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## THE FORMATION OF THE ECCENTRIC-ORBIT MILLISECOND PULSAR J1903+0327 AND THE ORIGIN OF SINGLE MILLISECOND PULSARS

S. PORTEGIES ZWART<sup>1</sup>, E.P.J. VAN DEN HEUVEL<sup>2</sup>, J. VAN LEEUWEN<sup>3</sup>, AND G. NELEMANS<sup>4</sup>

<sup>1</sup>LEIDEN OBSERVATORY, LEIDEN UNIVERSITY, P.O. BOX 9513, 2300 RA LEIDEN, THE NETHERLANDS

<sup>2</sup> ASTRONOMICAL INSTITUTE ‘ANTON PANNEKOEK’, SCIENCE PARK 904 1098 XH AMSTERDAM, THE NETHERLANDS

<sup>3</sup> STICHTING ASTRON, PO BOX 2, 7990 AA DWINGELOO, THE NETHERLANDS

<sup>4</sup> DEPT. OF ASTROPHYSICS, RADBOUD UNIVERSITY NIJMEGEN, HEYENDAALSEWEG 135, NL-6525 AJ NIJMEGEN, THE NETHERLANDS

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### ABSTRACT

The millisecond pulsar J1903+0327 is accompanied by an ordinary G-dwarf star in an unusually wide ( $P_{\text{orb}} \simeq 95.2$  days) and eccentric ( $e \simeq 0.44$ ) orbit. The standard model for producing MSPs fails to explain the orbital characteristics of this extraordinary binary, and alternative binary models are unable to explain the observables. We present a triple-star model for producing MSPs in relatively wide eccentric binaries with a normal (main-sequence) stellar companion. We start from a stable triple system consisting of a Low-Mass X-ray Binary (LMXB) with an orbital period of at least 1 day, accompanied by a G-dwarf in a wide and possibly eccentric orbit. Variations in the initial conditions naturally provide a satisfactory explanation for the unexplained triple component in the eclipsing soft X-ray transient 4U 2129+47 or the cataclysmic variable EC 19314-5915. The best explanation for J1903 + 0327 however, results from the expansion of the orbit of the LMXB, driven by the mass transfer from the evolving donor star to its neutron star companion, which causes the triple eventually to become dynamically unstable. Using numerical computations we show that, depending on the precise system configuration at the moment the triple becomes dynamically unstable, the ejection of each of the three components is possible. If the donor star of the LMXB is ejected, a system resembling J1903 + 0327 will result. If the neutron star is ejected, a single MSP results. This model therefore also provides a straightforward mechanism for forming single MSP in the Galactic disk. We conclude that the Galaxy contains some 30–300 binaries with characteristics similar to J1903 + 0327 and about an order of magnitude fewer single millisecond pulsars produced with the proposed triple scenario.

### 1. INTRODUCTION

The classic channel for the formation of a millisecond pulsar (MSP) requires a close binary with an extreme mass ratio ( $\lesssim 2/10$ ). This binary survives a common-envelope evolution and the subsequent supernova explosion of the primary star. The neutron star, formed in the supernova, can subsequently be spun up to a millisecond pulsar (MSP) in a phase of mass transfer from the  $\lesssim 2M_{\odot}$  Roche-lobe filling companion star, which in the process is slowly stripped from its envelope. During this phase the binary is visible as a low-mass x-ray binary (LMXB), eventually resulting in a MSP that is accompanied by a low-mass white dwarf in a relatively wide, almost circular orbit ( $e \lesssim 10^{-3}$ ) (Bhattacharya & van den Heuvel, 1991). In the Galaxy 50 such systems are known, while about 15 MSPs in the Galaxy have no companion at all (Lorimer, 2008).

The formation of the recently observed binary millisecond pulsar J1903 + 0327 cannot be reconciled with the above scenario. Its characteristics are too different: the companion star is a G-dwarf instead of a white dwarf, and the orbit is highly eccentric,  $e \simeq 0.44$  instead of the expected  $\lesssim 10^{-3}$  (Cordes & Chernoff, 1998). In addition, the average mass of the companion of known Galactic MSPs with pulse period  $< 10$  ms is  $0.22 \pm 0.17 M_{\odot}$ , whereas for J1903 + 0327 the companion mass is  $1.03 M_{\odot}$  Freire *et al.* (2010); and binary MSPs with a companion

mass  $> 0.6 M_{\odot}$  tend to have a long pulse period ( $P$ ) =  $62 \pm 76$  ms and short orbital periods ( $P_{\text{orb}} = 5.2 \pm 4.8$  days), whereas J1903 + 0327 has an extremely short pulse period of 2.15 ms and an extraordinary long orbital period of 95 days. These discrepancies with respect to the expected outcome of the standard scenario for producing a millisecond pulsar in a binary requires an exotic solution.

We propose that J1903 + 0327 was born as a rather ordinary triple star of which the inner binary is the progenitor of a LMXB, and with an outer (tertiary) star that initially is less massive than the secondary so that the inner secondary evolved first. After a common-envelope phase and a supernova explosion, mass transfer in the inner binary leads to expansion of its orbit. Depending on the orbit of the outer star a dynamical instability ensues in which one of the three stars is ejected. Such an evolution results in a MSP binary with an outer companion in either a wide orbit (if the instability is avoided), or a MSP binary if the outer companion is ejected, or a normal binary plus a single MSP if the neutron star is ejected, or if the inner secondary is ejected, a MSP with a low-mass companion in an eccentric orbit, like J1903 + 0327.

The scenario sounds exotic, and it is, but in §3 and §5 we estimate the available parameter space and calculate that this model leads to an acceptable birthrate. (We notice that in a recent paper Freire *et al.* (2010) independently also suggest this model one of possible triple

star models for  $J1903 + 0327$ .) We will now dwell on the details of our scenario in §2 and quantify the results by performing simulations of triple star systems in §4. We discuss the shortcomings of earlier proposed scenarios for the formation of  $J1903 + 0327$  in §6 and summarize our conclusions in §7

## 2. THE TRIPLE SCENARIO FOR FORMING $J1903 + 0327$

We propose that the binary  $J1903 + 0327$  was born as a rather ordinary triple star. We envision a configuration at birth where a relatively massive  $9\text{--}12 M_{\odot}$  primary star was orbited by a secondary star of  $\sim 0.8$  to  $2.0 M_{\odot}$  in a relatively close ( $\sim 200 R_{\odot}$ ) orbit, and a tertiary star which is less massive than the secondary and has a rather wide  $\gtrsim 560 R_{\odot}$  orbit around the inner binary. Adopting a tertiary mass that exceeds the secondary would considerably change the outcome of the evolution, because in that case it is the outer star that ascends the giant branch and possibly fills its Roche lobe before the inner binary has turned into a LMXB. The evolution of such triples has not yet been subject to any study (Eggleton & Kiseleva, 1996; Eggleton, 2006).

