TRANSIENT LOW-MASS X-RAY BINARY POPULATIONS IN ELLIPTICAL GALAXIES NGC 3379 AND NGC 4278

T. Fragos[1], V. Kalogera[1], B. Willems[1], K. Belczynski[2], G. Fabbiano[3], N. J. Brassington[3], D.-W. Kim[3], L. Angelini[4], R. L. Davies[5], J. S. Gallagher[6], A. R. King[7], S. Pellegrini[8], G. Trinchieri[9], S. E. Zepf[10], A. Zezas[3]

`tassosfragos@northwestern.edu`, `vicky@northwestern.edu`, `kbelczyn@nmsu.edu`, `gfabbiano@cfa.harvard.edu`, `kim@cfa.harvard.edu`, `nbrassington@head.cfa.harvard.edu`, `angelini@davide.gsfc.nasa.gov`, `rld@astro.ox.ac.uk`, `jsg@astro.wisc.edu`, `ark@star.le.ac.uk`,

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[1] Northwestern University, Department of Physics and Astronomy, 2145 Sheridan Road, Evanston, IL 60208, USA

[2] New Mexico State University, Department of Astronomy, 1320 Frenger Mall, Las Cruces, NM 88003, USA

[3] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

[4] Laboratory for High Energy Astrophysics, NASA Goddard Space Flight Center, Code 660, Greenbelt, MD 20771

[5] Denys Wilkinson Building, University of Oxford, Keble Road, Oxford OX1 3RH, UK

[6] Astronomy Department, University of Wisconsin, 475 North Charter Street, Madison, WI 53706

[7] University of Leicester, Leicester LE1 7RH, UK

[8] Dipartimento di Astronomia, Universita‘ di Bologna, Via Ranzani 1, 40127 Bologna, Italy

[9] INAF Observatorio Astronomico di Brera, Via Brera 28, 20121 Milan, Italy

[10] Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824-2320

`silvia.pellegrini@unibo.it`, `ginevra.trinchieri@brera.inaf.it`,
`zepf@pa.msu.edu`, `azezas@cfa.harvard.edu`

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ABSTRACT

We propose a physically motivated and self-consistent prescription for the modeling of transient neutron star (NS) low-mass X-ray binary (LMXB) properties, such as duty cycle (DC), outburst duration and recurrence time. We apply this prescription to the population synthesis (PS) models of field LMXBs presented by Fragos et al. (2008), and compare the transient LMXB population to the *Chandra* X-ray survey of the two elliptical galaxies NGC 3379 and NGC 4278, which revealed several transient sources (Brassington et al. 2008, 2009). We are able to exclude models with a constant DC for all transient systems, while models with a variable DC based on the properties of each system are consistent with the observed transient populations. We predict that the majority of the observed transient sources in these two galaxies are LMXBs with red giant donors. Finally our comparison suggests that transient LMXBs are very rare in globular clusters (GC), and thus the number of identified transient LMXBs may be used as a tracer of the relative contribution of field and GC LMXB populations.

Subject headings: Stars: Binaries: Close, Stars: Evolution, X-rays: Binaries, Galaxies: Ellipticals

1. INTRODUCTION

Recent *Chandra* observations (Kim et al. 2006; Brassington et al. 2008, 2009) have yielded the first low-luminosity X-ray luminosity functions (XLF) of LMXBs for two typical old elliptical galaxies, NGC 3379 and NGC 4278. The detection limit in these observations was $\sim 3 \times 10^{36}\,\mathrm{erg\,s^{-1}}$, an order of magnitude lower than in most previous similar surveys, while the completeness limit was $\sim 10^{37}\,\mathrm{erg\,s^{-1}}$. In a followup study, Brassington et al. (2008, 2009) used multiple *Chandra* pointings to identify potential transient sources. In that work, a *transient candidate* was defined as a source with X-ray luminosities varying by at least a factor of 10, above the completeness limit, between different pointings. Similarly a *potential transient candidate* was defined as a source with X-ray luminosities varying by at least a factor of 5. Using these definitions, 5 transient candidates and 3 additional potential transient candidates were identified in NGC 3379, while for NGC 4278 the corresponding numbers were 3 and 3 respectively.

