ON THE CHANDRA X-RAY SOURCES IN THE GALACTIC CENTER

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ABSTRACT

Recent deep Chandra surveys of the Galactic center region have revealed the existence of a faint, hard X-ray source population. While the nature of this population is unknown, it is likely that several types of stellar objects contribute. For sources involving binary systems, accreting white dwarfs and accreting neutron stars with main-sequence companions have been proposed. Among the accreting neutron star systems, previous studies have focused on stellar wind-fed sources. In this paper, we point out that binary systems in which mass transfer occurs via Roche lobe overflow (RLOF) can also contribute to this X-ray source population. A binary population synthesis study of the Galactic center region has been carried out, and it is found that evolutionary channels for neutron star formation involving the accretion-induced collapse of a massive ONeMg white dwarf, in addition to the core collapse of massive stars, can contribute to this population. The RLOF systems would appear as transients with quiescent luminosities, above 2 keV, in the range from \(10^{31}\) to \(10^{32}\) ergs s\(^{-1}\). The results reveal that RLOF systems primarily contribute to the faint X-ray source population in the Muno et al. survey and that wind-fed systems can contribute to the less sensitive Wang et al. survey. However, our results suggest that accreting neutron star systems are not likely to be the major contributor to the faint X-ray source population in the Galactic center.

Subject headings: binaries: close — stars: evolution — stars: formation — stars: neutron — X-rays: binaries

1. INTRODUCTION

Recent Chandra observations of the Galactic center region (e.g., Wang et al. 2002, hereafter WGL02; Muno et al. 2003, hereafter MM03) have led to a renewed interest in the understanding of compact stellar X-ray sources. Both of these long-exposure surveys have revealed a great number of X-ray point sources with luminosities \(L_X \lesssim 10^{35}\) ergs s\(^{-1}\) and spectra that can be fitted by an absorbed power law.

Although the nature of these low-luminosity sources is unknown, several possible interpretations have been proposed. In particular, Muno et al. (2004) suggest that the intermediate polar subclass of magnetic cataclysmic variables may dominate this lower mass binary population. In particular, Muno et al. (2004) suggest that the intermediate polar subclass of magnetic cataclysmic variables may dominate the faint population characterized by luminosities less than \(10^{33}\) ergs s\(^{-1}\) and a photon power-law index ranging between 0 and 1. Among models involving accreting neutron stars (NS), Pfahl et al. (2002, hereafter PRP02) explored the hypothesis that wind-fed neutron star systems with intermediate and massive main-sequence (MS) donors \((M \approx 3 M_\odot)\) may account for the majority of sources with \(L_X = 10^{34} - 10^{35}\) ergs s\(^{-1}\). Furthermore, the contributions from a population of pre–low-mass X-ray binaries in which the neutron stars accrete from the wind of low-mass MS companions \((\lesssim 2 M_\odot)\) has also been studied by Bleach (2002) and Willems & Kolb (2003). However, it was recently pointed out by Popov (2004) that the neutron stars in this lower mass binary population may not necessarily accrete all the transferred material, implying that only a fraction of these types of systems would be continuous X-ray emitters. Among the nonstellar models that have been proposed, Bykov (2003) has suggested that the faint, hard sources result from the interaction of fast-moving supernova ejecta fragments with the dense interstellar medium of the Galactic center region. These sources, because of their low intrinsic brightness, may only contribute to the deeper MM03 survey.

The aforementioned stellar studies focused on only wind-fed NS systems; however, there are a number of RLOF transient systems that, in quiescence, emit at X-ray luminosities very similar to those of the many point sources observed in the Galactic center. Specifically, transients with neutron stars in their quiescent state are observed to have X-ray luminosities in the range \(10^{32} - 10^{33}\) ergs s\(^{-1}\) (see Campana & Stella 2004), while transient systems with black hole (BH) accretors tend to be observed at lower luminosities of \(\sim 2 \times 10^{31}\) ergs s\(^{-1}\) (e.g., Tomsick et al. 2003) in their inactive state. Although many of the NS transient systems are characterized by soft spectra in their quiescent state and are difficult to detect from the Galactic center region, some fraction have a power-law component extending beyond 2 keV with luminosities in the range \(\sim 10^{31} - 10^{32}\) ergs s\(^{-1}\) (see Jonker et al. 2004). Such systems may have been detected in the deeper survey of MM03. The systems with BH accretors are also known to emit at energies greater than 2 keV and may also contribute to the faint source population at this luminosity level.

X-ray transient systems with large outburst to quiescent flux ratios are known to have either an NS or BH accretor and a predominantly low-mass companion (classified as a low-mass X-ray binary, LMXB). The outburst phenomenon is generally believed to result from a thermal/viscous instability in an accretion disk surrounding the compact object. Only those systems with mass transfer rates below a critical value (e.g., Dubus et al. 1999; Menou et al. 2002) can exhibit such transient behavior. In general, the donors of LMXBs are believed to be either low-mass MS or giant-like stars. However, observations of ultra–short-period LMXBs (with orbital periods less than about 80 minutes), so-called ultracompacts, have revealed that at least some of them must host very low mass \((0.01 - 0.1 M_\odot)\) white dwarf (WD) donors (e.g., Markwardt et al. 2002; Galloway et al. 2002; see also Deloye & Bildsten 2003). In a recent study, Belczynski & Taam (2004) showed...
that the population of LMXBs with low-mass WD donors (and thus with very low mass transfer rates leading to transient behavior) may be more significant than previously anticipated. Since the majority of transient sources are expected to be in quiescence because of the very low X-ray duty cycle, we suggest that a fraction of the low-luminosity sources observed in the Galactic center region may reflect a population of transient systems in their quiescent state, while the same systems in outburst may contribute to a bright source population.

