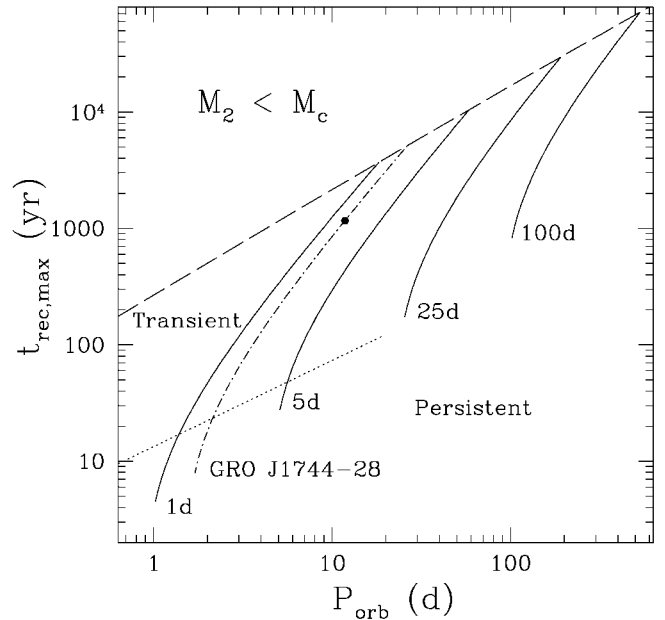


FIG. 2.—Estimated maximum recurrence time as a function of the orbital period. The curves are the same as in Fig. 1. The additional dot-dashed line is the predicted evolutionary path of GRO J1744–28. The filled circle denotes this binary's current orbital period of 11.8 days.

optical counterpart would be a red giant branch star just about to reach helium core ignition (a tip of the red giant branch [TRGB] star). For metallicities  $[\text{Fe}/\text{H}] < -1$ ,  $M_v(\text{TRGB}) \approx -2.5$ , whereas for  $[\text{Fe}/\text{H}] \approx -0.7$ ,  $M_v(\text{TRGB}) \approx -1.5$  (Saviane et al. 2000). For a slightly metal-rich star (such as is likely the case for these elliptical galaxies; Trager et al. 2000), the peak brightness is even fainter,  $M_v(\text{TRGB}) \approx -1.0$  (Garnavich et al. 1994). Hence, the optical counterpart to a wide LMXB will be brighter at  $V$  (and especially so in  $B$  or  $U$ ) than any red giant branch star in an elliptical galaxy.

The surface brightness of an elliptical galaxy would make such a search difficult in the central regions. However, beyond  $\approx 2'$ , the surface brightness at  $V$  (e.g., in NGC 4697) is below the sky level (for the *Hubble Space Telescope* [HST]) of  $22\text{--}23 \text{ mag arcsec}^{-2}$  (Goudfrooij et al. 1994). In that limit, and using the measured *Chandra* position of sources at such locations, such a wide (10 day) binary would be detectable at  $B$  or  $V$  in a  $5 \times 10^4 \text{ s}$  observation with the Advanced Camera for Surveys on HST. Of course, such optical counterparts are easy to find in the nearby bulge of M31, where  $V \approx 22$ .

### 3. DISK INSTABILITY, TRANSIENT FRACTION, AND RECURRENCE TIMES

If the disk is thermally stable and transfers matter to the NS at the supplied rate, there is nearly a one-to-one relation between  $P_i$  and the X-ray luminosity (see Fig. 1) that would allow the orbital period distribution to be inferred from the luminosity distribution (Webbink, Rappaport, & Savonije 1983). However, this argument fails because these wide binaries are almost always transient accretors.