Piro & Bildsten (2002) conjectured that LMXBs in the field of ellipticals must be dominated by NS accreting from red giants. Using analytical approximating formulae for the evolution of binary systems they estimated that such binaries are expected to be transient, with maximum recurrence times of $100 - 10000\,\mathrm{yr}$, for at least 75% of their lifetimes. However, they limited their study only to LMXBs with red giant donors, and were unable to calculate the duration of the outburst phase or to predict how many transients would be identified in repeated *Chandra* visits.

Fragos et al. (2008) presented results from extensive LMXB population synthesis (PS) simulations for NGC 3379 and NGC 4278. They considered models for the formation and evolution of LMXBs from primordial and isolated field binaries with different common envelope efficiencies, stellar wind prescriptions, magnetic braking laws, and initial mass functions. They identified models that produce XLFs consistent with observations both in shape and normalization, suggesting that a primordial galactic field LMXB population can have a significant contribution to the total population of an elliptical galaxy.

In this letter we expand on the work by Fragos et al. (2008), and propose a physically motivated and self-consistent prescription for the modeling of transient LMXB properties. Furthermore, we carry out Monte Carlo simulations to compare our findings to the recent observational work by Brassington et al. (2008, 2009).

2. LMXB POPULATION SYNTHESIS MODELS

The models presented in the study by Fragos et al. (2008) were focused on LMXBs formed in the galactic field as products of the evolution of isolated primordial binaries. The simulations were performed using *StarTrack* (Belczynski et al. 2002, 2008), an advanced PS code that has been tested against and calibrated using detailed MT calculations with stellar structure and evolution codes, and observations of binary populations. In the development of these models, all current knowledge about the stellar population in these galaxies were incorporated (see Tables 1 and 2 in Fragos et al. 2008). The observationally determined parameters, such as their age ($9.5 - 10.5\,\mathrm{Gyr}$) and metallicity ($[Fe/H] = 0.14 - 0.16$), or their total stellar mass ($8.6 \times 10^{10} - 9.4 \times 10^{10}\,\mathrm{M}_{\odot}$), are similar for NGC3379 and NGC4278. However, there are physical processes involved in the formation and evolution of a binary system, such as stellar winds, initial mass function, common envelope efficiency, magnetic braking and transient behavior, which are not fully understood quantitatively. Therefore various prescriptions were used to model them. A total of 336 models were studied. See Tables 3 and 4 in Fragos et al. (2008) for all the model parameters and naming conventions.

Fragos et al. (2008) found that a small subset of their models produce XLFs in good agreement with the observations, based on both the XLF shape and absolute normalization.

They concluded that formation of LMXBs in the galactic field via evolution of primordial binaries *can* have a significant contribution to the total population of an elliptical galaxy, especially the GC poor ones like NGC3379 (Fabbiano et al. 2007). In our analysis here, we adopt their best-fitting model (hereafter model 14^{IT}), which produces the XLF in best agreement with observations. Model 14^{IT} assumes a moderate common envelope efficiency $\alpha_{CE} = 0.5$, a standard stellar wind prescription (Hurley et al. 2002), weak magnetic braking (Ivanova & Taam 2003), and a Salpeter initial mass function.

The LMXB population predicted by model 14^{IT} has a significant contribution from transient systems, which with reasonable outburst DC can even dominate the XLF. As a consequence the XLF shape is rather sensitive to the treatment of these transient systems. Fragos et al. (2008) tried different methods of modeling the outburst characteristics of transient LMXBs and got the best agreement with observations when they consider a variable DC for NS LMXB based on the binary properties, hereafter model $14A^{IT}$. However, a constant low DC ($\sim 1\%$), hereafter model $14B^{IT}$, was also statistically consistent with the observed XLF. In both cases, the outburst luminosity was calculated as described in section 3.1.

