Young X-Ray Binary Populations: Metallicity Effects and a Diagnostic for Electron-Capture Supernovae

Senior Honors Thesis

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1. Introduction

High mass X-Ray binaries (HMXBs) are two body systems that consist of a nuclear burning star accreting matter onto a compact object (CO) such as a neutron star (NS) or black hole (BH). Stellar material from the donor heats up as it falls into the deep potential well of the accretor, emitting blackbody radiation with a characteristic X-Ray spectrum. There are two separate processes through which HMXBs can produce X-Rays. In wind accretion systems, plasma in the stellar winds of the donor star is propelled isotropically, with some falling directly onto the compact object. In Roche Lobe Overflow (RLO) HMXBs, the two stars begin to orbit so closely, that the first Lagrange point for the two body system falls inside the radius of the donor. Mass outside the equipotential surface will be transfered onto the compact object, resulting in the accretion of large quantities of matter.

There are many inputs which determine the likelihood of a given binary system developing into a HMXB. Most importantly, the primary (initially more massive) star must be large enough to form a NS or BH. The orbital separation and eccentricity of the binary must be set such that the donor is close enough to transfer substantial quantities of matter onto the accretor, but not so closely that the two stars merge early in their lifetimes. Usually, stars in a binary system evolve almost independently of each other, following a stellar track depending on the initial mass and chemical composition of the star. However, if the binary system experiences a common envelope (CE) phase (where the outer layers of the two stars merge), mass can be transfered between stars, altering their subsequent single star evolution tracks.

Matter falling into a CO loses a tremendous amount of potential energy which must be lost in the form of black body radiation. Thus, HMXBs are extremely bright, almost always with a luminosity of at least 10^{32} erg s^{-1} and sometimes emitting radiation at the Eddington limit. The lifetime of HMXBs is highly variable, bound first by the longevity of the donor star after the supernova event of the accretor. HMXBs may also appear bright only during certain stages of the donors stellar evolution, increasing the variability of HMXB sources over time. While some small RLO systems can maintain stable X-Ray luminosities for hundreds of Myr, the total number of bright sources is strongly dependent on the age of the star formation region.

2. Motivation

The launch of the *Chandra* X-Ray Observatory in 1999 has allowed for detection of HMXBs at megaparsec (Mpc) distances. Hundreds of HMXBs have been detected, allowing for rigorous observational comparison with theoretical models.

Several previous studies have modeled XRB luminosity as a function of time in clusters with recent intense star formation episodes. Sipior et al. (2003) examined the time dependence of the HMXB luminosity function (XLF) at solar metallicity for a constant star formation rate (SFR) lasting 20 Myrs, while Dray (2006) (hereafter D06) notes the sharp decrease in the number of bright HMXBs as a function of time in models at several metal concentrations. However, a model of the time dependent XLF has not been examined at different metallicities. We focus our study on examining the number of HMXB sources as a function of time at differing metallicities, paying particular attention to an alternative route of CO formation called an electron-capture supernova.

2.1. Metallicity

Metals, defined in astrophysics as any element which is not hydrogen or helium, have a huge impact on stellar evolution, affecting stellar lifetimes, photon absorption (and subsequently stellar radius and temperature), the strength of stellar winds, and myriad other parameters (Schaller et al. 1992; Pols et al. 1998; Tout et al. 1996). Through altering the parameters of stellar evolution, metallicity exerts an equally great effect on HMXB creation. Majid et al. (2004) observed an overabundance of HMXBs by a factor of approximately 50 in the metal-poor Small Magellanic Cloud (SMC) compared to the Large Macellanic Cloud (LMC) and the Milky Way, while models by D06 found a strong inverse correlation between cluster metallicity and HMXB number.

There are a number of reasons for this correlation. Belczynski et al. (2006) explain that the strong winds in high metallicity systems serve to disrupt binary black hole formation by decreasing progenitor mass and robbing angular momentum from the binary system, making them more susceptible to subsequent supernova kicks. Single stars at very low and near solar metallicities may be impeded from forming black holes due to the effects of pair-instability and mass loss due to solar winds respectively (Heger et al. 2003). Bromm et al. (2001) find the cluster initial mass function (IMF) to favor heavier stars at low metallicies. Lower metallicities may decrease the minimum mass of ECS progenitors (Podsiadlowski et al. 2004; Han et al. 1994) which would increase the survival rate of neutron star binaries. Lastly, metallicity could play an important indirect effect in determining the parameters of natal kick velocities. We should note however, that even if these latter explanations are true, D06 finds a statistically significant overabundance of HMXBs at low metallicity given non-metallicity dependent kick velocities and initial mass functions.

A full exploration of single star evolution tracks as a function of metallicity is beyond the scope of this research, and thus we will refer to Tout et al. (1996) and Hurley et al. (2000), which detail the single star evolution tracks we assume. In D06, HMXB evolution was evaluated at four metallicities, z=(0.02, 0.01, 0.004, 0.001). In order to match these results, and obtain analysis relevent to nearby star formation regions such as the Small Magellanic clouds, we analyze systems at z=(0.02, 0.004, 0.001)

2.2. Electron-Capture Supernovae

Electron-Capture supernovae (ECS) are an important subset of supernova events where gravitational pressure from a stellar core above 1.38 $M_\odot$ forces ^{20}Ne and ^{24}Mg to capture electrons from the surrounding plasma, leading to a cascading loss in electron degeneracy pressure and a very quick collapse of the stellar core into a NS of approximately 1.26 $M_\odot$ (Miyaji et al. 1980; Nomoto 1984, 1987). ECS events are underenergetic compared to iron core-collapse SN by at least an order of magnitude, due to the low envelope mass and fast declining density of the neutrino-driven explosions, leading to a greatly diminished natal kick velocity compared to iron core-collapse SN (Dessart et al. 2006; Kitaura et al. 2006).

Because a NS exists as the end state of both ECS and iron-core collapse events, observation of single star ECS NSs is extremely difficult. However, in a binary system the smaller mass and low kick velocity of ECS NSs will create a detectable effect on the orbital characteristics of the companion. Pfahl et al. (2002) examined a new class of HMXBs with wide orbits and low eccentricities, finding these characteristics could only be matched by NSs with small natal kicks. Recently the first double pulsar, J0737-3039 was discovered, and the smaller component (Pulsar B) was found to have the surprisingly low mass of 1.249 $\pm$ 0.001 $M_\odot$ (Kramer et al. 2005). This mass is too small to come from the accepted pathways of iron core collapse supernovae, but fits well with the most recent mass estimates of ECS systems. The eccentricity of J0737-3039 is also far below the expected range for a strong NS kick, lending further credence to the hypothesis that the second pulsar underwent an ECS event (Podsiadlowski et al. 2005; Piran & Shaviv 2005). Still, we are careful to term Pulsar B as a definite ECS remnant, as current observations may also be consistent with the effects of a RLO period during Pulsar B's supernova event (Kalogera et al. 2008). However, we do note that ECS events provide a consistent picture to explain the system.

Perhaps better evidence for ECS stems from the large observed population of Be-HMXBs, which are HMXBs with a highly eccentric B type (2-16 $M_\odot$ Eggleton et al.

(1989)) donor star. Chevalier & Ilovaisky (1998) used *Hipparcos* data on galactic sources and found Be-HMXBs to have extremely small proper velocities. These velocities were so small that they originally proposed the CO in these systems must be a white dwarf, in order to account for the lack of a strong natal kick. These claims were disputed by Negueruela (1998) who found that the high luminosity of these systems required a NS companion. van den Heuvel et al. (2000) found that a NS natal kick of approximately 60 $km\ s^{-1}$ (approximately one-fourth of the accepted mean kick for iron core-collapse SN) is necessary to match the eccentricity of discovered Be-HMXBs. Podsiadlowski et al. (2004) and van den Heuvel (2007) have postulated that these low kick velocities may be created by ECS NSs.

Unfortunately, uncertainty in the parameters of ECS formation allows a wide variety of observations to match models within our parameter space. The mass range for an electron-capture collapse is highly uncertain. While the Nomoto (1984, 1987) simulations predicted an initial stellar mass range of 8-10 $M_{\odot}$ at solar metallicity, recent models have proposed much stricter ECS boundaries for single stars. Poelarends et al. (2007) produced estimates of 9-9.25 $M_{\odot}$ which corresponds to approximately 4% of core-collapse SN. Running simulations for different stellar metallicities, Siess (2007) found a metallicity dependent mass range which stays consistently narrow (smaller than 1.5 $M_{\odot}$) and could be nonexistent given certain parameters for the metallicity dependence of asymptotic giant branch winds. Pols et al. (1998) found the lower bound for non-degenerate Ne ignition to be 2.2 $M_{\odot}$, which sets an upper bound on the He core mass for ECS progenitors. This bound was later revised to 2.25 $M_{\odot}$ by Hurley et al. (2000).

However, Podsiadlowski et al. (2004) proposed that binary star systems have a much larger zero age mass range of 8 - 11 $M_{\odot}$ for ECS progenitors. They find the existence of companion stars to promote ECS in two unique ways. For stars over 11 $M_{\odot}$, binary stripping of the hydrogen envelope during helium core burning decreases the size of the core, preventing an iron collapse SN. However, for stars near the lower boundary for ECS events, the stripping of the hydrogen envelope prevents the second dredge up, preserving the complete mass of the helium core and allowing ECS at lower mass ranges. In the closest binaries, the first dredge up phase may also be disrupted, leading to ECS activity in the much lower mass range of 6 - 8 $M_{\odot}$.

3. Methods

Utilizing the *StarTrack* population synthesis code developed by Chris Belczynski (Belczynski et al. 2005, 2008), we employ Monte Carlo methods to create and evolve binary star systems throughout the parameter space of possible HMXB progenitors. We create models at three different metallicities: z=0.02 (solar), z=0.004 (SMC), and z=0.001. While we employ single-star evolution tracks to independently evolve each companion based on initial mass and metallicity (Hurley et al. 2000), binary effects such as mass transfer, tidal evolution, magnetic breaking and mass loss are calculated in order to create accurate binary models. For calculational simplicity, all interactions between separate binary systems are ignored. We note that the parameter space of Monte Carlo population synthesis is extremely large for HMXB formation, and thus a full exploration of the parameter space is impossible. We use default values of many parameters, following the layout set forth in Belczynski et al. (2008). Most importantly for our results, we employ a delta function star formation rate following a Salpeter ($M^{-2.35}$) initial mass function with primary mass above 4 $M_{\odot}$ and secondary mass distributed uniformly between 0.15 $M_{\odot}$ and the mass of the primary. We set the maximum NS mass at 2.5 $M_{\odot}$. Supernova kicks are computed using a single Maxwellian kick distribution with mean 265 km s^{-1} (Hobbs et al. 2005). We assume conservative mass transfer. In order to obtain statistically significant results, we sample at least 10^6 binaries for each set of input parameters, evolving the systems for a duration of 100 Myr. We calculate the number of bright systems at every 0.1 Myr, and exponentially interpolate between the two nearest *StarTrack* outputs. We note that as

StarTrack output files have a large density of data over time, our interpolation methods rarely if ever have any substantial effect on the results.

In order to correlate our results with new *Chandra* observations, we determine the percentage of the total X-Ray luminosity in the telescope's sensitive range of 0.3 - 7 keV. Following the procedure set forth in Belczynski et al. (2008), we multiply our calculated X-Ray luminosity by 0.7 for all BH systems, 0.5 for Roche-Lobe Overflow NSs, and 0.15 for NS wind systems. We then make two luminosity cuts of our population of systems, one at L_X = 1e32 erg s^{-1} and a second at L_X = 1e34 erg s^{-1}.

To handle ECS events, our code employs bounds adopted by Hurley et al. (2000), allowing a system to undergo a supernova explosion via the ECS mechanism if the star enters the asymptotic giant branch with a He core mass between 1.83-2.25 M$_\odot$ (Ivanova et al. 2007). We adopt a parameter $0 \leq ECS_{lower} \leq 1$ which diminishes ECS kicks compared to our default kick distribution. Due to the uncertainty in the masses of NSs created by the ECS process, we set the mass of NSs formed via ECS to 1.26 M$_\odot$ immediately after the SN explosion (Nomoto 1987; Podsiadlowski et al. 2004; Ivanova et al. 2007). We note that this mass is uncertain with Dessart et al. (2006), Kitaura et al. (2006), and Poelarends et al. (2007) finding slightly higher end masses for single star ECS events.

An important problem in the population synthesis of binary stars is the treatment of common envelope (CE) phases. In a CE phase, we follow the prescription of Webbink (1984) (hereafter W84), and assume the companions inspiral to the point where the decrease in gravitational potential energy is equal to the binding energy of the envelope. However, for stars in the main sequence (MS) and Hertzsprung Gap (HG), there is no clear entropy jump to distinguish the core-envelope boundary (Ivanova & Taam 2004). In these systems, we follow the standard assumption that dynamic instabilities arise during the CE phase which lead to merger on the thermal timescale (Taam & Sandquist 2000; Belczynski et al. 2008). A discussion of the non-negligible impact of this assumption can be found in Section 4.1.

4. Results and Discussion

Our results show that the evolution of bright HMXBs varies greatly as a function of metallicity. Figure 1 shows the number of systems with luminosity $L_X > 1e32$ erg s^{-1} as a function of time for a delta function star formation episode at three different metallicities (z=0.001, z=0.004, z=0.02). A common feature exhibited at each metallicity is the sharp peak in bright systems between 4-10 Myr. HMXB luminosities at this stage are primarily generated by wind accretion from massive donor stars onto large black holes. These wind systems quickly die off as donors large enough to create the necessary stellar winds undergo their own supernova events, forming non-luminous compact object binaries. As the active binary population switches toward low mass donors, the HMXB population shifts towards tightly orbiting wind and RLO systems. At 10 Myr, we see a drastic metallicity effect emerge, as low metallicity systems dominate high metallicity systems by nearly an order of magnitude. The only major contribution to high metallicity HMXBs stems from a large bump between 25-55 Myr produced entirely by ECS systems. This bump will be explained in detail in Section 5.

In Figure 2 we depict the same plot with the lower luminosity cutoff of $L_X > 1e34$ erg s^{-1}. This cut selects a different subset of systems, with separate trends from Figure 1. While we still observe a large wind peak between 4-10 Myr, the shape is quite different. We note a precipitous drop in the number of bright systems at approximately 10 Myr, followed by a very stable number of systems through the end of the simulation. The bumps seen centered around 40 Myr again correspond to the ECS phenomenon.

In Sections 4.2 through 4.4 we will analyze Figures 1 and 2 at various time slices, in order to fully explain the types of systems which are active at different stages of stellar evolution. However, we must first investigate an important method of system death for all binaries: mergers due to dynamically unstable common envelope phases as either star travels through the Hertzsprung Gap.

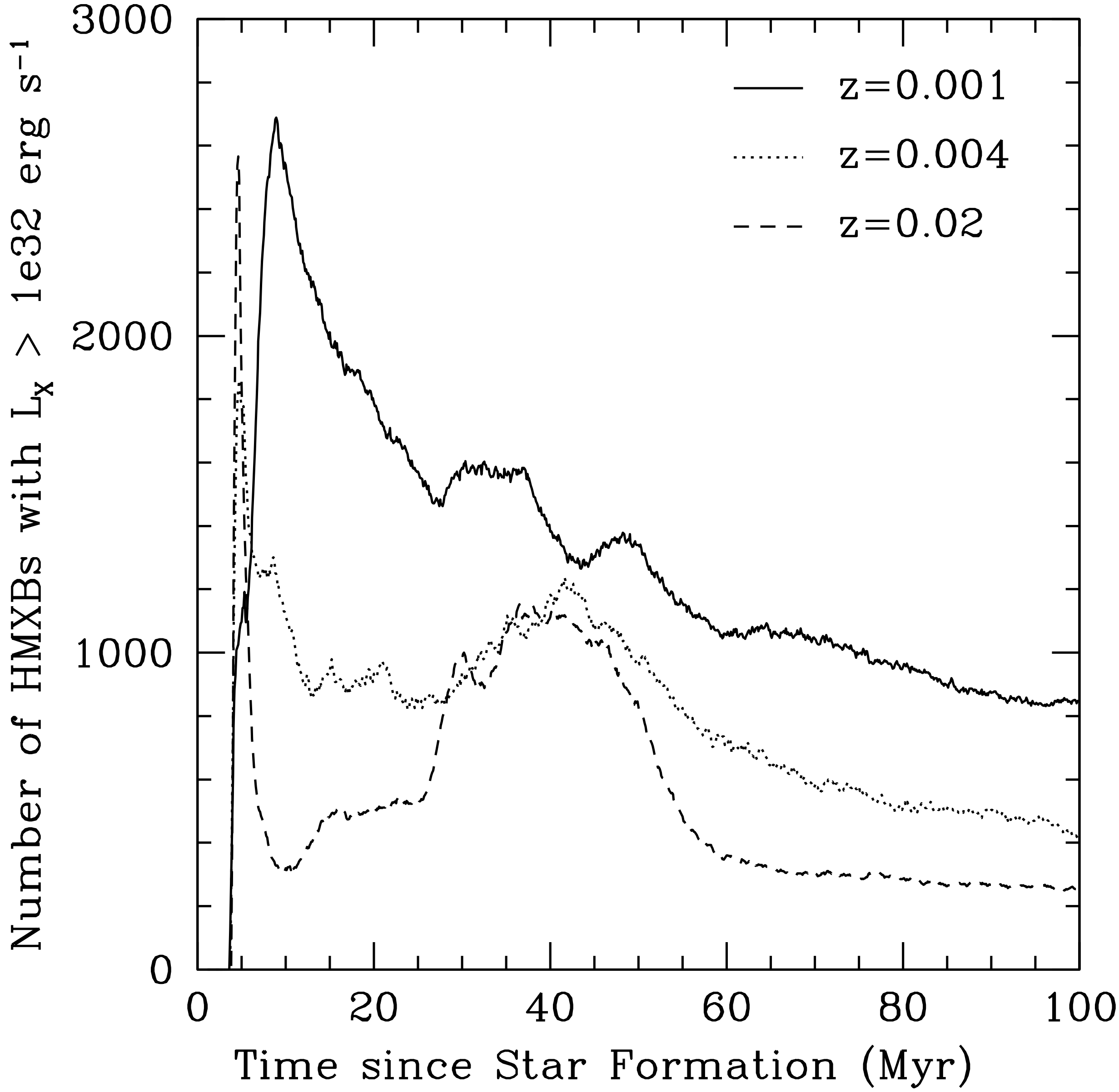

Fig. 1.— Number of HMXB with luminosity $L_X > 1e32$ erg s^{-1} per million binary systems for a delta function star formation event

