THE ASTROPHYSICAL JOURNAL, 493:368–374, 1998 January 20

FORMATION OF LOW-MASS X-RAY BINARIES. III. A NEW FORMATION MECHANISM: DIRECT SUPERNOVA

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Received 1996 June 6; accepted 1996 July 7

ABSTRACT

We propose a new formation mechanism (direct-supernova) for low-mass X-ray binaries (LMXBs) that does not involve any prior phase of mass transfer. Survival through the supernova (SN) explosion and shrinkage of the orbit is achieved by a kick velocity of appropriate magnitude and direction imparted to the neutron star at its birth. We present analytical population synthesis calculations of LMXBs forming via both the direct-SN and the helium star SN mechanisms and compare the results. We find that the direct-SN channel contributes a nonnegligible fraction of the total LMXB population, depending strongly on the rms magnitude of the kick velocity. More importantly, the direct-SN mechanism provides a natural way for the formation of low-mass binary pulsars in nearly circular orbits with orbital periods in excess of $\sim 100^{\mathrm{d}}$, which cannot have been formed via the helium star SN mechanism.

Subject headings: binaries: close — pulsars: general — stars: evolution — stars: neutron — supernovae: general — X-rays: stars

1. INTRODUCTION

Since their discovery, low-mass X-ray binaries (LMXBs) have been a puzzle for theories of close binary evolution. The existence of a low-mass star in a small orbit around a compact object (neutron star or black hole) appeared to require a quite intriguing explanation concerning the evolutionary path followed by the progenitors of these systems. The present orbits of LMXBs are too small to have accommodated the growth in size of the progenitors of the compact objects. In addition, the masses of the companions to the compact objects (donor stars) are so small that the survival probability through a supernova (SN) explosion is expected to be small. The small number of observed LMXBs (~ 100; van Paradijs 1995) along with their relatively long lifetimes suggests that the evolutionary path responsible for their formation is a quite improbable one (Webbink 1992).

Over the years, three formation mechanisms have been put forward in an effort to understand the existence of LMXBs. All of them invoke evolution through a common envelope (CE) phase (Paczyński 1976), during which the low-mass star spirals inward through the extended envelope of the massive primary star, and the phase is terminated upon ejection of the common envelope. This phase results in the reduction of both the mass of the progenitor of the compact object and the orbital separation. One of the three formation mechanisms involves the collapse into a neutron star of a massive white dwarf, accreting mass from a low-mass companion, in a small orbit (the outcome of an earlier CE phase). The collapse of a white dwarf into a neutron star in the context of formation of X-ray binaries was first proposed by Flannery & van den Heuvel (1975) and Canal & Schatzman (1976). A second mechanism, the He star SN, involves a CE phase leaving a helium star in a small orbit with a low-mass companion. The helium star evolves to core collapse and undergoes a supernova explosion, forming a neutron star remnant (Sutantyo 1975; van den Heuvel 1983). The third evolutionary sequence invokes the formation of a Thorne-Żytkow object as the end product of a massive X-ray binary with a third component in a very wide orbit. This low-mass third star is engulfed in the envelope of the Thorne-Żytkow object. The ejection of the common envelope leaves the low-mass star in orbit with the neutron star (Eggleton & Verbunt 1986; however, see Fryer, Benz, & Herant 1996).

Recent reassessments of pulsar kinematics have reinforced earlier suggestions that neutron stars are endowed at birth with large kick velocities, the apparent result of asymmetric core collapse. Studies of the radio pulsar population (see, e.g., Harrison, Lyne, & Anderson 1993; Lyne & Lorimer 1994) show that pulsars have space velocities much higher than those of their massive progenitors and that they extend to large distances away from the Galactic plane.[2] Using a new electron density model, they conclude from pulsar proper motions that the mean pulsar velocity is $\sim 450 \pm 90$ km s^{-1}, a result that appears to be corroborated by studies of pulsar-supernova remnant associations (Frail 1996; although see Hartman 1996; Ramachadran & Bhattacharya 1997). Moreover, results of simulations of supernova explosions (see, e.g., Herant, Benz, & Colgate 1992; Janka & Müller 1994; Burrows, Hayes, & Fryxell 1995; Burrows & Hayes 1996) also support the idea that kick velocities are imparted to neutron stars at birth, although more detailed numerical calculations are needed to settle the issue.

In this paper we explore the possibility that a simple evolutionary sequence can lead to the formation of LMXBs. The essence of the mechanism lies in the possibility that even if the orbits of the primordial binaries are so wide that the two stars do not interact and a common envelope is not formed, the systems remain bound and the orbital separations decrease after the supernova explosion due to a kick of

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[2] Recently, Iben & Tutukov (1995) have argued against the existence of kick velocities. However, they need to assume a binary fraction equal to unity, and even then their results are marginally consistent with early estimates of pulsar velocities (Harrison et al. 1993).

appropriate magnitude and direction imparted to the neutron star at birth.

