MERGERS OF CLOSE PRIMORDIAL BINARIES

N. ANDRONOV, M. H. PINSONNEAULT, AND D. M. TERNDRUP

Department of Astronomy, Ohio State University, 140 West 18th Avenue, Columbus, OH 43210; andronov@astronomy.ohio-state.edu, pinsonneault@astronomy.ohio-state.edu, terndrup@astronomy.ohio-state.edu

Received 2005 August 8; accepted 2006 March 27

ABSTRACT

We study the production of main-sequence mergers of tidally synchronized primordial short-period binaries. The principal ingredients of our calculation are the angular momentum loss rates inferred from the spin-down of open cluster stars and the distribution of binary properties in young open clusters. We compare our results with the expected number of systems that experience mass transfer in the post–main-sequence phases of evolution and compute the uncertainties in the theoretical predictions. We estimate that main-sequence mergers can account for the observed number of single blue stragglers in M67. Applied to the blue straggler population, this implies that such mergers are responsible for about one-quarter of the population of halo blue metal-poor stars and at least one-third of the blue stragglers in open clusters for systems older than 1 Gyr. The observed trends as a function of age are consistent with a saturated angular momentum loss rate for rapidly rotating tidally synchronized systems. The predicted number of blue stragglers from main-sequence mergers alone is comparable to the number observed in globular clusters, indicating that the net effect of dynamical interactions in dense stellar environments is to reduce rather than increase the blue straggler population. A population of subturnoff mergers of order 3%–4% of the upper main sequence population is also predicted for stars older than 4 Gyr, which is roughly comparable to the small population of highly Li-depleted halo dwarfs. Other observational tests are discussed.

Subject headings: binaries: close — blue stragglers — open clusters and associations: individual (M67) — stars: evolution

Online material: color figures

1. INTRODUCTION

About half of all stars are found in binaries, and about 30% of binary stars will interact at some point in their lifetime. Interacting binaries can therefore represent a significant fraction of all stars, and the consequences of interactions can be important for understanding stellar populations. In fact, studies of star clusters often reveal examples of stellar anomalies that can be attributed to interacting binaries (Bailyn 1995).

Nature provides a variety of ways that binary stars can interact, with many possibilities depending on the relative masses and evolutionary states of the components (see Paczyński 1971; Iben &Livio 1993). In particular, binary interactions or mergers may be responsible for the existence of blue stragglers (BSs), which on a color-magnitude diagram (CMD) appear on a natural extension of the main sequence (MS) above the turnoff point. The existence of BSs was discovered by Sandage (1953) in the globular cluster M3. Over the years BSs have been identified in many globular and open clusters, as reviewed by Stryker (1993), and they are numerous in some systems; the number of BSs found in individual globular clusters ranges from 10 to 400 (Bailyn 1995; Davies et al. 2004).

Binary mergers are by no means the only way to produce BSs, and not all mergers would manifest themselves as BSs. Many mechanisms for the origin of BSs have been proposed; a summary can be found in Abt (1985). There are two general categories: those in which BSs were formed later than the general stellar population of a cluster and those in which some mechanism prolongs the MS lifetime of a minority of stars. In the former category are proposals that BSs may arise from stellar mergers or collisions (see Davies et al. 2004 for a discussion). In sufficiently dense stellar environments, collisions between stars can be an important production mechanism.

Alternatively or concurrently, binaries with a wide range of orbital periods can either merge or experience mass transfer. Binary systems with orbital periods above 5 days but with initial separations below 3 AU may overfill their Roche lobes after one of the members leaves the main sequence. The ensuing mass transfer would produce a variety of unusual stellar objects such as common-envelope systems, BSs, X-ray binaries, and binary pulsars (Bailyn 1995). Shorter period systems, however, can even interact on the main sequence, and because of angular momentum loss, complete mergers are more likely.

There are two main mechanisms that can cause angular momentum loss in close binaries. Binary orbits decay from gravitational radiation. In addition, angular momentum loss from the magnetized winds of late-type stars (e.g., Weber & Davis 1967) results in a slowing of stellar rotation rates with time (Skumanich 1972). In tidally synchronized systems of short initial period, such angular momentum loss would lead to a reduction of the size of the orbit and produce contact systems or eventual mergers. Although short-period binaries are rare in the field, they are substantially more common in young open clusters, which supports the idea that such systems eventually merge. For example, 11% of Hyades binaries have orbital periods between 0.5 and 5 days (Duquennoy & Mayor 1991). The collision and merger categories are not completely distinct, since close stellar encounters can form tight binaries that subsequently merge. Following the conventional naming (e.g., Davies et al. 2004), we would call the first type dynamical BSs and the second type primordial BSs.

Although most work on the origin of BSs has focused on mergers, recent theoretical work on rotational mixing has revived the possibility that some BSs are “normal” stars that have had their lifetime increased relative to other stars of the same initial mass. The most promising candidate for main-sequence lifetime extension is mixing induced by rapid rotation in some
massive stars (see Maeder & Meynet 2000 for a review). This is probably not a major channel for producing low-mass (≤1.5 \( M_\odot \)) BSs because extensive angular momentum loss in lower main sequence stars makes rotational mixing relatively inefficient (Pinsonneault 1997). However, it may be important in explaining the presence of BSs in open clusters that are too young for the effective production of dynamical or primordial BSs (Mermilliod 1982).