A binary population synthesis model StarTrack (presented in § 2) is used to determine the number of X-ray binaries (NS or BH accretor, wind-fed or RLOF) in the Galactic center region. The entire mass spectrum of evolved and unevolved donors is considered. In particular, low-, intermediate-, and high-mass MS stars are investigated to account for the models considered in previous studies. The results of our studies are described in § 3, and their implications are discussed in § 4.

2. MODEL DESCRIPTION

The StarTrack population synthesis code developed originally for the modeling of binaries with two compact objects (Belczynski et al. 2002) is used. This code has recently undergone major revisions (K. Belczynski et al. 2004, in preparation), reflecting the new features associated with the improved treatments of the physical processes important for the formation and evolution of X-ray binary systems. Specifically, the additions and revisions include a detailed treatment of tidal synchronization and circularization, individual treatment of various RLOF mass transfer phases, and a full numerical orbit evolution with angular momentum losses due to magnetic braking (MB), gravitational radiation (GR), mass transfer/loss, and tides.

In contrast to population synthesis studies of other groups, we also include the possibility that neutron star formation can occur via an accretion-induced collapse (AIC) of a massive ONeMg white dwarf (Belczynski & Taam 2004). Such white dwarfs in binaries form from stars within the mass range of \( \sim 7-12 \, M_\odot \) (Belczynski & Taam 2004; Tauris & van den Heuvel 2003; see also Nomoto & Hashimoto 1988), which is wider than for the formation of ONeMg cores in single stars \( \sim 8-10 \, M_\odot \) because of tidal mass loss (Nomoto & Kondo 1991) and rejuvenation (Belczynski & Taam 2004). The ability to accumulate matter on the white dwarf is enhanced, paradoxically, by the effect of an optically thick wind from the white dwarf surface, which can stabilize the mass transfer in the system at high mass transfer rates (see Kato & Hachisu 1999; Hachisu et al. 1999). The accumulation ratio of hydrogen-rich and helium-rich matter is taken from Hachisu et al. (1999) and Kato & Hachisu (1999), respectively (see also Ivanova & Taam 2004). For the direct accretion of helium or carbon/oxygen matter onto the ONeMg white dwarfs, we make use of the work of Kawai et al. (1987) in determining the evolution of the accreting white dwarf. Our population synthesis study of the Galactic center should therefore be considered complementary to that of PRP02, who did not consider the AIC process nor RLOF X-ray sources.

The tidal effects have been calibrated using the observations of binary periods and eccentricities in several stellar clusters (Mathieu et al. 1992), recovering the orbital decay rate in high-mass X-ray binaries (Levine et al. 2000). The StarTrack RLOF calculation involves the detailed calculation of the mass transfer rates based on radius mass exponents calculated both for the donor stars and their Roche lobes. The results of our calculations have been compared to a set of published RLOF sequences (e.g., Beer & Podsiadlowski 2002) as well as to calculations obtained with an updated stellar evolution code (Ivanova et al. 2003). Our approach to the mass transfer calculations allows for the possibility of (1) conservative versus nonconservative RLOF episodes, (2) thermally driven RLOF versus nuclear/MB/GR loss–driven RLOF, and (3) a separation of systems as persistent or transient depending on whether the donor RLOF mass transfer rate lies below the critical rate for instability to develop in the accretion disk (adopted from Dubus et al. 1999 or Menou et al. 2002 for different compositions of transferred material). Persistent X-ray emitters remain at an X-ray luminosity level corresponding to the secular RLOF mass transfer rate. Transient X-ray systems remain at very low luminosities for most of their lifetime; however, they exhibit outbursts with luminosities that can reach the Eddington limit. We account for wind accretion onto compact objects following Hurley et al. (2002) with the wind mass-loss rates adopted from Hurley et al. (2000) extended to include low-mass and intermediate-mass MS stars utilizing the formulae of Nieuwenhuijzen & de Jager (1990). The wind velocities are assumed to be proportional to the escape velocity from the stellar surface with a normalization proposed by Hurley et al. (2002). For all wind-fed systems, we assume an orbit-averaged accretion rate. The flaring behavior associated with Be stars and the periastron passage–enhanced mass accretion onto the NS are not taken into account.