The proposed evolutionary path is described in detail in the next section. The constraints and limits on the parameter space of the progenitors specific to this mechanism are identified in § 3. We have performed population synthesis calculations, the method and results of which are presented in § 4. A discussion of the implications and our conclusions are presented in § 5.

2. FORMATION MECHANISM

Let us consider a primordial binary with an extreme mass ratio, in which the primary is massive enough to explode as a supernova and form a neutron star at the end of its evolution, and the secondary is a low-mass star ($M_2 \lesssim 2\ M_\odot$).

During its evolution, the primary loses mass in a stellar wind, and the orbital separation of the binary increases. If the initial orbit is wide enough, the primary never fills its Roche lobe, despite its growth in radius, and its evolution is terminated when it reaches the core collapse stage. Thus, the binary components do not interact in any way prior to the supernova explosion, except perhaps for some small (in our case, negligible because of the wide orbits considered) accretion by the secondary from the wind of the primary.

The mass loss during the collapse of the primary is so severe that the system would be disrupted if the explosion were symmetric. However, in the presence of a kick velocity imparted to the newborn neutron star, there is a finite probability that the post-SN system remains bound. The survival probability depends primarily on the magnitude and direction of the kick velocity and less on the amount of mass lost.

Although the supernova explosion is the most crucial event in the evolution of an LMXB progenitor, keeping the post-SN system bound is not enough for an observable LMXB to be formed. The orbit after the explosion must be small enough so that the low mass star can fill its Roche lobe (1) in a time shorter than the Galactic disk age and (2) before it reaches the end of its evolution and acquires its maximum radius. A kick velocity of the appropriate magnitude and direction can not only keep the post-SN system from becoming unbound but can also decrease the orbital separation. The subsequent decrease of the post-SN orbital separation due to a combination of (1) tidal dissipation and orbital circularization and (2) angular momentum losses (caused by gravitational radiation and the magnetic stellar wind of the secondary), aided by nuclear evolution of the secondary, eventually brings the system into contact. For the first time in the evolutionary history of the binary, the stellar components interact, and the system may appear as a luminous X-ray source, depending on the characteristics of the mass transfer phase. We name this formation mechanism direct supernova, since the binary members do not experience any phase of interaction prior to the supernova explosion.

3. CONSTRAINTS ON THE PARAMETER SPACE OF THE PROGENITORS

A primordial binary follows the evolutionary path described above and becomes a LMXB only if it satisfies a number of constraints. The simplicity of the formation mechanism results in a set of simple constraints, as well.

There is only one constraint imposed on the characteristics of the binaries before the supernova explosion. The initial orbital separation of the system must be large enough so that the primary does not fill its Roche lobe before it reaches core collapse. Otherwise, unstable mass transfer is initiated, and the system will evolve according to the He star SN mechanism.

We have used the evolutionary calculations presented by Schaller et al. (1992) for solar composition to fit the maximum radius acquired by a massive star undergoing wind mass loss, as a function of its initial mass (see Appendix in Kalogera & Webbink 1998; hereafter Paper II). Using this relation and the radius of the Roche lobe of the primary expressed in units of the orbital separation (Eggleton 1983), we can calculate the orbital separation of systems with their primaries just filling their Roche lobes at the time of their maximum extent. This separation represents a lower limit to the orbital size of those primordial binaries that will evolve according to the direct-SN mechanism. The limiting orbital separations for 1 $M_\odot$ and 2 $M_\odot$ companions and for a range of primary masses are shown in Figure 1. It is evident that the LMXB progenitors specific to the direct-SN mechanism have initial orbital separations and periods in excess of $\sim$600–2000 $R_\odot$ and $\sim$1–5 yr, respectively.

The fact that the pre-SN binary orbits are so wide, along with the large amounts of mass lost at supernovae, results into highly eccentric orbits immediately after the explosions. These orbits are similar to those of tidal capture binaries formed in dense stellar environments, as globular clusters. Recent detailed studies of the tidal capture process presented by Mardling (1995a, 1995b) show that there is a region in the parameter space of eccentricity, e, and ratio of the periastron distance to the stellar radius, R_p/r_*, where binaries exhibit chaotic behavior, with large changes in eccentricity, that may even lead to self-ionization. Binaries outside this region circularize only via dissipation of energy. During this long quiescent phase, the eccentricity varies quasi-periodically owing to a quasi-periodic exchange of energy between the orbit and the tides, and a merger is avoided. To secure that the post-SN binaries formed via the direct-SN mechanism survive and eventually become circularized, their post-SN characteristics must be such that they populate the nonchaotic region of the R_p/r_*-e parameter