Determining the relative importance of these different channels can provide important insights into a number of related fields in stellar astrophysics. Are star clusters valid templates for stellar population studies, or do dynamical effects significantly modify their global properties relative to field stars? How important are BSs for the integrated light of stellar populations? In addition, the production rate for stellar mergers can potentially be used as a test of the angular momentum loss rate for tidally synchronized binaries.

There may also be interesting consequences of stellar mergers for our understanding of surface abundance anomalies. There is no a priori reason why all stellar mergers or mass transfer events must manifest themselves as BSs. Some merger products will appear below the main-sequence turnoff. Such objects would be slightly less evolved than their single counterparts but might have unusual rotation rates and surface abundances. There is an interesting subpopulation of highly overdepleted stars found in lithium studies in open clusters (e.g., Thorburn et al. 1993) and halo field samples (Thorburn 1994). Because lithium is destroyed at low temperatures in stellar interiors, either internal mixing or mergers could produce low surface lithium abundances. Ryan et al. (2001a, 2001b) have argued that the highly lithium depleted halo stars may have experienced mass transfer from a companion and found that some such stars close to the turnoff rotate significantly more rapidly than their lithium-normal counterparts. The frequency of mergers needs to be quantified, however, to distinguish between the merger and mixing hypotheses.

In this paper we use recent prescriptions of angular momentum loss to compute the rates of mergers of main-sequence tidally synchronized binaries with short initial periods (≤5 days). Our paper is organized as follows. We describe recent observational advances in the study of BSs and potential subturnoff merger products in § 2.1. In § 2.2 we outline our motivation for studying BSs formed from primordial binaries in open clusters. Section 3 gives an overview of our model; then we proceed with discussion of observational data and selection in § 4. We present our results in § 5, and § 6 contains our summary and conclusions.

2. BACKGROUND ON THE POPULATION OF BLUE STRAGGLERS

2.1. Stragglers in Different Environments

A considerable amount of ground-based data on blue stragglers in globular clusters has been collected (e.g., Stryker 1993). With the use of the Hubble Space Telescope the amount and quality of the data has increased, which has provided additional clues about the origins of BSs.

Most globular clusters have a centrally concentrated radial distribution of BSs (e.g., Stryker 1993). There are two known exceptions to date. The first is M3; it has been studied both from the ground (Ferraro et al. 1993) and subsequently from space (Guhathakurta et al. 1994), and it was found to have a peculiar bimodal radial distribution of BSs. Ferraro et al. (2004) also found that 47 Tuc has a bimodal radial distribution of BSs similar to that of M3. The existence of two radial peaks is suggestive that environmental effects are important. It is plausible that dynamical effects could be important for BSs produced in globular clusters (e.g., Bailyn 1992). In high-density stellar environments (i.e., globular cluster cores) collisional mergers may be created. The other production mechanism (MS mergers and post-MS mass transfer in primordial binaries) would dominate when the stellar density is low (e.g., McCrea 1964). This would be the case in the outer parts of globular clusters, open clusters, and in the Galactic halo. This idea is somewhat supported by differences in the luminosity functions of BSs in the inner and outer regions of M3 (Bailyn & Pinsonneault 1995).

The similarities in the M3 and 47 Tuc BS populations are, however, problematic for models that rely on collisions alone because the two clusters are very different dynamically (Ferraro et al. 2004). The central density of 47 Tuc is about 40 times larger than that of M3 (see Pryor & Meylan 1993); also, other tracers of dynamical interactions, such as X-ray binaries, are relatively abundant in 47 Tuc but not in M3 (Ferraro et al. 2001). Ferraro et al. (2003) argued that the BS frequency cannot be parameterized uniquely by the collision rate. This result has been strengthened to some extent recently by Piotto et al. (2004), who summarized data on about 3000 BSs in 56 globular clusters and found that there is no statistically significant correlation between BS frequency and the collision rate of stars in the cluster cores.

BSs have also been found in open clusters; for a summary, see Ahumada & Lapasset (1995). Open clusters have much lower central stellar densities than globular clusters do, and therefore dynamical effects are less important in open clusters than in globular clusters. Field populations provide another potential test of environmental effects. Blue stragglers are more difficult to discover in the field, which contains stars with a wide range of ages. It is possible, however, to look in the Galactic halo for field analogs of the blue stragglers seen in clusters. High-velocity, blue metal-poor (BMP) stars in the Galactic halo have been studied by Preston & Sneden (2000) and by Carney et al. (2001). Both groups found that a large fraction of BMP stars (50%–60%) are members of binaries with orbital periods from half a year up to a few years. The unseen companions are consistent with being white dwarfs of mass \( \approx 0.55 M_\odot \). Preston & Sneden (2000) found that such systems are about 4 times more abundant than horizontal branch (HB) stars in the same field. In globular clusters, by comparison, the number of blue stragglers and HB stars are approximately equal. They have associated BMP stars with BSs and argued that mass transfer from an expanding giant onto a main-sequence star would be the dominant mechanism of formation of BSs in low-density stellar environments.