3. MODELING THE TRANSIENT BEHAVIOR OF LMXBS

3.1. Duty Cycle of Transient X-ray Binaries

In our models we keep track of all binary properties, including the MT rates, as a function of time for all accreting compact objects. Here we focus only on NS LMXBs, which dominate the total population (see Fig. 2 in Fragos et al. 2008). We use the MT rate $\dot{M}_{\rm d}$ to identify transient sources in our simulation results. In the context of the thermal disk instability model, mass transferring binaries with MT rate lower than the critical rate $\dot{M}_{\rm crit}$

for the thermal disk instability to develop (van Paradijs 1996; King et al. 1996; Dubus et al. 1999; Menou et al. 2002), are considered transient sources, meaning that they spend most of their life in quiescence ($T_{\rm quiescence}$), when they are too faint to be detectable, and they occasionally go into an outburst. The fraction of the time that they are in outburst ($T_{\rm outburst}$) defines their DC:

$$\mathrm{DC} \equiv T_{\rm outburst}/\left(T_{\rm outburst} + T_{\rm quiescence}\right). \tag{1}$$

The details of the thermal disk instability model are not well understood therefore the values of the outburst luminosity and the DC cannot be calculated directly from first principles. A simple but physically motivated treatment is to assume that in the quiescent state the NS does not accrete any (or accretes an insignificant amount of) mass, and matter from the donor is accumulated in the disk. In the outburst state all this matter is accreted onto the NS emptying the disk. Taking into account also that the X-ray luminosity probably cannot exceed the Eddington luminosity ($L_{\rm Edd}$) by more than a factor of 2 (cf. Taam et al. 1997), we define the outburst luminosity as:

$$L_{\rm x} = \eta_{\rm bol} \times \min\left(2 \times L_{\rm Edd}, \frac{GM_{\rm a}\dot{M}_{\rm d}}{R_{\rm a}} \times \frac{1}{\mathrm{DC}}\right), \tag{2}$$

where $M_{\rm a}$ and $R_{\rm a}$ are the mass and the radius of the accretor, $\dot{M}_{\rm d}$ is the mass-loss rate of the donor and $\eta_{\rm bol}$ is correction factor that converts the bolometric luminosity to the observed *Chandra* band. When the luminosity inferred by the outburst accretion rate $\dot{M}_{\rm d}/DC$ exceeds the upper limit of $2 \times L_{\rm Edd}$, we assume that the extra material is lost from the disk in the form of outflows.

In equation 2, DC is unknown. Dobrotka et al. (2006) studied accretion disk models for dwarf novae which are thought to experience the same thermal disk instability and found a correlation between the DC and $\dot{M}_{\rm d}$. The exact relation between these quantities depends on the disk's viscosity parameters, but the general behavior can be approximated by:

$$DC \approx \left(\dot{M}_{\rm d}/\dot{M}_{\rm crit}\right)^2 . \tag{3}$$

Plugging equation (3) into equation (2) we eliminate the DC dependence and get an expression that depends only on quantities which are directly calculated in our PS modeling.

3.2. Recurrence Time and Duration of X-ray Outbursts

The derivation of the critical MT rate $\dot{M}_{\rm crit}$ for the thermal disk instability, comes from requiring that some part of the accretion disc has a temperature below the hydrogen ionization temperature. In the thin disk approximation the effective temperature decreases with increasing disk radius, so it is sufficient to require that the effective temperature at the outer edge of the disk is below the hydrogen ionization temperature. In X-ray binaries with NS accretors, the surface temperature of the disk is regulated by irradiation from the accretor (van Paradijs 1996; Dubus et al. 2001).