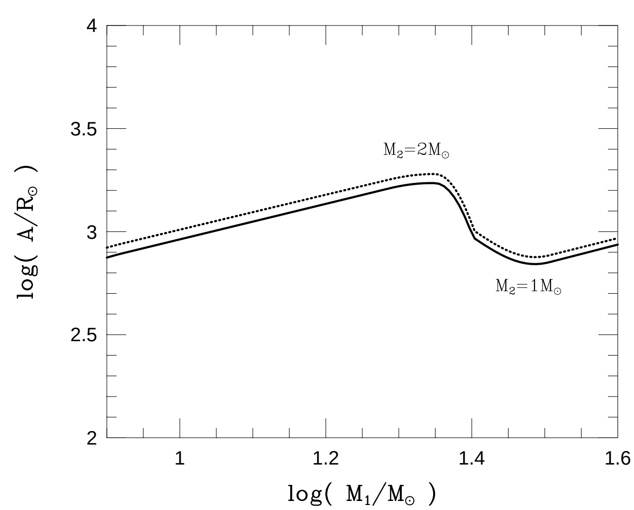

FIG. 1.—Minimum orbital separations of primordial binaries that follow the direct-SN formation mechanism for two different companion masses: $M_2 = 1\ M_\odot$ (*solid line*) and $M_2 = 2\ M_\odot$ (*dotted line*).

space. Indeed, we find that although the mean eccentricity of the binaries produced by our synthesis models is high, $\langle e \rangle = 0.93$, the ratio of the periastron distance to the stellar radius also acquires high values, $\langle R_p/r_* \rangle \simeq 100$. These values greatly exceed the limit on R_p/r_*, below which chaotic behavior is possible ($R_p/r_* < 5$; Mardling 1995a). Tidal circularization of these binaries proceeds initially at a time scale much longer than the Hubble time, but by the time Roche lobe filling occurs and mass transfer is initiated, the timescale has become extremely small, and the orbits are most probably circular.

The post-SN binaries at the onset of the mass transfer phase must satisfy a set of structural and evolutionary constraints, which are independent of the specific LMXB formation mechanism and which must be satisfied by neutron star–normal star binaries if they are to appear as LMXBs. These constraints have been studied by Kalogera & Webbink (1996; hereafter Paper I) and they concern (1) the age of the systems, which must not exceed the age of the Galactic disk, and (2) the ability of the donors to remain in hydrostatic and thermal equilibrium at the onset of mass transfer. Systems are further divided into two groups, those transferring mass at sub-Eddington rates (conservative mode) and those with donors driving mass transfer at super-Eddington rates (nonconservative mode). We note that the process of super-Eddington accretion is not well understood, and it is possible that matter surrounding super-Eddington systems may quench the X-rays and that these systems do not appear as LMXBs.

4. POPULATION SYNTHESIS

4.1. *The Model*

We have performed population synthesis calculations for LMXBs forming according to the direct supernova mechanism, using the analytic method presented in Paper II. We transform the distribution of primordial binaries through the various evolutionary stages, i.e., wind mass loss from the primary, supernova explosion of the primary imparting a kick velocity to the newborn neutron star, shrinkage of the orbit due to angular momentum losses, and nuclear evolution of the low-mass companion until Roche lobe filling by the companion is achieved and the nascent LMXB is formed. In order to model the physical processes involved, we have employed analytic approximations of results from evolutionary calculations, which are given in Paper I and Paper II. We have assumed a Maxwellian distribution for the kick velocities; the method for incorporating their effects developed by Kalogera (1996) has been used. We have made the same assumptions for the parent binary population as in the study of LMXB formation via the helium star SN mechanism (Paper II), except for one modification appropriate to the specifics of the direct-SN mechanism. These assumptions have been extensively discussed in Paper II. Here, we summarize only the key points and describe the modification applied.

We assume that primordial binaries are characterized by three parameters: the primary mass, M_1; the mass ratio, $q \equiv M_2/M_1$, where M_2 is the mass of the secondary; and the orbital separation, A. It is conceivable that a fourth parameter is the eccentricity of the orbits. For the wide systems of interest to us, the timescale for circularization (see, e.g., Zahn 1977, 1989) is initially much longer than the lifetime of the primary. However, we find that the direct-SN channel is primarily fed by binaries with orbital separations comparable (within a factor of less than 2) to the limiting values for Roche lobe overflow at the time of maximum extent of the primary. For these binaries, as the massive star evolves to the giant branch, the circularization timescale becomes shorter than about 1/100 of its main-sequence lifetime, which is short enough for the orbits to become circular prior to the supernova event. Moreover, for a scaleless distribution in orbital separations, as we will assume, the distribution of separations is not altered by the circularization process. Therefore, we may assume that all LMXB progenitors feeding the direct-SN formation channel are formed with circular orbits.