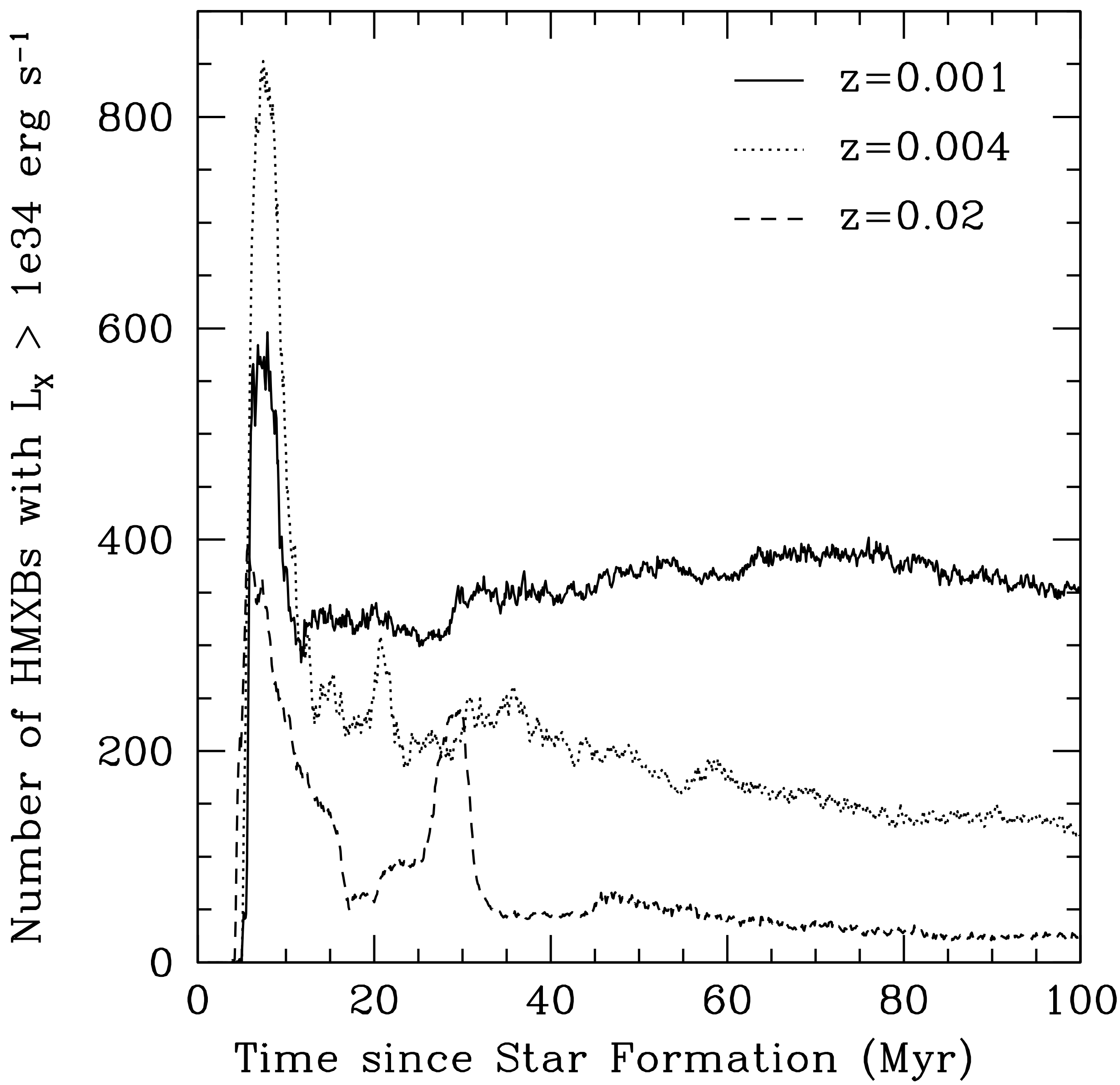

Fig. 2.— Same as Figure 1 for a luminosity cutoff $L_X > 1e34$ erg s^{-1}

4.1. Hertzsprung Gap Common Envelope Evolution

As a star passes through the HG, its radius significantly expands as hydrogen burning ends and the star quickly transforms to establish a stable helium burning core with an extremely large hydrogen envelope. As noted previously, this dual layer structure is not yet well established, and lacks a clear entropy jump (Ivanova & Taam 2004). Thus, CE activity in the HG stage cannot simply remove the hydrogen envelope while leaving the helium core intact. Without a distinct envelope to remove, CEs during the HG period are thought to lead to dynamical instabilities and merger (Taam & Sandquist 2000; Belczynski et al. 2008). Recently, HG CE instabilities were found to be a major impediment to BH-BH binary formation (Belczynski et al. 2007).

The calculation to determine whether a given Roche-lobe overflow binary will enter stable mass transfer or develop a common envelope is dependent on several parameters. Analyzing low mass X-Ray binaries, Kalogera & Webbink (1998) describe the difficulties associated with producing stable mass transfer between binary systems. Depending on the method of donor star mass loss, matter will be transfered at either the radiative or thermal timescale of the donor. However, the accretor can only accept matter on it's own thermal timescale. In order to maintain stable mass transfer, the accretor must accept all matter flowing onto it; any other matter will fill up the equipotential surface, creating a common envelope. While the exact ratio of the donor to accretor masses are uncertain, due to dependences on the composition and evolution states of each star, the donor star in general cannot be much larger than the accretor (Hjellming & Webbnik 1987).

We find that HG CEs are a significant cause of system death in potential HMXB progenitors. In Figures 3 and 4 we plot the number of bright HMXBs as a function of time, allowing HG CE evolution using the energy formalism (W84). In order to calculate the amount of envelope which must be ejected, we define the core as the region currently undergoing nuclear burning, and the envelope as everything else. Allowing HG CEs greatly

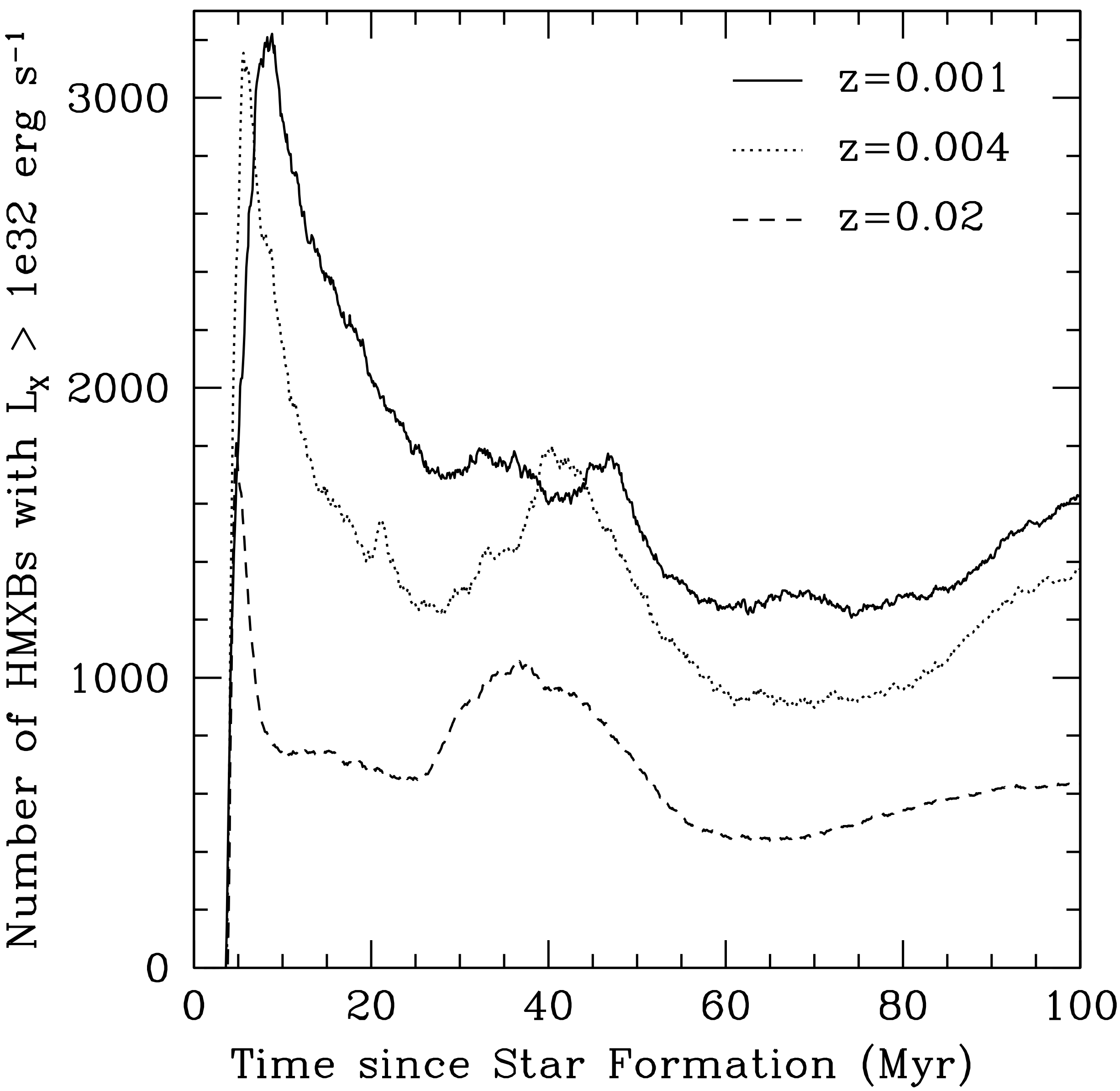

Fig. 3.— Same as Figure 1 when we allow Hertzsprung Gap Common Envelope Systems to evolve following the prescription of W84 ($L_X > $ 1e32 erg s^{-1})

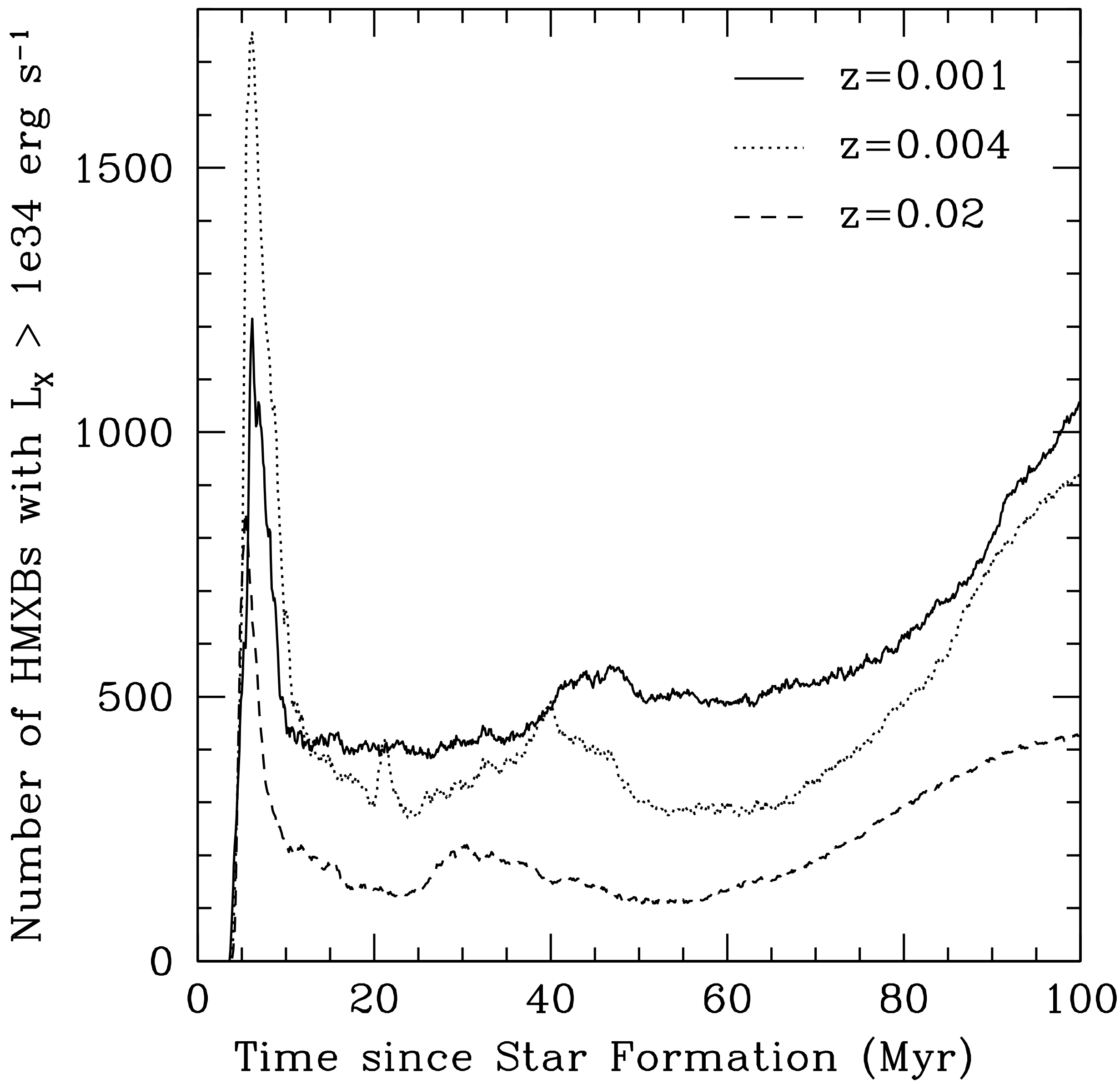

Fig. 4.— Same as Figure 3 for a luminosity cutoff $L_X > 1\mathrm{e}34$ erg s^{-1}

alters the evolution pathways of HMXB progenitors by allowing closely bound systems with extreme mass ratios to inspiral into binaries consisting of an evolved helium star primary and main sequence secondary. For these systems, as in Figures 1 and 2, there is a large peak between 4-10 Myr created by massive wind accretion systems, followed by a rapid decline in the number of systems. Since we allow systems to possibly survive HG CE phases, instead of forcing immediate system death, we obviously obtain more HMXBs at all stages and luminosity cutoffs. It is important to note that the systems we destroy when we force HG CE merger are disproportionately bright compared to our HMXB population. This trend is especially clear upon examining the size of the black hole driven peak between 4-10 Myr at both luminosity cutoffs. We note that nearly all systems added for the $L_X > 1\text{e}32$ erg s^{-1} are also added at the $L_X > 1\text{e}34$ erg s^{-1} cut.

The lost parameter space due to forced HG CE mergers is clear. In order to become X-Ray bright, a binary system must have a small orbital separation so that mass can be transfered onto the compact object. For small separations, a larger percentage of the donors mass can fall onto the accretor resulting in brighter HMXBs. However, since the primary stars radius expands significantly during the HG period, merging all HG CE systems sets a strict minimum bound on the periastron of the binary orbit.

Often, binaries far enough apart to avoid a HG common envelope are too distant to be bright HMXB sources. Thus, they must utilize a mechanism to stably fall towards a tighter orbit. There are three mechanisms through which a binary can inspiral to create tightly bound systems from loosely bound progenitors. First, a CE phase will create an inspiral via the previously noted energy formalism (W84). Secondly, the natal kick delivered to the primary upon compact object formation could move the two systems into a tighter orbit. However, the probability of a “lucky” kick is low, and for systems that are not already tightly bound, it is much more likely that the system is split entirely by the natal kick. Lastly, conservative mass transfer which moves matter from the larger to the smaller star will create a deeper potential well, leading to inspirals (Sepinsky et al. 2007). However, this change in orbital separation occurs on the timescale of mass transfer and usually causes no more than slight adjustments in the total orbital separation. Of these three mechanisms, CE phases are by far the most important because they both remove large amounts of energy from the system and are non-probablistic for progenitors in the correct parameter space.

A somewhat surprising trend in Figures 3 and 4 is the sharply rising number of bright systems between 60-100 Myr at all metallicities. Comparison to Figures 1 and 2, which show a monotonically decreasing number of bright systems, informs us that new systems are being created at this late stage, which are highly suppressed by HG CE phases. In fact, in this time period, a new pathway to bright X-Ray emission opens up which *relies* on HG CE phases in order to create bright systems. The compact object in these systems has a progenitor not quite massive enough to form a NS, and instead it ends its life as a massive white dwarf. Normally, this would prevent the detection of bright accretion, because the Eddington luminosity for a white dwarf is often below reasonable detection levels. However, in these systems a common envelope between the white dwarf and the small donor star forms while the donor crosses through the HG. Since we allow the binary to survive, it subsequently inspirals considerably and begins mass transfer onto the white dwarf. The extra mass transferred onto already massive white dwarf pushes it over the mass supportable by electron degeneracy pressure, and the white dwarf undergoes an accretion induced collapse to a NS. This creates a tight and often Eddington limited mass transfer system, that remains bright for the remaining lifetime of the helium star donor. This system is highly dependent on HG CEs, because any donor star massive enough to evolve into an HG in the first 100 Myr, will be too large to stably transfer mass onto a white dwarf. Finally, we note that these systems cannot occur until after we have progenitors which can produce a white dwarf compact object, which is at approximately 60 Myr.

It is important to note that, since stellar radius scales positively with metallicity (Tout et al. 1996; Hurley et al. 2000), the radius at which HG CEs destroy binary systems is also strongly dependent on metallicity. This metallicity effect is substantial, and HG CEs cut out a much larger portion of parameter space at high metallicity than for low metallicity systems. Since the brightest HMXBs come from the tightest systems that are not destroyed by HG CE mergers, we often find the most luminous systems at z=0.001 to be destroyed by the HG CE effect at z=0.02.

4.2. The Early Wind Fed Peak: 4-10 Myr

We note two important features of the wind fed peak in Figure 1. First the metallicity dependence of this population is non-monotonic with the fewest number of systems produced at z=0.004. Secondly, the timing of the peak is metallicity dependent, with the peak production of z=0.001 HMXBs arriving much later than for higher metallicity stars. However, comparison to Figure 2, which depicts the same dataset with a more stringent luminosity cutoff ($L_X > 1e34$ erg s^{-1}) is problematic. We note that the relative production of HMXBs as a function of metallicity has reversed; HMXB production is now *greatest* at z=0.004. Furthermore, all three simulations show peak production at nearly the same time. These stark inconsistencies indicate that we are examining at least two distinct populations of systems. Because we know that our population at this stage is dominated by wind accretion at all luminosity cutoffs, we divide wind fed systems into three categories based on the evolution state of the donor: main sequence (MS), He core burning (CHeB), or He (He) stars. Upon creating this division, we see several trends emerge that were not obvious in the combined data.