A large sample of single \( (10^6) \) and binary \( (10^6) \) stars in the Galactic center are evolved for 10 Gyr assuming a constant star formation rate. We choose parameters from the reference model in Belczynski et al. (2002) with a few differences. Specifically, the maximum NS mass is set equal to 2 \( M_\odot \), and the most recently inferred natal NS kick distribution (for NSs formed from the core collapse of massive stars) of Arzoumanian et al. (2002) is incorporated. For cases in which NS formation occurs via the accretion-induced collapse evolutionary channel, no kicks are applied (see Belczynski & Taam 2004). However, we calculate one model in which we allow for the full kicks imparted to NSs formed through AIC, to assess the effect of our no AIC kick assumption. In the primordial progenitor population, the primary masses are selected in the range 4–100 \( M_\odot \) (with an initial mass function slope of \(-2.7\); see Kroupa et al. 1993), and the secondary masses are selected in the range 0.08–100 \( M_\odot \) with a flat mass ratio (secondary divided by primary mass) distribution. In the rapid phases of binary evolution, the accretion rate onto the NS and the BH is limited at the maximum Eddington limit with the remaining transferred material lost with a specific orbital angular momentum of the accretor, but allowing for hypercritical accretion in the common envelope (CE) phases (e.g., Blondin 1986; Chevalier 1989; Brown 1995). In addition to the dynamically unstable RLOF mass transfer events leading to a CE phase, we also allow for evolution into the CE phase in the cases in which the trapping radius of the accretion flow exceeds the Roche lobe radius of the accretor (e.g., King & Begelman 1999; Ivanova et al. 2003). Finally, in comparison with our previous study, we have assumed that all systems that enter a CE phase with the donor in the Hertzsprung gap merge into a single star (Ivanova & Taam 2004; Belczynski & Taam 2004).

The updated version of the code has been tested and used for a study of Galactic ultracompact binaries (Belczynski & Taam 2004) and Galactic young black hole populations (Belczynski et al. 2004b), and used to reproduce the X-ray luminosity function of the nearby starburst galaxy NGC 1569 (Belczynski et al. 2004a).
3. RESULTS

3.1. Source Type and X-Ray Luminosity

In our study only accreting binaries with NS and BH primaries, which are brighter than \( L_X = 10^{30} \text{ ergs s}^{-1} \), are considered. The secondaries in these X-ray binaries may lose material either through a stellar wind or via RLOF. In the latter case, the donors transfer all the material toward the accretor, whereas for the wind-fed systems only a fraction of the material is captured by the compact object. For every accreting system, the bolometric luminosity \( (L_{bol}) \) is calculated based on the secular average mass accretion rate \( (\dot{M}_{acc}) \) as

\[
L_{bol} = \epsilon \frac{G \dot{M}_{acc} M_{acc}}{R_{acc}},
\]

(1)

where \( G \) is the gravitational constant, \( \dot{M}_{acc} \) is the mass of the accretor, \( R_{acc} \) is the radius of the accretor (10 km for an NS and 3 Schwarzschild radii for a BH), and \( \epsilon \) gives the conversion efficiency of gravitational binding energy to radiation associated with accretion onto an NS (surface accretion \( \epsilon = 1.0 \)) and onto a BH (disk accretion \( \epsilon = 0.5 \)).

To determine the simulated X-ray luminosities of our population synthesis, we note that very little of the transferred material is accreted for transient systems during their inactive state. The spectra of neutron stars during this state consist of a soft blackbody component and a hard power law component with a tendency for a larger contribution from the power-law component for sources characterized by lower quiescent luminosities (Jonker et al. 2004; see also Tomsick et al. 2004). The soft component is described by energies of \( \sim 0.1\sim 0.3 \text{ keV} \) (see Campana & Stella 2004). The theoretical models based on deep crustal heating associated with pycnonuclear reactions (Brown et al. 1998; Colpi et al. 2001) can provide an understanding of the blackbody-like nature of the spectrum and the observed emission level \( (\sim 10^{32}\sim 10^{33} \text{ ergs s}^{-1}) \) without necessarily invoking the accretion of matter. However, short-term variability during the quiescent state in Aql X-1 (Rutledge et al. 2002) and Cen X-4 (Campana et al. 2004) has also been observed, suggesting that accretion of matter may be occurring in Aql X-1 and Cen X-4 (Asai et al. 1996, 1998; Campana et al. 1998, 2000; Campana 2004). The accretion rate during this phase is likely to be at a low level, since the inferred luminosities above 2 keV are \( \sim 10^{31} \text{ ergs s}^{-1} \). In contrast to the majority of transient systems in quiescence, the spectral energy distribution of the millisecond accreting X-ray pulsar, SAX J1808.4–3658, is dominated by a hard component with a luminosity of \( \sim 5 \times 10^{33} \text{ ergs s}^{-1} \). Such a nonthermal component may arise from synchrotron emission in a shock front produced by the interaction of a relativistic pulsar wind with matter from the companion star (Tavani & Arons 1997; Campana et al. 1998). Based on these observational results, we adopt \( 10^{31} \text{ ergs s}^{-1} \) as a lower limit for the hard X-ray luminosity, above 2 keV, for transient NS systems in quiescence, recognizing that the average luminosity level can be higher, \( \gtrsim 10^{32} \text{ ergs s}^{-1} \) (e.g., Rutledge et al. 2001, 2002; see also Jonker et al. 2004). Because of the lack of a definitive theory for the hard X-ray emission component of transient systems in quiescence, we take a semiempirical approach for the quiescent NS transients and adopt an X-ray luminosity level of \( 10^{31} \sim 10^{32} \text{ ergs s}^{-1} \) above 2 keV. Furthermore, we assume that the quiescent NS transient X-ray luminosities are evenly distributed in the above range.