For the primordial binary population, we adopt the same initial distributions as in Paper II (eqs. [4] and [5]), except for the integral in the expression for the distribution of binaries over mass ratios and orbital separations, $g(q,A)$. The difference arises from the fact that, in the direct-SN evolutionary channel, additional companions to the primary in inner stable orbits need not be excluded, as in the case of the He SN channel. The presence of such companions and their possible interaction with the primary does not affect the evolution of the binary under study, which follows the direct-SN channel as long as its orbit is wide enough. In fact, it is conceivable that when the neutron star forms there is more than one companion for it to remain with in a bound orbit, but we will not consider the evolution of multiple systems here. The distribution of primary binaries over mass ratio, q, and orbital separation, A, is then given by

$$g(q, A) = \frac{0.075}{A}\, 0.04 q^{-2.7} \times \exp\left(-\int_{A\cdot(6.3)^{-2/3}}^{A\cdot(6.3)^{2/3}} \int_q^1 0.075 A'^{-1} 0.04 q'^{-2.7}\, dA'\, dq'\right). \quad (1)$$

The exponential term (Poisson probability) excludes from the distribution any companions more massive than the secondary in dynamically unstable orbits (see also Paper II). A plot of both the above distribution and the one appropriate for the helium star SN mechanism, for specified primary mass and orbital separation, is shown in Figure 2. Since the "exclusion zone" in orbital separation is narrower for the direct-SN channel the frequency of available progenitors is increased.

4.2. *Results*

The analytical method of our synthesis computations enables us to calculate the two-dimensional distribution, $\Phi_P(\log M_2, \log P_X)$, of neutron star–normal star binaries over donor masses, M_2, and orbital periods, P_X, at the onset of the mass transfer phase. The distribution of systems with donors in hydrostatic and thermal equilibrium, initiating mass transfer in less than 10^{10} yr and transferring mass at both sub- and super-Eddington rates, is shown in Figure 3*a*. We have chosen an intermediate value of the rms kick velocity, $\langle V_k^2 \rangle^{1/2}$, equal to 300 km s^{-1}. In Figure 3*b*, the distribution of the corresponding group of binaries formed via the helium star SN mechanism is also shown (taken from Paper II), for $\langle V_k^2 \rangle^{1/2} = 300$ km s^{-1} and $\alpha_{CE} = 0.3$ (consistent with the reference case studied in Paper II), where α_{CE} is the common envelope efficiency.

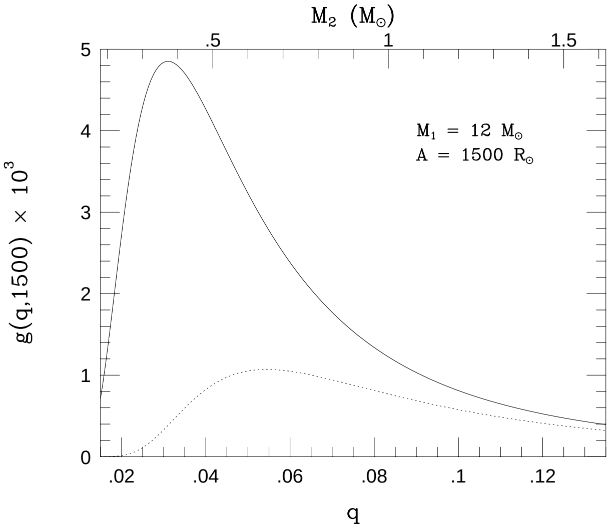

FIG. 2.—Distributions of primordial binaries with primary mass $M_1 = 12\ M_\odot$ and orbital separation $A = 1500\ R_\odot$ over mass ratios, q. The solid line corresponds to the distribution appropriate for the direct-SN channel and the dotted line to that appropriate for the helium star SN channel. The corresponding secondary masses, M_2, are also shown.

The qualitative characteristics of both distributions in Figures 3*a* and 3*b* bear many similarities, which are primarily dictated by physical processes, such as angular momentum losses and nuclear evolution of the low-mass star, common to both formation mechanisms. As we have also discussed in Paper II, the evolution of short-period binaries is dominated by angular momentum losses due to a magnetic stellar wind from the donor, and they populate a narrow range of orbital periods forming a prominent "ridge" along the zero-age main sequence. As the orbital period increases, magnetic braking becomes less effective, and a "valley" is created at $P_X \sim 1^{\rm d}$. At longer periods, it is the expansion of the donors due to nuclear evolution that is responsible for Roche lobe overflow. These systems with evolved donors populate the "hump" in the distributions at long periods and masses from ~ 1 to $\sim 1.5\ M_\odot$. We note that these systems initially drive mass transfer at super-Eddington rates (see Paper I).

By integrating $\Phi_P(\log M_2, \log P_X)$ over $\log M_2$, we obtain the distributions of systems over orbital periods, shown in Figure 4 for both the direct-SN and the He star SN mechanisms. The origin of the peaks at short orbital periods is related not only to the effect of magnetic braking but also to the flattening of the radius-mass relation along the zero-age main sequence. The plateau that appears as soon as magnetic braking becomes efficient, between 3 and 5 hr, is related to the increased incidence of primordial binaries with very low-mass companions relative to those for the He star SN formation mechanism (see Fig. 2). Systems with evolved donors formed via the He star supernova peak at orbital periods of $\sim 2^{\rm d}$, whereas for the direct-SN mechanism, systems with much longer periods are favored. This is the result of the obvious difference in orbital separation of the pre-SN binaries in the two mechanisms: systems following the direct-SN evolutionary channel are much wider ($A^{\rm DSN}_{\rm pre\text{-}SN} \sim 1000\ R_\odot$) than those following the He star SN channel ($A^{\rm DSN}_{\rm pre\text{-}SN} \sim 10\ R_\odot$), which experienced dramatic orbital shrinkage occurring during the common envelope phase.