When the massive primary of the initial triple ascends the red-giant branch a common-envelope ensues (Webbink, 1984; Taam & Sandquist, 2000; Deloye & Taam, 2010; Ge *et al.*, 2010), in which the inner secondary and the degenerate core of the giant spiral in towards each other. A few Myr later, the stellar core explodes as a supernova, forming a neutron star with a low-mass companion in an eccentric orbit with a period of a few to several tens of days (Deloye & Taam, 2010). The outer orbit is likely influenced both by the mass shell ejected in the common envelope, as well as by the supernova explosion. The mass shell containing 6 to  $10 M_{\odot}$ , may slow down the outer companion star, which may cause its orbit to shrink, but the removal of mass from the system may also widen it. The supernova explosion causes the inner binary to receive a velocity kick (Blaauw, 1961; Dewey & Cordes, 1987) which changes the orbits and may disrupt the triple. The kick results from two subsequent effects; the mass loss in the explosion and the intrinsic velocity kick imparted to the newly formed neutron star (see §5.2 for details). In the case of an electron-capture supernova the latter effect is expected to result in a relatively low-velocity kick  $< 50 \text{ km/s}$  (Dewey *et al.*, 2005), which generally suffices to keep the outer orbit bound by compensating the effect of the mass loss in the supernova. In the surviving systems mass transfer will ensue in the inner binary after several Gyr. This rapidly circularizes the inner orbit by tidal forces and turns the system in a Low Mass X-ray Binary (LMXB) resembling the bright Galactic bulge LMXBs (Webbink *et al.*, 1983; Taam, 1983). An example of such a triple is 4U 2129+47 (V1727 Cyg), in which a 5.24 hour LMXB is accompanied by a spectral type F-dwarf in an eccentric orbit of about 175 days (Garcia *et al.*, 1989; Bothwell *et al.*, 2008; Lin *et al.*, 2009). For our model we require that, contrary to 4U 2129+47, at the moment of RLOF the LMXB has a period of at least  $\sim 1$  day and will evolve to longer periods, rather than shrink due to the emission of gravitational waves (Pylyser & Savonije, 1988, 1989). In the case of 4U 2129+47, the inner orbit will not expand due to the mass transfer and therefore will not perturb the outer orbit.

Mass transfer in the inner binary causes the accreting neutron star to be spun up to a millisecond spin period (Alpar *et al.*, 1982; Radhakrishnan & Srinivasan, 1982). After several tens of millions of years, the expansion of the inner orbit leads to a dynamically unstable situation with respect to the orbit of the outer star. Depending on the precise configuration at the moment when the system becomes dynamically unstable, either the donor of the LMXB, or the outer tertiary star or the neutron star can be ejected from the unstable triple. In the latter case a single MSP results, in the first-mentioned case a wide eccentric millisecond binary pulsar with a G-dwarf companion is produced, resembling  $J1903 + 0327$ .

## 3. CONSTRAINING THE BIRTH CONDITIONS FOR $J1903 + 0327$

We investigate the conditions under which the proposed triple scenario produces a system similar to  $J1903 + 0327$ . With the currently observed orbital parameters of  $J1903 + 0327$  ( $a \simeq 123.2 R_{\odot}$ ,  $e \sim 0.44$ ,  $m_G \simeq 1.03 M_{\odot}$  and  $M_{\text{MSP}} \simeq 1.67 M_{\odot}$  (Freire *et al.*, 2010)) the binding energy of the binary is about  $E_b \simeq 2.65 \times 10^{46}$  erg. This poses a minimum to the binding energy of the triple just before it became dynamically unstable, and allows us to calculate the orbital separation of both the inner and the outer orbit at the moment that the dynamical instability sets in. In practice the binding energy of the stable triple will be higher than  $E_b$  by the ratio of the masses of the ejected star with respect to the triple, or  $\sim 20\%$  (Heggie, 1975; Fregeau *et al.*, 2004), because the escaping star carries off some fraction of the binding energy to infinity.

The requirement that the binding energy of the triple must exceed  $E_b$  allows us to calculate the orbital separation of both the inner and the outer orbit at the moment that the dynamical instability sets in. The criterion for dynamical stability sensitively depends on the separation and the eccentricity of the inner and outer orbits, and on the masses of the three stars (Mardling & Aarseth, 2001). However, for the observed system  $J1903 + 0327$  only the masses of two of the stars (the MSP and its current G-dwarf companion) are known, as the initial secondary star was ejected from the binary.

The initial donor in the LMXB must have been more massive than the current MSP companion in order to evolve first, but not so massive that mass transfer in the LMXB would be unstable; we therefore adopt a mass of the original close companion of the neutron star of  $1.0\text{--}2.0 M_{\odot}$  (In principle a secondary mass as low as  $0.8 M_{\odot}$  would suffice to warrant the inner binary to evolve into a LMXB, but in that case the tertiary star should be  $< 0.8 M_{\odot}$ , which is smaller than than the observed  $1.03 M_{\odot}$ ). For the neutron star we adopt a mass of  $1.30 M_{\odot}$  before it starts accreting mass (Schwab *et al.*, 2010), and in the same range of masses, but less massive than the inner secondary star for the outer companion. In the specific case of  $J1903 + 0327$  the observed star is an  $1.03 M_{\odot}$  G-dwarf, which in our scenario would be identical to the initial tertiary star. The best match to the orbital characteristics are then obtained when we adopt the initial secondary mass to be  $\sim 1.1 M_{\odot}$ .

During the LMXB phase mass is transferred from the inner companion (donor) to the neutron star. The time averaged mass-transfer rate can be estimated from the em-

irical relation based on the initial orbital period of the LMXB (Shore *et al.*, 1994). In our model we assume that the neutron star accretes at most at the Eddington limit; for which we adopted  $\dot{m} = 1.5 \times 10^{-8} M_{\odot}/\text{yr}$ . The left-over mass that is provided by the donor but that is not accreted by the neutron star is assumed to leave the inner binary with the specific orbital angular momentum of the neutron star (Portegies Zwart, 1995). The currently observed mass of the neutron star is  $1.67 M_{\odot}$ , which indicates that in our model it must have accreted about  $0.37 M_{\odot}$ , and that the donor star must have lost at least that same amount of mass. Mass transfer in such a binary system causes the orbit to expand quite dramatically, in particular if the mass transfer was not conservative.