4.2.1. Main Sequence Wind Accretion HMXBs

MS stars, shown in Figures 5 and 6, contribute a large peak at 4.7 Myr which dominates the population of systems at a cutoff of L_X = 1e32 erg s^{-1}. This peak corresponds to wind accretion onto black holes with the most massive progenitors. The trend favoring high metallicity systems is clear. At high metallicity, metals in the outer envelope of the donor star absorb more stellar radiation and are subsequently hotter, creating stronger winds than in the low metallicity case. Since the donors have not evolved from the main sequence, only the evolution of the BH affects the timing of the peak. For compact objects this massive, the metallicity dependence of stellar lifetimes is very small (Schaller et al. 1992), and thus we see almost no temporal separation in the peaks of HMXB activity

Interestingly, in Figure 6 we note that despite the existence of massive BHs, we see only very dim accretion, with almost no systems above the L_X = 1e34 erg s^{-1} cutoff. We find the number of bright systems to be suppressed purely through the HG CE constraint placed on the orbital separation of the binary system. We note several reasons why this constraint is extremely strict for low age MS systems. First, BHs on this timescale have CO core masses above 7.6 $M_\odot$ and form via direct collapse of the stellar core, which imparts no natal kick to the system (Fryer & Kalogera 2001). Secondly, there is also no possibility for a CE phase, as most stars with initial masses above 40 $M_\odot$ are Luminous Blue Variables (LBVs) which follow a stellar track where so much envelope mass is lost in stellar winds that the stars depart from the main sequence and never enter the CHeB phase where helium core burning exists with an established hydrogen envelope outside (Massey 2003). Furthermore, the MS donor has undergone no evolutionary changes which would move the envelope closer to the compact object. Thus these systems must perform a delicate dance. Forming in very tight binaries, the systems are slowly pushed apart by the strong stellar winds of both stars, reaching a safe radius where no HG CE phase will result. At this radius, however, the stars are too far apart to become bright sources, and thus MT from

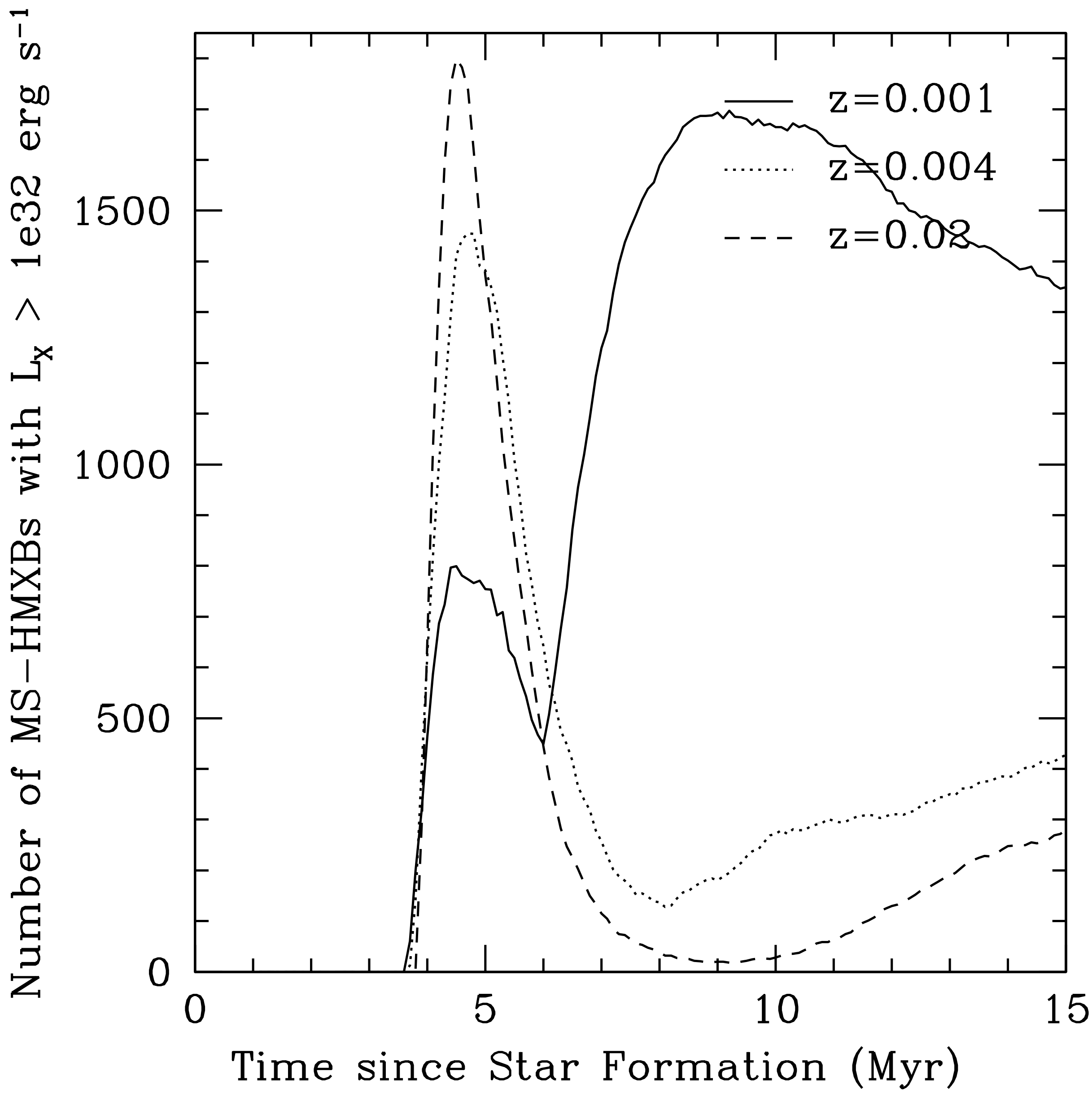

Fig. 5.— Number of wind accretion HMXBs with a main sequence donor with a luminosity $L_X > 1\text{e}32$ erg s^{-1} as a function of time

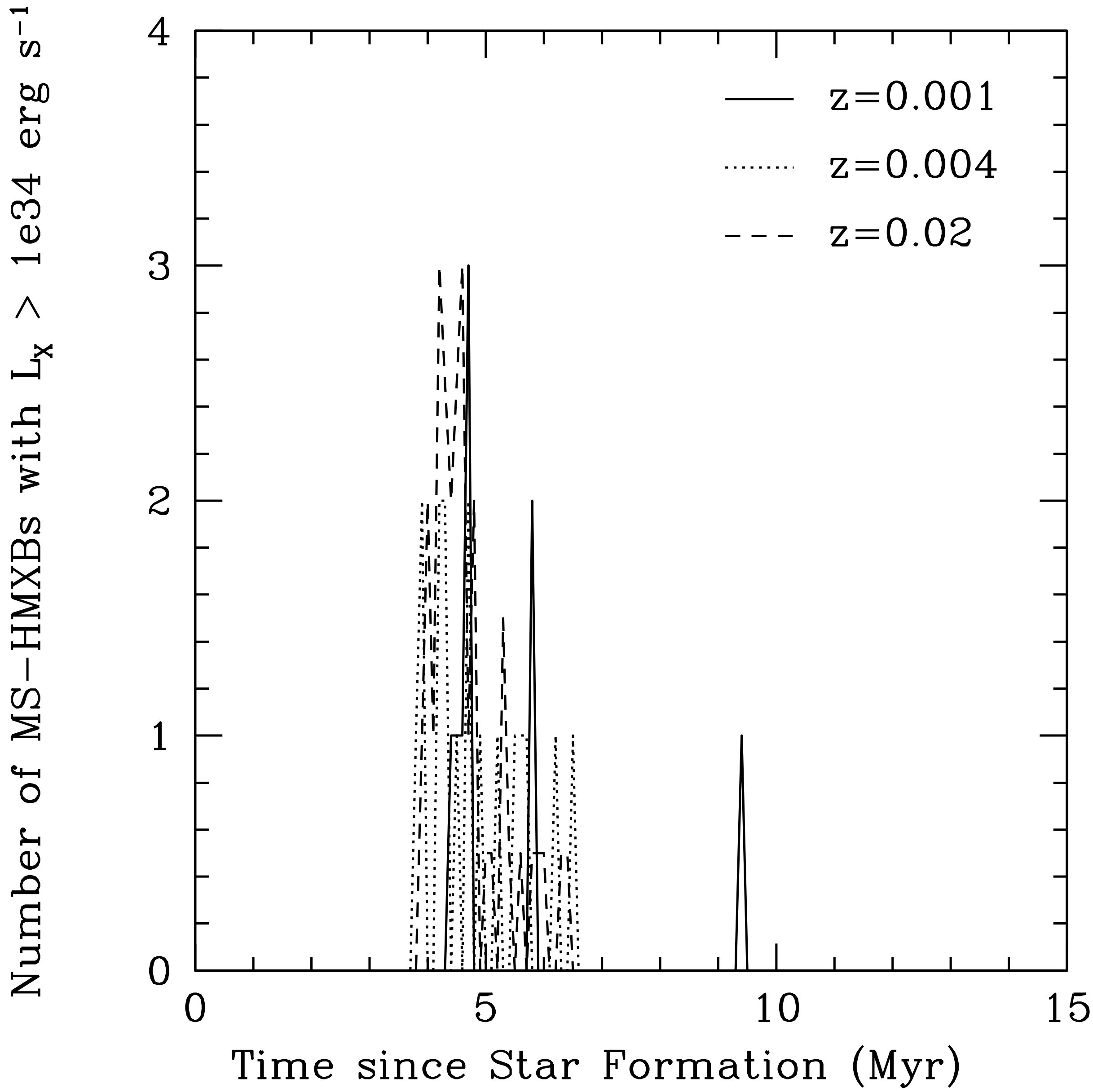

Fig. 6.— Same as Figure 5 for a luminosity cutoff $L_X > 1\mathrm{e}34$ erg s^{-1}

the HG primary star to the MS secondary must occur, in order to bring the systems close enough together to become bright HMXBs after the supernova of the primary star.

As described in Section 4.1, the necessity of stable mass transfer puts a limit on the maximum ratio of the donor to accretor mass. In Figure 7 we plot the initial (zero age main sequence) primary and secondary masses for main sequence wind accretors between 4-6 Myr with a luminosity $L_X >$ 1e32 erg s^{-1} in our z=0.001 simulation. We note a nearly linear relation between the two, with a lower bound on the donor mass at approximately one half the primary mass. The sharp cutoff in low mass primaries is due to the fact that any star with mass below 40 $M_\odot$ would not have had its supernova explosion before the 6 Myr cutoff. In Figure 8 we show the same plot when we allow Hertzsprung Gap Common envelope systems to follow prescription of W84 as described in Section 4.1. We note that under these weakened constraints we obtain many more systems with large primary to secondary mass ratios. However, we do not get the same density of systems, because unstable common envelopes can still develop under the W84 prescription if less potential energy exists in the binary orbit than the amount necessary to unbind the large donor star envelopes.

We note a peculiar feature of the z=0.001 line in Figure 5. At 6 Myr, there is a sudden, nearly discontinuous change in the number of bright MS-HMXBs. This abrupt change clearly signals that new channels of star formation are being opened. In fact, there are two such changes occurring almost simultaneously. First, we suddenly move below the threshold of direct collapse BH formation, and begin imparting natal kicks to BH supernovae. More importantly, we move out of the LBV phase and allow the primary star to enter the CHeB stage. This allows for a CE system to form between the BH progenitor and donor star, allowing the system to eject the common envelope and inspiral without a system merger.

In Figure 9 we plot the primary and secondary masses of HMXBs found between 6-8 Myr with a luminosity $L_X >$ 1e32 erg s^{-1} for the metallicity z=0.001. Comparison to Figure 7 shows that as soon as this pathway unfolds, the restriction on the primary to

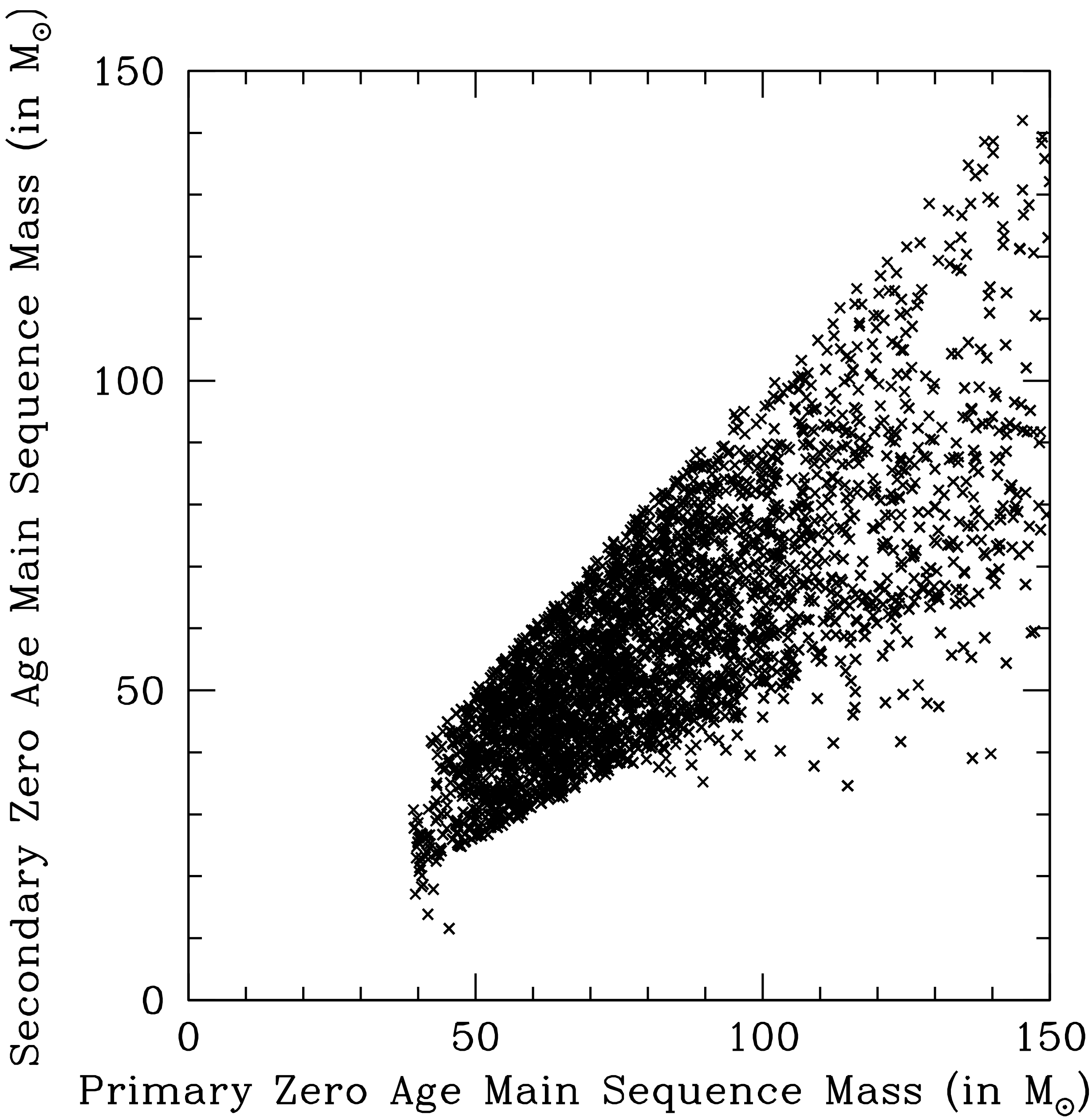

Fig. 7.— Primary versus secondary mass at z=0.001 for all wind accretion MS-HMXBs with $L_X > 1e32$ erg s^{-1} between 4-6 Myr (For clarity, we note that the early stable mass transfer phase in these systems moves mass from the primary onto the secondary, the opposite direction of its later wind fed HMXB stage)

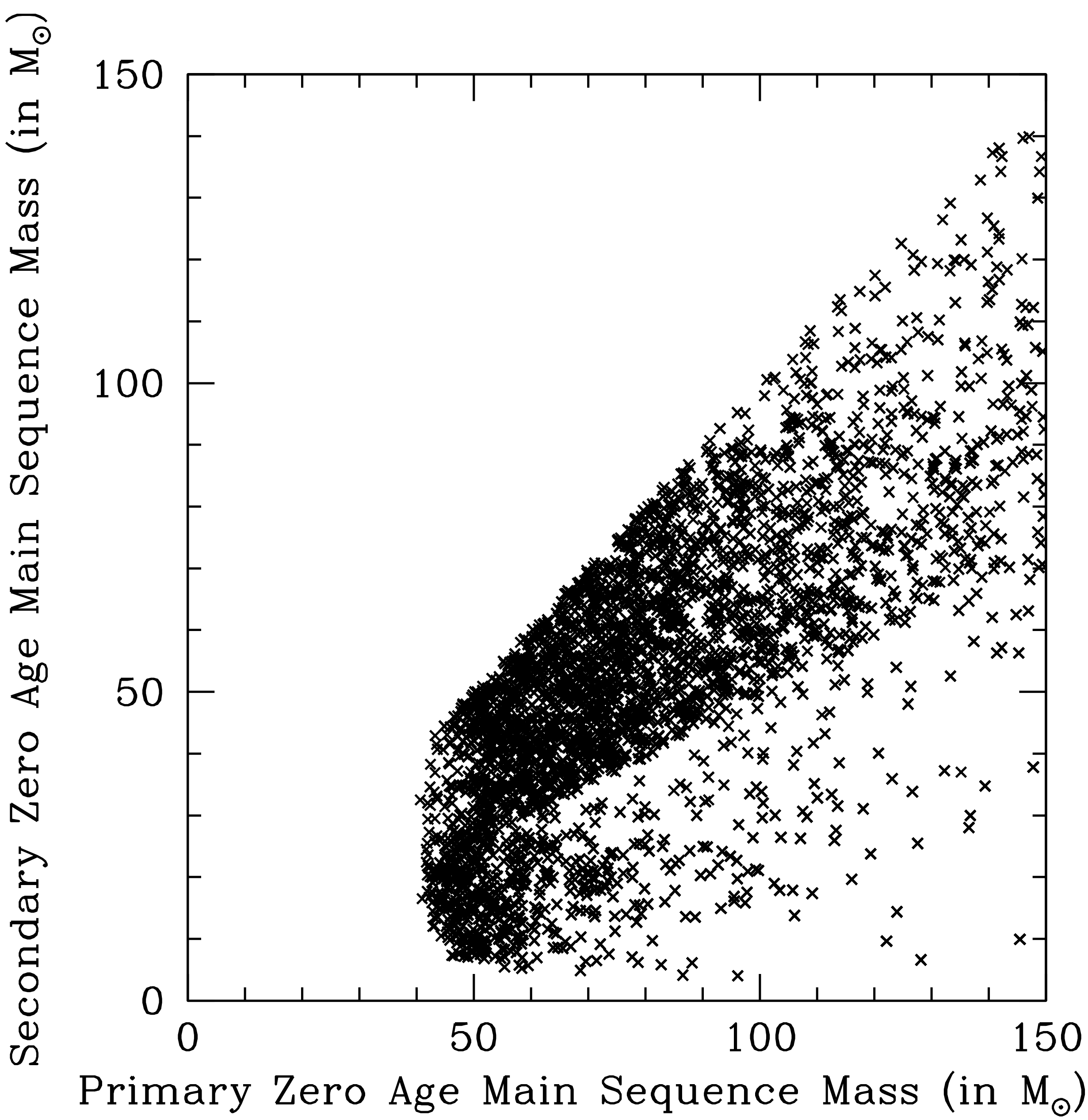

Fig. 8.— Same as Figure 7 when we allow Hertzsprung Gap Common Envelope Systems to evolve following the energy formalism (W84) ($L_X > 1\mathrm{e}32$ erg s^{-1})

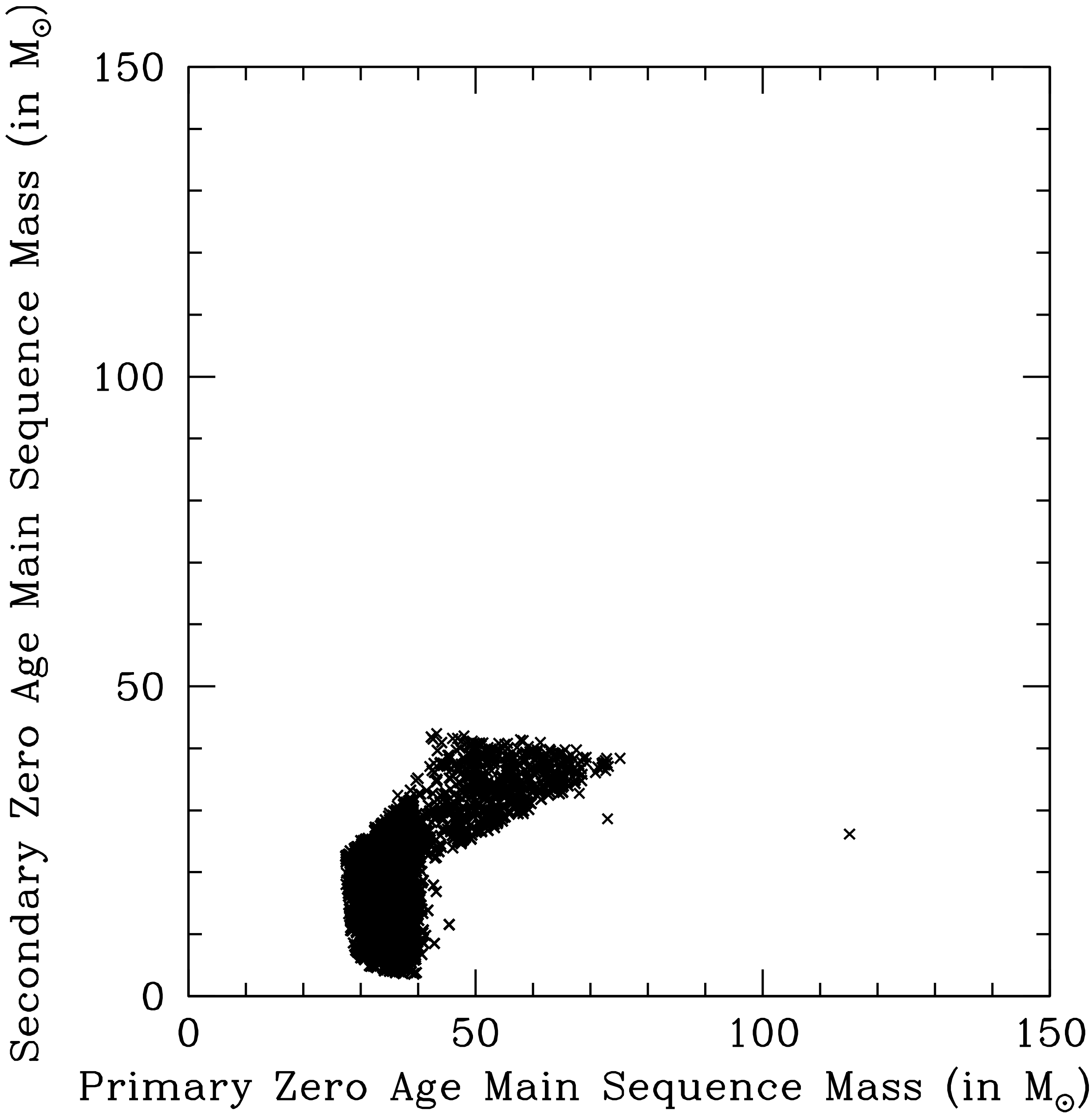

Fig. 9.— Same as Figure 7 for MS-HMXBs with a luminosity L_X > 1e32 erg s^{-1} between 6-8 Myr (We note that the plot is extremely dense in points, and thus the meaningful information is the parameter space of points, instead of the density of points in any given portion of parameter space)

secondary mass ratio is lifted, as common envelope phases replace mass transfer phases as the dominant method of creating binary inspiral. Since CE phases are so much more effective at creating large scale inspiral than MT, we are suddenly selecting a much larger parameter space of progenitor systems. Starting at 6 Myr, we now start to see many HMXBs created from systems with initial binary separations on the order of of 10^3 $R_\odot$, instead of only the very narrow range just outside of the zone restricted by HG CE mergers. The simultaneous onset of BH kicks, which have low velocities in such massive systems, are initially less important, as they are not able to break apart a large number of tightly orbiting binaries.