Following the analysis presented by Piro & Bildsten (2002), we assume that the accretion disk around the NS extends up to a radius of 70% of the Roche lobe radius of the NS ($R_{\rm RL,1}$), and that a transient NS LMXB is in the quiescent state until the surface density at the edge of the disk reaches the critical surface density

$$\Sigma_{\rm max} = 644\,(M_{\rm a}/M_{\odot})^{-0.37}\,(R/R_{\odot})^{1.11}\ {\rm g\,cm^{-2}} \tag{4}$$

that will lead to instability (Dubus et al. 2001). In equation 4, R is the radius coordinate of the disk, and we assume a pure hydrogen disk with viscosity parameter $\alpha = 0.1$, and no irradiation of the disk while the binary is in the quiescent state. For systems with helium accretion disks, such as LMXB with white dwarf donors, we modify equation 4 accordingly (see equation 2 in Lasota et al. 2008). Hence, the maximum mass accumulated in the accretion disk ($M_{\rm disk,max}$), before the X-ray binary goes into outburst, is:

$$M_{\rm disk,max} = \int_{R_{\rm NS}}^{0.7R_{\rm RL,1}} \Sigma_{\rm max}(R) 2\pi R dR \tag{5}$$

Formally, the equation above gives only an upper limit on the maximum mass accumulated in the accretion disk. However, based on numerical simulations by Dubus et al. (2001), the surface density profile of the disk in quiescence is generally not far from $\Sigma_{\rm max}$. Thus equation 5 can actually be used as an estimate of the accretion disk mass just before the outburst. In order to take into account this uncertainty, we also considered models where the mass of the accretion disk is half of what equation 5 predicts, and we found the effect in our results is minor (see Table 1).

From equation 5 we can then estimate the duration of the quiescent phase and the outburst. Using the mass-loss rate of the secondary star, as given by our PS models, and equations 1 and 3, the time duration of the quiescent and outburst phase becomes:

$$T_{\rm quiescence} = \frac{M_{\rm disk,max}}{\dot{M}_{\rm d}}, \quad T_{\rm outburst} = \frac{\dot{M}_{\rm d}^2}{\dot{M}_{\rm crit}^2 - \dot{M}_{\rm d}^2} M_{\rm disk,max}. \tag{6}$$

3.3. Detection probability of transient LMXBs

The probability that a transient LMXB is detected as a bright X-ray source is equal to its DC. However, the probability that a LMXB is identified as a transient source in a survey with multiple observations depends on the duration and the recurrence time of the outbursts of the source, as well as the time spacing between the observations. In our analysis we assume that a transient LMXB can be in two states, outburst or quiescent, and that its luminosity in outburst is given by equation 2, while in quiescence it is undetectable (i.e. we do not take into account rise and decay characteristics of the outburst). Hence, in order for a source to be identified as a transient, it has to be found at a different state, in at least one out of the multiple observations (see Figure 1).