We can now determine the separation of the inner and the outer orbit for the initial triple (before the LMXB-phase) by an iterative procedure under the constraints that the total binding energy of the triple at the moment it became dynamically unstable is known, and by taking the effect of the mass-transfer process during the LMXB phase into account. Here we assumed that the mass lost from the LMXB leaves the triple in the form of a stellar wind. The resulting orbital constraints of this iterative procedure are presented in Fig. 1 as the solid and dashed curves; these give the most likely initial conditions for forming J1903 + 0327.

With the semi-analytic procedure just described we still cannot predict the consequence of the dynamical instability, in particular because the final stage of the triple is highly dynamic and the orbital parameters do not allow us to predict the identity of the ejected star from first principles. However, one can imagine that it is quite likely that the less massive donor ( $< 0.73 M_{\odot}$  when we adopt an initial secondary mass of  $1.1 M_{\odot}$ ) is ejected, rather than the more massive MSP ( $\sim 1.67 M_{\odot}$ ) or the outer star ( $\sim 1.03 M_{\odot}$ ). At the moment when the dynamical instability sets in the donor still has part of its Hydrogen envelope, which explains why its mass exceeds that of the degenerate Helium core.

#### 4. SIMULATING MASS TRANSFER IN A TRIPLE SYSTEM

We quantify our proposed formation channel for J1903 + 0327 by performing extensive computer simulations of triple systems, starting at the onset of the LMXB phase. The calculations were performed using the Astrophysics Multipurpose Software Environment (AMUSE)<sup>a</sup>(Portegies Zwart *et al.*, 2009).

In the AMUSE environment we resolve the dynamical evolution of the triple-star by a specialized numerical orbit integration, which is written in FORTRAN77. The mass transfer in the inner binary is implemented in python. The outer star is treated as a point-mass and was not evolved during the simulation. The coupling between the numerical orbit integration of the three stars and the stellar evolution calculations is realized using AMUSE (Portegies Zwart *et al.*, 2009). The most important role of AMUSE is converting the units and to realize the communication between the two codes. The former is done with a specialized unit conversion module and for the latter we spawned the different processes using the Message Passing Interface (MPI) to transfer the required data in the proper

units and in discrete instances between the two codes.

#### 4.1. Numerical Method

The orbits of the triple stars were integrated using a regularized version of the Burlish-Stoer integrator (Aarseth & Zare, 1974a,b), keeping the numerical error at machine precision, and allowing a maximum relative energy error of  $O(10^{-14})$  per integration of the outer orbit.

During the dynamical evolution we resolved the mass transfer and consequential change in orbital parameters of the LMXB that is orbited by the outer star.

The rate of mass-transfer in the inner binary is calculated from the empirical relation based on the orbital period at the onset of RLOF in the LMXB:  $\langle \dot{m} \rangle = 6 \times 10^{-10} (P_{\text{orb}}(\text{initial})/1\text{day}) M_{\odot}/\text{yr}$  (Shore *et al.*, 1994).

The neutron star was allowed to accrete at most at the Eddington rate and any surplus mass is assumed to leave the binary with the angular momentum of the accreting neutron star, but lost adiabatically from the triple.

We perform the mass transfer in the inner binary every time the outer orbit has had 10 revolutions, after which the numerical orbit integration was updated using the newly calculated orbital parameters which resulted from carrying out the mass transfer. We varied the interval between which mass transfer in the inner binary was conducted between every 1 to 1000 outer orbits, but this choice did not significantly affect the results. (In § 5.3 we present the results of a series of simulations where we decoupled the mass-transfer process from the gravitational evolution after the triple has become dynamically unstable.)

#### 4.2. Results of the simulations

We initialized  $10^3$  binaries and calculated the evolution for each up to an age of at most 10 Gyr or until the mass of the donor star drops to the mass of the degenerate helium core for a population-II star ( $\lesssim 0.4 M_{\odot}$ , Tauris & Savonije, 1999).

Each triple was initialized by randomly selecting the eccentricity of the outer orbit from the thermal distribution and the initial separations of the inner and outer orbits for each triple-evolution calculation are selected using the iterative procedure described in § 3 (see the thick solid and dashed curves in Fig. 1). For each simulated binary we randomly selected the inclination of the inner orbit with respect to the outer orbit, the longitude of the ascending node, the argument of periastron and the phases of the two orbits. The preference in the orbital elements introduced by the supernova explosion may affect the rate of ejected MSPs relative to those that stay in a binary, but we ignore that complication. We found no significant correlations between the final outcome of the simulations and longitude of the ascending node, the argument of periastron or the phases of the two orbits. The anisotropic velocity caused by the mass loss in the supernova of the inner binary therefore is not expected to have a significant effect on the surviveability of the triple.

During the evolution of the triples, small eccentricities ( $\lesssim 0.1$ ) are commonly induced in the inner orbit, in particular when the triple approaches the regime where it becomes dynamically unstable. We stop a simulation when the eccentricity of the inner (LMXB) orbit exceeds 0.3 for

<sup>a</sup>see <http://www.amusecode.org>

more than  $10^5$  years. Such high eccentricities can be induced shortly by a strong interaction with the outer star, which typically results in the break-up of the triple, or by a long term secular perturbations of the inner orbit by the outer star (Kozai, 1979). In the latter case orbital variations result naturally from the secular evolution of the triple and do not directly lead to a dynamical instability. We still decided to terminate such simulations because it becomes hard to follow the mass-transfer process within the inner binary. It would require extensive hydro-dynamical simulations to study the consequences of a Kozai resonances in a triple with a Roche-lobe filling inner binary. About 10% of our simulations were stopped as a consequence of this effect. Mass transfer in eccentric orbits is generally ill understood, although courageous attempts are underway to tackle this problem (Sepinsky *et al.*, 2009, 2010; Lajoie & Sills, 2010a,b).

The majority (917) of the binaries become dynamically unstable long before the other stopping criteria apply, in which cases we continue to resolve the dynamics by integrating the equations of motion and resolving the internal mass transfer until one of the stars escapes. The orbital separation of the LMXB at which the triple is expected to become unstable is indicated by the dotted curve in Fig. 1.