Most of the arguments above are indirect. However, there is recent observational support for the idea that some close MS binaries become contact systems and therefore might be associated with BSs (by their position on a color-magnitude diagram) or produce single stars above turnoff if coalescence is sufficiently rapid. Studying the BS population of NGC 5466, Mateo et al. (1990) have discovered that three of the BSs are close binaries, two of them being full contact systems. Eclipsing and/or contact binaries have later been found in NGC 4372 (Kaluzny & Krzeminski 1993), M71 (Yan & Mateo 1994), NGC 6791 (Rucinski et al. 1996), NGC 2354 (Lapasset & Ahumada 1996), NGC 6752 (Thompson et al. 1999), and NGC 6362 (Mazur et al. 1999). Finally, van den Berg et al. (2001) studied a blue straggler in the old open cluster M67 and found that it is a triple system with inner binary having a mass more than twice the cluster’s turnoff. This implies that at least one of the stars has a mass greater than the turnoff mass and is therefore a BS. In addition, the third star is also a BS. BS production can therefore be linked firmly to at least some close binary systems.
2.2. Prior Theory

The numerous theoretical possibilities for BS production have naturally simulated a number of theoretical papers. Some have included elaborate dynamical and evolutionary calculations for specific interesting systems that we do not include. A good example is the work of Hurley et al. (2001). They combined dynamical N-body simulations with simplified models of stellar and binary evolution (Hurley et al. 2000). Dynamical effects can increase the production of BSs, explain the existence of those in binaries, and quantify the number of other stellar exotica observed (such as RS CVns and post-mass-transfer BSs). The authors claimed that binary evolution alone cannot account for the number of observed BSs in open clusters or the binary properties of these BSs. These models are potentially much more powerful than the relatively simple treatment of binary populations used in this work. However, they suffer from difficult-to-quantify effects related to the choice of initial conditions (including the spatial distribution of stars) and their impact on the subsequent dynamical phenomena. There are also numerical challenges such as integrating binary trajectories during encounters with sufficient precision.

A simple treatment of binary evolution may be more transparent as a test for the initial properties of the stellar population and magnetic braking for a larger sample of systems. It is also straightforward to estimate the theoretical uncertainties involved. Even if dynamical phenomena are required in M67, such massive open clusters are rather unusual in the Galactic open cluster population. Numerous low-mass clusters, where dynamical effects can be neglected, provide a wealth of data on BSs whose formation should not be influenced by dynamical effects. A comparison of the number of open cluster BSs with the predictions of our model can in principle provide stronger constraints than the study of one cluster on the initial period distribution, mass function, and angular momentum loss rate of close binaries.

In addition, there have been fewer papers devoted to computing the MS binary merger rates, which is our primary concern. Vilhu (1982) and Stepien (1995) concluded that contact systems can form from a population of close binaries with period below about 4–6 days and that orbital decay of primordial binaries is sufficient to explain the existence of contact systems. Their models were restricted to the study of a small set of initial binary parameters. The theoretical uncertainties were also only roughly estimated. We take the next logical step, assuming that the formation of a rapidly rotating single star will result from the formation of such contact binaries. Then, given the lifetime of a merged product, we can compute the abundance of such mergers and compare them to a much more numerous population of BSs in open clusters.

Our work therefore extends prior studies and in a few aspects differs from previous models. We use a more realistic model of angular momentum loss, motivated by recent studies on the spin-down of low-mass MS stars. We model merger production from a distribution of masses, rather than calculating a few representative mass ratios. We also investigate the effects of choosing different stellar mass functions and initial period distribution of binaries, supported by the latest available empirical data. We calculate the total number of mergers, taking into account the lifetime of a merged product for different assumptions about its physics. A constant lifetime for the contact binary phase was used in Vilhu (1982). We also compute the expected number of subturnoff mergers. We compare predictions of our model with observed BSs in open clusters with a variety of ages, where the statistics are better than those for the sparse population of contact MS binaries. We investigate the impact of observational selection criteria.

3. THE MODEL

Observational studies of BSs usually concentrate on inferring the relative number of blue stragglers with respect to the number on the upper main sequence or the HB population. The theoretical models presented here, therefore, reduce to the problem of determining the rate of merger production relative to the lifetimes in the other evolutionary states. We begin with an overview of the ingredients of the theoretical models, which can be divided into three broad categories. We then follow with detailed discussions of the individual components of the models.

The initial conditions (distribution of primary masses, relative primary and secondary masses, binary fraction, and the starting binary period distribution) are considered in § 3.1, while § 3.2 discusses the rate at which mergers take place; this depends primarily on the rate of angular momentum loss and the timescale for tidal synchronization. Finally, the physics of the merger process itself will have a significant impact on the lifetimes and predicted positions of merger products in the H-R diagram, as discussed in § 3.3. In § 3.4 we compute the relative number of BS stars and of subturnoff mergers.

3.1. Properties of Stellar Population

We first assume that all stars in an open cluster have the same age and metallicity. Then we assume that the mass function of stars, binary fraction, and binary period distribution are independent of the age, mass, and metallicity of a cluster. Evaporation of stars via dynamical effects (e.g., de la Fuente Marcos 1995; Kim et al. 1999) is not included in the model, since evaporation will mainly remove low-mass stars. Such objects do not have the combined mass to appear as BSs after merging, and because BSs counts are expressed relative to the upper MS population, the loss of low-mass stars does not impact the observational interpretation. Finally, we assume that collisions do not alter the binary period distribution.