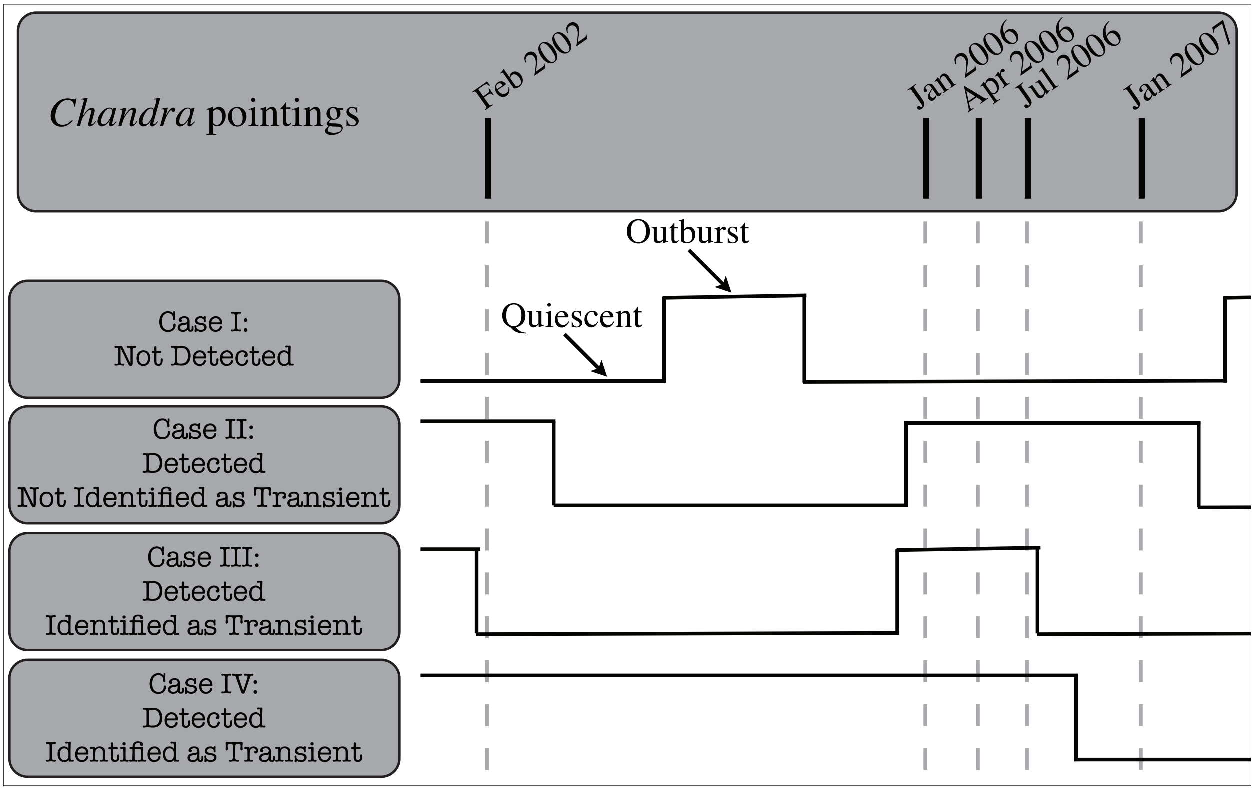

Fig. 1.— Schematic description of the procedure followed to calculate the probability that a LMXB is identified as a transient source in a survey.

Given a model population of LMXBs, we calculate for each transient LMXB the probability that it would be identified as a transient source in an observational survey like the ones for the elliptical galaxies NGC 3379 and NGC 4278 (Kim et al. 2006). In order to estimate this probability, we first calculate the outburst and recurrence time for the specific binary as described in section 3.2, and then create an artificial lightcurve. This lightcurve should include at least one full cycle of the transient and be at least twice as long as the time interval between the first and the last observation. Next, we choose randomly a time in this artificial light curve to position the first pointing of the survey with the other pointings following according to the time intervals between the pointing of the survey we are simulating. For this random positioning of the first pointing, we attain the state of the transient LMXB (outburst or quiescent) at each of the pointings, and assess whether this system would be identified as a transient source (see Figure 1). We repeat the procedure 10^5 times, choosing randomly a different starting time in the artificial lightcurve, which enable us to estimate the probability that a specific system would be identified as a transient source.

Based on this probability for each transient LMXB of the model population, we perform another Monte Carlo simulation, this time to estimate the total number of transients that would be identified in the modeled survey. Repeating this procedure 10^5 times, we are able to derive a probability density function (PDF) of the number of identified transient sources, for a combination of PS and X-ray survey parameters.

4. RESULTS

As mentioned earlier, we adopt the PS model 14^{IT}, which was chosen based on comparison of the shape of the modeled XLF to the observed one (Fragos et al. 2008). We examine two prescriptions for the transient characteristics of LMXBs: a variable DC based on the properties of each binary as described in section 3.1 (model $14A^{IT}$), and a low constant DC of 1% (model $14B^{IT}$). For more details on the model parameters see sections 2.3 and 3.1 in Fragos et al. (2008). We normalize the total number of LMXBs in our models in two different ways: based on the total number of observed LMXBs above the completeness limit of the observations, or based on the number of observed field LMXBs, i.e. the ones that do non coincide with GCs (Kim et al. 2009). We note here that if we instead normalize the synthetic LMXB population based on stellar mass of the galaxies, we get results very similar to normalizing based on the number of observed field LMXBs.