An illustrative example of the evolution of the period of the inner and outer orbits is presented in Fig. 2. The evolution of the inner LMXB also drives the expansion of the outer orbit, in particular by the dynamical coupling between both orbits and in a lesser extend by the mass lost from the inner LMXB in those cases that mass transfer proceeds non-conservatively. This relative softening causes the final MSP binaries to be somewhat wider than observed in *J1903 + 0327*, and as a consequence the triple remains stable for somewhat longer than expected based on our analytic energy balance (see §3), and eventually results in the MSP to be somewhat more massive (by about  $0.2 M_{\odot}$ ) than observed in *J1903 + 0327*. We can compensate for this by adopting a slightly ( $\sim 20\%$ ) smaller outer orbital separation at the onset of the LMXB phase.

The resulting parameters of the MSP with G-star binary are presented in Fig. 3, and straddle the observed orbital separation and eccentricity of *J1903 + 0327*. The phase of mass transfer for these binaries lasted for about  $23.4 \pm 9.3$  Myr, after which the donor was ejected in about one-fifth  $\sim 20\%$  of the cases. The resulting binaries, for those with  $a < 10^4 R_{\odot}$ , had an average orbital separation of  $175 \pm 145 R_{\odot}$ , and an eccentricity of  $0.65 \pm 0.19$ . During the LMXB phase, the neutron stars were able to grow from  $1.30 M_{\odot}$  to  $1.64 \pm 0.12 M_{\odot}$ . The mean mass of the ejected donor was  $0.72 \pm 0.13 M_{\odot}$ .

Our success in reproducing the observed parameters of the binary MSP *J1903 + 0327* demonstrates that its progenitor may well have been born as a triple star. However, the here described pin-pointed search of parameter space makes it impossible to derive the birthrate for *J1903 + 0327*, which we will calculate in the next §.

## 5. HOW MANY *J1903 + 0327*-LIKE SYSTEMS ARE THERE IN THE GALAXY?

We calculate the formation rate of *J1903 + 0327*-like systems by determining their birth rate with respect to that of ordinary LMXBs. The reason for this approach is the great uncertainty in the number of LMXB progen-

itors because binaries with such extreme mass ratios are observationally unknown.

This ratio depends on several factors

1. The number of triple systems with suitable parameters.
2. The fraction of triples that ensues and survive the common-envelope phase and the supernova explosion in which the neutron stars is formed
3. The fraction of those triples that lead to *J1903 + 0327*-like systems (instead of single MSPs, classic MSP binaries or MSP binaries with a triple companion)

We will discuss each these factors below, in § 5.1, §5.2 and § 5.3, respectively.

### 5.1. *The number of suitable triple stars*

According to the Hipparcos database the ratio of hierarchical higher order multiple stellar systems (404) to binaries (1438) is  $404/1438 \sim 0.22$  and the outer star have a rather flat mass distribution (Eggleton & Tokovinin, 2008, 2010). We assume that for (inner) binaries that are progenitors to LMXBs the same ratio holds, even though there are none in this catalogue. We further require that the mass of the outer stars is about ten times lower than that of the inner binary. We then find a ratio of suitable triples to LMXB progenitor binaries of a few per cent. We present in §6.2 observational evidence that indeed such triples exist.

### 5.2. *The fraction of triples that survive the supernova explosion*

We will not dwell on the details of the common envelope evolution, but assume that it leads to the spiral-in of the inner two components without much affecting the outer star. The consequences of the common envelope do not qualitatively affect our result, but have a strong effect on the derived birth rate (see §5.4). In §6.2 we discuss that the orbit of the tertiary star that orbits the LMXB 4U 2129+47 may have experienced a considerable reduction during the common-envelope, but we consider this insufficient evidence to draw general conclusions regarding the effect of the common envelope on the outer orbit.

The effect of the supernova explosion in the inner binary on the orbital parameters of the triple can be calculated relatively straight-forward, and has a profound effect on the survivability of the triple because the weakly bound outer orbit is easily disrupted.

The mass loss in the supernova explosion causes the inner binary to be ejected (Blaauw, 1961; Boersma, 1961). In order to keep the triple bound a small asymmetric velocity kick imparted to the newly formed neutron star is required (Hills, 1983; Brandt & Podsiadlowski, 1995; Tauris & Takens, 1998). In Fig. 4 we show the survival probability of several combinations of inner and outer orbits as function of the asymmetric kick magnitude. In these calculations the effect of the Blaauw-Boersma kick was self-consistently taken into account to calculate the survival probability. This fraction ranges from  $\sim 40\%$  for small kicks to zero for kicks significantly above  $100 \text{ km s}^{-1}$ .

To study the future evolution of the triple through the LMXB phase, we need to derive the orbital parameters as a function of the most probable kick velocity and the amount of mass lost in the supernova. We consider several combinations of both, and the distinction between them can be made by the mass of the initial primary star and the moment it filled its Roche-lobe.

In §3 we discussed the most likely range of parameters at birth, and we adopt these same numbers here to study the survivability of the triple. Here we make a distinction between two types of supernovae; in one case we adopt that the inner primary at the moment of the supernova is a  $1.9M_{\odot}$  Helium star with a degenerate ONeMg core that is the left-over of the initial  $9\text{--}12M_{\odot}$  primary star. If the initial primary star was born somewhat more massive,  $10\text{--}13M_{\odot}$  and was stripped from its Hydrogen envelope at a later stage of its evolution its Helium core may have grown to  $\sim 2.7M_{\odot}$ . The ONeMg star that experiences an electron-capture supernova loses  $\sim 0.6M_{\odot}$  and if the exploding star has a more massive Helium core the mass loss is  $\sim 1.4M_{\odot}$ . In both cases we adopt a neutron star mass of  $1.30M_{\odot}$ .

Apart from the smaller mass lost in the explosion of the ONeMg core, the neutron star is also expected to receive a smaller velocity kick upon birth. For these electron capture supernovae we adopted a Gaussian distribution for the velocity kick with a dispersion of  $20\text{ km/s}$  (Podsiadlowski *et al.*, 2004; Scheck *et al.*, 2004) in a random direction. From studies of single radio pulsars in the solar neighborhood several kick velocity distributions have been constructed (Lyne & Lorimer, 1994; Hansen & Phinney, 1997; Cordes & Chernoff, 1998; Arzoumanian *et al.*, 2002), most of them with considerably higher velocity than for the ONeMg supernovae. These latter kick velocity distributions are expected to be more suitable for neutron stars formed from an isolated star or a non-interacting binary, in which case the neutron star is formed by the collapse of an iron core (van den Heuvel, 2004; Podsiadlowski *et al.*, 2004). These kicks range from single (zero-centered) Gaussian distributions with a velocity dispersion of  $265\text{ km/s}$  Hobbs *et al.* (2005) to more complicated distributions like the proposed two Gaussians with dispersions of  $175\text{ km/s}$  and  $700\text{ km/s}$  and relative probability of  $0.86$  and  $0.14$ , respectively (Cordes & Chernoff, 1998).