The quiescent emission from BH transient systems, on the other hand, is likely related to a low level of mass accretion. In contrast to the NS transient systems, the spectra are typically harder and are not described by a blackbody. Observations of the 14 black hole transient systems for which the quiescent emission has been obtained reveal luminosities in the range from \( \sim 10^{30} \sim 10^{32} \text{ ergs s}^{-1} \) with a median luminosity of \( \sim 2 \times 10^{31} \text{ ergs s}^{-1} \) (see Tomsick et al. 2003). As for the NS transient systems, a semiempirical approach is adopted for the BH transient systems. In particular, we assume that most (80%) of the quiescent BH transient X-ray luminosities above 2 keV are evenly distributed in the \( 10^{30} \sim 10^{32} \text{ ergs s}^{-1} \) range, while the rest (20%) of the systems are slightly brighter: luminosities evenly distributed in the \( 10^{32} \sim 10^{33} \text{ ergs s}^{-1} \) range (see Fig. 3 of Tomsick et al. 2003).

Transient RLOF systems in outburst are bright X-ray sources, with luminosities corresponding to a fraction \( (\eta_{bol}) \) of the critical Eddington luminosity. The long-period systems, with orbits that are sufficiently extensive for a large accretion disk to be formed, are usually found to emit at the Eddington luminosity \( (L_{edd}) \) during outburst, while the outburst luminosities of short-period systems are lower by about an order of magnitude. Therefore, we apply an X-ray luminosity correction factor at an outburst corresponding to \( \eta_{bol} = 0.1 \) and \( \eta_{bol} = 1 \) for the short- and long-period systems, respectively. The critical periods, over which the Eddington luminosity is adopted, are taken to be 1 day and 10 hr for NS and BH transients in outburst, respectively (Chen et al. 1997; Garcia et al. 2003; T. Maccarone 2003, private communication).

For the persistent sources (both RLOF- and wind-fed) and all transients in the outburst stage, where accretion is the dominant contributor to the observed luminosity, we apply a correction factor \( \eta_{bol} \) to the bolometric luminosity to account for the fraction of energy emitted above 2 keV. For different types of systems, one may expect corrections of the order of \( 0.1\sim 0.5 \). However, for clarity and comparison with previous studies, the same correction is applied to all the sources within the limits \( \eta_{bol} = 0.1\sim 1.0 \), with \( \eta_{bol} = 0.1 \) chosen as a standard value.

Therefore, we can obtain the simulated X-ray luminosity (ergs s\(^{-1}\)) from

\[
L_X = \begin{cases} 
10^{31} \sim 10^{32} & \text{all quiescent NS transients,} \\
10^{30} \sim 10^{32} & 80\% \text{ quiescent BH transients,} \\
10^{32} \sim 10^{33} & 20\% \text{ quiescent BH transients,} \\
\eta_{bol} L_{bol} & \text{outburst NS/BH transients,} \\
\eta_{bol} L_{bol} L_{edd} & \text{persistent (RLOF- and wind-fed),}
\end{cases}
\]

(2)

where \( L_{edd} \) represents the Eddington luminosity.

3.2. Standard Model Calculations

The simulated X-ray luminosity distributions of both wind-fed and RLOF-fed systems with NS and BH accretors are illustrated in Figure 1. The RLOF-fed systems dominate the overall X-ray population at luminosities greater than \( L_X = 10^{30} \text{ ergs s}^{-1} \), with most of the systems lying within the range of \( L_X \sim 10^{31} \sim 10^{32} \text{ ergs s}^{-1} \). The majority of these RLOF systems are transient X-ray sources in quiescence formed through the AIC scenario presented in Belczynski & Taam...
The number of X-ray systems (435 of RLOF-fed and 56 of wind-fed sources) were calibrated to represent the Galactic center population in the MM03 survey and are also listed in Table 1 (for details, see § 3.4).

In Table 1 the relative frequencies for various types of systems categorized by their donors and accretors found in our simulation are listed. As expected from the examination of Figure 1, the RLOF-fed systems dominate (88.6%) the population. The majority of these systems are NS transient sources in quiescence with typical luminosities of $L_X \approx 10^{31}-10^{32}$ ergs s$^{-1}$. Most of the RLOF-fed systems have low-mass WD donors with mass transfer rates of $\sim 10^{-11} \, M_\odot \, yr^{-1}$ leading to transient behavior through a long-lived ($\sim 1$ Gyr) phase (for details, see Belczynski & Taam 2004). Over half of the systems belong to the ultra-short-period LMXB class with orbital periods below 2 hr (60.7%), while the remaining RLOF-fed binaries (27.9%) are characterized by longer periods extending beyond 1 month.

A small but significant fraction of wind-fed systems (11.4%) are found, mostly with low-mass ($M \leq 3 \, M_\odot$; 7.9%) and intermediate-mass companions ($3 \, M_\odot < M \leq 8 \, M_\odot$; 3.3%). However, there is no statistically significant population of systems found with massive ($M > 8 \, M_\odot$) companions (HMXBs). Most of the wind-fed systems are NS-MS binaries; however, several have an evolved (red giant) donor, and a few have a BH accretor. For the wind-fed systems, most are characterized by eccentric orbits with the most massive donors possibly exhibiting a Be X-ray binary phase, although we do not follow orbit-dependent accretion.