However, at higher metallicities, we do not see this abrupt change. Instead, in Figure 5 we note the number of bright systems bottom out between 8-10 Myr with a smaller number of new systems emerging thereafter. There are several effects which highly suppress the parameter space added by CHeB phases at high metallicity. In systems with initially tighter orbits, the much large HG radius of the primary star continues to create HG CE mergers before the primary star can transition to the CHeB stage (before the entropy jump between the core and envelope is well defined). For systems with wide enough orbits to avoid HG CE phases, the stronger winds in high metallicity systems tend to disrupt the CHeB inspiral in two ways. First, matter ejected from stellar winds tends to move the two systems apart, so the systems are required to inspiral greater distances at high metallicity. Secondly, the winds remove much of the matter from the envelope, meaning less inspiral is required to remove the entire envelope. Thus following the CE prescriptions in W84, we obtain less inspiral for systems which are initially more distant, which decreases the luminosity of HMXBs formed via this pathway to far below our $L_X > 1e32$ erg s^{-1} cutoff. Our results agree with the sum of these effects, as wind mass loss rates decrease strongly with decreasing mass (Schaller et al. 1992), we observe a slow increase in the number of bright HMXBs at high metallicity. Finally we note that the many dim HMXBs formed via this process often become bright HMXBs as the donor star evolves into CHeB and He star phases.

4.2.2. Helium Core Burning Wind Accretion HMXBs

In Figures 10 and 11 we plot the number of bright wind HMXBs with CHeB donor stars as a function of time. The number of systems in this evolution track scales non-monotonically with metallicity, peaking at z=0.004 for both luminosity cuts. This indicates that there are at least two metallicity dependent parameters which contribute to system survival. CHeB-HMXBs are extremely bright, owing to the large radius (over 10^3 $R_\odot$), and thus high velocities, of helium core burning stars . Thus, the CHeB parameter space forms around systems with initial binary separations on order of 10^3-10^4 $R_\odot$. Because this preferred range of binary separations is much larger than the radius of the primary star as it passed through the HG, we do not see any effect of HG CEs on CHeB HMXBs.

The timing of the CHeB peak has a stronger metallicity dependence and tends towards later peak times than the MS peak. However, it is important to note that systems in the CHeB peak are not simply the same systems as those in the MS peak at a later timestep. Because of the substantial binary separation in CHeB-HMXBs, wind accretion between the unevolved donor and black hole is extremely faint (far below the L_X = 1e32 erg s^{-1} cutoff) until helium core burning sets in and increases the donor radius. The later timing of this peak is due to the necessity that the donor star be small enough to avoid the LBV stellar track and enter the CHeB stage. Metallicity affects the number of bright CHeB-HMXBs in two ways. At high metallicity, stellar winds are stronger, creating more luminous systems. However, because the size of a star's radius scales positively with metallicity, we require larger periastron orbits at high metallicity in order to avoid CE phases. Following the W84 prescription, these CE phases will remove the hydrogen envelope and create a He

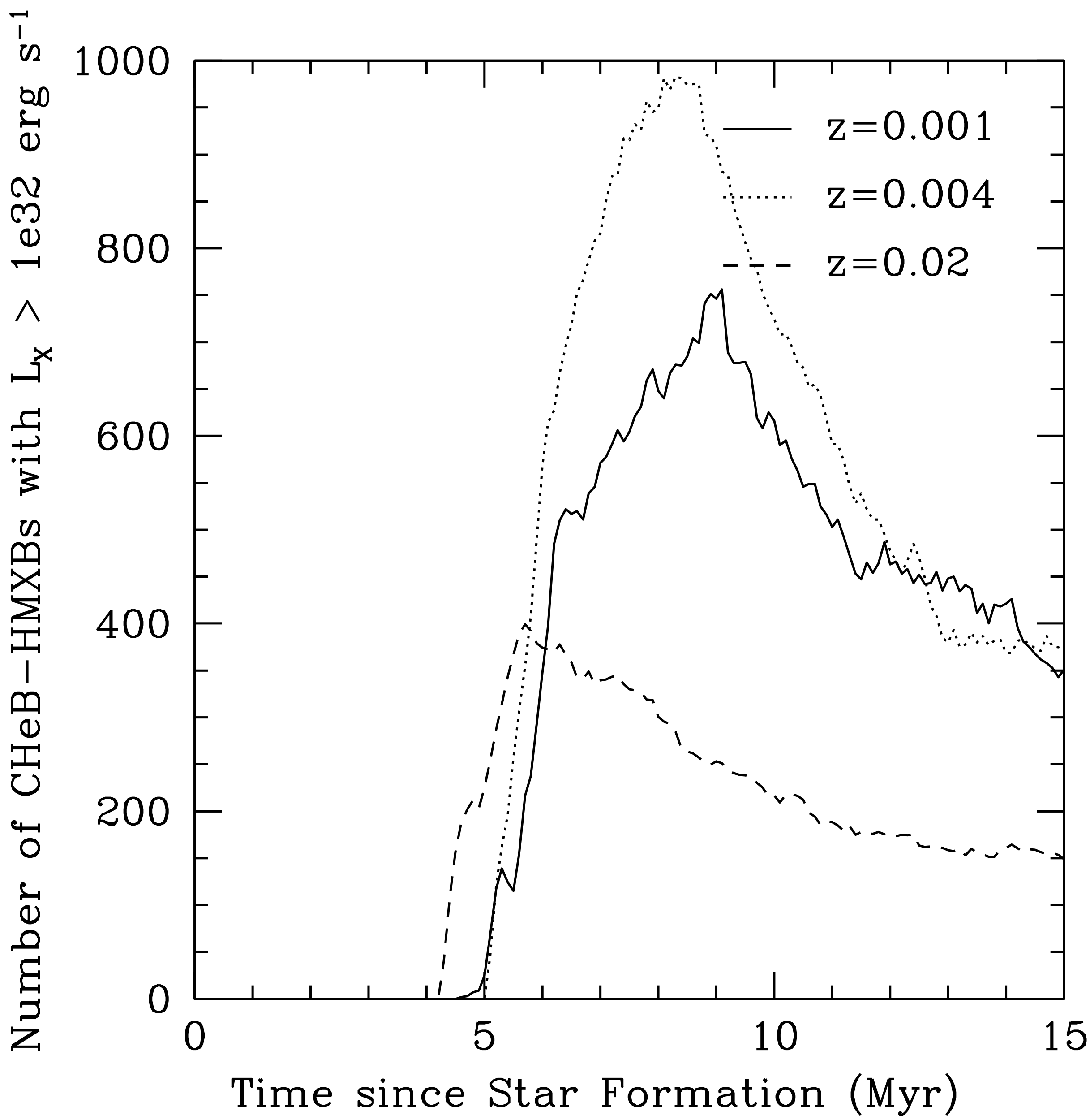

Fig. 10.— Same as Figure 5 for Helium core burning donors

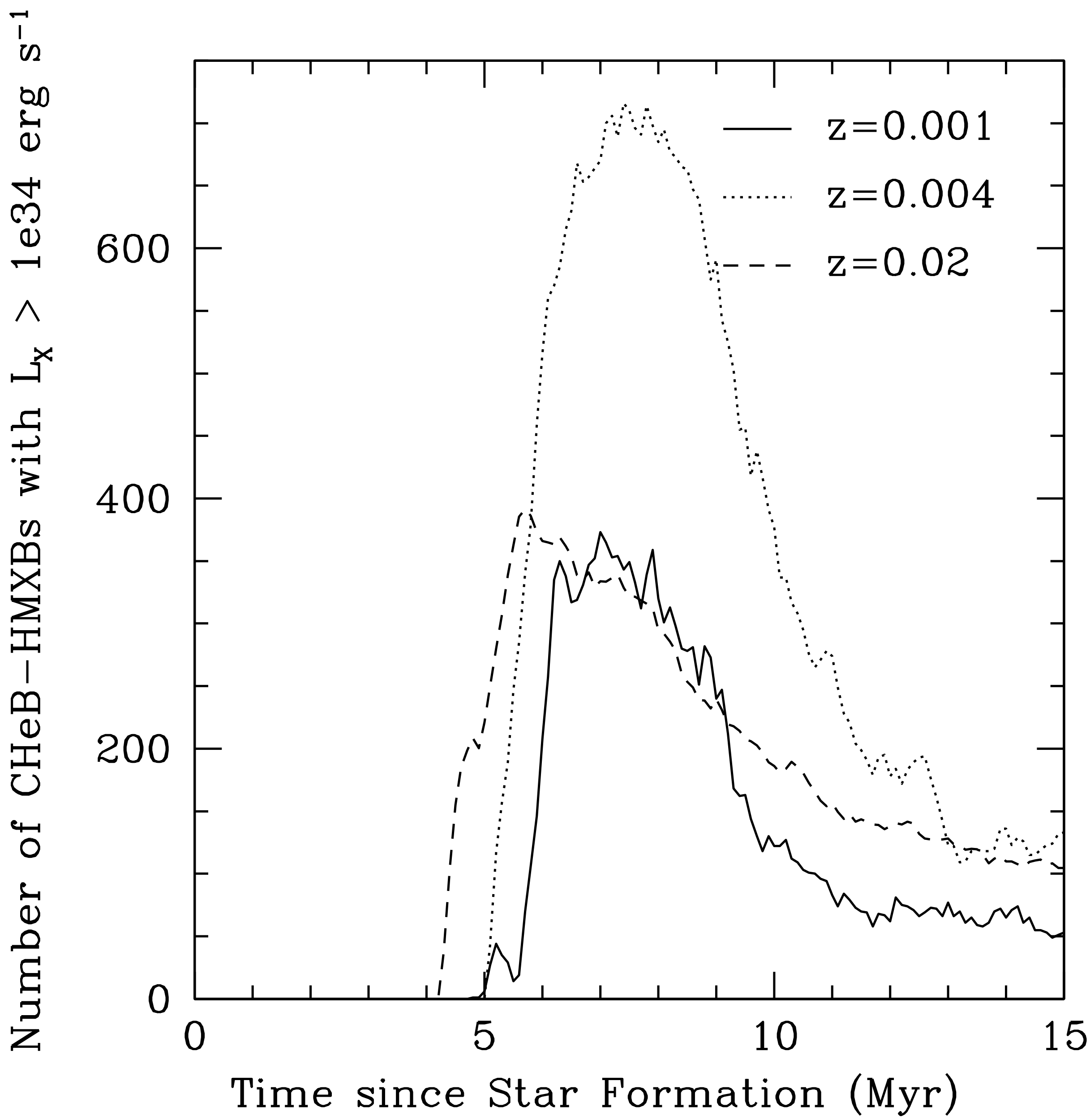

Fig. 11.— Same as Figure 10 for a luminosity cutoff $L_X > 1\text{e}34$ erg s^{-1}

star donor. The necessity for larger orbits eliminate some of our parameter space at high metallicity, and these two effects trade off to create a peak in bright systems at z=0.004.

Due to the extremely high wind mass loss rates for all CHeB systems, their sudden disappearance from the parameter space of bright HMXBs cannot be explained by the necessity for large donor stars. However, we note that the large binary separation necessary to support these systems makes them extremely sensitive to binary kicks. Thus, the only two methods for creating a CHeB-HMXB come from stellar remnants receiving greatly diminished kicks (direct collapse BHs and ECS NSs.), and "lucky" high velocity kicks which do not break apart the systems. Since the CHeB stage of stellar evolution is extremely short compared to the lifetime of the star, CHeB-HXMBs come from a specific subset of stars at each point in time. As our model uses a uniform distribution to prescribe the donor star with a portion of the primary mass, our selection of extremely massive BHs also tends to select massive donor stars, creating a tendency towards young ages in these systems. Since the lifetime of a star increases greatly with decreasing mass, the density of donor stars in the CHeB phase at any time drops off quickly as a function of time. When we analyze the impact of CHeB at later timescales, we will find these background systems to provide a decreasing background of systems throughout our entire simulations.

4.2.3. Helium Star Wind Accretion HMXBs

The last subset of bright wind systems shown in Figures 12 and 13 contain Helium star donors. There are two separate pathways for the formation of He wind systems. The first subset consists of two LBV stars which due to stellar winds and binary interactions, avoid motion through the Helium core burning stage completely. These systems live near the HG constraint, as they may be able to use mass transfer to avoid HG CEs. We note that this is a similar parameter space as the MS-HMXBs described previously. In fact, many of these systems form the earliest X-Ray bright MS-HMXBs at approximately 4 Myr before evolving to form a sharp peak of He-HMXBs between 4.5 and 6.0 Myr (with later peaks corresponding to lower metallicity). Systems at high metallicity are slightly preferred for this mechanism due to their stronger winds, which is the dominant factor as the HG CE restriction is not vitally important for systems of nearly similar mass. We note this entire subset of systems is relatively dim and unimportant at the L_X = 1e34 erg s^{-1} cutoff.

The second method of He-HMXB creation results from smaller systems which evolve through the CHeB-HMXB pathway, and then lose large amounts of orbital potential energy as the secondary loses its hydrogen envelope, causing the orbital separation to shrink drastically. If the system falls deep enough into the binary potential well, it can remain X-Ray bright despite the small radius of the donor star, due to the faster wind velocities of He stars. Because these systems are the progeny of bright CHeB-HMXBs, they obey the same time dependence and binary separation constraints imposed for their progenitor systems. They are not responsive to the HG CE restriction, and have a smaller number of systems than CHeB-HMXBs at all timesteps because the He phase of the donor has a shorter lifetime than the CHeB phase.

We note two reasons for the large metallicity dependence of Figure 13 at approximately 6 Myr. First, at low metallicity we have a wider range of progenitors, as systems of a higher mass can avoid the LBV phase which lead to the first He-HMXB subset above. Secondly, more systems are split in the high metallicity case, due to the lower mass, and earlier termination of kickless black holes in high metallicity systems (Belczynski et al. 2006). At later times, we notice the total number of systems are similar, but z=0.001 systems tend to be brighter. This is sensible since a smaller portion of the low metallicity envelope is lost to stellar winds, allowing for a greater inspiral following the W84 prescription.