We study the probability that a triple survives the supernova by means of Monte-Carlo simulations. The simulated triples had the following characteristics: The inner binary consists of a  $1.9M_{\odot}$  Helium star with a degenerate ONeMg core or a  $\sim 2.7M_{\odot}$  Helium star, and a  $0.8\text{--}2.0M_{\odot}$  secondary. The latter was selected randomly with equal probability within the interval. The orbital separation of the circular inner binary was taken flat in log between  $1R_{\odot}$  and  $100R_{\odot}$ . We adopted these parameters from the population synthesis calculation of LMXBs (Willems & Kolb, 2003), in particular using the results of their models KM25 to KM100 of (Willems & Kolb, 2003).

The mass of the tertiary star was selected to be less massive than the secondary, but not smaller than  $0.8M_{\odot}$  (in theory there is no lower limit for the mass of the tertiary star). The outer orbital separation was chosen with a probability distribution flat in log with a maximum of  $10^4R_{\odot}$ . The minimum separation was chosen to be consistent with

a dynamically stable initial triple (adopting a  $10M_{\odot}$  primary and an inner orbital separation of  $200R_{\odot}$ ) and the earlier selected secondary and tertiary masses. The latter two stars were assumed not to accrete any material throughout the common envelope and supernova explosion. The eccentricity of the outer orbit before the supernova was selected at random from the thermal distribution between a circular orbit and a maximum which was chosen such that the triple is dynamical stable. The selection of the minimum orbital separation of the outer star and its eccentricity therewith becomes an iterative procedure. The other orbital elements are selected randomly, as we described in §4.2.

For each system we calculate the effect of the combined Blaauw-Boersma and intrinsic velocity kick on the inner and the outer orbit, the latter kick was assumed to be isotropic. In our simulations we varied the mass loss in the supernova and the velocity distribution of the asymmetric kick. For electron-capture supernovae (Podsiadlowski *et al.*, 2004) the fraction of surviving triples is  $1/3$ . For higher kick velocities we adopted that the exploding star was  $2.7M_{\odot}$  and as a consequence the fraction of survivors drops to  $1/25$  (Arzoumanian *et al.*, 2002),  $1/28$  (Hobbs *et al.*, 2005) and  $1/50$  (Cordes & Chernoff, 1998) where the quoted literature refers to the adopted kick velocity distribution. Note here that the smaller amount of mass lost in the electron-capture supernova explosions helps considerably in preserving more triples, as opposed to the more violent kicks.

We conclude that for every 3 inner binaries that survive the electron-capture supernova the outer tertiary star remains in orbit around the inner binary, but that this fraction may drop considerably (to  $1/50$ ) when more mass is ejected in the supernova shell and the kick velocity is higher. Varying the amount of mass lost in the supernova explosion has a profound effect on the survivability of the triple, in particular since the Blaauw-Boersma kick imparted on the inner binary is proportional to this mass loss, and to the relative orbital velocity of the inner binary. It is interesting to note that the vast majority of the triples that survive the supernova explosion are dynamically stable, but their orbital eccentricity tend to be considerably higher than according to the thermal distribution.

### 5.3. The fraction of surviving triples that lead to systems like J1903 + 0327

We synthesize the Galactic population of binaries like J1903 + 0327 by randomly selecting  $10^4$  triples that survived the supernova explosion of the previous §, and continue their evolution in AMUSE (see §4.1). Instead of performing a self-consistent evolution as adopted in §4.2 to validate the proposed scenario, we tentatively decoupled the mass transfer process from the orbit integration. The population synthesis simulations start by resolving the mass transfer in the inner binary until the triple becomes dynamically unstable (Mardling & Aarseth, 2001), after which we continue the simulation by resolving the dynamics of the 3-body system until one star is ejected. During this latter part we ignore the mass transfer.

Note that this decoupled approach, though computationally cheaper by about a factor of  $10^3$ , is not a-priori less reliable than the self-consistent simulations in §4.2, because our numerical methods provide no self consistent

way to resolve the mass transfer process in eccentric orbits.

The majority ( $\gtrsim 90\%$ ) of our simulations lead to the disruption of the triple, which results in the ejection of the initial primary (MSP), the secondary (partially stripped sub-giant or white dwarf) or the tertiary (main-sequence F-, G- or K-dwarf) star, leaving the other two stars in a binary. The respective ratio at which these occur are 0.013, 0.683 and 0.304 for circular outer orbits (which is unlikely after the supernova) to 0.03, 0.489, and 0.481 for highly eccentric ( $e \sim 0.9$ ) orbits. For extremely high eccentricities ( $e \sim 0.99$ ) these fractions become 0.05, 0.75 and 0.20, respectively. The outer orbits tend to have high eccentricities because they often barely survive the supernova kick, and as a consequence the total fraction of systems in which the MSP remains in a binary with the original outer component is  $\lesssim 0.5$ ; the fraction of single MSPs is  $\sim 0.05$ .

The two methods through which we resolved the triples (self-consistent, see § 4.1, as opposed the here adopted decoupled approach) give slightly different results, but these can be related to the variation of the implementations. The biggest effect is illustrated in Fig. 2, where we demonstrated how the slow changes in the inner orbit drive the secular evolution of the outer orbit. The main consequences of this coupling are the higher mass of the neutron star by the time the triple becomes dynamically unstable and the small fraction of triples that survive the entire evolution because the adiabatic expansion of the outer orbit prevents the triple from becoming dynamically unstable. The consequential loss of systems however, is well compensated by the increased probability that the donor in the LMXB is ejected when the triple becomes dynamically unstable. The differences between the two numerical implementations affect our estimates for the birthrate (see § 5.4) on a  $\lesssim 20\%$  level. For clarity, the statistical uncertainties between the two different numerical approaches depend on Poissonian arguments rather than on the lack of our understanding of parts of the physical process, such as the common envelop evolution, the process of mass transfer in non-circular orbits and the non-linear effects in the dynamically unstable configuration just before the triple is resolved. We control the latter by adopting a high order and numerically extremely precise algorithm (see § 4.1). However, the tipping-point physics of ejecting the MSP, its close white-dwarf companion or the main-sequence outer star remains elusive, even when integrating near machine precision.