Our X-ray population will remain confined to the Galactic center region, since the spatial velocities induced as a result of the mass-loss and nascent kick velocities accompanying NS/BH formation are small compared to their mean spatial velocities in this region. In particular, the average velocities acquired are $\sim 60–100$ km s$^{-1}$ for both the wind-fed and RLOF mass-transferring systems. They are significantly smaller than the velocities of $\sim 200$ km s$^{-1}$ characteristic of the stellar motions in this region. We point out that the velocities calculated for the RLOF mass-transferring systems only refer to a minor subgroup (71 out of 435 systems; see Table 1) that have undergone a core-collapse supernova since the majority of these systems are formed via the AIC mechanism with no nascent kick. The low velocities are a direct consequence of the use of the recent NS kick distribution of Arzoumanian et al. (2002).

### 3.3. Parameter Study

To determine the sensitivity of the results to the major uncertainties of the binary evolution, we have recalculated several models with different choices of evolutionary parameters. In particular, a model with a reduced efficiency of the CE ejection of $\alpha = 0.1$ (in the standard model $\alpha = 1$) was simulated; for details, see Belczynski et al. (2002). In this case, the number of NS/BH X-ray binaries (XRBs) in the Galactic center is significantly decreased (109), with the relative number of wind-fed to RLOF-fed systems remaining comparable to the standard model. The sensitivity of the model simulation to the assumed mass ratio distribution was also studied. Specifically, a model in which both masses were drawn independently (as opposed to correlated initial masses for the two binary components via a flat mass ratio distribution in the standard model) was calculated. This led to an increase in the number of systems that enter and merge in the CE phase, decreasing the number of NS/BH XRBs in the Galactic center (296) and lowering the importance of RLOF-fed systems relative to wind-fed systems (245 RLOF-fed systems compared to 51 wind-fed systems). This decrease in the number of XRBs for the above two models provides an indication of the influence of the uncertainties associated with our treatment of the CE evolution phase (for details, see Belczynski & Taam 2004).

Since the stellar wind mass-loss rates are somewhat uncertain, an additional model with the stellar wind mass-loss rates reduced by a factor of 2 for all mass-losing stars was calculated. The smaller wind mass-loss rates have two opposing tendencies on wind-fed systems. First, there is an obvious decrease of the mass accretion rate, and thus a decrease in the number of wind-fed X-ray systems above certain critical value of $L_X$. Second, the systems tend to be tighter, because of the fact that less mass is carried away (Jeans mode of mass loss).
Therefore, the fraction of matter lost in the wind that is captured increases, leading to a tendency for an increase in the accretion rate. The latter effect dominates over the former, and there is an overall increase in the number of wind-fed systems (82) as compared to the standard model (56). The number of RLOF-fed systems is not greatly affected (416).

A model in which we use the full natal kicks (Arzoumanian et al. 2002) for NSs formed via AIC as opposed to no AIC kicks in the standard model was also calculated. In this model wind-fed systems are not affected; however, a number of RLOF system progenitors are disrupted at the formation of the NS. In addition, many of the surviving RLOF systems formed in AIC acquire high (>200 km s\(^{-1}\)) systemic speeds, exceeding the escape velocity from the Galactic center (but still bound to the Galaxy). This follows from the result that the AIC channel occurs, in general, for systems at short orbital periods (where the components orbit about their common center at high velocities), and the systems that survive can acquire a significant additional systemic speed (comparable to the component’s orbital velocity). The total number of NS/BH XRBs decreases to 201, while the relative contribution of wind-fed sources in the X-ray population significantly increases (see Fig. 3) as compared to the standard model.

An additional model, without tidal binary component interactions, was calculated to compare the results to the other studies. In this model, we find the highest number of wind-fed sources (87) in the simulations and a slight decrease of RLOF-fed systems (387) in comparison with our standard model calculation. In the absence of tidal interaction, the orbital expansion associated with transfer of spin angular momentum to the orbit does not take place, and the X-ray binary progenitors are generally found in shorter period orbits. For the tightest systems (progenitors of RLOF sources), this leads to more frequent mergers in CE episodes (decreasing the formation rates). On the other hand, the absence of tidal effects leads to tighter orbits for wider systems (the progenitors of wind-fed sources) and therefore to brighter systems resulting from higher wind capture rates, increasing their number in the studied sample. In particular, the X-ray luminosities of wind-fed sources can exceed \(L_X \sim 10^{34} \text{ ergs s}^{-1}\) for intermediate-mass X-ray binaries. In this calculation, similar to the standard model, the number of HMXBs is negligible, as expected for the small sampled volume corresponding to the MM03 survey.