Each model cluster initially consists of \( N \) stars. Let \( N_1 \) be the number of single stars and \( N_2 \) the number of binary systems; then \( N = N_1 + 2N_2 \).

The binary fraction can be characterized by

\[
\epsilon \equiv \frac{N_2}{N_1 + N_2}.
\]

Typically, \( \epsilon \) has a value of 0.2–0.5 (e.g., Duquennoy & Mayor 1991). In terms of the binary fraction, the number of binaries is then given by

\[
N_2 = N \left( \frac{\epsilon}{1 + \epsilon} \right).
\]

and the number of single stars is

\[
N_1 = N \left( \frac{1 - \epsilon}{1 + \epsilon} \right).
\]

We model the binary population by a distribution function over primary mass \( m_1 \), secondary mass \( m_2 \), and orbital period \( P \), here \( m_1 \) and \( m_2 \) are in solar units and \( m_1 \geq m_2 \). The number of binaries in the interval between \((m_1, m_2, P)\) and \((m_1 + dm_1, m_2 + dm_2, P + dP)\) is given by

\[
dN = F(m_1, m_2, P)dm_1 dm_2 dP.
\]
We assume that the mass distribution function \( F(m_1, m_2, P) \) can be decomposed as a product of distribution functions over \( m_1 \), \( m_2 \), and \( P \), namely,

\[
F(m_1, m_2, P) = \xi_1(m_1)\xi_2(m_2)f(P),
\]

where \( f(P) \) is an initial period distribution and \( \xi_1(m_1) \) and \( \xi_2(m_2) \) are mass functions for the primary and the secondary stars, respectively, which are not necessarily identical.

The mass distribution of single stars is generated from a variety of mass functions (MFs). Our base case is the Miller & Scalo (1979) function, which can be expressed as

\[
\xi(m) \propto m^{-2.5} \log m.
\]

In addition, we also explored the effect of including an MF that is much steeper at lower masses, namely, the Salpeter (1955) function

\[
\xi(m) \propto m^{-2.35},
\]

and a shallower MF that characterizes the distribution of stars in the open cluster M35 as obtained by Barrado y Navascúes et al. (2001). Our examination of their data yields approximately

\[
\xi(m) \propto m^{-1.5} \log m.
\]

Recent observations of the Pleiades down to the hydrogen-burning boundary showed that the cluster also has a mass function similar to that of M35 (Moraux et al. 2003). These three MFs are shown in Figure 1, all normalized at the solar mass. We treat the Salpeter and M35 mass functions as limiting cases. We demonstrate that the model is mostly sensitive to the slope of the MF in the interval 0.4–1.0 \( M_\odot \), so our results are relatively insensitive to the primary star MF.

We assume that the masses of the primary stars are distributed according to the same MF as the single stars. For the secondaries, we test two possibilities: that they have the same MF as the primaries or that they have a flat mass function \( \xi_2(m_2) = \text{const} \). The second choice is dictated by accumulating observational evidence that the relative masses of close binary stars are more likely to be equal than would be expected if they were drawn from the same MF as the primary masses (Abt & Willamarth 2004).

For the binary period distribution we use an empirical fit to the data summarized by Duquennoy & Mayor (1991) for G dwarfs in the solar neighborhood, which is characterized by a Gaussian in \( \log P \). The period distribution of dwarf stars in the Hyades (Griffin 1985) is consistent with this form for periods over 10 days but has more shortened periods. Duquennoy & Mayor (1991) speculate that since the Hyades field is significantly younger than the field population (the age of Hyades is about 600 Myr), the excess at short periods is a characteristic feature of young populations, which evolves away with time due to the coalescence of short-period binaries. We demonstrate below that short-period systems must be frequent relative to the field distribution in order to produce a significant number of BSS from mergers.

We therefore assume that the period distribution of binaries is given by

\[
\frac{dN}{d(\log P)} \propto \exp \left[ -\frac{(\log P - \alpha)^2}{2\sigma_1^2} \right] + \frac{2}{3} \exp \left[ -\frac{(\log P)^2}{2\sigma_2^2} \right],
\]

where \( P \) is the orbital period in days. The first term describes the field distribution from Duquennoy & Mayor (1991), who derived \( \alpha = 4.8 \) and \( \sigma_1 = 2.3 \); we adopted these values in our model. The second term describes short-period systems that we assume exist in young stellar systems. An inspection of the Hyades data from Griffin (1985) yielded \( \sigma_2 \approx 0.6 \) and gave us the \( \frac{2}{3} \) term characterizing the relative normalization of the distributions of short and long periods. We truncate this distribution at short periods, setting the boundary at either 0.5 days or the initial period for which the binary would immediately be a contact system, whichever is longer.

3.2. Orbital Decay of Close Binaries

3.2.1. Tidal Synchronization

Loss of orbital angular momentum will result in a reduction of the orbital size in binaries, leading eventually to contact and merger. There are two mechanisms for angular momentum loss. The first is gravitational radiation (e.g., Landau & Lifshitz 1962), which is inefficient for periods above about 0.5 days. The second is loss by magnetized winds from MS stars, discussed below.