#### 5.4. *The number of J1903 + 0327-like systems in the Galaxy*

The ratio of the birth rates of ordinary LMXBs to systems like J1903 + 0327 is a combination of the factors derived above: a few per cent for the number of suitable triples, a reduction of a factor of  $\sim 3$  owing to the effect of an electron-capture supernova, and then a fraction  $\lesssim 0.5$  of systems in which the inner secondary is ejected. For larger average kick velocities (Cordes & Chernoff, 1998; Arzoumanian *et al.*, 2002) the fraction of triples that survive the supernova drops from 1/3 to 1/50 (see § 5.2). The higher kicks cause an even stronger reduction in the number of single MSPs, because outer orbits tend to be highly eccentric, which leads to a reduction of the probability that the MSP is ejected once the triple becomes dynamically

unstable. The birth rate for systems like J1903 + 0327 is then in the range of  $2 \times 10^{-4}$  to  $3 \times 10^{-3}$  times the birth rate of ordinary LMXBs. Estimates of the total number of LMXBs in the Galaxy are in the range  $10^4 - 10^5$  (Cote & Pylyser, 1989). The typical life time of a LMXB is of the order of a Gyr, whereas the life time of systems like J1903 + 0327 is limited by the life time of the MSP and the difference between that of the inner secondary star and the outer tertiary star. Both stars have a mass of the order of  $1 M_{\odot}$  and their lifetimes exceed several Gyr, which is a factor of a few longer than the lifetime of the LMXB phase. The number of J1903 + 0327-like systems in the Galaxy then is at least 30–300 for electron-capture supernovae but drops to 3–30 when we adopt considerably more mass to be lost in the supernova and higher velocity kicks (Cordes & Chernoff, 1998; Arzoumanian *et al.*, 2002).

## 6. DISCUSSION

We went through considerable effort to explain the existence of J1903 + 0327 as the result of the complex evolution in a hierarchical triple star system. In this section we will argue that though, unlikely as it sounds, our proposed model is currently the only viable model available, and that all other existing models fail to explain all the characteristics of J1903 + 0327. After that we will indicate a number of other sources that have evolved in quite a similar way, and that therefore support the triple scenario.

### 6.1. *Shortcomings of earlier models for J1903 + 0327*

In the triple scenario for the formation of J1903 + 0327 proposed by Champion *et al.* (2008), the observed  $\sim 95$  day orbital period is that of an unobserved massive  $0.9-1.1 M_{\odot}$  white dwarf, while the observed G-dwarf has a considerably wider orbit. The observed eccentricity of the inner orbit would in this case be driven by the secular evolution via the Kozai mechanism (Kozai, 1962). This scenario has a number of serious shortcomings, one of which is the unusually high white-dwarf mass, which leaves little room to produce a massive  $1.67 M_{\odot}$  neutron star. Since its discovery, the observed change in eccentricity  $\dot{e} \sim 10^{-16} s^{-1}$  is three orders of magnitude smaller than predictions based on the Kozai mechanism (Gopakumar *et al.*, 2009), which excludes the presence of a highly inclined tertiary star. We exclude this scenario therefore from further consideration.

An alternative to the previous model would be the direct formation of a MSP in a supernova explosion, or via the fall-back of material in a circum neutron-star disk (Liu & Li, 2009). A variety of arguments against the direct formation of rapidly spinning pulsar with a small surface magnetic field ( $2 \times 10^8$  G) was provided by Champion *et al.* (2008). These include: first, of the 50 neutron stars in young supernova remnants, none are fast-spinning low-field pulsars (Kaspi & Helfand, 2002). Second, a "born-fast" scenario for J1903 + 0327 would likely account for the 15 isolated MSPs detected in the galactic disk, but the spin distribution, space velocities and energetics of these single MSPs are indistinguishable from those of recycled, not "born fast" binary MSPs (Archibald *et al.*, 2009); while their space velocities and scale heights do not match those of non-recycled single pulsars (Lorimer *et al.*, 2007). Third, magnetic fields in young pulsars likely originate either from dynamo action

in the proto-NS (Thompson & Duncan, 1993) or through compression of “frozen-in” fields of the progenitor star during collapse (Ferrario & Wickramasinghe, 2006), and no young pulsars with  $B \lesssim 10^{10}$  Gauss, like  $J1903 + 0327$ , are known. We add a fourth argument: before the direct collapse, the NS progenitor ascends the giant branch star and common-envelope evolution with the 95 day-orbit G-dwarf would have dramatically reduced the orbital period, in the same way as normal LMXBs form. For these four reasons, a core-collapse “born-fast” MSP can be ruled out.

The above arguments hold equally well against the accretion-induced collapse of a massive and rapidly rotating white dwarf to a neutron star (NS). While this may lead to millisecond rotation periods, the NS formed here will be just as hot and differentially rotating during the early liquid phases as a NS formed by core collapse. In both cases  $10^{53}$  erg in gravitational energy is released, which will erase all memory of the violent mechanism in which the NS was formed. Therefore, dynamo action in both cases will not depend on the formation mechanism, and there is no fundamental reason for expecting a weak magnetic field in NSs formed by accretion-induced collapse. Furthermore, the direct accretion-induced collapse of a white dwarf to a MSP in population studies produces binaries with an orbital period  $\lesssim 20$  days, which is considerably shorter than observed in  $J1903 + 0327$  (Chen *et al.*, 2010). In addition this scenario requires the white dwarf to accrete from an evolved companion star, which is inconsistent with the observed main-sequence companion G-star. This model thus fails to explain  $J1903 + 0327$ .

Finally, a formation scenario where  $J1903 + 0327$  is formed when the donor star in the inner binary is ablated and destroyed, like is the case for the “black-widow” system PSR B1957+20 (Fruchter *et al.*, 1988), has three problems. First, the observed timescales for straightforward evaporation of the donor star are too long (Champion *et al.*, 2008). Second, formation of such a system likely involves an exchange interaction (King *et al.*, 2003), which would be greatly impeded by the outer G-dwarf companion. Third, even if no exchange took place, the slow evaporation of the donor in the inner binary requires the triple to be dynamically stable with respect to the G-star in its current orbit. Since the supernova explosion can at most account for a reduction of a factor of 2 in the orbital separation, the common-envelope should in that case be responsible for a further reduction from the initial orbital separation of  $\gtrsim 560 R_{\odot}$  to the currently observed  $\sim 123 R_{\odot}$ , which requires considerable fine tuning. We therefore conclude that  $J1903 + 0327$  is unlikely to have originated through a black-widow-like scenario.

Each of the above models has serious shortcomings, and we conclude that none of the scenarios discussed above give a satisfactory explanation for the formation of  $J1903 + 0327$ .