Apart from the comparison of the qualitative characteristics of nascent LMXBs, it is also important to compare the results quantitatively based on the birthrates of the two evolutionary sequences. Although the absolute birthrates depend strongly on the assumptions regarding the essentially unknown properties of the primordial binary population and are relatively insensitive to the evolutionary stages involved in each channel, the relative birthrates are quite useful in determining the efficiency of the mechanisms in LMXB formation. In addition, the fact that both mechanisms have been modeled under the same set of assumptions renders the comparison meaningful. For our typical cases of $\langle V_k^2 \rangle^{1/2} = 300$ km s^{-1} and $\alpha_{\rm CE} = 0.3$, the birthrates of sub- and super-Eddington systems together are 6×10^{-8} yr^{-1} and 3×10^{-6} yr^{-1} for the direct-SN and the He star SN mechanisms, respectively.

5. DISCUSSION

In the direct-SN formation mechanism proposed here, there is only one free parameter, besides the assumed parent population, namely the rms kick velocity, $\langle V_k^2 \rangle^{1/2}$. We have performed synthesis calculations for a wide range of values of $\langle V_k^2 \rangle^{1/2}$ from 10 km s^{-1} up to 500 km s^{-1}. The predicted birthrates show a strong dependence on the kick velocity (Fig. 5); they span a range from $\sim 10^{-8}$ yr^{-1} to $\sim 10^{-6}$ yr^{-1} for the total population and from $\sim 10^{-9}$ yr^{-1} to $\sim 10^{-7}$ yr^{-1} for systems transferring mass at sub-Eddington rates only. The masses of the neutron star progenitors are such that all the pre-SN binaries would be disrupted in the case of a symmetric explosion. However, the survival probability through an asymmetric supernova peaks when $\langle V_k^2 \rangle^{1/2}$ is comparable to the average relative orbital velocity, $\langle V_r \rangle$, of the stars in the pre-SN binaries (Kalogera 1996). For the progenitors specific to the direct-SN mechanism we find that $\langle V_r \rangle \simeq 37$ km s^{-1}, and indeed the predicted birthrate peaks at $\langle V_k^2 \rangle^{1/2} \simeq 50$ km s^{-1} (see Fig. 5).

We can estimate the efficiency of the direct-SN mechanism relative to that involving a He star SN by comparing the corresponding birthrates. Their ratio as a function of $\langle V_k^2 \rangle^{1/2}$ is shown in Figure 6. For rms kick velocities exceeding ~ 300 km s^{-1}, the direct-SN channel appears to be responsible for a few percent of the LMXB population. For smaller kick velocities, the direct-SN mechanism contributes a growing share of the total population, with the birthrate ratio exceeding 0.5 for $\langle V_k^2 \rangle^{1/2} \sim 100$ km s^{-1} for both sub- and super-Eddington systems. In the case of the sub-Eddington systems, the direct-SN channel in fact dominates for $\langle V_k^2 \rangle^{1/2} \lesssim 50$ km s^{-1} because of the inefficiency of the He star SN channel in producing short-period systems when kick velocities are small (Paper II). We note that for more efficient common envelope ejection (e.g., for $\alpha_{\rm CE} = 1$), the direct-SN to He SN birthrate ratio decreases by a factor of 2 at high kick velocities and by about 4 at $\langle V_k^2 \rangle^{1/2} = 100$ km s^{-1}. It is evident that for the current estimates of $\langle V_k^2 \rangle^{1/2}$ the direct-SN mechanism accounts for a small but nonnegligible fraction of the total LMXB observed population. However, recent studies of the radio pulsar population (Hartman 1996) and of the Galactic distribution of LMXBs (Ramachadran & Bhattacharya 1997) provide evidence that the fraction of low-velocity pulsars may be higher than that implied by Lyne & Lorimer (1994). Such an excess of low kick velocities greatly enhances the importance of the direct-SN formation mechanism.