Each binary is assumed to begin already in tidal synchronization. This assumption is valid if the timescale for synchronization is shorter than any other timescale involved in the problem. According to Zahn (1977), the time to synchronization at any given orbital period \( P \) can be approximated by

\[
\tau \approx 10^4 \left( \frac{1 + q}{2q} \right)^2 P^4,
\]

where \( P \) is in days, \( \tau \) is in years, and \( q = m_2/m_1 \).

As is discussed below, our prescription for angular momentum loss means that the longest initial orbital period that would
produce a contact binary in 10 Gyr is about 5–6 days; this is valid mainly for cases where \( m_2 \approx m_1 > 1 \, M_\odot \). In these circumstances, \( \tau \approx 10^7 \) yr. If the secondary is considerably less massive than the primary, the synchronization time for the primary increases significantly, proportional to the square of the mass ratio \( q \). For \( m_1 = 1.0 \) and \( m_2 = 0.1 \), \( \tau \) is about 1 Gyr for an initial period of 6 days. In this case, the angular momentum loss from the primary would not be removed from the orbital angular momentum and instead the primary would simply spin down as it loses angular momentum. To take this effect into account, we introduce a synchronization parameter, as discussed below.

In the case in which both stars are in synchrony with the orbit, the total angular momentum in the binary system is given by

\[
J = M_\odot^{5/3} G^{2/3} m_1 m_2 m^{-1/3} \omega^{-1/3} + \left[I(m_1) + I(m_2)\right] \omega. \tag{1}
\]

Here \( M_\odot \) is the solar mass, \( G \) is the gravitational constant, \( m = m_1 + m_2 \), \( \omega \) is the angular rate of the orbit, and \( I_1 \) and \( I_2 \) are the stellar moments of inertia for the primary and secondary, respectively. The first term represents the orbital angular momentum, while the term in brackets is the rotational angular momentum of two stars.

To account for the longer timescale for synchronization when \( m_1 \gg m_2 \), we modify equation (1) by assuming that the secondary is always tidally locked, but the primary is locked only when the secondary is sufficiently massive. We define a parameter \( q_{\text{lock}} = m_2/m_1 \) to represent the binary mass ratio above which the primary will be locked. Then the angular momentum of the binary system is

\[
J = M_\odot^{5/3} G^{2/3} m_1 m_2 m^{-1/3} \omega^{-1/3} + \left[I(m_1) + I(m_2)\right] \omega, \tag{2}
\]

where \( \chi = 1 \) for \( q > q_{\text{lock}} \) and \( \chi = 0 \) otherwise. The value of \( q_{\text{lock}} \) should, formally, be some function of the age of the cluster, but for simplicity we set it to be a constant in the range between 0.1 and 0.5. As shown below, the rate of mergers is only slightly sensitive to the adopted \( \chi \), mainly because binaries with \( q \approx 1 \) contribute most to the production of BSs.

### 3.2.2. Prescription for Angular Momentum Loss

For the magnetic braking, we use an empirical prescription derived from studies of the rotation rates of stars in young open clusters (Keppens et al. 1995; Krishnamurthi et al. 1997; Ternaryrup et al. 1997). The total angular momentum extracted from the orbit for a fully synchronized system per unit time can be written as

\[
J_{\text{tot}}(m_1, m_2, \omega) = J_{\text{wind}}(m_2, \omega) + \chi J_{\text{wind}}(m_1, \omega). \tag{3}
\]

The empirical data require a mass-dependent saturation of the loss rate compared to the Skumanich (1972) law, which simply scales as \( \omega^3 \). This is usually written as

\[
J_{\text{wind}} = -K_w \left( \frac{\rho}{m} \right)^{1/2} \times \begin{cases} \omega^3, & \omega \leq \omega_{\text{crit}}^1, \\ \omega_{\text{crit}}^2, & \omega > \omega_{\text{crit}}^1, \end{cases} \tag{4}
\]

The saturation threshold \( \omega_{\text{crit}}^1 \) is the critical angular speed at which the magnetic field saturates and is a function of mass. We chose the same mass dependence as Andronov & Pinsonneau (2004). Here \( K_w \) is a constant calibrated to reproduce the solar rotation at the age of the Sun and has the value of \( 2.59 \times 10^{17} \) g cm s (see Krishnamurthi et al. 1997). In addition, we also investigated the case in which dynamo saturation was neglected, i.e., \( \omega \). This is analogous to Figure 2 from Stepien (1995). We examine three mass combinations: \( (1 + 1), (1 + 0.6), \) and \( (0.6 + 0.6) \) \( M_\odot \). The initial periods were 2, 4, and 6 days. Given either the Stepien (1995) magnetic braking prescription (see his formulae [14] and [15]) or our method described above, none of the systems would reach contact in 10 Gyr, with the initial period of 6 days. Stepien (1995) tested magnetic braking rates with different efficiencies, some of which produced considerable orbital decay rates even for longer periods. As a result, in one of his models a binary system of \( (0.6 + 0.6) \) \( M_\odot \) reached contact in about 8 Gyr. We believe that recent observational data make these choices unlikely.