### 6.2. The missing link

There are currently no triples known with parameters suitable for evolving into systems like  $J1903 + 0327$ . However, there is observational evidence that such triples exist, as it is proposed that 4U 2129+47 (V1727 Cyg), a 5.24 hour LMXB, is accompanied by a spectral type F-dwarf in an eccentric orbit of about 175 days (Garcia *et al.*, 1989; Bothwell *et al.*, 2008; Lin *et al.*, 2009). This triple

can have formed in the same way as  $J1903 + 0327$  with the exception that after the common-envelope and the subsequent supernova explosion the inner binary period was smaller than the bifurcation period, of about one day (Pylyser & Savonije, 1988, 1989). The consequence of such a short orbital period is that the LMXB evolves to an even shorter orbital period. Interestingly the 175 day orbit of the outer star is too small to have been dynamically stable at the birth of the triple (Mardling & Aarseth, 2001). We argue that the common-envelope and/or the supernova may have reduced the orbital separation of the outer star.

We validated the probability that a binary orbit shrinks as a result of the supernova by means of population synthesis and conclude that in a fraction of 0.511 of the triples that survive the supernova the separation of the circularized outer orbit is smaller than the initial orbit. However, if the progenitor of 4U 2129+47 had parameters comparable to what we derived for  $J1903 + 0327$  in §2, the common-envelope phase of the inner binary must have resulted in a reduction of the outer orbit as well, by  $\gtrsim 210 R_{\odot}$ . Such a reduction in the separation of the outer orbit by the common envelope enormously boosts the survivability of the triple in the supernova explosion (see Fig. 4), and therefore dramatically increases the birthrate of binaries like  $J1903 + 0327$ .

Following the same scenario as for forming 4U 2129+47 but with a less massive ( $\lesssim 8 M_{\odot}$ ) initial inner primary star the inner binary could evolve into a cataclysmic variable such as EC 19314-5915, with an orbital period of 4.75 hours. The observed radial velocity of  $\sim 9$  km/s has been attributed to a G8-dwarf in orbit around the CV (Buckley *et al.*, 1992), which is consistent with a semi-major axis of  $\sim 2400 R_{\odot}$ .

The real missing link would be the discovery of a relatively wide ( $\gtrsim 30 R_{\odot}$ ) LMXB that is orbited by a tertiary low-mass main-sequence star. The mass-transfer phase in our simulations averaged about 23 Myr (see §4.2), while the lifetime of the MSP in  $J1903 + 0327$  is at least 1 Gyr. We therefore expect that the Galaxy contains at most 7 such wide triple LMXBs.

## 7. CONCLUSIONS

We discussed the evolution of triple star systems through a range of dramatic events, including several tidal circularizations, a common-envelope phase, a supernova and a stable phase of mass transfer that eventually leads to a dynamical instability in which one star is ejected.

In particular for producing a system like  $J1903 + 0327$  we require a triple to be born as a rather ordinary dynamically stable hierarchical system of which the inner binary consists of a 9–13  $M_{\odot}$  and a 0.8–2.0  $M_{\odot}$  star in a  $\gtrsim 200 R_{\odot}$  separation. This binary is orbited by a main sequence star with a mass smaller than the initial secondary ( $< 2.0 M_{\odot}$ ) with a semi-major axis  $\gtrsim 560 R_{\odot}$ . The chance that the triple survives the inevitable chain of events is not large but the result is profound and provides a satisfactory explanation for a number of known systems in the Galaxy, including  $J1903 + 0327$ , 4U 2129+47 (see §6.2) and EC 19314-5915.

The range in possible observable stages in the evolutionary sequence for forming a system like  $J1903 + 0327$  sensitively depends on the orbital separation of the inner bi-

nary after the supernova, which makes the distinction between evolving into a binary MSP like *J1903 + 0327* or a LMXB with an outer tertiary companion like 4U 2129+47. The evolution of the triple naturally leads to a cataclysmic variable like EC 19314-4915, if in addition to a short post-common envelope period the initial primary star evolves into a white-dwarf rather than a neutron star. We expect that such triple CV's are rather common in the Galaxy.

We demonstrated that our model can indeed reproduce *J1903 + 0327* qualitatively, and we estimate the number in the Galaxy by performing extensive population synthesis of post-common envelope triple systems (see §5). Our starting conditions are the progenitor of a LMXB which is accompanied by a third low-mass companion in a relatively wide orbit. Based on the observed statistics for such systems, their survival in the electron-capture supernova explosion of an ONeMg star and the consequences of the dynamical instability which results from the mass transfer in the inner binary, we conclude that the formation rate of *J1903 + 0327*-like systems is  $\sim 3 \times 10^{-3}$  times that of LMXBs. With a life time at least as long as that of LMXBs, and an estimated total number of  $10^4 - 10^5$  LMXBs in the Galaxy (Cote & Pylyser, 1989), we expect at least 30–300 systems like *J1903 + 0327* in the Galaxy and an order of magnitude smaller number of single MSPs. The longer lifetime of the MSP binary compared to LMXB's results in an increase of this number of a factor of a few. In the most pessimistic scenario, when we adopt a higher velocity kick, this number drops to about 3–30 MSP binaries like *J1903 + 0327* in the Galaxy, and a few single MSPs.

With a birthrate for Galactic LMXBs of  $3.2 \times 10^{-6}/\text{yr}$  (Kalogera & Webbink, 1998) to  $7 \times 10^{-6}/\text{yr}$  (Cote & Pylyser, 1989) we conclude that systems like *J1903 + 0327* form at a rate of  $\lesssim 2.1 \times 10^{-8}$ , and a ten times smaller rate for single MSPs. These low rates makes the proposed scenario unlikely, as we already expected, but sufficiently probable that the Galaxy should contain a few tens to hundreds of objects with characteristics similar to *J1903 + 0327* and consequently provides a satisfactory explanation for *J1903 + 0327*. Since the birthrate of single MSPs is expected to be quite similar to that of LMXBs (Dai & Li, 2010) our proposed triple scenario does not significantly contribute to the formation of single MSPs.