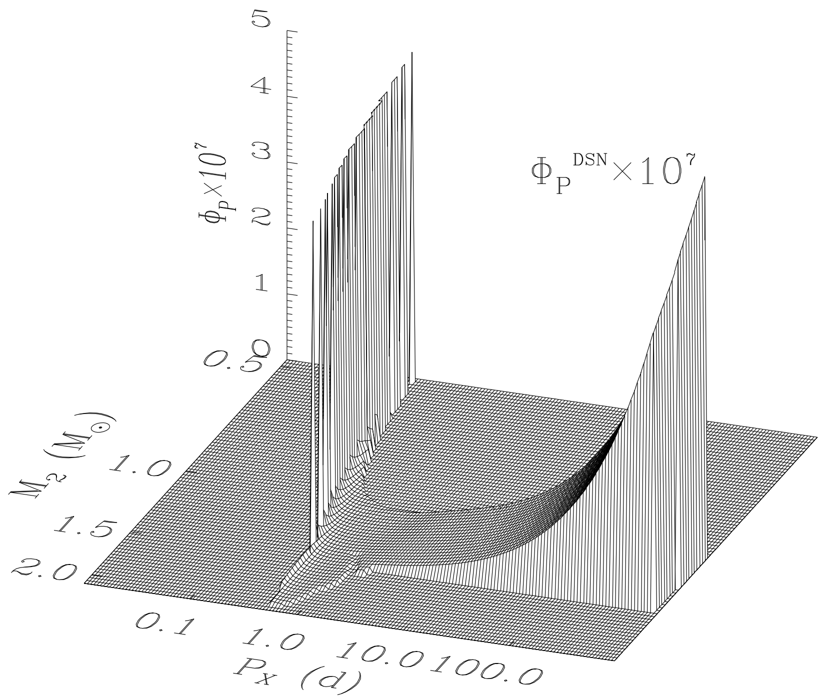

FIG. 3*a*

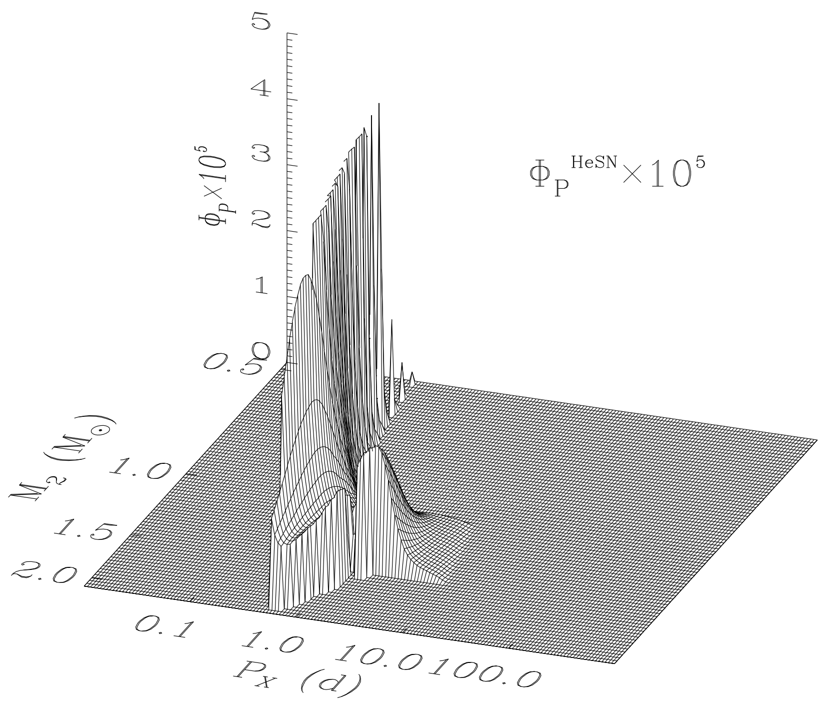

FIG. 3*b*

FIG. 3.—Distribution of binaries that transfer mass at both sub- and super-Eddington rates over donor masses, M_d, and orbital periods, P_X, for (*a*) the direct-SN and (*b*) the He star SN ($\alpha_{CE} = 0.3$) formation mechanisms.

Using our synthesis models, we can calculate the typical orbital parameters of the progenitors of LMXBs produced by the evolutionary channel studied here. For the primordial binaries, the mean primary and secondary masses are 10 $M_\odot$ and 1.2 $M_\odot$, respectively, and the mean orbital separation is 1900 $R_\odot$. The mean relative orbital velocity just prior to the supernova explosion is 37 km s^{-1}. These values, along with the two limits imposed on systemic velocities of post-SN binaries (Kalogera 1996), result in recoil velocities for these systems in the range 20–50 km s^{-1}, which are significantly lower than those of LMXBs formed via the He star SN mechanism ($\gtrsim$100 km s^{-1}; see Kalogera 1996). These low systemic velocities also indicate that LMXBs produced via the direct-SN channel in globular clusters can remain bound to the clusters, contrary to the ones produced by the He star SN channel, provided that their wide progenitors survive in such a dense stellar environment.

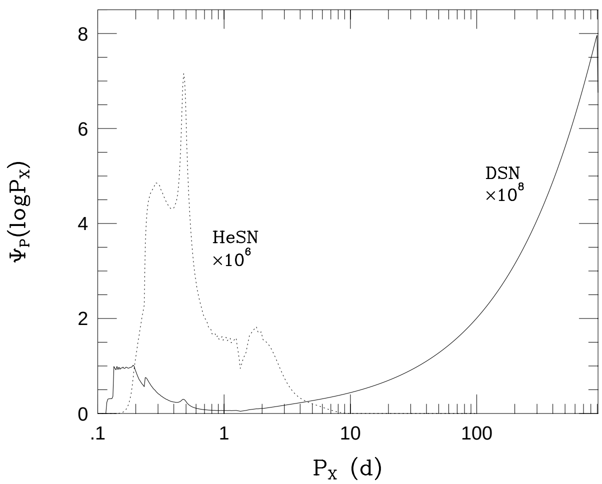

FIG. 4.—Distribution of binaries transferring mass at both sub- and super-Eddington rates over orbital periods, P_X, for the direct-SN (*solid line*) and the He star SN (*dotted line*, $\alpha_{CE} = 0.3$) mechanisms. The predicted birthrates are 3×10^{-8} yr^{-1} and 2.5×10^{-6} yr^{-1}, respectively.