---

1 See Andronov & Pinsonneau (2004) for an application of this braking law to the evolution of cataclysmic variables.
Our results for shorter period systems differ with Stepien (1995) because our braking law is calibrated on the observed spin-down of open cluster stars and includes mass-dependent saturation in the loss rate. As a consequence, angular momentum loss is less efficient than for the cases considered by Stepien (1995). The mass dependence of our results is therefore considerably different for systems with an initial period of 2 days. Further, the angular momentum loss model that we are using, a (0.6 + 0.6) $M_\odot$ binary system does not become a contact system in the age of the Galaxy. This is in marked contrast to the Stepien (1995) result, for which such a binary reaches contact before the higher mass systems do. In our model, the angular momentum loss rate decreases rapidly for decreasing mass at short periods. At long periods, all binaries would be in the unsaturated regime and would have angular momentum loss rates comparable to the earlier work represented by Stepien (1995) because the mass dependence in this regime is weak.

3.3. Mergers of Contact Systems

In our model we assume that once a binary forms a contact system, the two stars merge on a timescale that is short compared to other scales of interest. We designate a BS to be a single star formed in such a merger, provided that the combined mass is larger than the mass of the turnoff of a cluster at the time the merger takes place.

The timescale for such coalescence is uncertain. Estimates based on observed frequencies of contact systems in various environments range from $10^7$ to $10^8$ yr (e.g., van’t Veer 1979; Eggen & Iben 1989), while some theoretical models of the merger process can yield times on the order of 10 Gyr (Mochanacki 1981). Here we adopt the empirically estimated values.

Clearly, if the duration of the contact phase is long, it will result in fewer BSs in young open clusters. We can obtain an order-of-magnitude estimate of the contact phase lifetime from recent observations of contact binaries in the relatively well studied cluster NGC 188. Kafka & Honeycutt (2003) found 13 variables with orbital periods below 2 days in the upper two magnitudes of the main sequence. Two of 13 stars appear to be binaries that reached contact during the post-MS expansion of the primary; both of them are on the turnoff of the cluster, and their orbital periods are above 1.7 days. Two more systems have long periods of about 0.9 days, so they should be precontact MS binaries. We therefore are left with nine binaries that probably set an upper limit on the number of contact systems. There are about 1450 stars in the two brightest magnitudes of the MS (Platais et al. 2003). The fraction of contact binaries, therefore, relative to the number of stars in this range is about 0.6%. Based on Hipparcos data, Rucinski (2002) found that the normalized fraction of contact systems was lower, of the order of 0.2%, but with an uncertainty of a factor of 2. For old clusters the ratio of merged binaries to contact systems will be about the ratio of lifetimes in the BS phase to that in the contact phase. As we show in § 4.3, the expected merger fraction is between 4% and 5%. This will set an upper limit on the timescale of the contact phase to be somewhere between 12% and 15% of the lifetime of the merged product. If the lower specific frequency indicated by the Hipparcos results is used instead, the inferred contact phase lifetime is 3 times shorter and our assumption that the timescale is small compared to the straggler lifetime is strengthened.

Once the stars merge, the product can be chemically homogenized, or else the gradient in abundance caused by previous nuclear reactions can be preserved (i.e., the product has a helium-enriched core, while the merger added essentially unprocessed material to the envelope). See Bailyn & Pinsonneault (1995) and Lombardi et al. (1995, 1996) for detailed discussion of the internal structure of mergers.

The assumed nature of the merged product will affect the main-sequence lifetime, with unmixed products having lower MS lifetime than mixed ones. As a result, the number of BS stars would be reduced if the mergers were fully mixed. For the case when the merged product is completely mixed, the subsequent lifetime in the BS phase $\tau_{BS}$ is approximately given by the MS lifetime of a star with mass $(m_1 + m_2)$ and a starting hydrogen abundance $X$ that is determined by the prior nuclear evolution. For the unmixed case, the lifetime of the merger product is approximately

$$\tau_{BS} \approx \tau_{MS}(m_1 + m_2) \left(1 - \frac{\tau_{merg}}{\tau_{MSMcore}}\right).$$

The last factor describes the maximum fraction of unprocessed hydrogen in the center of whichever star ends up as the core of the merger product. For our base case we consider a model where the secondary is the core, e.g., $m_{core} = m_2$. We also discuss in the text the consequences of assuming that the primary is the core of the merger product; this reduces the predicted number of BSs by about 30% relative to having the lower degree of hydrogen burning for the secondary.

3.4. Number of Mergers

The properties of primordial binaries is specified by a distribution in $(m_1, m_2, P)$ space. In order to calculate the number of mergers that would form in the age of a cluster by coalescence, we need to integrate this distribution over a region of parameter space specified by several inequalities:

1. The initial orbital period of a binary should not be higher than the largest period that would lead to the formation of a contact binary in the age of a cluster. It should also be longer...
than the contact period for a binary of given masses. This condition is given by

\[ P_{\text{contact}}(m_1, m_2) \leq P_{\text{init}} \leq P_{\text{max}}(\tau_{\text{clus}}, m_1, m_2), \]

where \( P_{\text{max}} \) is calculated using equation (7).