In order to simulate the observational identification of transient sources as realistically as possible, for each of the two elliptical galaxies we use the actual time intervals between the successive pointings of the survey. Furthermore, we try to mimic the definitions of transient candidate and potential transient candidate of Brassington et al. (2008, 2009). In our simulated observations, a transient candidate is a system that is identified as transient and has outburst luminosity above $10^{38}\,\mathrm{erg\,s^{-1}}$, while a potential transient candidate has outburst luminosity between $5 \times 10^{37}\,\mathrm{erg\,s^{-1}}$ and $10^{38}\,\mathrm{erg\,s^{-1}}$.

Figure 2 shows the PDF for the number of detected sources in an X-ray survey such as that by Brassington et al. (2008, 2009). When we normalize the total number of LMXBs in our synthetic population to the number of observed field LMXBs above the completeness limit of the observation ($\sim 10^{37}\,\mathrm{erg\,s^{-1}}$), for each of the two galaxies separately, model $14A^{IT}$ (variable DC) gives PDFs consistent with observations for both transient candidates and potential transient candidates, and for both galaxies (see Table 1). On the other hand, model $14B^{IT}$ (constant DC $\sim 1\%$) is consistent with observations only when we look at the bright transient sources (i.e., transient candidates). A constant DC significantly overproduces the number of potential transient candidates.