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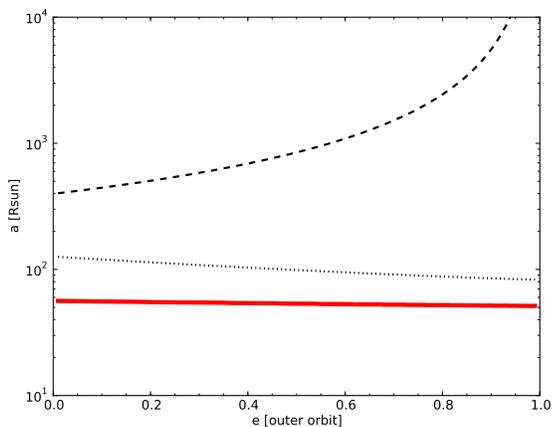


FIG. 1.— A triple with a  $1.3 M_{\odot}$  neutron star and  $1.1 M_{\odot}$  G-dwarf in a circular inner orbit (thick solid curve [red]) and a  $1.0 M_{\odot}$  G-dwarf in an eccentric outer orbit (dashes) is stable and has the same binding energy as *J1903 + 0327*. These curves are calculated using the iterative procedure described in § 3. The orbit of the LMXB expands as a consequence of the mass that is transferred from the initial secondary donor star to the neutron star. According to the analytic expression provided by (Mardling & Aarseth, 2001, their Eq. 90), the triple becomes dynamically unstable as soon as the orbital separation of the LMXB reaches the dotted curve. At this moment the triple dissolves and one of the three stars is ejected, leaving behind a binary with an orbital separation roughly somewhere between the dotted and the dashed (black) curve (see Fig. 3).

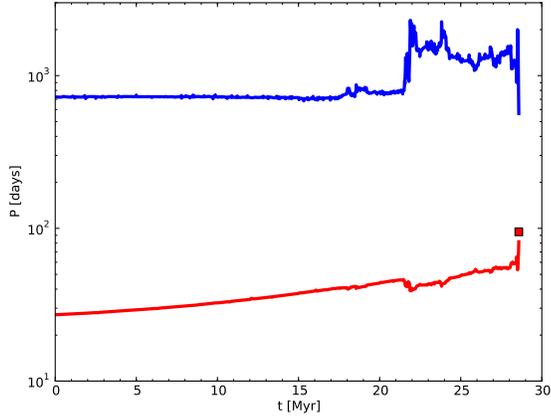


FIG. 2.— Evolution of the orbital period of a rather typical case which evolves to a system very similar to *J1903 + 0327*. The square (red) represents the final orbit of this simulation, which in this particular case resulted in a binary consisting of a  $1.73 M_{\odot}$  MSP and a  $1.0 M_{\odot}$  companion in a  $\sim 100$  day orbit with  $e \simeq 0.43$ . The bottom line (red) indicates, as a function of time the evolution of the inner LMXB, whereas the top line (blue) represents the evolution of the outer orbit.

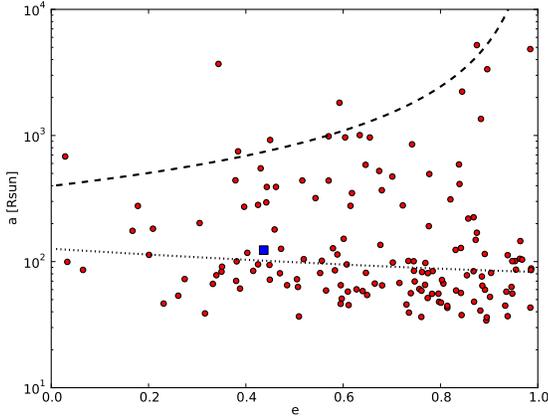


FIG. 3.— The eccentricity ( $e$ ) and semi-major axis ( $a$ ) of the MSP binaries with G-dwarf companions that resulted out from simulations (dots [red], see §3). These binaries are initialized to mimic *J1903 + 0327*, and which are described in §3 and represented by the thick solid and dashed curves in Fig. 1, and which are reproduced here to guide the eye regarding the most likely range of final binary parameters. The square (blue) indicates the current orbital separation and eccentricity of *J1903 + 0327*. Note that the final eccentricity of the surviving binary is unrelated to the eccentricity of the initial outer orbit (black dashed curve).

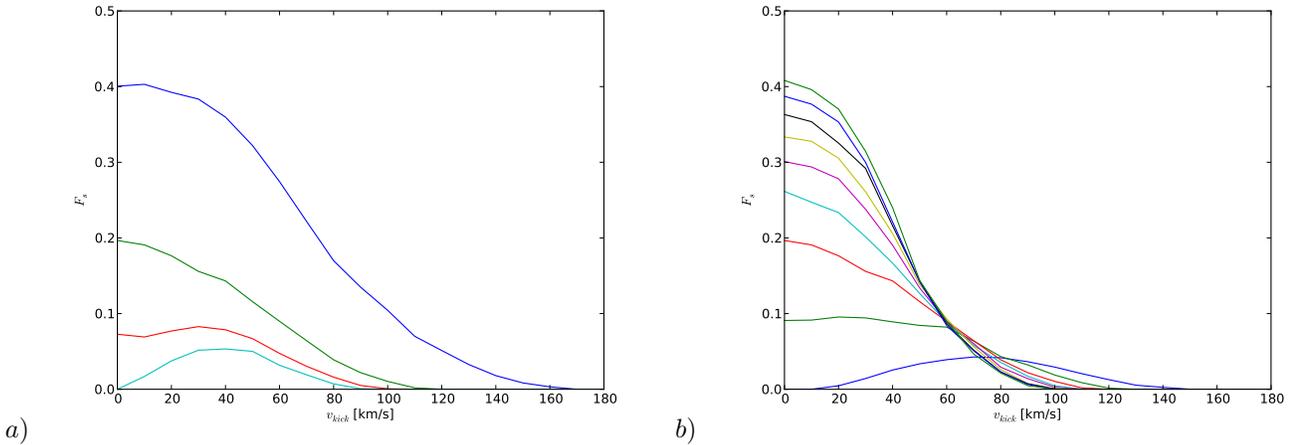


FIG. 4.— Survival probability for a triple in which a  $2.7 M_{\odot}$  star explodes in a supernova explosion to a  $1.3 M_{\odot}$  neutron star. The inner companion star is  $1.1 M_{\odot}$  and the outer star is  $1.03 M_{\odot}$ . The inner orbit is circular and with a semi-major axis of  $30 R_{\odot}$  (panel *a*) and a circular outer orbit is  $1000 R_{\odot}$ ,  $3000$ , ...,  $9000 R_{\odot}$  (top to bottom). Panel *b* gives the supernova survival fraction for an outer separation of  $10$ ,  $20$ , ...,  $90 R_{\odot}$  (bottom to top curve). Note that we adopted here high mass-loss in the supernova contrary to an electron-capture supernova, which suppresses the survival rate.