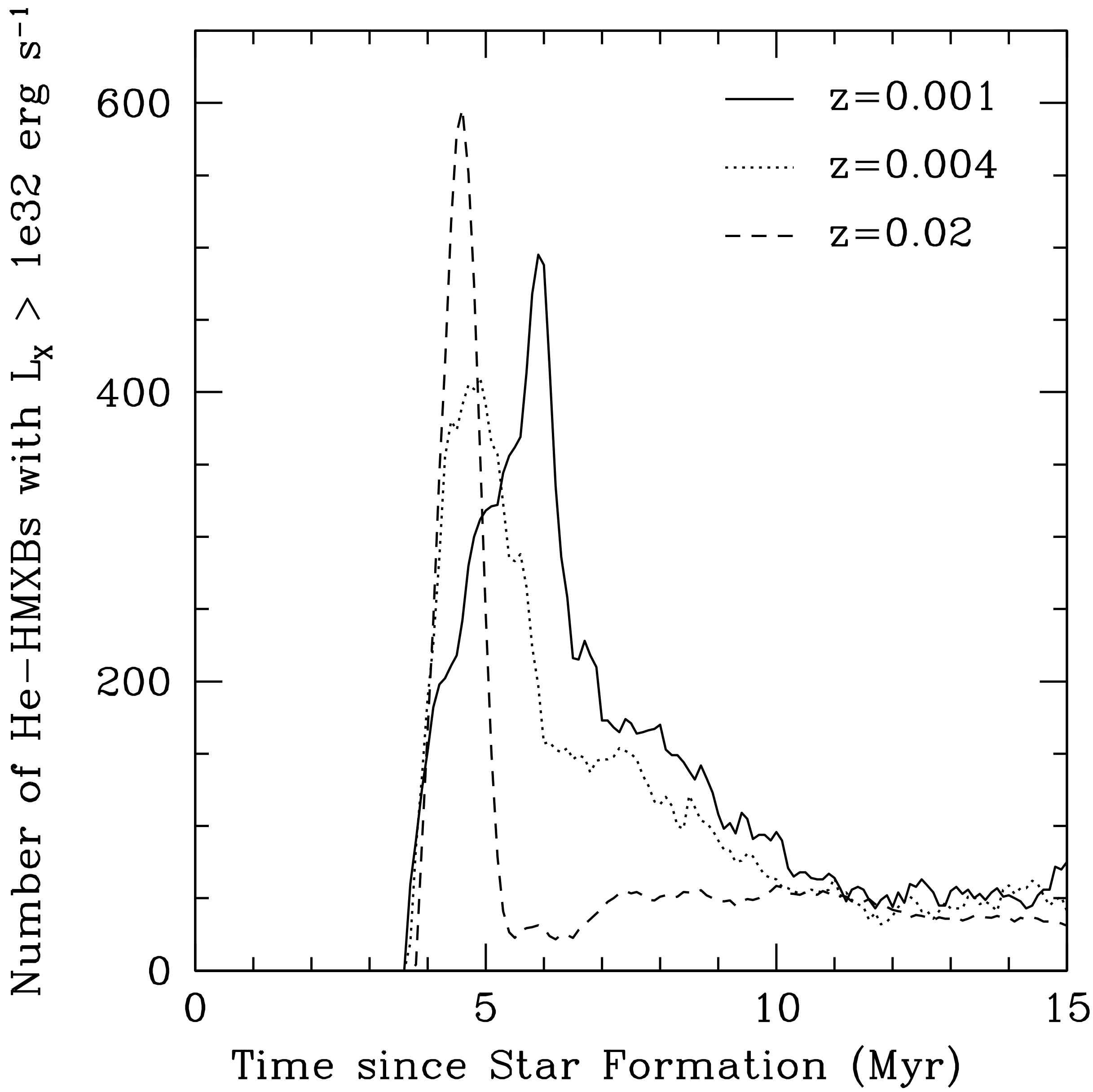

Fig. 12.— Same as Figure 5 for Helium star donors

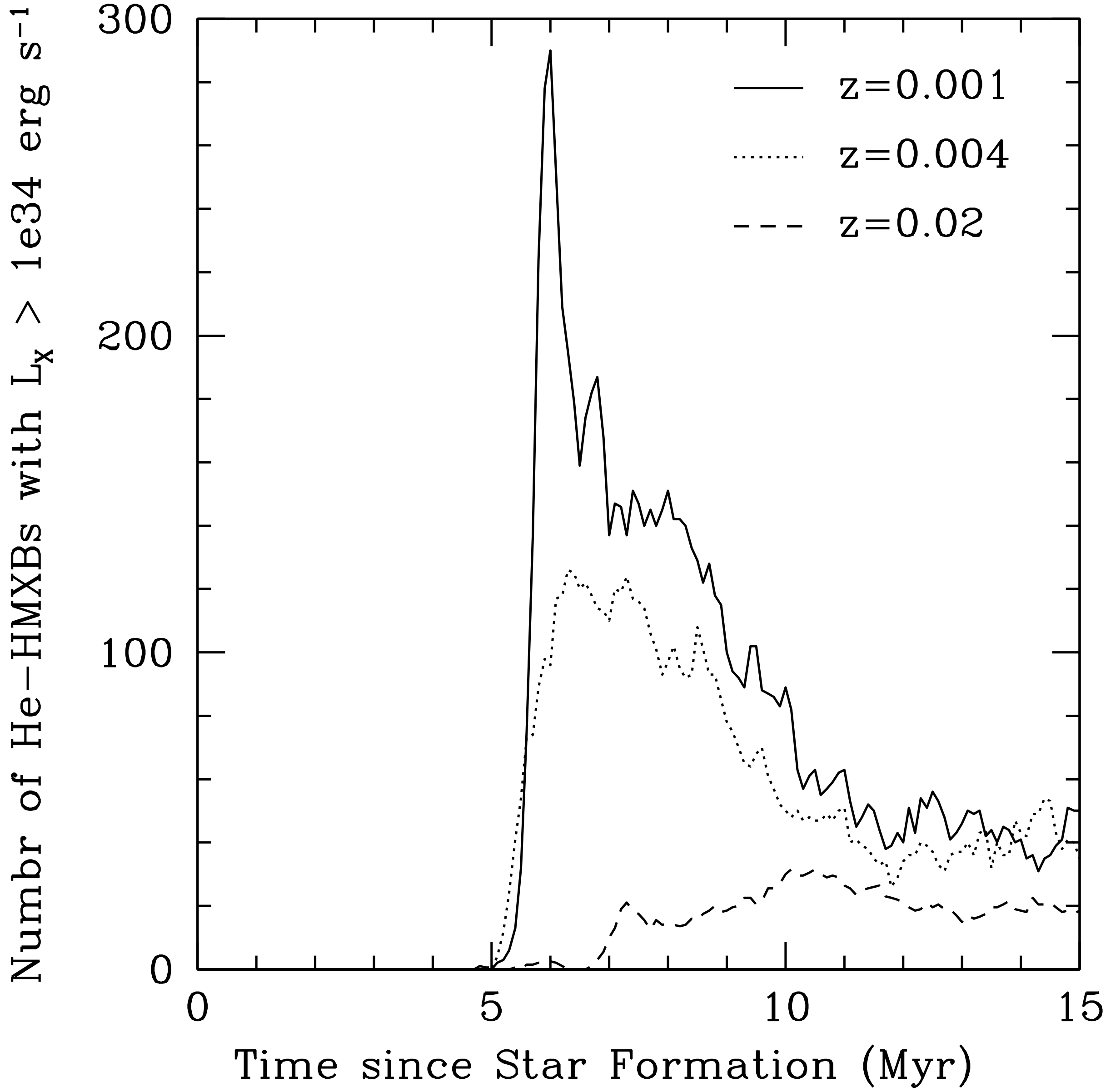

Fig. 13.— Same as Figure 12 for a luminosity cutoff $L_X > 1e34$ erg s^{-1}

4.3. The Transition Period: 10-20 Myr

During this stage of HMXB evolution we see a drastic metallicity dependence emerge. From Figure 1, we note that high metallicity systems bottom out at both luminosity cutoffs in this period, while low metallicity systems reach a peak at low luminosity, and maintain a high number of systems at the high luminosity cut. This creates nearly an order of magnitude change in the number of systems depending on the stellar metallicity, and provides the clearest point for observational comparisons of high metallicity and low metallicity starburst clusters.

In this period we also see a large shift in the parameter space of bright HMXB progenitors, most notably a rapid decline in evolved donor systems due to the effects listed above. CHeB donors require a large orbital separation, and thus are highly sensitive to SN natal kicks, thus they require massive BH companions that undergo direct collapse. He donors are either remnants of CHeB systems which thus fall under the same constraints, or they exist independently as a short scale burst of LBV-LBV binaries where both the donor and accretor must be very massive in order to avoid the CHeB stage completely. The only mechanism that can create bright evolved systems at later time scales is a "lucky" kick which, for instance, takes a system with an orbital radius on order 10^2 $R_\odot$, and moves it to a system of order 10^4 $R_\odot$, before the donor system enters the CHeB phase. This an extremely unlikely event, because the difference in velocity between this change, and a change that splits the binary is very small. Thus, systems with evolved donors will form a background of the HMXB population after approximately 20 Myr. One possible exception to this rule depends on the existence of low kick ECSe, and is discussed in Section 5.

Hand picking a scattering of low metallicity systems which are bright at z=0.001 we created systems with the same initial parameters at z=0.02 in order to determine the primary method of system death for high metallicity systems. Instead of seeing merely an accelerated evolution at high metallicity, which might have moved the systems back into the high metallicity wind peak at approximately 5 Myr, we instead found that nearly all systems which were bright at 10 Myr in the low metallicity runs, had been destroyed by HG mergers at approximately 5 Myr in the high metallicity runs. The only systems which are found to avoid this death were CHeB donor stars, which lie outside the HG limit and are for the most part bright at both metallicities.

Instead picking systems which are bright at solar metallicity and running these parameters at z=0.001, we find that most MS donor systems are either very dim or kicked out of the binary in the low metallicity case. The observation of dim systems stems from the fact that donor winds are less powerful at low metallicities and thus accrete less mass onto the compact object. However, we find that systems which are split by the first supernova kick at low metallicity fall in the parameter space of potentially bright systems, but happened to receive a much stronger kick than the system at higher metallicity received. A problem with our comparisons is the inability to set the natal kick imparted to our systems equal for both metallicities. Thus the binaries broken by kicks in the low metallicity case could have been broken by kicks in the high metallicity case, but we are selecting out only the systems which happened to receive small kicks, and thus we see only surviving high metallicity systems. Low metallicity systems are in fact slightly more resilient to kicks in this range, as less mass is lost to winds creating systems in a deeper potential well prior to the first supernova kick, but this is a very small effect and has little impact on the probability of system survival.

We witness one final population shift emerge as MT systems begin to form a sizable population of our bright HMXBs. As with wind systems at this time period, we see the bright HMXB population dominated by systems with MS donor stars. In fact, the distinction is even stricter in the case of MT systems, where we see almost no evolved donor stars. Figure 14 shows the number of bright MT systems as a function of time from 0-100 Myr of age with a luminosity cutoff of $L_X = 1\text{e}34$ erg s^{-1}. We do not show a graph for $L_X > 1e32$ erg s^{-1} because practically all MT systems lie above the higher luminosity cut and the two graphs are indistinguishable. We note a strong metallicity dependence in the number of bright systems, and the stability in the number of systems as a function of time. The metallicity effect for RLO binaries is the same HG CE restriction that has been observed throughout all stages of HMXB evolution. In the case of MT-HMXBs, however, the effect is even stronger, as systems must be extremely tightly bound at the end of their evolution in order to fill their Roche-lobe. Since these systems form a large population of the extremely bright extragalactic sources which are observable, we should expect observations to heavily favor low metallicity systems for all but the most recent starbursts.

4.4. Low Mass Systems: 20-100 Myr

From 20-100 Myr, we see a strengthening of the trends noted in the transition period. Stable MS-MT systems produce HMXBs that are bright on the entire timespan of 20-100 Myr and dominant the number of systems produced at our high luminosity cutoff. However, at the lower luminosity threshold of $L_X > 1e32$ erg s^{-1}, most systems still emit X-Rays via wind accretion. In Figures 15 through 20 we plot the number of bright wind systems for each type of donor star from 20-100 Myr at both luminosity cutoffs. In Figure 15 we see a mostly exponential decrease in the number of bright systems as a function of time. The reason for this time variation is easily explained. Since the mass cutoff for iron-core collapse SNe is approximately 12 $M_\odot$, we expect all compact objects to be created by $\sim$20 Myr. Since there are no changes in the evolution state of the donor star after this time period, we expect all MS-HMXBs to be created by 20 Myr. Thus the only change in the system number at this point should stem from donor stars leaving the MS phase, which should carry the nearly exponential dependence seen in our figures. We note from Figure 16 that there are practically no systems with unevolved donors which fall above our higher luminosity cutoff.

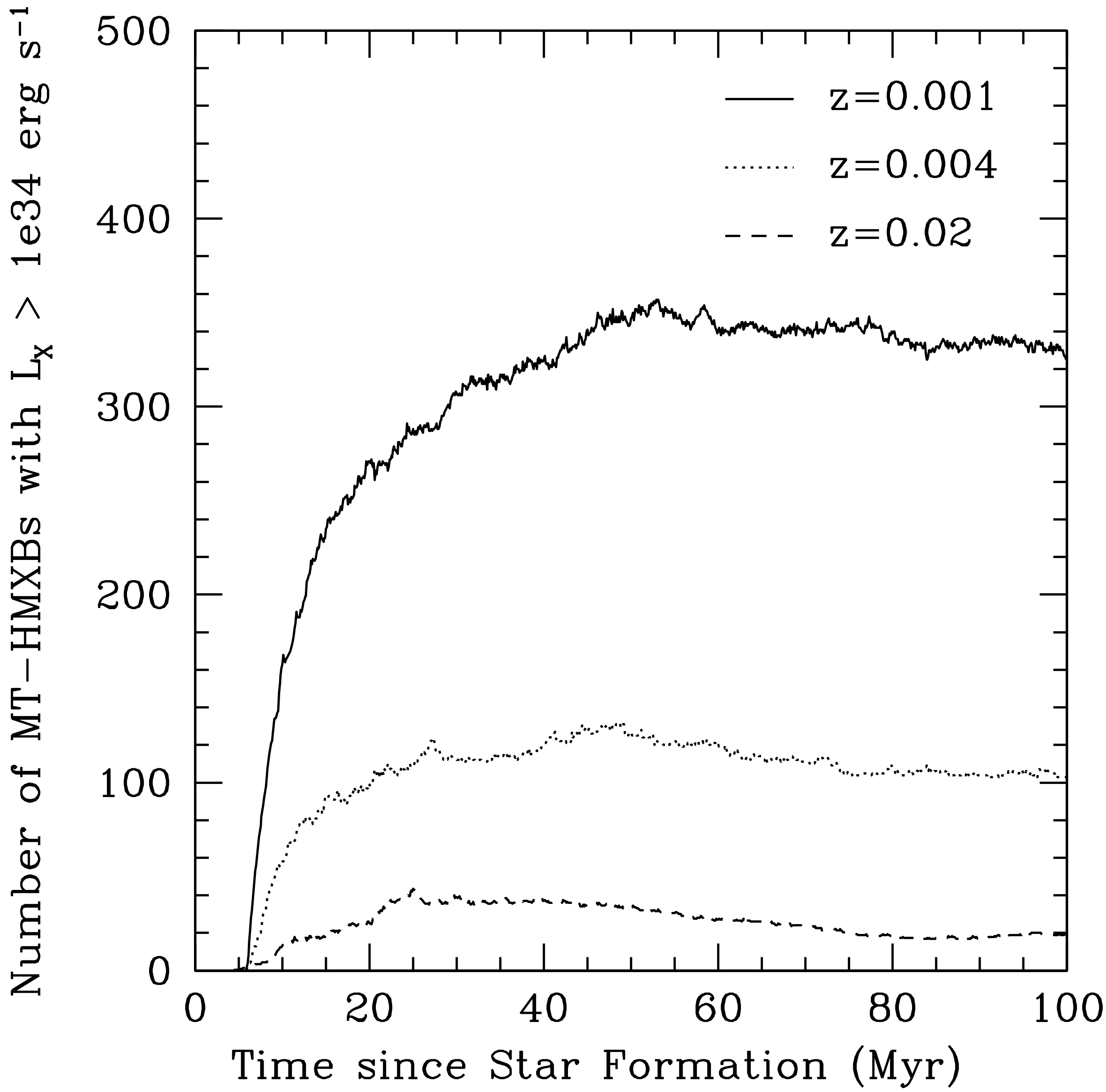

Fig. 14.— Number of mass transfer HMXBs above a luminosity of L_X = 1e34 erg s^{-1} as a function of time (Note that nearly all MT systems are very bright, and thus this graph is indistinguishable from the graph at L_X = 1e32 erg s^{-1})

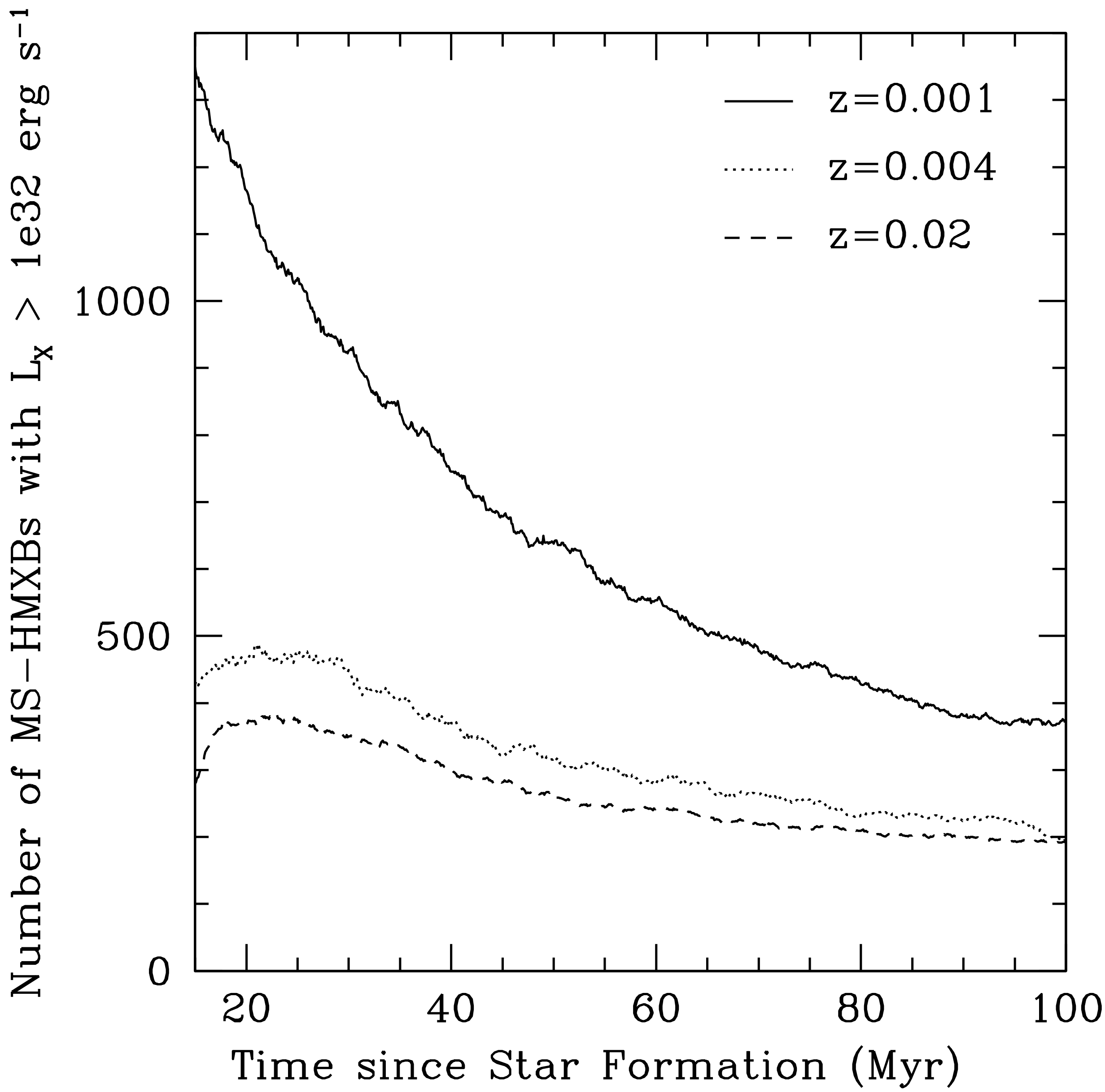

Fig. 15.— Number of wind accretion HMXBs with a main sequence donor with a luminosity $L_X > 1\mathrm{e}32$ erg s^{-1} as a function of time