The usual condition used for the disk instability is that some portion of the disk is below the hydrogen ionization temperature ( $\approx 6500 \text{ K}$ ). Since the effective temperature of the disk decreases with increasing radius, it is usually adequate to check that the outer radius of the disk is below the critical temperature. In X-ray binaries, however, this temperature is fixed by irra-

diation from the central accreting source (van Paradijs 1996). The surface temperature is then estimated as (Dubus et al. 2001)

$$T_{\text{irr}}^4 \approx \frac{C\eta\dot{M}_1 c^2}{4\pi\sigma R^2}, \quad (3)$$

where  $R$  is the disk radius,  $\sigma$  is the Stefan-Boltzmann constant,  $\eta = 0.1$  is the conversion efficiency for accretion onto the NS, and  $C$  measures the fraction of the X-ray luminosity that reaches the disk (and contains information on the irradiation geometry). We take  $C = 5.7 \times 10^{-3}$  (slightly larger than the preferred value,  $C = 5 \times 10^{-3}$ , of Dubus et al. 2001) so as to maximize the persistent fraction. The disk is assumed to extend out to 70% of the Roche lobe around the NS (King et al. 1997).

Setting  $T_{\text{irr}} = 6500$  K allows us to solve for the critical time, accretion rate, and orbital period at which the instability sets in as a function of the donor's mass. The critical mass transfer rate is then

$$-\dot{M}_{2,\text{crit}} = 3.3 \times 10^{-9} M_{\odot} \text{ yr}^{-1} M_2^{14/9} (2.3 - M_2)^{-14/9} \times \left( \frac{5}{3} \frac{1}{M_2} - \frac{2}{2.3 - M_2} \right)^{-10/3}, \quad (4)$$

which is used for the instability boundary shown in Figures 1 and 2 as the dotted line. The critical orbital period is

$$P_{\text{orb,crit}} = 5.5 \text{ days } M_2^{7/6} (2.3 - M_2)^{-5/3} \times \left( \frac{5}{3} \frac{1}{M_2} - \frac{2}{2.3 - M_2} \right)^{-5/2}, \quad (5)$$

and this is used for the instability boundary in Figure 2. The fraction of time spent transient is then found (numerically to better than a percent) as a function of the initial orbital period,

$$\text{transient fraction} = -0.0500\chi^2 + 0.2385\chi + 0.7655, \quad (6)$$

where  $\chi = \log(P_i/\text{days})$ . For  $P_i$  in excess of a day, the binary is transient at least 75% of the time, and this does not include binaries containing black holes that are transient almost all the time (e.g., King et al. 1996).

We estimate a maximum recurrence time for outbursts by assuming the outside-in model. We assume that the binary is quiescent until a critical surface density in the outer accretion disk (at radius  $R$ ) has been reached (Dubus et al. 2001),

$$\Sigma_{\text{max}} = 644 \text{ g cm}^{-2} (M_1/M_{\odot})^{-0.37} (R/R_{\odot})^{1.11}, \quad (7)$$

where we assume that the viscosity parameter  $\alpha = 0.1$  and that there is no irradiation of the disk in quiescence. This expression gives a maximum recurrence time

$$t_{\text{rec,max}} = 15 \text{ yr } P_i^{1.14} M_2^{-3.88} (2.3 - M_2)^{-2.75} \times \left( \frac{5}{3} \frac{1}{M_2} - \frac{2}{2.3 - M_2} \right) \quad (8)$$

that should be viewed with some caution given the uncertainties in the accretion disk physics. This recurrence time is  $\sim 100$ – $10,000$  yr (depending on the initial orbital period; see Fig. 2) and is consistent with current estimates from observations of galactic millisecond radio pulsar/He white dwarf binaries (Rit-

ter & King 2002). Our estimate is maximal because it is possible (and maybe even likely) that the LMXB may have an outburst before the outer disk reaches the critical mass, such as an outburst initiated in the inner disk.

#### 4. COMPARISON WITH GALACTIC SOURCES

One difficulty with comparing these evolutionary models with observations is the lack of long orbital period LMXBs in our Galaxy. Many persistent sources have low enough orbital periods ( $\sim 1$ – $20$  hr) that they are probably not accurately described by the evolutionary model used above. However, a lack of persistent sources at  $P_{\text{orb}} > 1$  day is in agreement with our calculations and generally expected from previous work (e.g., King et al. 1997). Figure 1 shows that such NS binaries spend most of their lifetime as transient rather than persistent sources ( $>75\%$  of the time). Although all these relations are consistent, it is still hard to claim that the instability criterion has been fully scrutinized by the galactic population.