We also relaxed our assumption on the bolometric correction and recalculated the NS/BH system X-ray luminosities with \(\eta_{\text{bol}} = 1.0\) (no bolometric correction). As expected (see eq. [2]), only the brightest sources in the RLOF class (either persistent or transients in outburst) are affected, with \(L_X\) extending to \(\sim 10^{38} \text{ ergs s}^{-1}\). Since the wind-fed systems are brighter (by a factor of 10), the number of wind-fed sources increases to 80, as additional systems are brighter than our adopted critical threshold luminosity \((L_X = 10^{30} \text{ ergs s}^{-1})\).

Throughout our study we have allowed for the possibility of accretion-induced collapse of a heavy WD to an NS. The specific arguments and new input physics supporting AIC was presented and discussed in detail by Belczynski & Taam (2004). As an indication of its importance, we examine the implications of its neglect on the results of our study. The primary effect is a decrease in the number of NS/BH X-ray sources to 126 (as compared with 491 in the standard model; see also Table 1). This decrease results in a significant depletion of RLOF population (71), while wind-fed sources would remain virtually unchanged (55). In this model the majority of RLOF systems are found with long periods (45), but some systems are still found within the ultra-short-period class (26). As a result, the number of transients and the number of bright sources decrease. The shape of the X-ray luminosity distribution is not significantly altered, although the relative contribution of wind-fed to RLOF-fed sources is increased.

Notwithstanding the models with rather extreme assumptions on accretion-induced collapse (full natal kicks applied during NS formation in the AIC process and a model in which AIC is not allowed), the RLOF-fed NS/BH XRBs are found to be more numerous than their wind-fed counterparts by more than a factor of 2. For comparison, the X-ray luminosity distributions for the most extreme model assumptions are shown in Figures 2 and 3. Note the change of vertical scale between different plots. For all of the models most systems are found at low luminosities \((L_X \sim 10^{30} - 10^{33} \text{ ergs s}^{-1})\), with several bright systems usually found at \(L_X \sim 10^{34} - 10^{38} \text{ ergs s}^{-1}\). Although the shape of the distribution is very similar, the number of sources and the ratio of wind-fed sources to RLOF sources may change significantly from model to model.

### 3.4. Expected Numbers

The total mass contained in stars corresponding to our simulation with \(10^6\) massive binaries (primary component more massive than \(4 M_\odot\)) can be estimated based on the three-component
broken law of Kroupa et al. (1993). By extending our simulation mass range to 0.08 \( M_\odot \) and including a 50% contribution due to single stars, we estimate the total mass to be \( \sim 1.5 \times 10^8 \, M_\odot \). As based on the recent mass model by Launhardt et al. (2002), this is comparable to the stellar mass in a cylindrical radius of 20 pc and a depth of 440 pc centered on the Galactic center (Muno et al. 2004). We note, however, that the stellar mass would be overestimated by a factor of 5 if the MM03 survey corresponded to a sphere of radius 20 pc. Our results (Table 1; see also \( \S \, 3.1 \)–3.3) can also be applied to the WGL02 survey by taking into account that the larger field is about 4 times more massive than modeled in our population synthesis. In our standard simulation it is found that there are \( \sim 500 \) and \( \sim 2000 \) NS/BH X-ray binaries with luminosities \( L_X > 10^{30} \) ergs s\(^{-1} \) (see Table 1) for the MM03 and WGL02 fields, respectively. However, the majority of the synthetic NS/BH accretion sources are expected to be characterized by low X-ray luminosities (\( L_X \sim 10^{31} - 10^{32} \) ergs s\(^{-1} \)) in the hard X-ray band (see Figs. 1, 2, and 3). We note that many of our simulated sources can have a significant soft component with higher luminosities (see discussion in \( \S \, 3.1 \)).

The majority (\( \sim 500 \)) of the Galactic center sources discovered in the WGL02 survey were characterized by \( L_X \sim 10^{33} - 10^{35} \) ergs s\(^{-1} \) and hard spectra. In our standard model calculation, there are no statistically significant sources in that luminosity range. However, in the model with no bolometric correction applied (\( \eta_{\text{bol}} = 1.0 \)), 44 sources in that range are found, all of which are wind-fed systems. This simply reflects the fact that all of the wind-fed systems found at \( L_X \sim 10^{32} - 10^{33} \) ergs s\(^{-1} \) in the standard model are shifted to the higher luminosities with \( \eta_{\text{bol}} = 1.0 \). In addition, for the models with altered assumptions on AIC (either full AIC kicks or AIC not allowed), the number of wind-fed systems (amounting to the same as for the standard model) dominates over RLOF-fed binaries in this specific luminosity range. Although these systems are promising candidates for the unidentified X-ray population, it is likely that they represent a small fraction (\( \lesssim 20\% \)) of the observed sources in the WGL02 survey. Our results suggest that other sources, and not the accretion-powered NS/BH binaries, constitute the majority of point sources in the WGL02 survey.