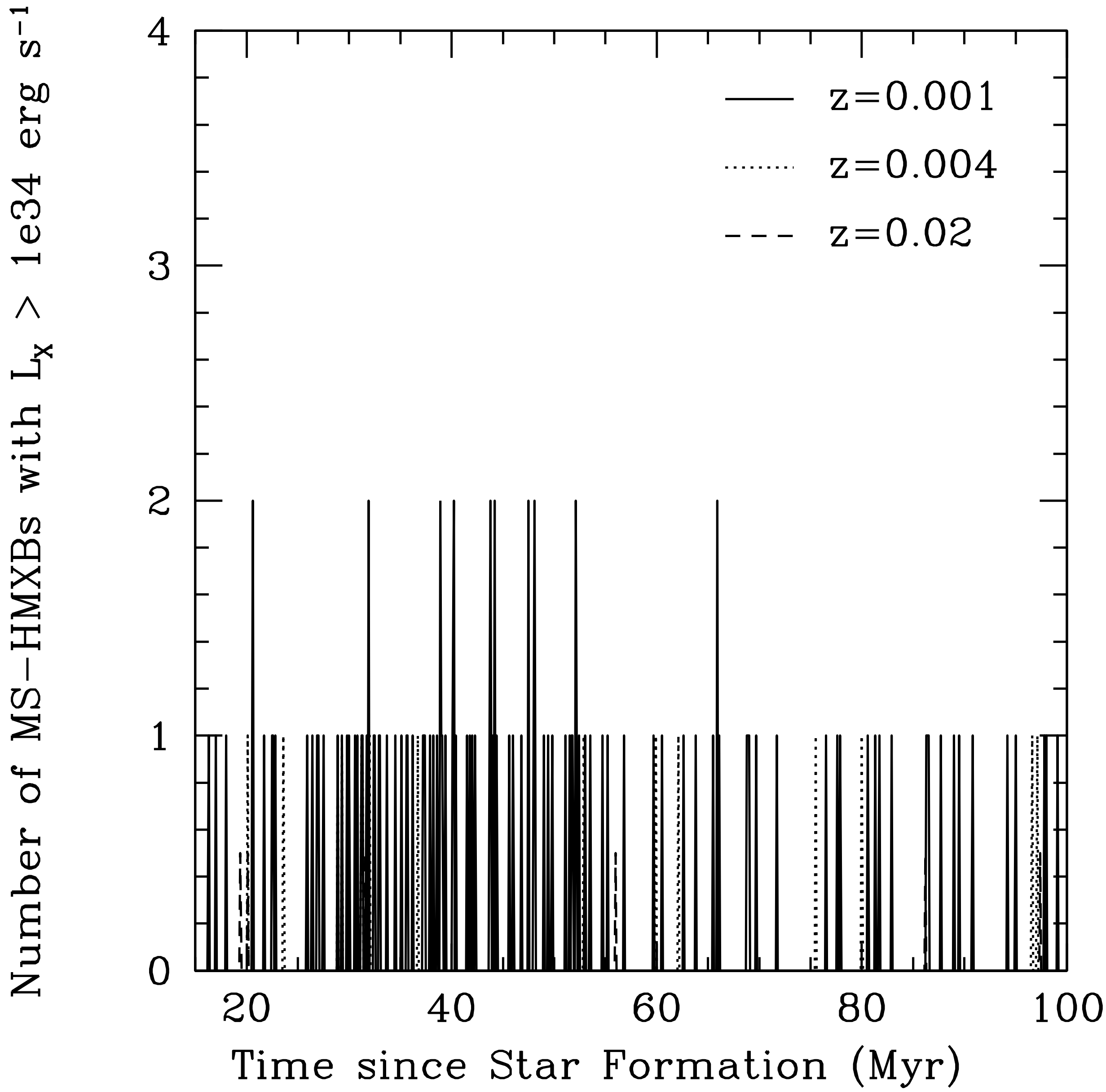

Fig. 16.— Same as Figure 15 for a luminosity $L_X > 1e34$ erg s^{-1}

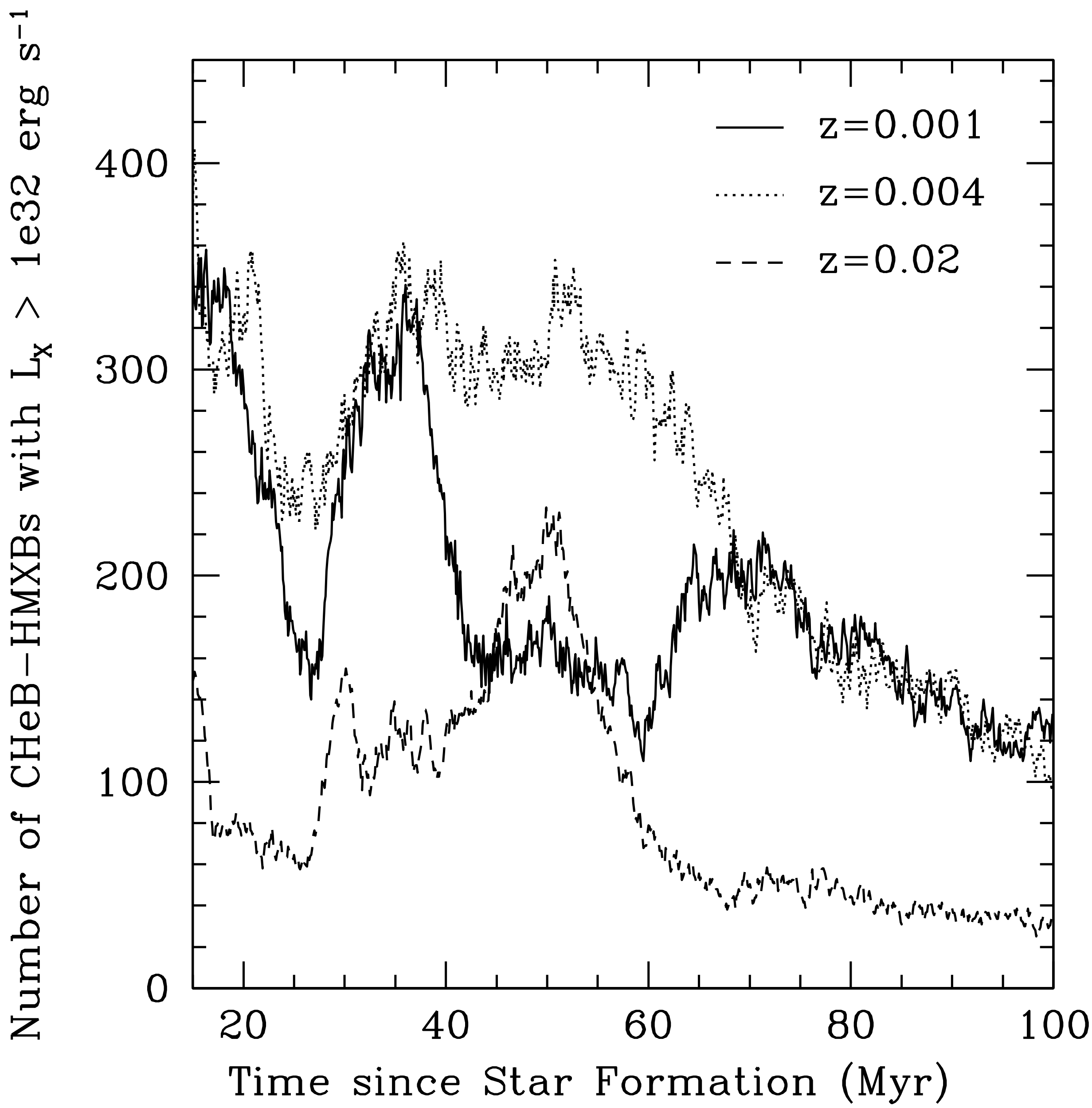

Fig. 17.— Same as Figure 15 except for CHeB donors

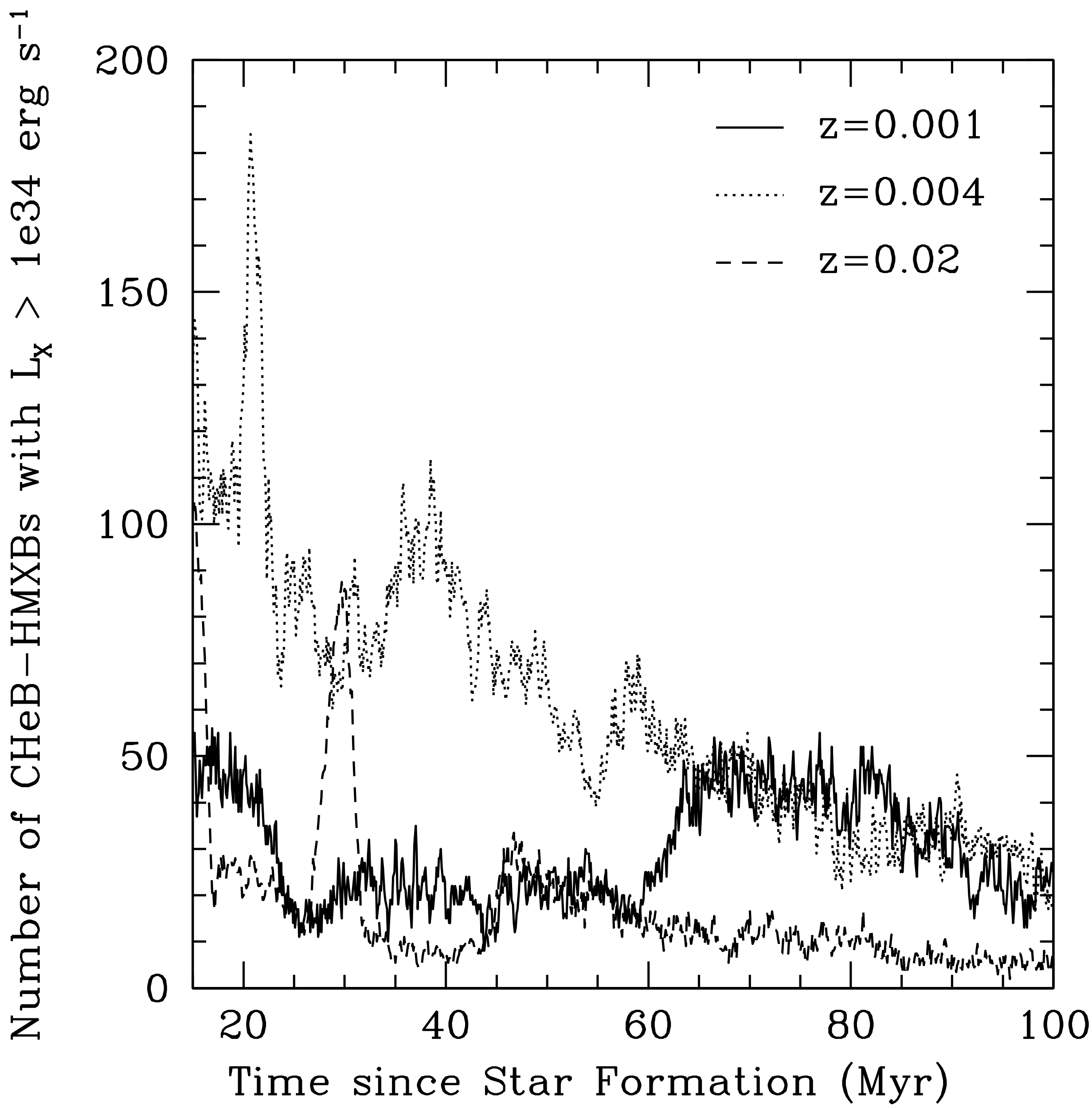

Fig. 18.— Same as Figure 17 for a luminosity $L_X > 1e34$ erg s^{-1}

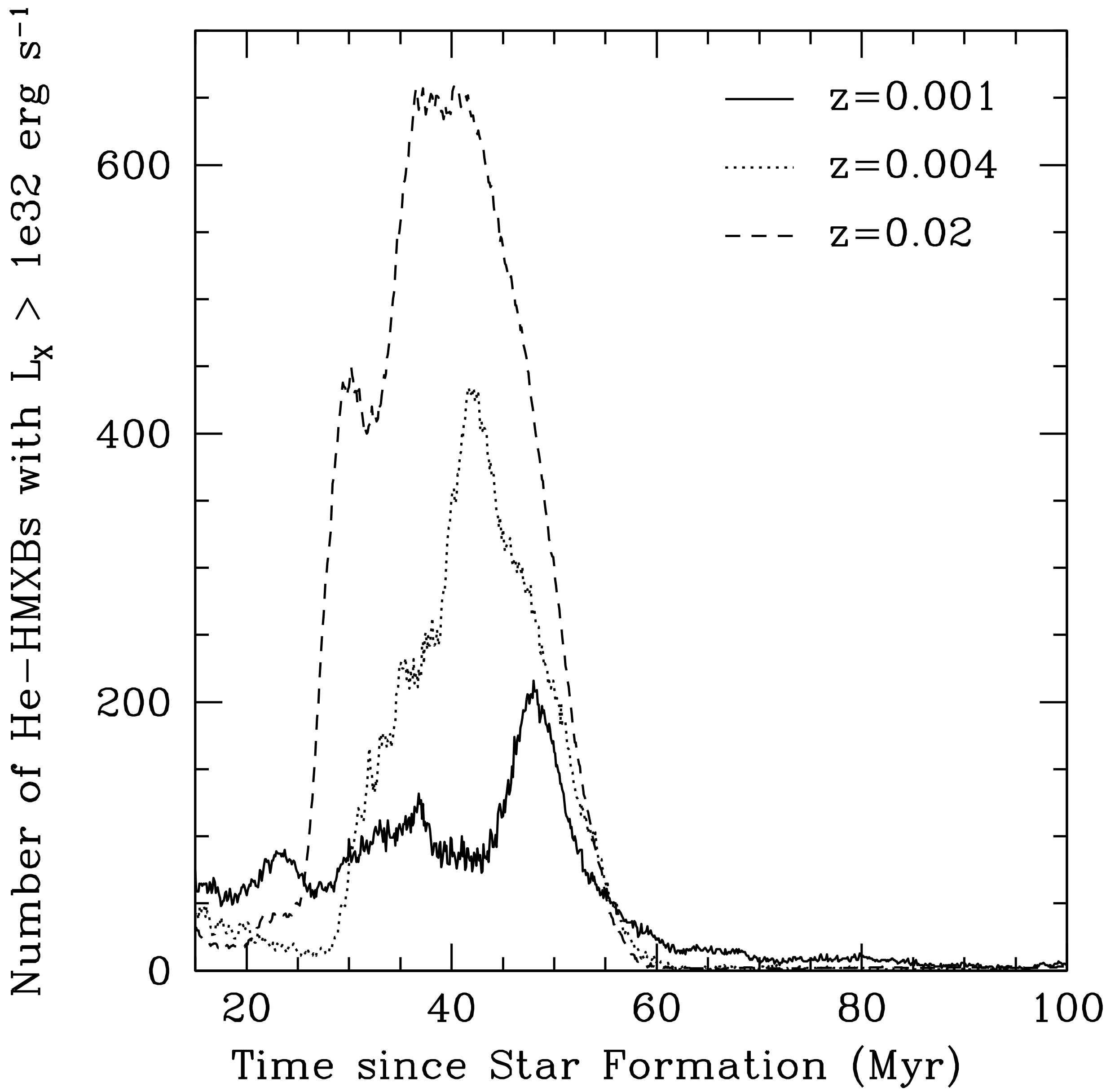

Fig. 19.— Same as Figure 15 except for He donors

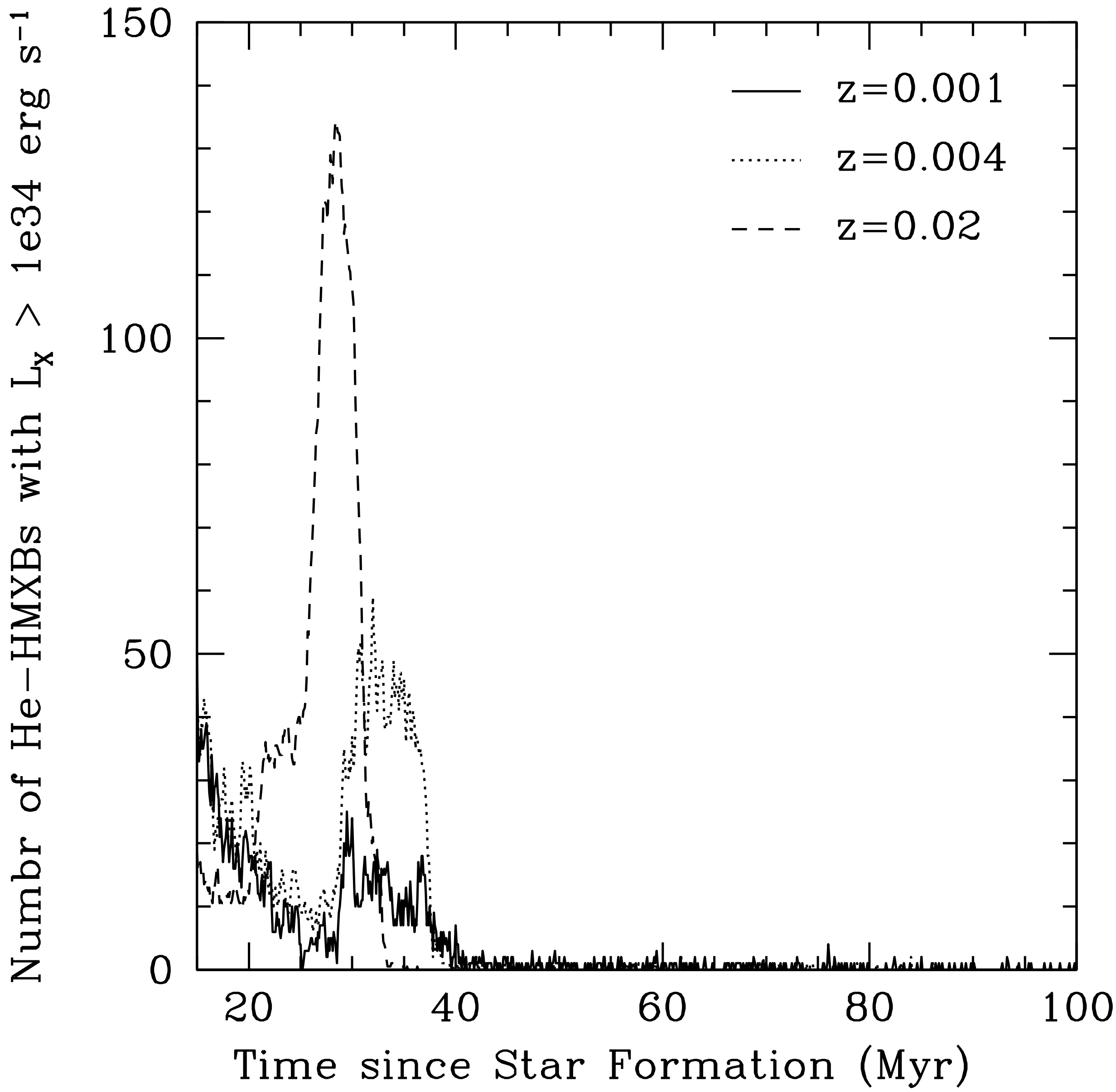

Fig. 20.— Same as Figure 19 for a luminosity $L_X > 1e34$ erg s^{-1}

Figures 17 and 18 show a nearly linearly decreasing number of systems, punctuated by a huge bump in systems between 25-55 Myr, which we have found to be created by NSs following the ECS mechanism. As we mentioned previously, most non-ECS evolved HMXBs have very massive kickless BH primaries. In Figures 19 and 20 we see our non-ECS background almost completely disappear for He star donors. At first, this may appear confusing, as we would not expect our method of inspiraling CHeB-HMXBs into He-HMXBs to begin failing at later timesteps. However, we note two reasons for this change. First, many of these systems will never form common envelopes at all due to the much smaller CHeB radii of the smaller donors. Secondly, since we continue to have massive BHs but begin to have very small donor envelope masses, we will begin to require less inspiralling in order to remove the donor envelope, leading to smaller inspirals for smaller donor stars.

These overall trends mirror our expectations that MS-HMXBs are long lived and fairly stable without replacement, while evolved systems are short lived and require constant replacement by new HMXBs. Throughout these timeframes, we find most systems to follow the same pathways we have described in Section 4.2, and thus we will not discuss these systems in detail here. Instead we will investigate the interesting processes which create the large bump found in systems with evolved donors between 25-55 Myr.

5. Electron-Capture Supernovae

We find that ECS systems lend an extremely important contribution to the number of bright HMXB between 25-55 Myr. We first note that in this section we adopt z=0.02 in order to limit the number of free parameters. While we also find that ECS systems are most important at this metallicity (due to strong wind speeds and a greatly restricted background), our qualitative understanding of ECS effects and variability remain constant, meaning our qualitative discussion would remain the same at all metallicities.

In Figure 21 we depict the number of bright HMXBs as a function of time at z=0.02 for different Maxwellian ECS kick strengths, using a luminosity cut of L_X = 1e32 erg s^{-1}. We see that as we increase the strength of natal kicks imparted to ECS, the substantial peak between 25-55 Myr disappears, while the remainder of the graph is unaffected. This shows that ECS are only an important effect due to the decreased kick velocity of the electron-capture phenomena. However, our models also show that ECS systems are reasonably resilient to the small kicks ($\sigma_{kick} = 26.5kms^{-1}$) which should occur in any realistic physical model. In Figure 22 we show the same graph at a luminosity cutoff of L_X = 1e34 erg s^{-1}, and note a much sharper bump of systems centered around 30 Myr. This sharp peak is the same as the earliest peak at the lower luminosity cutoff, and corresponds to the ECS neutron stars with the largest progenitors. We also note that even our bright ECS systems have luminosities of only a few times 10^{34} erg s^{-1}, and thus a deep survey is necessary for extra-galactic detection of these systems.