2. For MS mergers, the primary must be on the main sequence when the system reaches contact and merges. Therefore, \( m_1 \leq m_{\text{to}}(\tau_{\text{clus}}). \)

3. The finite age of the merged products should be taken into account. At the time of an observation \( \tau_{\text{clus}} \) the formed merger should still be on the main sequence. If the orbital decay time is too short, the merger will go through all its MS evolution. In this case we will not see it as a BS. This is a lower limit on the initial period of the binary star. It can be written as

\[ \tau_{\text{orbital}}(P_{\text{init}} \rightarrow P_{\text{contact}}) + \tau_{\text{product}} \geq \tau_{\text{clus}}, \]

where \( P_{\text{init}} \) is the initial binary period.

4. For comparison of the predicted number of mergers with the number of BSs, a proper set of selection criteria should be invoked. We count only those mergers that closely suit the selection criteria used in a particular sample. Different observers use different selection criteria, and the selection criteria in our model must be modified accordingly. In particular, we considered two possible selections.

One is a simple luminosity cut; a merger product should have a luminosity at least 0.5 mag greater than the turnoff luminosity of a cluster. This criterion closely resembles the one used in studies of globular clusters (e.g., Piotto et al. 2004). Another selection is based on a color cut; the effective temperature of a star should still be on the main sequence. If the orbital decay time is too short, the merger product would have ended its MS lifetime before the time of observation. On the other hand, if the initial period was above the shaded region, it would have spun down too quickly, and the merger product would have ended its MS lifetime before the time of observation. The example illustrated corresponds to an age of 10 Gyr and a secondary mass \( m_2 = 0.5 \). The period range that would produce BSs observable at the specified age is illustrated by the shaded region and is plotted as a function of the primary mass \( m_1 \). If the binary has an initial period below the shaded region, it would have spun down too quickly, and the merger product would have ended its MS lifetime before the time of observation. On the other hand, if the initial period was above the shaded region, the binary will not have merged yet at the age of the cluster. Two solid vertical lines denote the lower mass limit for the primary (more massive than the secondary) and the upper mass limit (less massive than the cluster turnoff mass).

[See the electronic edition of the Journal for a color version of this figure.]

We normalize it to the number of stars in the 2 brightest magnitudes of the MS for a given age and compare to the observations of Ahumada & Lapasset (1995) or to the number of HB stars to compare our predictions with the fraction of BSs in globular clusters.

4. OBSERVATIONAL DATA

In this section we summarize the observational data that we use. Open cluster data are considered in § 4.1, data on BSs in globular clusters and BMP field stars in the field are described in § 4.2, and subturnoff mergers in § 4.3.

4.1. Open Clusters

Our goal is to see how different ingredients of the model will affect the predicted number of single BSs and subturnoff mergers. To confront the predictions of our models with observations we have to bring both to the same denominator. From a theoretical perspective, we should use a selection function for defining BSs among mergers that closely resembles the one used to select observed BS candidates. From the observational side, only single BSs that are highly probable members of open clusters should be included as BS candidates. For open clusters we use the catalog compiled by Ahumada & Lapasset (1995). This is the largest compilation of information on BSs in Galactic open clusters to date, although the definition of BSs used is unusual and many candidates lack important information about binarity and cluster membership, reducing the quality of their database. They gathered information on 959 BS...
candidates in 390 open clusters of different ages. A BS candidate in their paper is defined as a star that appears in a specified region of the H-R diagram (illustrated in their Fig. 1). Roughly, this area is bounded by the zero-age main sequence (ZAMS) from the left, the cutoff color from the right, and the lowest point on the ZAMS that appears differentiated from the sequence of cluster stars from the bottom. The number of BS candidates is quantified as a ratio of the number of candidates to the number of MS stars in the 2 brightest magnitudes of the upper MS.

We need to understand the effects of observational selection both to estimate the level of contamination of the observed sample and to develop a theoretical selection criterion that closely resembles the observed sample for further comparison. We define a clean BS sample as all single MS stars that are members of a cluster under consideration and are in the specified area of the H-R diagram. If a clean sample is defined this way, several other types of stars may appear as BS candidates and contaminate the sample.

The main contamination source of this is the presence of non-members. The majority of BS candidates selected by Ahumada & Lapasset (1995) are not confirmed to be cluster members: 567 stars have one indicator of cluster membership (radial velocity or proper motion), and only 161 stars have both indicators of membership. Background contamination will be most severe for older systems (where the turnoff of the cluster is in a more populated portion of the H-R diagram) and in systems close to the Galactic plane. In addition, there is no spectroscopic study of the selected BS candidates in their sample, and therefore binaries will contaminate the sample. This is particularly important in young clusters. Finally, either photometric errors or gaps in the CMD for intermediate-aged clusters can complicate the identification of candidates near the turnoff. Such would be the case of the Pleiades, considered below.

To give an impression of how the effects described above affect BS selection, we show CMDs for three clusters in Figure 4. These clusters were chosen to represent young, middle-aged, and old open clusters with modern CCD data and large BS candidate populations.

From Figure 4, the claimed BSs in a young open cluster such as NGC 2477 belong to an extension of the tip of the MS, close to the turnoff point. The main sequence is nearly vertical when the most common temperature indicator $B - V$ is used. As a result, this area can be occupied either by binaries or by turnoff MS stars. The degree of contamination of the sample in such systems is likely to be high.