In the deeper survey of MM03 a faint-source population of 2079 point sources, characterized by \( L_X \sim 10^{30} - 10^{33} \) ergs s\(^{-1} \), was discovered. The spectra of these sources were fitted to an absorbed power law with photon index \( \Gamma \). The majority of these sources is described by hard spectra \( \Gamma < 1 \) (1427), with an important subpopulation characterized by softer spectra \( \Gamma > 1 \) (652). We note that the majority of our synthetic XRBs have luminosities in a range very similar to these found for point sources in MM03 with a significant number of these systems corresponding to ultra–short-period RLOF-fed NS-WD binaries. Because of the very low mass transfer rates in these binaries, the sources are expected to be transient and would most likely be observed during their quiescent state at low luminosities. Muno et al. (2004) suggest that the faint hard source population (\( \Gamma < 1 \)) can be consistent with magnetic cataclysmic variable systems. It is suggested that the transient RLOF-fed NS-WD transients in quiescence studied in this paper may contribute to the faint population characterized by softer spectra.

For the bright systems, 15 XRBs are found in our simulated population of the MM03 field. These sources are characterized by luminosities \( \sim 10^{36} - 10^{38} \) ergs s\(^{-1} \) and are RLOF-persistent and RLOF-transient systems in outburst. However, only a few bright transients have been observed in the field of the MM03 survey (M. Muno 2003, private communication), suggesting that the simulation leads to an overproduction of such systems (see \( \S \, 4 \)).

For the WGL02 field, our standard model calculation shows \( \sim 60 \) X-ray sources brighter than \( 10^{36} \) ergs s\(^{-1} \). Most of these systems in our simulation are persistent X-ray sources. However, only \( \lesssim 20 \) bright sources were observed (WGL02) with most being transient systems in outburst in the Galactic center. This suggests that the parameters intrinsic to our standard model affecting the bright population require modification. For the alternative models (full AIC kicks, lowered CE efficiency, reduced stellar winds, and AIC not allowed), it is found that the number of bright sources is reduced to less than \( \sim 20 \). We note that the number of transient sources exceeds the number of persistent sources only for the simulation with reduced stellar winds.

To account for the entire bright Galactic field XRB population, we increase the above number by a factor of \( \sim 100 \), yielding \( \sim 6000 \) bright systems (4000 persistent and 2000 transient in outburst). This is an overestimate, since only 150

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Figure 3.—X-ray luminosity distributions for RLOF-fed (thick line) and wind-fed (thin line) binaries for different assumptions concerning accretion-induced collapse: full natal kicks incorporated (top) and AIC systems removed from the sample. Details on the models are in \( \S \, 3.3 \).
of these systems are observed. This overproduction of bright systems is common to all our models (including the neglect of AIC) and the other studies of the RLOF X-ray sources in the Galaxy (e.g., Pfahl et al. 2003) and implies an overproduction of the bright population in the Galactic center as well. We note that the overproduction may not be as great for the faint population, since the relative number of faint to bright sources can change from model to model. In particular, the number of bright sources decreases by a factor of 5, whereas the number of faint sources is relatively unchanged for a model with reduced stellar winds.

3.5. Comparison with Other Studies

Willems & Kolb (2003) estimated the number of pre-LMXBs with main-sequence companions at less than about $2 M_\odot$ in the Galaxy. Their number may be directly rescaled to the smaller expected population in the Galactic center, yielding $\sim 10^2$–$10^3$ sources for the WGL02 survey field (B. Willems 2003, private communication). Since the study of Willems & Kolb (2003) assumes no bolometric correction, we use our model with no bolometric correction for comparison. In this case, we expect $\sim 250$ wind-fed low-mass X-ray binaries (pre-LMXBs), a number that is consistent with the Willems & Kolb (2003) findings. If the bolometric correction were applied, the expected number of pre-LMXBs with luminosities $\gtrsim 10^{30}$ ergs s$^{-1}$ would decrease by a factor of $\sim 2$.

A direct comparison with PRP02 is not easily accomplished since the initial input (e.g., IMF and eccentricities) and treatment of the RLOF phases, as well as model assumptions (e.g., natal kicks), differ. Despite the model differences, it is found that the numbers of wind-fed systems predicted by PRP02 and in the present study for the WGL02 survey can be comparable (see below). In addition, the X-ray luminosity distributions show that the majority of the synthetic wind-fed sources of both studies are characterized by rather low luminosity $L_X \sim 10^{32}$–$10^{33}$ ergs s$^{-1}$ (although we are unclear about the adopted choice for the bolometric correction in PRP02). The primary difference stems from the fact that the wind-fed sources in our study are characterized by low- and intermediate-mass MS companions, while PRP02 accounted only for the wind-fed sources with either intermediate- or high-mass companions.

In the present study the intermediate-mass X-ray binaries (IMXBs) greatly dominate over HMXBs, in contrast to that found by PRP02. In fact, PRP02 obtain in their model K2 about equal numbers of HMXBs and IMXBs. This arises from their specific choice of kick scenario, which favors the survival of HMXBs. We prefer to use the observationally derived distribution of kicks (Arzoumanian et al. 2002). With the use of standard kick velocity distribution (model K1), the PRP02 calculation results in the dominance of IMXBs over HMXBs (by a factor of about 5–10; as one can infer from the middle panel of their Fig. 1). This result is already comparable to the results obtained in the present study. Moreover, there is an additional factor that lowers the number of HMXBs as compared to IMXBs within our population synthesis model. Specifically, PRP02 use a constant escape wind speed independent of mass (or spectral type). However, it is known that this speed depends on the star mass (e.g., Lamers et al. 1995). For the mass range used in our study, it varies by about an order of magnitude. The capture rate (and thus resulting X-ray luminosity of wind-fed system) depends strongly on this velocity. The higher the wind velocity, the smaller the capture rate and the lower the X-ray luminosity. In our simulation, the most massive stars have wind speeds as high as 5 times the escape speed (Lamers et al. 1995), while PRP02 consider wind speeds not greater than twice the escape speed. This effect results in a smaller number of bright X-ray binaries with massive companions (HMXBs) as compared to the PRP02 study.