Analyzing Figures 17 and 19, we note that the vast majority of ECS-HMXBs contain either a CHeB or He donor. While we have a substantial background of BH-HMXBs in Figure 17, we have almost no background in Figure 19, which gives us a clear observational method to detect a probable ECS-HMXB. Meanwhile our background contains almost entirely MS donors, as seen in Figure 15, which contains no ECS bump. We find two very different pathways for the creation of HMXBs with main sequence and evolved donor stars.

For bright systems with unevolved donors, we find the initial semiminor axis to lie a bit outside the minimum separation specified by the HG CE restriction. Thus there is no orbital evolution as the primary moves through the HG stage, and the system remains stable until the binary enters a common envelope when the primary is in the CHeB phase. This common envelope phase results in orbital circularization and a large drop in the orbital separation as the primary loses its hydrogen envelope. As the stars are now tightly bound, they can survive a large supernova kick and maintain the close orbit necessary to become

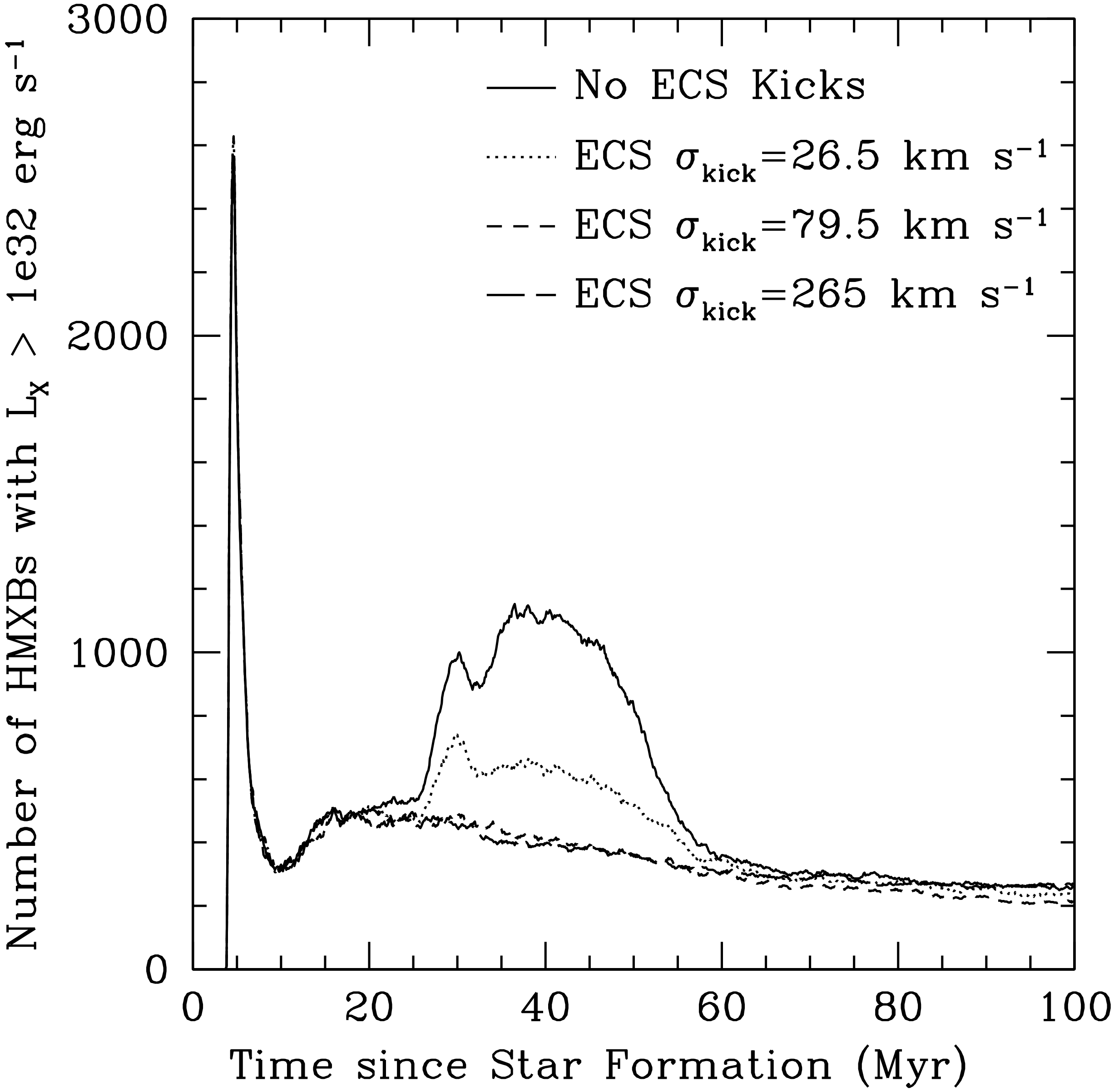

Fig. 21.— Number of HMXBs with $L_X > 1\text{e}32$ erg s^{-1} as a function of time for ECS systems with a kick following a Maxwellian probability density with various route mean squared values at z=0.02

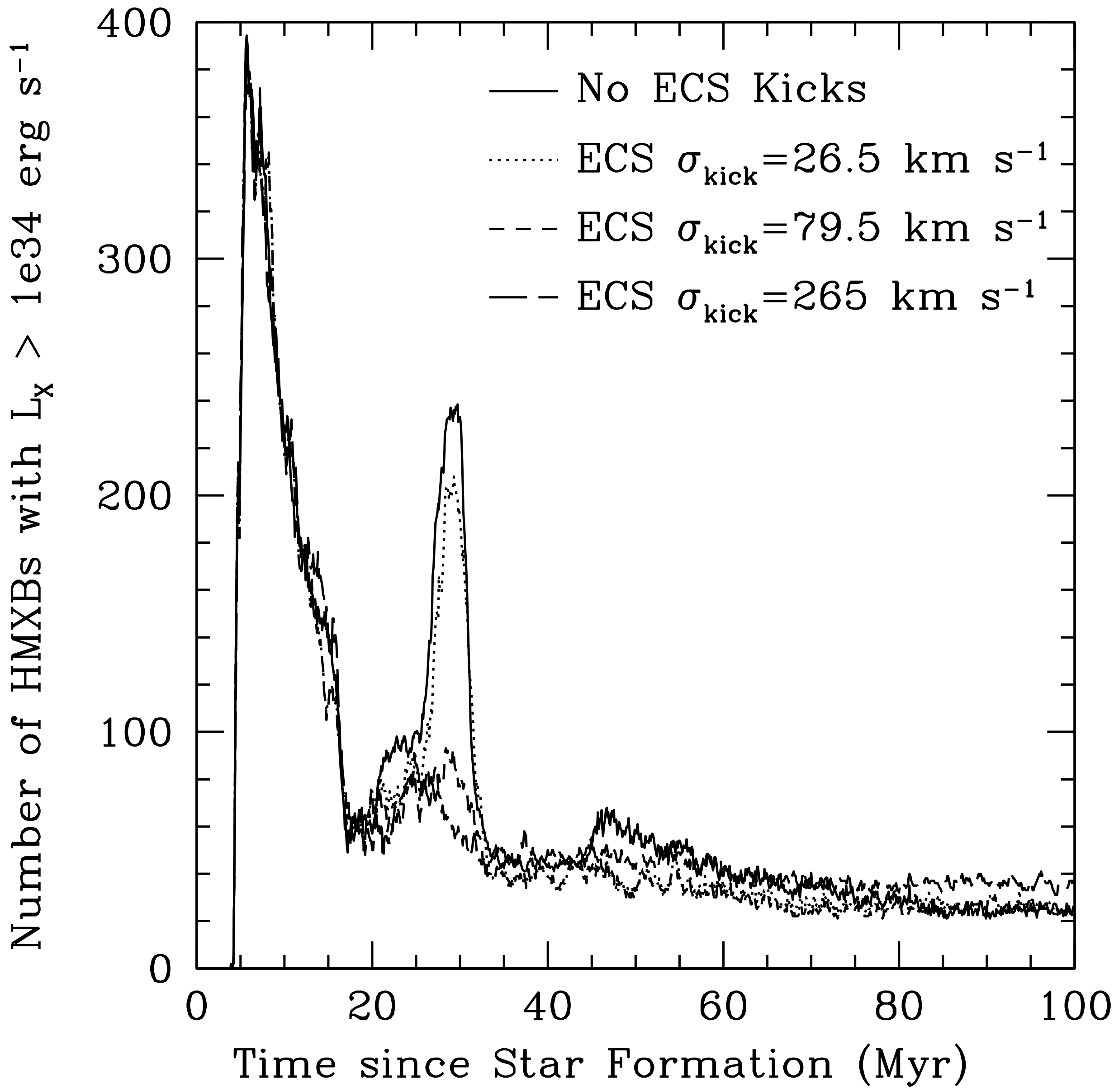

Fig. 22.— Same as Figure 21 except with luminosity cutoff of $L_X >$ 1e34 erg s^{-1}

bright HMXBs despite the weak wind accretion of main sequence stars.

A slightly confusing result is the lack of MS-HMXBs with ECS NSs. We ran two tests in order to understand the role ECS play in destroying these systems. Knowing that the key distinction between ECS and core-collapse SNe is the lack of a supernova kick in ECS systems, we eliminate supernova kicks for all systems, and find this not to inhibit bright MS-HMXB formation in non ECS NSs. In addition we attempted to force a system to undergo the ECS mechanism despite the presence of a very heavy core, and found these artificial ECS-HMXBs to remain bright. These results lead us to believe that it is not the ECS mechanism that is impaired from forming MS-HMXBs, but instead it is the primaries in the mass range that create ECS systems which cannot form MS-HMXBs. There is some logic behind this result, as we note that smaller ECS progenitors will have smaller donor stars. The combination of smaller donors with weaker winds, and smaller ECS NS masses, may lead to dim accretion below our cutoff. However the exact reason this mass regime is impaired is still somewhat uncertain, and the obvious next test involves looking for these systems by decreasing our luminosity cutoff below $L_X = 1\mathrm{e}32$ erg s^{-1}.

Bright systems with evolved donor stars form via two separate pathway. First, we may begin with two small systems in a wide binary orbit just as in the case of our young age CHeB-HMXBs. However, a much more important effect for ECS systems emerges. Beginning with the tightest possible systems outside of the zone restricted by HG CE effects, the system enters stable mass transfer without a common envelope during the HG stage, leading to circularization of the system. In progenitors with two nearly equal masses, the mass ratio between the two systems will flip causing the binary separation to begin widening (Sepinsky et al. 2007). This process continues as the primary moves through the HG and first giant branch, eventually creating a radial separation nearly an order of magnitude greater than the original separation. Mass transfer then ceases, and without a common envelope being formed, there is no inspiral as the primary loses its hydrogen envelope and forms a helium rich star. This method of creating wide binary orbits comes from a much larger parameter space, but requires small binary companions in order for a small amount of mass transfer to be able to move the system considerably. We note that we are now in the same system configuration as the CHeB and He HMXBs that we described earlier, and the following evolution continues in the same way. For high velocity natal kicks, these systems will be disrupted, thus we see entirely low kick systems, leading to the preponderance of ECS NSs. If the system is not disrupted, the system will be extremely dim until CHeB in the donor widens the donor radius and allows bright accretion and eventual inspiral to bright He-HMXBs.

ECS are highly selected as low kicks are necessary for maintaining the binary system. While there is a consistent background of non-ECS NSs which happen to gain a "lucky", or very small, kick, these are dominated by ECS systems.

A second critical parameter in determining the influence of ECS on the HMXB population is the chosen mass range for the ECS phenomena. In our default runs we allow ECS formation if the AGB begins with an He core mass from 1.83-2.25 M$\odot$ (Ivanova et al. 2007; Hurley et al. 2000; Pols et al. 1998). Investigating mass ranges of 2.5-2.7 $M_\odot$ and 1.66-3.24 $M_\odot$, in Figures 23 and 24 we show the significant changes in the strength and timing of the NS peak based on the mass range of systems allowed to undergo ECS. Intuitively, we find that higher mass ranges lead to earlier ECS peaks, as a larger He core mass results from a larger zero-age mass. Since these wind systems are generally luminous directly after the primary SN, the timing of the ECS is the determinant of the timing of bright accretion. However the size of the HMXB population associated with a given ECS mass range is more complicated, sloped towards higher mass ECS systems despite the larger numbers of systems with lower masses. Since the final ECS remnant mass is the same in both occasions, this stems mostly from the larger donor mass allowed for larger ECS progenitors. These larger donors create stronger winds which drives brighter accretion. Due

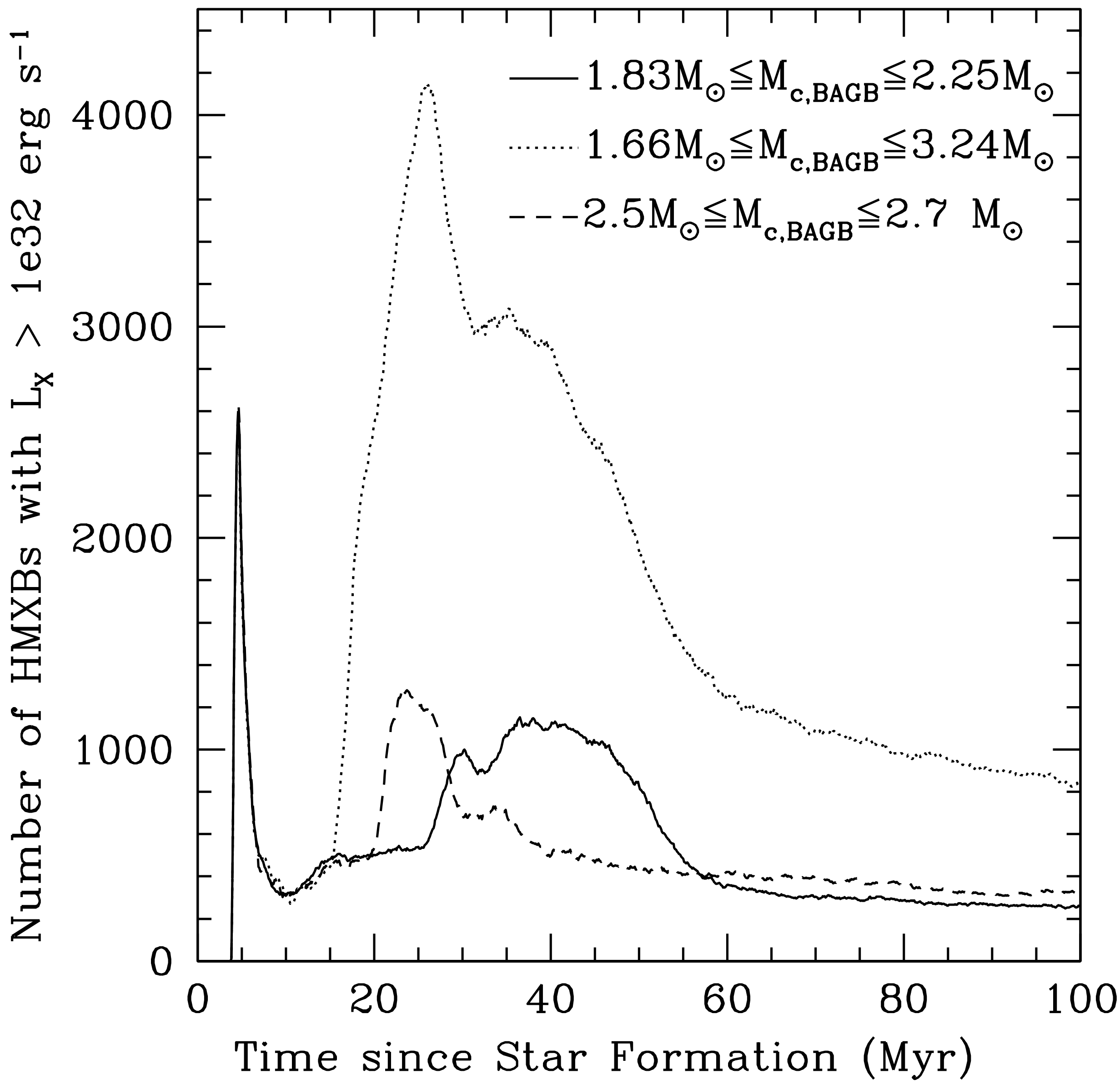

Fig. 23.— Number of HMXBs with L_X = 1e32 erg s^{-1} for different He core mass ranges allowing supernovae via the ECS mechanism at z=0.02(ECS assumed to be kickless, lines lay on top of eachother near beginning of plot)

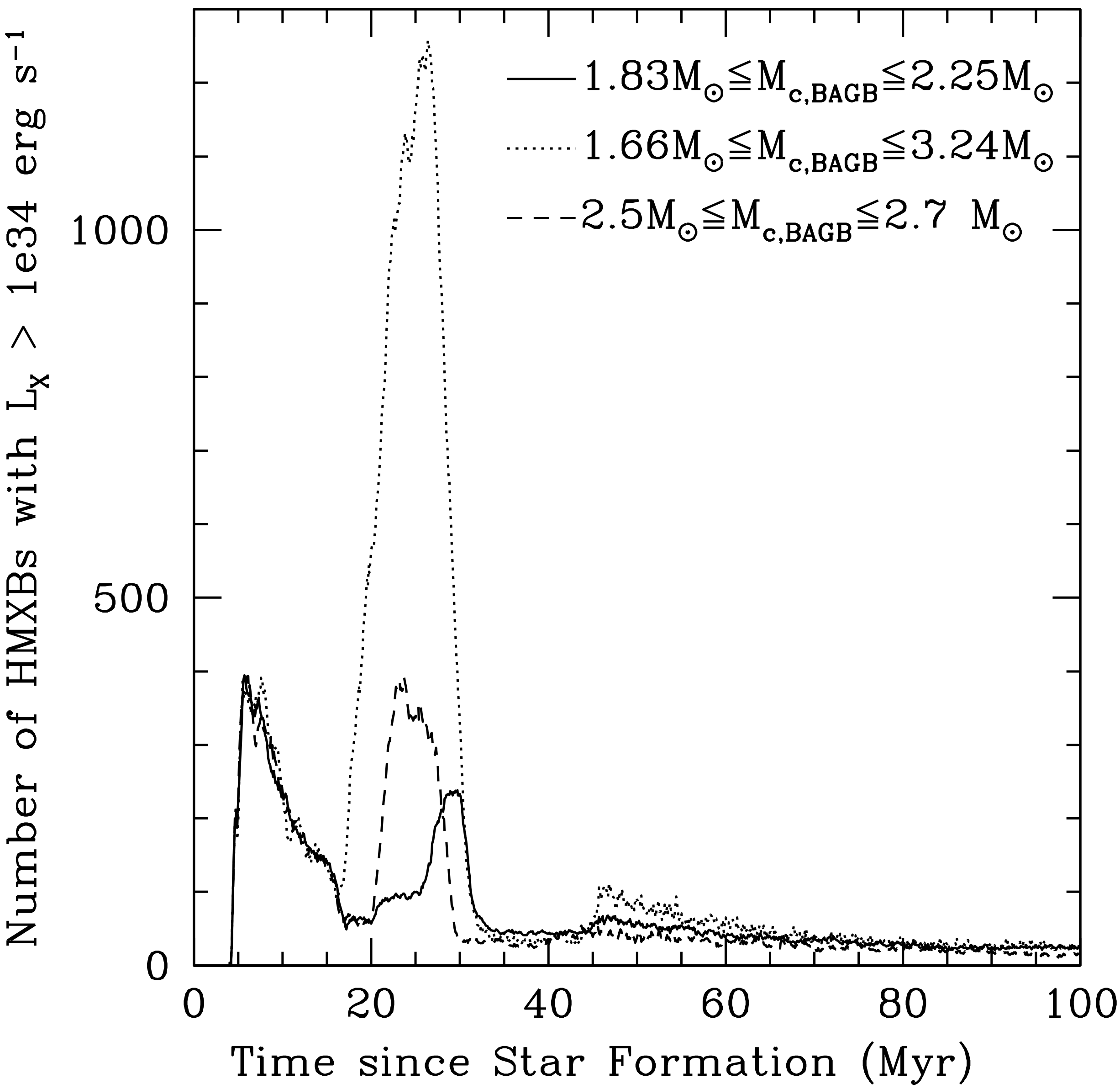

Fig. 24.— Same as Figure 23 except with luminosity cutoff of $L_X > $ 1e34 erg s^{-1}

to the large space of fits allowed by variations in the ECS core mass, precise simulations of the ECS mechanism are required to rigorously match our modelling predictions to starburst observations. In both figures, we note the decreasing tails of systems from 60-100 Myr, noting that both contain an exponentially decaying number of systems. Upon analyzing our results, we note that these systems are in fact MS-HMXBs, leading further credence to the idea that ECS MS-HMXBs in our default run are suppressed not due to any physics involving the ECS process, but instead due to the chosen progenitor mass range for ECS systems.