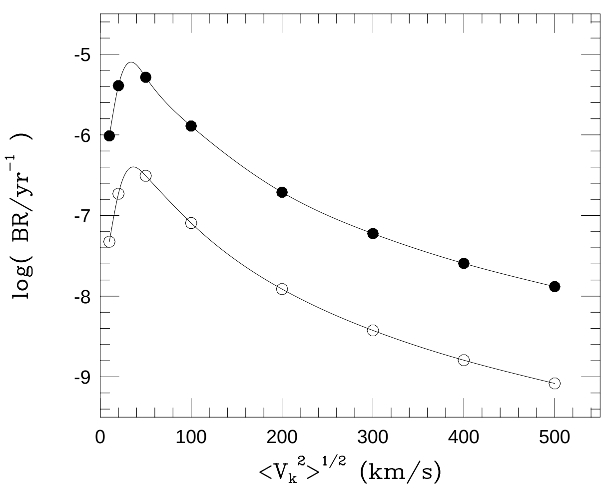

FIG. 5.—Predicted birthrates as a function of rms kick velocity, $\langle V_k^2 \rangle^{1/2}$, for both sub- and super-Eddington systems (*filled circles*) and for sub-Eddington systems only (*open circles*).

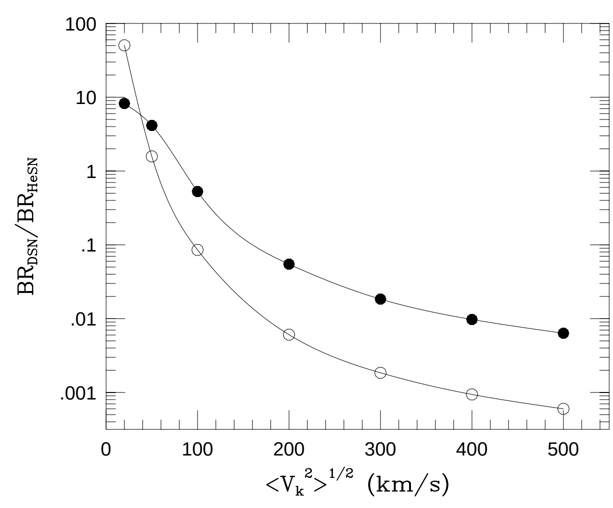

FIG. 6.—Ratio of the direct-SN birthrate to the He star SN (for $\alpha_{CE} = 0.3$) birthrate as a function of rms kick velocity, $\langle V_k^2 \rangle^{1/2}$, for both sub- and super-Eddington systems (*filled circles*) and for sub-Eddington systems only (*open circles*). For smaller common-envelope efficiencies, α_{CE}, the ratios are higher.

For the synthesis calculations presented here, we have assumed that the kick velocities follow a Maxwellian distribution. As discussed above, survival after the explosion is favored only if the kick velocity has magnitude comparable and direction opposite to that of the relative orbital velocity of the pre-SN system. Comparison between the mean orbital parameters of the progenitors and the lower limits imposed on them (see Fig. 1) indicates that the orbital separation of systems that eventually become LMXBs is restricted in a very narrow range (factor of ~ 2 from the mean value). Consequently, their systemic velocities are also concentrated in a narrow range (factor of ~ 1.4 from the mean value), and therefore kick velocities that favor survival have magnitudes between ~ 25 and ~ 50 km s^{-1}. This range of velocities is so narrow that our results become insensitive to the shape of the velocity distribution and depend merely on the relative fraction of velocities with magnitude in the appropriate range. The observed distribution of pulsar velocities (Lyne & Lorimer 1994) cannot distinguish between a Maxwellian kick distribution and a distribution that is flat up to the average velocity and has a smooth cutoff (remark made by an anonymous referee). Using a simple estimate of the relative fraction of kick velocities within the appropriate range of values, we expect that for a flat distribution the birthrate of LMXBs will be increased by a factor of ~ 10 compared to the birthrate calculated when a Maxwellian distribution is assumed with $\langle V_k^2 \rangle^{1/2} = 300$ km s^{-1}.