Normalizing the number of LMXBs of our models to total number of observed LMXBs

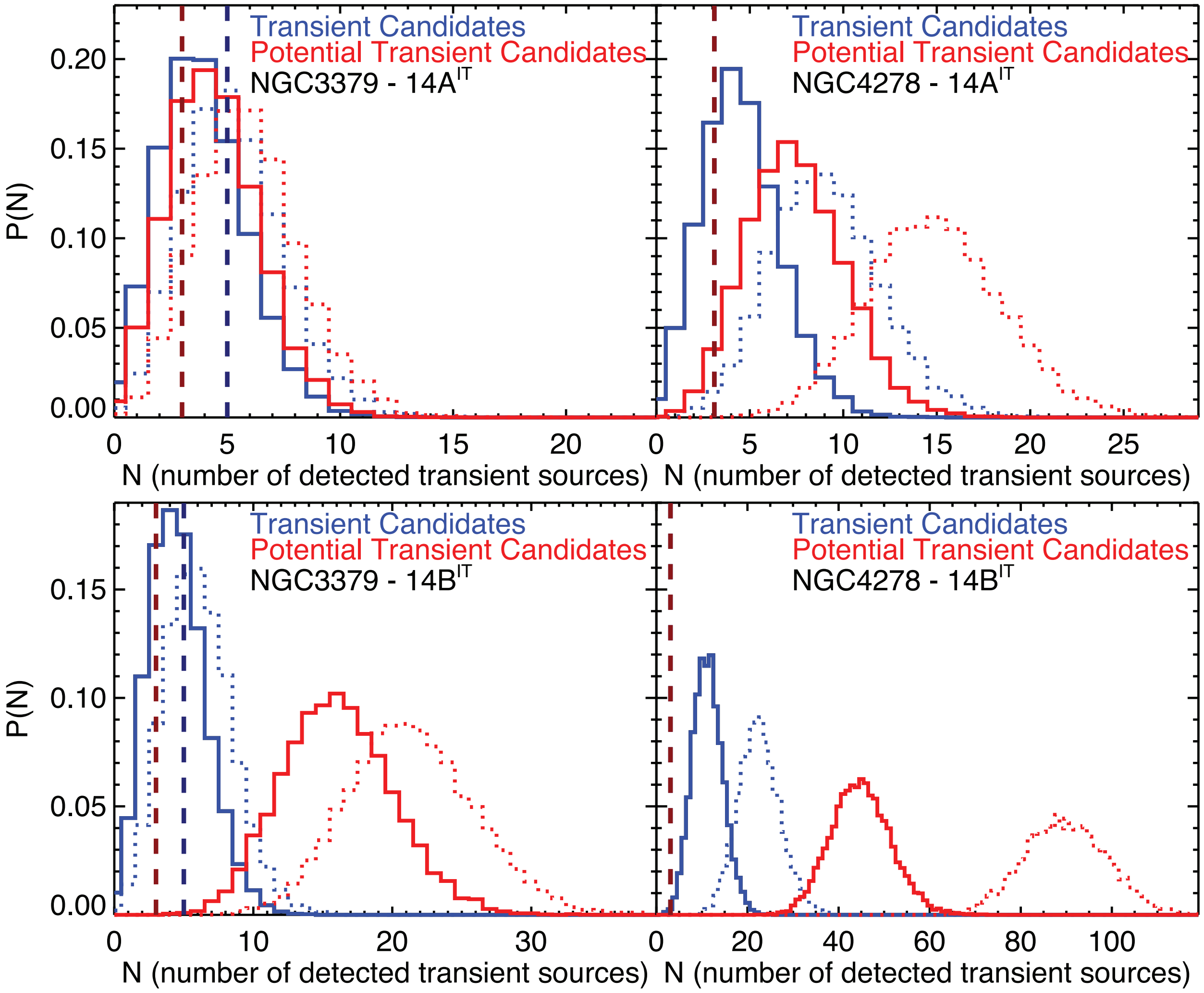

Fig. 2.— PDF of the number of detected transient sources in an X-ray survey such as that by Brassington et al. (2008, 2009), for model $14A^{IT}$ in panels (a) and (b) and model $14B^{IT}$ in panels (c) and (d). Panels (a) and (c) correspond to the elliptical galaxy NGC 3379, while panels (b) and (d) refer to NGC 4278. Solid lines are used when the normalization of the total number of LMXBs in our models is based on the number of observed field LMXBs in these galaxies, whereas dotted lines signify a normalization based on the total number of observed LMXBs above the detection limit. The vertical dashed lines refer to the actual observations by Brassington et al. (2008, 2009)

above the completeness limit, alters our findings. In the case of NGC 3379, and for model $14A^{IT}$, the PDFs of both transient candidates and potential transient candidates are still in excellent agreement with the observations. For the case of NGC 4278 on the other hand, this normalization results to a very high number of expected identified transient source, which is inconsistent with observations. However, this does not come as a surprise, since the elliptical galaxy NGC 4278 has a large number of GC (~ 5 times more than NGC 3379) and a significant fraction ($\sim 50\%$) of the observed LMXB population resides in GC (Kim et al. 2009). It has already been suggested that luminous GC LMXBs are predominantly persistent source (Bildsten & Deloye 2004; Ivanova et al. 2008) in which case the similar number of identified transients in the two elliptical galaxies, despite the difference by a factor of ~ 3 in the total number of observed LMXBs, is expected.

Fragos et al. (2008) analyzed their model LMXB populations and found that the sub-populations that mainly contribute to the model XLFs are transient and persistent NS-LMXBs with red giant donors. Following a similar analysis, in Table 1 we show the expected number of identified TC and PTC for each of our model, where we split the modeled population into sub-populations based on the type of the donor star. We find that in model $14A^{IT}$, the majority of identified transient sources are LMXBs with red giant donors, as already argued in the literature (King et al. 1996; Piro & Bildsten 2002; Fragos et al. 2008). In contrast, model $14B^{IT}$ predicts a much higher than the observed number of identified transient LMXBs and the majority of them have main sequence donors. This results from assigning the same low DC to all systems, whereas transient LMXBs with main sequence donors have usually MT rates close to $M_{\rm crit}$. These systems would otherwise have $DC \approx 1$ and low outburst luminosity, and thus would be undetectable at X-ray luminosities above $5 \times 10^{37}\,{\rm erg\,s^{-1}}$.

Table 1. Transient model comparison.