Finally, as our analysis shows the ECS mechanism to create a peak in systems purely due to its diminished kick strength, we infer that any mechanism of decreasing the natal kick for a particular portion of the HMXB progenitor parameter space should create a bright peak right after those systems undergo their first supernova event. However, the timing, ratio of bright systems, and metallicity dependence of each peak is specifically decided by the internal structure of our kick lowering mechanism, and thus we should be able to observationally distinguish between various proposed methods of decreasing NS kicks by observing systems with different initial parameter spaces of HMXB formation.

6. Discussion and Conclusions

We have provided metallicity and time dependent models for HMXB formation, explaining the dominant channels for HMXB formation for each combination of parameters. We have shown the HMXB population to be restricted by both instabilities during common envelope phases that result when the primary moves through the Hertzsprung gap, as well as large natal kicks during the systems first supernova event. Classifying the bright HMXB population at early times by the evolution state of the donor star, we described the widely varying constraints in mass ranges and orbital separations that allow each category of system to become X-Ray bright. Finally, we analyzed the effect of metallicity on each set of parameters, determining which metallicities are most supportive to each portion of the HMXB parameter space.

In analyzing the bright peak of systems in Figure 1 between 25-55 Myr, we presented a rigorous observational test for the electron capture mechanism of stellar collapse. We note that while the existence of a peak in the number of bright HMXBs is not specific to the electron-capture process as opposed to separate methods of creating low kick supernova events, the timing and metallicity dependence of the peak should allow results which can exclude various methods of low kick supernova creation. We explained how ECS systems create an extremely bright division between main sequence and evolved donor stars, which allow us to eliminate a large percentage of our background systems in observational tests of the ECS mechanism. Finally we showed the effect of the two most important uncertainties in ECS models, the NS natal kick provided by ECS, and the mass range of progenitors of the ECS process.

6.1. Comparison with Dray (2006)

D06 analyzed the population of HMXBs given a constant star formation rate at metalicities z=(0.02, 0.01, 0.004, 0.001), analyzing both the variance of the HMXB population with respect to metallicity and the parameter space restrictions of the propeller effect, which occurs when strong magenetic fields around a rapidly rotating neutron star expel plasma from the accretion disk surrounding it, preventing stellar material from accreting onto the compact object.

We attempted runs with several altered parameters in order to match our results with D06. We consider runs with a constant star formation rate for 2 Gyr. Although the D06 definition of HMXB is vague, we shift our minimum donor mass to 2 $M_{\odot}$, to fit previous literature better than our choice of 0.15 $M_\odot$. We set the maximum NS mass to 2.2 $M_\odot$. We eliminate the ECS mechanism and allow HG CEs to follow the energy formalism with an efficiency parameter λ=0.5 which moves half of the potential energy into envelope ejection for all CEs. Finally, we increase the mean of the Maxwellian kick distribution to 450 km s^{-1}.

However, we find several important differences between our runs and those of D06. Most troubling, D06 does not see a strong metallicity dependent change in the ratio of NSs to BHs, noting a ratio of approximately 8 to 1 at all metallicities. However our results show a clear trend towards less NSs per BH at lower metallicity, with a change from approximately 1-1.3 at z=0.02, to 1-6 at z=0.001. There are many changes in the parameter space of HMXB formation, which can allow us to linearly adjust the NS to BH ratio in order to match D06. However, we are unable to create conditions which eliminate the metallicity dependence of the ratio entirely. We note several effects that are not similarly handled in both simulations: most importantly the propeller effect, and the necessity of an accretion disc to form in order to create bright wind accretion.

In our analysis, we ignore the disruption of NS HMXBs due to the propeller effect, which may create a metallicity dependent destruction of NS systems, creating the metallicity dependance of the NS to BH ratio. D06 notes that the theoretical and observed metallicity dependance of the propeller effect are not in agreement. Maeder & Meynet (2001) produced models showing that NS rotation rates are faster at low metallicity, leading to more potentially bright NS-HMXBs being destroyed at low metallicity. However, Penny et al. (2004) found no metallicity dependance in the rotation rate, using observations from the Space Telescope Imaging Spectrograph on the Hubble Space Telescope to observe the rotation rates of O-type stars in the Magellenic clouds. In either case, these results cannot lead to agreement between our results and D06, as we would require more NS to be destroyed at high metallicities to eliminate our metallicity dependence.

D06 operates under the assumption that wind systems are not bright unless an accretion disc is formed around the CO. While disk formation is necessary to produce extremely bright wind accretion systems, both papers operate with a luminosity cutoff of only $L_X = 1\text{e}32$ erg s^{-1}. At this luminosity cutoff, the assumption does not necessarily hold. Upon implementing the D06 constraint, we found a significant drop in HMXB production, especially in the first 10 Myr of stellar evolution. We note that this greatly decreases the number of bright BH-HMXBs we observe, greatly moving our overall results towards the D06 ratio. However, we did not find any metallicity dependent restriction which would affect the BH-NS ratio.

We note some theoretical support for our metallicity dependent ratios. (Belczynski et al. 2006) find a factor of 4 increase in the number of BHs in binaries at z=0.01 compared to z=0.02, which mirrors our results, as see only a small rise in the number of NSs at low metallicity. Analytical treatments of wind mass loss have shown that massive stars lose mass proportional to the square root of the metallicity (Kudritzki et al. 1987, 1989), which should increase the range of pre-SN masses stemming from equal progenitor masses. However, we lack previous literature detailing the survival of BH and NS HMXB formation pathways, and are thus unable to make a rigorous comparison.

There are several other changes in our runs, most notably the eccentricity distribution of bright systems. However, we note that these distributions are all highly dependent on the population of BHs and NSs which result from our runs, and thus we find that a close comparison of these systems would be a pointless endeavor without a matching background population.

6.2. Future Research

Our results are particularly interesting in light of the recent observational studies of the Small Magellanic Cloud (SMC) which contains a large population of low-velocity

NS Be-HMXB systems that cannot be accounted for by high velocity iron core supernova explosions following a single Maxwellian distribution (Coe 2005). Be-HMXBs are transient HMXB sources with an eccentric B type (initial mass of 2-16 $M_{\odot}$ (Eggleton et al. 1989)) donor. Due to the high rotational speed of the Be star, the wind mass is not lost isotropically, but is strongly dominated by equatorial winds. As the compact object moves through the equatorial plane, it suddenly accretes significantly more mass, leading to periodic bursts of bright accretion. (Reig 2007; Raguzova & Lipunov 1998) As noted earlier, Be-HMXBs have been observed in both galactic and extragalactic observations, and have parameters which suggest they result from a supernova with a greatly reduced natal kick (Raguzova & Popov 2005).

Our preliminary results above seem to support the idea that ECS systems could be responsible for the large overabundance of SMC HMXBs. The SMC is known to have experienced a large burst of star formation activity between 30-60 Myr, concurrent with our theoretically predicted peaks of ECS activity (Maragoudaki et al. 2001; Harris & Zaritsky 2004; Bekki & Chiba 2005). The metallicity of the SMC is z=0.004, lower than the local galactic metallicity of z=0.02, which slightly lowers the preponderance of ECS sources, but they still form a significant portion of the HMXB peak during their active lifetime.

6.3. Comparison with McSwain & Gies (2005)

This research has already produced one particularly beautiful agreement with McSwain & Gies (2005), who studied the properties of Be stars in the Southern Open Clusters. They produced models which demonstrate that Be stars are created preferentially in binaries, utilizing a mass transfer phase where the Be star receives mass from a more massive orbital companion in the HG and spins up. The Be star eventually becomes the more massive star, causing MT to begin increasing the orbital separation of the system, which slows tidal syncronization. The Be star gains enormous amounts of angular momentum and begins rotating at significant percentages of the breakup velocity, eventually evolving to become a quickly rotating He star. They find approximately 73% of Be stars to follow this route, with the remainder of Be stars likely born as fast rotators.

We note that this is exactly the same process as the dominant process of ECS HMXB formation (see Section 5). Moreover, as shown in Figure 19, there is almost no non-ECS NS background systems. This allows us to propose that the ECS mechanism is not just a possible method for the creation of ECS-HMXBs, with limitations in observational scope rendering them the most probable form to be found. Instead, ECS systems are the *dominant* method of Be-HMXB formation. At z=0.02, we find that ECS systems are responsible for over 98% of the bright HMXB which follow the Be-HMXB spinup pathway described in McSwain & Gies (2005). Finally we note a good correlation between our ECS peaks from 25-55 Myr, and the observed peak in Be Systems between 20-50 Myr.

There are several other models of Be star formation. Models by Zorec & Briot (1997) find all Be stars to be formed at birth. Meynet & Maeder (2000) showed that stars born with Be characteristics should reach their breakup velocity near the beginning of the HG period. This would lead to a population of Be stars that are almost entirely MS stars, in stark contrast to the McSwain & Gies (2005) results. We note these results do not at all correlate with our ECS systems, and the preponderance of high kick core-collapse NSs with main sequence donors makes it unlikely that we could explain the SMC with our results using a model of Be stars created at system birth.

Theoretical models by van Bever & Vanbeveren (1997) and Pols et al. (1991) show that Be stars may form via both patterns, with slightly more systems formed via self-spinup at birth. Using these results we could still explain the high percentage of Be systems found with low kick velocities in the SMC. Since ECS systems have a much smaller kick, their survival will be highly preferred compared to MS-HMXBs which must survive a much higher natal kick. Although the number of bright HMXBs is similar for both systems, there are many more MS donor stars in a population at any point than evolved stars. Thus if roughly equal numbers of Be stars exist in each population, our ECS-HMXBs will be highly preferred.

6.4. Challenges with SMC Model

There are several obstacles in the way of forming a complete model of the SMC from the analysis presented here. First, Be systems are not handled by the *StarTrack* code. Using the mass ranges for B stars provided by Eggleton et al. (1989), we will have to determine a probability that a random B-type donor is in fact a Be star. Unfortunately there are disagreements over the ratio of B stars which are Be (McSwain & Gies 2005). We would not require knowledge of this probability if we create Be stars following the spinup method, as our results detail which systems contain the necessary mass transfer phases to create Bes. However, in order to determine the percentage of Bes formed by systems following our spinup process, we may need to weight our results against the creation rate of birth Be stars.

Since the *StarTrack* code does not calculate the X-Ray luminosity or additional wind mass loss in Be stars, this must be done in post-processing, ignoring the effects of the additional mass loss on the subsequent donor evolution. Luckily these effects should be minimal. Calculating the modified accretion onto the compact object, we can then modify our luminosity accordingly to compare our Be-HMXB sources against the SMC cutoff luminosity.

In order to match SMC observations, we must obtain a population of approximately 50 Be-HMXBs against a maximum of one or two background system. We neglect the transience of the Be-HMXBs in these calculations, as the wealth of observational data on the SMC suggests the completeness of our current dataset of HMXBs. (J. Gallagher and A. Zezas, 2008, private communication). There is however, an important incompleteness in the area covered by SMC observations. The "bar" region has been most highly studied, but its small size means that many high velocity HMXBs would escape observational detection, leading to a strong selection effect in favor of low kick Be-HMXB sources. As explained in previous work, a preliminary calculation found that over 90% of non-ECS sources escaped from the SMC "bar" region (Linden 2008).

6.5. Final Thoughts

A convincing model of Be-HMXB sources in the SMC would be a substantial step for the use of population synthesis in the prediction of stellar evolution phenomena. However, for our model to be convincing, we believe it will be necessary to match not only the number of SMC HMXB sources, but also the observed period and eccentricity distributions, a much more difficult task. A complete match with many observed parameters is necessary because uncertainties in the population synthesis inputs allow us to mix parameters to match several desired outputs simultaneously.

However, the qualitative description of HMXB formation pathways described here lends itself to a battery of tests against future observations of donor star evolution states, HMXB proper velocity measurements, and starburst cluster age measurements. Analyzing the existence and relative strength of each formation mechanism against observational data should provide important constraints on the theoretical models used for massive star formation and evolution.

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REFERENCES

Bekki, K., & Chiba, M. 2005, MNRAS, 356, 680

Belczynski, K., Kalogera, V., Rasio, F. A., Taam, R. E., Zezas, A., Bulik, T., Maccarone, T. J., & Ivanova, N. 2005, ArXiv Astrophysics e-prints

—. 2008, ApJS, 174, 223

Belczynski, K., Sadowski, A., Rasio, F. A., & Bulik, T. 2006, ApJ, 650, 303

Belczynski, K., Taam, R. E., Kalogera, V., Rasio, F. A., & Bulik, T. 2007, ApJ, 662, 504

Bromm, V., Ferrara, A., Coppi, P. S., & Larson, R. B. 2001, MNRAS, 328, 969

Chevalier, C., & Ilovaisky, S. A. 1998, A&A, 330, 201

Coe, M. J. 2005, MNRAS, 358, 1379

Dessart, L., Burrows, A., Ott, C. D., Livne, E., Yoon, S.-C., & Langer, N. 2006, ApJ, 644, 1063

Dray, L. M. 2006, MNRAS, 370, 2079

Eggleton, P. P., Tout, C. A., & Fitchett, M. J. 1989, ApJ, 347, 998

Fryer, C. L., & Kalogera, V. 2001, ApJ, 554, 548

Han, Z., Podsiadlowski, P., & Eggleton, P. P. 1994, MNRAS, 270, 121

Harris, J., & Zaritsky, D. 2004, AJ, 127, 1531

Heger, A., Fryer, C. L., Woosley, S. E., Langer, N., & Hartmann, D. H. 2003, ApJ, 591, 288

Hjellming, M. S., & Webbnik, R. F. 1987, ApJ, 318, 794

Hobbs, G., Lorimer, D. R., Lyne, A. G., & Kramer, M. 2005, MNRAS, 360, 974

Hurley, J. R., Pols, O. R., & Tout, C. A. 2000, MNRAS, 315, 543

Ivanova, N., Heinke, C., Rasio, F. A., Belczynski, K., & Fregeau, J. 2007, ArXiv e-prints, 706

Ivanova, N., & Taam, R. E. 2004, ApJ, 601, 1058

Kalogera, V., Valsecchi, F., & Willems, B. 2008, in American Institute of Physics Conference Series, Vol. 983, American Institute of Physics Conference Series, 433–441

Kalogera, V., & Webbink, R. F. 1998, ApJ, 493, 351

Kitaura, F. S., Janka, H.-T., & Hillebrandt, W. 2006, A&A, 450, 345

Kramer, M., Lorimer, D. R., Lyne, A. G., McLaughlin, M., Burgay, M., D'Amico, N., Possenti, A., Camilo, F., Freire, P. C. C., Joshi, B. C., Manchester, R. N., Reynolds, J., Sarkissian, J., Stairs, I. H., & Ferdman, R. D. 2005, ArXiv Astrophysics e-prints

Kudritzki, R. P., Pauldrach, A., & Puls, J. 1987, A&A, 173, 293

Kudritzki, R. P., Pauldrach, A., Puls, J., & Abbott, D. C. 1989, A&A, 219, 205

Linden, T. 2008, Undergraduate Senior ISP Thesis, Northwestern University, 1, 1

Maeder, A., & Meynet, G. 2001, A&A, 373, 555

Majid, W. A., Lamb, R. C., & Macomb, D. J. 2004, ApJ, 609, 133

Maragoudaki, F., Kontizas, M., Morgan, D. H., Kontizas, E., Dapergolas, A., & Livanou, E. 2001, A&A, 379, 864

Massey, P. 2003, ARA&A, 41, 15

McSwain, M. V., & Gies, D. R. 2005, ApJS, 161, 118

Meynet, G., & Maeder, A. 2000, A&A, 361, 101

Miyaji, S., Nomoto, K., Yokoi, K., & Sugimoto, D. 1980, PASJ, 32, 303

Negueruela, I. 1998, A&A, 338, 505

Nomoto, K. 1984, ApJ, 277, 791

—. 1987, ApJ, 322, 206

Penny, L. R., Sprague, A. J., Seago, G., & Gies, D. R. 2004, ApJ, 617, 1316

Pfahl, E., Rappaport, S., Podsiadlowski, P., & Spruit, H. 2002, ApJ, 574, 364

Piran, T., & Shaviv, N. J. 2005, Physical Review Letters, 94, 051102

Podsiadlowski, P., Dewi, J. D. M., Lesaffre, P., Miller, J. C., Newton, W. G., & Stone, J. R. 2005, MNRAS, 361, 1243

Podsiadlowski, P., Langer, N., Poelarends, A. J. T., Rappaport, S., Heger, A., & Pfahl, E. 2004, ApJ, 612, 1044

Poelarends, A. J. T., Herwig, F., Langer, N., & Heger, A. 2007, ArXiv e-prints, 705

Pols, O. R., Cote, J., Waters, L. B. F. M., & Heise, J. 1991, A&A, 241, 419

Pols, O. R., Schroder, K.-P., Hurley, J. R., Tout, C. A., & Eggleton, P. P. 1998, MNRAS, 298, 525

Raguzova, N. V., & Lipunov, V. M. 1998, A&A, 340, 85

Raguzova, N. V., & Popov, S. B. 2005, Astronomical and Astrophysical Transactions, 24, 151

Reig, P. 2007, MNRAS, 377, 867

Schaller, G., Schaerer, D., Meynet, G., & Maeder, A. 1992, A&AS, 96, 269

Sepinsky, J. F., Willems, B., Kalogera, V., & Rasio, F. A. 2007, ApJ, 667, 1170

Siess, L. 2007, A&A, 476, 893

Sipior, M. S., Eracleous, M., & Sigurdsson, S. 2003, ArXiv Astrophysics e-prints

Taam, R. E., & Sandquist, E. L. 2000, ARA&A, 38, 113

Tout, C. A., Pols, O. R., Eggleton, P. P., & Han, Z. 1996, MNRAS, 281, 257

van Bever, J., & Vanbeveren, D. 1997, A&A, 322, 116

van den Heuvel, E. P. J. 2007, in American Institute of Physics Conference Series, Vol. 924, American Institute of Physics Conference Series, 598–606

van den Heuvel, E. P. J., Portegies Zwart, S. F., Bhattacharya, D., & Kaper, L. 2000, A&A, 364, 563

Webbink, R. F. 1984, ApJ, 277, 355

Zorec, J., & Briot, D. 1997, A&A, 318, 443

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