Apart from the connection of the new formation mechanism to LMXB production, it is also relevant to the formation of low-mass binary pulsars in circular orbits and in particular to those with orbital periods in excess of $\sim 100^d$ (such as B0820+02, B1800−27, and B1953+29; see van den Heuvel 1995). We have previously pointed out (see Paper II) that these long-period systems could not have been formed via the He star SN mechanism: an upper limit to the orbital periods of the progenitors is imposed by the requirement that the primaries fill their Roche lobes prior to the supernova explosion, as translated through a common envelope phase. The radical reduction in binary separation during common envelope evolution results in an upper limit on the orbital periods of LMXBs with evolved donors of $\sim 30^d$. Such a low upper limit cannot explain the existence of low-mass binary pulsars with orbital periods up to $\sim 1200^d$, even if one takes into account the subsequent evolution of these systems through exhaustion of the envelope of the giant donor (see, e.g., Verbunt 1993). On the other hand, no upper limit is imposed on the orbital periods of LMXB progenitors following the direct-SN channel. The maximum orbital period of these LMXBs is limited only by the maximum possible extent of evolved stars with masses of $\sim 1\ M_\odot$ to $\sim 1.5\ M_\odot$ and therefore orbital periods of $\sim 1000^d$. In the case of $\langle V_k^2 \rangle^{1/2} = 100$ km s^{-1}, the predicted birthrate of LMXBs with orbital periods in excess of 30^d formed via the direct-SN channel matches the observed fraction (2–3/15; van den Heuvel 1995) of the long-period binary millisecond pulsars, and for higher average kick velocities, the birthrate lies within a factor of about 4 from their observed incidence. Therefore, the secular evolution of these long-period LMXBs produced via the direct-SN channel appears to be a promising formation mechanism of long-period low-mass binary pulsars in circular orbits, whose progenitors are absent from the LMXB population produced by the He star SN mechanism.

It is a pleasure to thank Ron Webbink for many stimulating discussions and for carefully reading this manuscript. I would also like to thank Fred Lamb and Dimitrios Psaltis for useful comments. This research was supported by National Science Foundation under grant AST 92-18074.

REFERENCES

Burrows, A., & Hayes, J. 1996, Phys. Rev. Lett., 76, 352
Burrows, A., Hayes, J., & Fryxell, B. A. 1995, ApJ, 450, 830
Canal, R., & Schatzman, E. 1976, A&A, 46, 229
Eggleton, P. P. 1983, ApJ, 268, 368
Eggleton, P. P., & Verbunt, F. 1986, MNRAS, 220, 13P
Flannery, B. P., & van den Heuvel, E. P. J. 1975, A&A, 39, 61
Frail, D. A. 1996, in Compact Stars in Binaries, ed. J. van Paradijs, E. P. J. van den Heuvel, & E. Kuulkers (Dordrecht: Kluwer), 257
Fryer, C. L., Benz, W., & Herant, M. 1996, ApJ, 460, 801
Harrison, P. A., Lyne, A. G., & Anderson, B. 1993, MNRAS, 261, 113
Hartman, J. W. 1996, in ASP Conf. Proc. 105, Pulsars: Problems and Progress, ed. S. Johnson, M. A. Walker, & M. Bailes (IAU Colloq. 160) (San Francisco: ASP), 53
Herant, M., Benz, W., & Colgate S. A. 1992, ApJ, 395, 642
Iben, I., Jr., & Tutukov, A. V. 1995, ApJ, 456, 738
Janka, H.-T., & Müller, E. 1994, A&A, 290, 496
Kalogera, V. 1996, ApJ, 471, 352
Kalogera, V., & Webbink, R. F. 1996a, ApJ, 458, 301 (Paper I)
———. 1998, ApJ, 493, 000 (Paper II)
Lyne, A. G., & Lorimer, D. R. 1994, Nature, 369, 127
Mardling, R. A. 1995a, ApJ, 450, 722
———. 1995b, ApJ, 450, 732
Paczyński, B. 1976, in IAU Symp. 73, Structure and Evolution of Close Binary Systems, ed. P. P. Eggleton, S. Milton, & J. Whelan (Dordrecht: Reidel), 75
Ramachadran, R., & Bhattacharya, D. 1997, MNRAS, 288, 565
Schaller, G., Schaerer, D., Meynet, G., & Maeder, A. 1992, A&AS, 96, 269
Sutantyo, W. 1975, A&A, 41, 47
van den Heuvel, E. P. J. 1983, in Accretion-driven Stellar X-Ray Sources, ed. W. H. G. Lewin & E. P. J. van den Heuvel (Cambridge: Cambridge Univ. Press), 303
———. 1995, J. Astrophys. Astron., 16, 255
van Paradijs, J. 1995, in X-Ray Binaries, ed. W. H. G. Lewin, J. van Paradijs & E. P. J. van den Heuvel (Cambridge: Cambridge Univ. Press), 536
Verbunt, F. 1993, ARA&A, 31, 93
Webbink, R. 1992, in X-Ray Binaries and Recycled Pulsars, ed. E. P. J. van den Heuvel & S. A. Rappaport (Dordrecht: Kluwer), 269
Zahn, J.-P. 1977, A&A, 57, 383
———. 1989, A&A, 220, 112