Indeed, the outburst durations of these systems might be so long that they appear to us as “persistent” sources (with accretion rates most likely in excess of the mass transfer rate expected from binary evolution) until they suddenly disappear. Indeed, one such source (and maybe others; Wijnands 2002) has now been clearly identified as KS 1731–260 (Wijnands et al. 2001; Rutledge et al. 2002). It was accreting at  $\dot{M} \approx 3 \times 10^{-9} M_{\odot} \text{ yr}^{-1}$  for at least a decade prior to its sudden decline in luminosity by a factor of greater than  $10^4$  (Rutledge et al. 2002). Analysis of the immediate quiescent emission in terms of thermal emission from the NS surface yielded constraints on the recurrence time from 300 to 1000 yr (Wijnands et al. 2001; Rutledge et al. 2002). Until this system's orbital period is found (current knowledge of the infrared counterpart points to a possibly evolved companion; Orosz, Bailyn, & Whitman 2001), we will not be able to say whether or not it is an LMXB of the type we are discussing. However, its existence does point to a likelihood of finding such similar systems in elliptical galaxies.

One galactic binary that does have a long orbital period is GRO J1744–28 (11.8 days; Finger et al. 1996). This system is transient and was shown by Bildsten & Brown (1997) to have a companion with mass  $M_2 \approx 0.334 M_{\odot}$  and core mass  $M_c \approx 0.22 M_{\odot}$  (if the companion is a Population I metallicity star). When this binary's evolutionary path is predicted and plotted, it is found to be transient (as it is) with a maximum outburst recurrence time of  $\sim 1000$  yr (see the dot-dashed line in Fig. 2), consistent with a single outburst.

#### 5. CONCLUSIONS AND DISCUSSION

We have shown that the expected mass transfer scenarios for LMXBs in the field of an elliptical galaxy (where the donors must be  $< 1 M_{\odot}$ ) that yield  $\dot{M} \approx 10^{-8} M_{\odot} \text{ yr}^{-1}$  (as observed by *Chandra*) have thermally unstable disks. Such binaries are expected to be transient accretors with maximum recurrence times of 100–10000 yr for at least 75% of their lifetimes. When active, it appears likely that they would easily reach the NS's Eddington limit.

Our inability to calculate the duration of the bright outbursting phase makes it difficult to predict how many such transients will be identified in repeated *Chandra* visits. If the duty cycle is bright for 10 yr out of 1000 (as implied for KS 1731–260; Rutledge et al. 2002), and there are 100 such binaries, then a year later, roughly 10 would have faded into quiescence to be replaced by new transients. This is not that

far off from what was seen over a 5 month interval in Cen A (Kraft et al. 2001), where four sources (out of 120 exposed in both epochs) were either nondetectable [ $L_x < (1-2) \times 10^{36}$  ergs  $s^{-1}$ ] or appeared bright ( $L_x > 4 \times 10^{37}$  ergs  $s^{-1}$ ) in either epoch. There were a larger number ( $\approx 35$ ) that showed significant variability (Kraft et al. 2001).

Such comparisons are also complicated by the discovery that many of the X-ray sources in elliptical galaxies are coincident with globular clusters (Sarazin et al. 2001; Angelini et al. 2001; White, Sarazin, & Kulkarni 2002). Other possible accretion scenarios then include accretion from lower mass main-sequence stars that are formed in this dense stellar environment (see Rasio, Pfahl, & Rappaport 2000 for a recent discussion). These tight systems would most likely be persistent accretors, thus apparently reducing the fraction of transients among the detected

sources. This might just be an impression, however, as if the duty cycle of the field transients is really 1%; then the underlying population is indeed larger than that in globular clusters. Namely, it is possible that the globular cluster population is only *apparently* a large fraction because LMXBs in globular clusters are persistently bright. The census of the much more numerous population of field transients can only be taken over a few thousand years.

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