For the WGL02 survey field, PRP02 obtain a total of 250 and 600 wind-fed neutron star systems with main-sequence companions more massive than $3 M_\odot$ for their kick models K1 and K2. The number of PRP02 systems is reduced because of the detection limit appropriate for the WGL02 survey ($L_X = 10^{33}$ ergs s$^{-1}$) by a factor of 2.5 for a wind speed equal to the escape velocity, or by a factor of 20 for a wind speed equal to twice the escape velocity. This leads to a reduction in the number of systems in the PRP02 K1 model from 250 to 12–100 systems in the WGL02 field.

Since the K1 kick distribution of PRP02 (a single Maxwellian with $\sigma = 300$ km s$^{-1}$) is comparable to the present study (bimodal distribution with 40% kicks with $\sigma = 90$ km s$^{-1}$ and 60% with $\sigma = 500$ km s$^{-1}$; Arzoumanian et al. 2002), we compare our results with the results from model K1. Our total number of wind-fed sources (standard model) for the WGL02 field is 224 (see Table 1; note an increase by a factor of 4 for the WGL02 field). In the following we give the different corrections factors in order to compare our results to that obtained by PRP02. First, in the model with no bolometric correction (assumed to be the case in PRP02) we expect a greater number of wind-fed sources (320). Of these, only 44 have luminosities in excess of $10^{33}$ ergs s$^{-1}$. Those systems with MS companions that are more massive than $3 M_\odot$ amounts to 32. Therefore, we conclude that the overall number of wind-fed neutron star systems in the PRP02 study for model K1 is in approximate agreement with the results obtained in our study for similar model assumptions. However, PRP02 increase the number of wind-fed NSs by using their alternative kick model (K2), which can reproduce the entire population of X-ray sources in the WGL02 field.

4. DISCUSSION

The population of low-luminosity X-ray binaries in the Galactic center region has been investigated within the framework of a population synthesis technique. Although it has been found that this population may be more heterogeneous than previously predicted, our results suggest that accreting neutron star systems are not likely to be the major contributor to the faint X-ray source population in the Galactic center. The RLOF systems investigated in this paper provide an additional low-luminosity component. Many of these additional systems are composed of neutron stars with white dwarf companions in ultrashort orbital periods ($\lesssim 2$ hr) in which mass is transferred at rates ranging from $10^{-12}$ to $10^{-10} M_\odot$ yr$^{-1}$ as a result of the action of angular momentum losses associated with gravitational radiation. Because the mass transfer rates are low, these systems are expected to exhibit transient quiescent/outburst behavior. For a small duty cycle of $\sim 1\%$, it is expected that most of these sources would be found in their quiescent state with X-ray luminosities in the range $10^{30}$–$10^{33}$ ergs s$^{-1}$.

The population of hard X-ray sources ($10^{33}$–$10^{35}$ ergs s$^{-1}$) discovered in the WGL02 survey was interpreted in the context of wind-fed NS-MS binary systems (PRP02). We find that such systems can be contributors to the X-ray population in this luminosity range, provided that $\eta_{bol} \sim 1$. However, our results cannot explain the entire population, since the predicted number of such systems ($\sim 30$) is much lower than the number of observed sources ($\gtrsim 100$).
The deeper MM03 exposure revealed a large population of faint \( (L_X \sim 10^{30} - 10^{33} \text{ ergs s}^{-1}) \) point sources. The majority of these sources are characterized by hard spectra and are too numerous to be explained by wind-fed NS/BH systems and too hard to be explained by RLOF-fed NS/BH systems. Muno et al. (2004) have suggested that the intermediate polar class systems can explain both their spectral properties and their observed number. The nature of the population characterized by softer spectra is unknown, although a number of candidates have been proposed. We have found that the number of RLOF-fed NS/BH transient systems in quiescence could be as high as 400 in comparison to the 652 observed, but this leads to an overproduction of bright LMXBs in the Galaxy. The sensitivity of our results to input parameters have been explored, which can lead to a reduced contribution of RLOF sources and to an overall reduction in the number of synthetic soft NS/BH X-ray sources to a level further below that observed in the MM03 survey.

The identification of the faint soft X-ray sources will be essential for confirming their nature. Such studies may be fruitfully carried out in the low extinction regions near the Galactic center where the contribution from the low-energy component of their spectra (corresponding to less than 1 keV) may be detectable. At these lower energy ranges, the X-ray luminosities of our proposed candidates could be as high as \( L_X \sim 10^{32} - 10^{33} \text{ ergs s}^{-1} \). The Chandra and Hubble Space Telescope surveys of Baade’s window have been carried out (Grindlay et al. 2003), and the forthcoming results may have some bearing on the importance of this population.

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