				TC				PTC			
Galaxy	PS Model	Normalization[a]	f[b]	P[c]	N_{MS}[d]	N_G[e]	N_{WD}[f]	P[c]	N_{MS}[d]	N_G[e]	N_{WD}[f]
NGC 3379	$14A^{IT}$	Total # of LMXBs	1.0	0.79	0.05	4.45	0.59	0.28	0.00	4.53	1.52
NGC 3379	$14A^{IT}$	# of field LMXBs	1.0	0.35	0.04	3.33	0.43	0.67	0.00	3.39	1.13
NGC 4278	$14A^{IT}$	Total # of LMXBs	1.0	0.03	0.20	6.50	2.72	0.00	0.00	8.59	6.12
NGC 4278	$14A^{IT}$	# of field LMXBs	1.0	0.60	0.10	3.25	1.37	0.11	0.00	4.31	3.07
NGC 3379	$14B^{IT}$	Total # of LMXBs	1.0	0.87	0.35	3.17	2.55	0.00	19.61	0.00	1.75
NGC 3379	$14B^{IT}$	# of field LMXBs	1.0	0.61	0.26	2.37	1.91	0.00	14.71	0.00	1.31
NGC 4278	$14B^{IT}$	Total # of LMXBs	1.0	0.00	1.34	11.06	10.15	0.00	82.93	0.00	7.07
NGC 4278	$14B^{IT}$	# of field LMXBs	1.0	0.01	0.68	5.51	5.01	0.00	41.42	0.00	3.56
NGC 3379	$14A^{IT}$	Total # of LMXBs	0.5	0.79	0.50	6.62	0.63	0.07	0.00	6.26	1.57
NGC 3379	$14A^{IT}$	# of field LMXBs	0.5	0.95	0.06	4.97	0.47	0.30	0.00	4.69	1.17
NGC 4278	$14A^{IT}$	Total # of LMXBs	0.5	0.00	0.22	12.97	2.39	0.00	0.00	15.10	5.72
NGC 4278	$14A^{IT}$	# of field LMXBs	0.5	0.08	0.11	6.45	1.20	0.02	0.00	7.51	2.86

[a] Normalization of the synthetic population.

[b] Mass of the accretion disk as a fraction f of $M_{\mathrm{disk,max}}$

[c] Probability that the model is consistent with observations, as calculated in our Monte Carlo simulations. Models with $P < 0.01$ are considered inconsistent with observations.

[d] Expected number of identified transient LMXBs with a main sequence donor.

[e] Expected number of identified transient LMXBs with a giant donor.

[f] Expected number of identified transient LMXBs with a white dwarf donor.

5. DISCUSSION

The goal of this work was to pose further constraints on our models based on the recent observational work by Brassington et al. (2008, 2009), and simultaneously gain a better understanding on the nature of transient LMXBs. We found that the populations of transient LMXBs produced by the PS model $14A^{IT}$ (Fragos et al. 2008) is consistent with the observed population. In this model a variable DC was assigned for each system based on its properties (see section 3.2). In contrast, we show that the widespread in the literature assumption of a constant low ($\sim 1\%$) DC for all transients, although it can result in a XLF consistent with the observed one (Fragos et al. 2008), is not consistent with the number of observationally identified transient LMXBs.

Comparing the GCpoor elliptical galaxy NGC 3379 to the GCrich NGC 4278, which otherwise have similar properties, **?** found that NGC 4278 has ~ 3 times more LMXBs with luminosity above $10^{37}\,\mathrm{erg\,s^{-1}}$. This excess of detected LMXBs in NGC 4278 can be attributed to the higher formation efficiency of LMXBs in GC (via dynamical interactions), of which NGC 4278 has 5 times more (see also related conclusions by Kim & Fabbiano 2004; Irwin 2005; Kim et al. 2009). At the same time, the number of TC and PTC is roughly the same in both elliptical galaxies.

Based on the comparison shown in this letter and keeping in mind the small statistical sample, one may suggest the number of transient sources is proportional to number of field LMXBs or the stellar mass of the galaxy, rather than the total number of LMXBs, or the number of GCs. We find that when we normalize our modeled LMXB populations to the number of observed field sources in NGC 4278, the total number of modeled LMXBs was smaller by a factor of ~ 2 compared with the observed number, but the models predicted correctly the number of observationally identified TCs. On the other hand, for the GCpoor NGC 3379, both the modelpredicted total number of LMXBs and the predicted number of observable transients were consistent with the observations. Given these results, we suggest that the observed transient LMXB population in old elliptical galaxies may be used as a tracer of the relative contribution of LMXBs formed from the evolution of primordial isolated binaries (whose number should scale as the stellar mass).

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