An old open cluster such as Berkeley 49 has a well-defined turnoff, and the area on the CMD occupied by BSs cannot be contaminated by binaries. However, the CMD can be severely contaminated by nonmembers, as is clear from Figure 4. Most of the BS candidates in this cluster are probably field stars. The degree of field contamination in such systems will, however, depend more on the position of the cluster with respect to the Galactic plane, rather than its age.

The turnoff point of a middle-age cluster such as M67 is well defined. The contamination of the BS sample from turnoff stars is not as severe as in young clusters. In addition, BS candidates lie on the prolongation of the MS, which is diagonal for such ages using $B - V$ as a temperature index. Binaries, therefore, do not contribute to contamination as heavily either. However, there is a well-known gap near the turnoff that arises from the rapid phase of evolution associated with hydrogen core exhaustion. Care must be taken to properly define the turnoff to avoid tagging normal stars experiencing core hydrogen exhaustion as blue stragglers. Although this effect is modest in systems such as M67 (4 Gyr), it becomes more pronounced in younger open clusters and is significant at ages of the order of 1 Gyr.

To quantify these effects we examined three well-studied open clusters in the Ahumada & Lapasset (1995) sample: the Pleiades (age about 130 Myr), Praesepe (age about 600 Myr), and M67 (age 4 Gyr). For the Pleiades and Praesepe we have extensive membership and binarity studies, while the blue straggler population of M67 has been well studied.

For the Pleiades, Ahumada & Lapasset (1995) counted three BS candidates with 35 stars in the 2 brightest magnitudes of the MS. All three stars turned out to be binaries. Due to gaps in the upper MS and the absence of giants, it is difficult to determine the turnoff point of such young clusters; about half of the Pleiades stars in the upper MS are binaries.

For Praesepe they claimed five BSs with 30 stars in the 2 brightest magnitudes of the MS. Three of these five stars appear to be binaries, one is a normal MS star above the turnoff gap, and only one is a BS. We counted 35 stars in the 2 brightest magnitudes of the MS, 17 of which were binaries.

In M67, where the blue straggler population is the most secure, only a small fraction of BS candidates are single stars. This is important because main-sequence mergers will produce single BSs, while interactions of evolved and MS stars will tend to leave white dwarf remnants and thus BSs that are still binaries. Hurley et al. (2001), for example, who studied BSs in this cluster, claim that only eight of the 28 stars selected from the CMD as BS candidates are single stars and/or fast rotators. The rest are binaries or RS CVn stars: short-period binaries that have not yet merged.

Unfortunately, it is impossible to do the same exercise on all of their clusters, as most of them do not have memberships.
and/or binarity studies. Given the discussion above, we choose to exclude systems younger than 300 Myr from our study on the grounds that detecting BSs in such systems is observationally complex and requires follow-up studies of the binarity of candidates that are usually not available. The most believable estimates for a number of BSs are obtained for clusters older than 3 Gyr, where the observational definition of the turnoff becomes unambiguous. The sample of BSs in many clusters is more prone to contamination by nonmembers, especially in systems close to the Galactic plane, which makes secure membership studies important. Even in the case of clusters, such as M67, in which the turnoff is well defined and it is easier to disentangle binaries and TO stars from bona fide blue stragglers, care must be taken when comparing MS merger models to the data. The majority of BSs are not single stars. Careful spectroscopic study of selected BS candidates is thus essential for a rigorous test of the models. We therefore only included systems where membership had been confirmed with both radial velocities and proper motions.

4.2. Globular Clusters and Galactic Halo

There have been numerous studies of BSs in globular clusters. For this paper we chose to use the Piotto et al. (2004) catalog. It contains about 3000 blue stragglers in 56 globular clusters and has been extracted from a homogeneous sample of CMDs obtained with the same instrument. The data are given as the normalized frequency of BSs to the number of either red giant branch (RGB) or HB stars. We used the latter in our comparison because the age of HB stars (and therefore the number of HB stars predicted) is not very sensitive to the assumed age and metallicity for the cluster. Piotto et al. (2004) have corrected the BS and HB star counts for completeness.

Based on this large sample, they concluded that the measured frequency of BSs, given by $\log (N_{\text{BS}}/N_{\text{HB}})$, is between $-1$ and $0$, with a couple of outliers at about 0.4. Surprisingly, these two outliers are also the two least luminous clusters in the sample: NGC 6717 and NGC 6338. As we see below, this high-BS population is similar to the fractional population of BMP stars in the Galactic halo (Preston & Sneden 2000; Carney et al. 2001).

There is also a significant anticorrelation between the relative frequency of BSs in a cluster and its total absolute luminosity (and therefore mass). The brightest clusters are found to harbor the smallest percentage of BSs. However, there is still a large dispersion in log $(N_{\text{BS}}/N_{\text{HB}})$ at fixed cluster luminosity.

A number of theoretical investigations have proposed that collisions could produce a significant number of BSs in globular clusters. However, Piotto et al. (2004) have found that there is no statistically significant correlation between $N_{\text{BS}}/N_{\text{HB}}$ and the expected collision rate predicted from the dynamical properties of the clusters. In particular, post-core-collapse clusters that on average have higher central densities behave as normal clusters, without clear evidence for a global increase of log $(N_{\text{BS}}/N_{\text{HB}})$.

Field star studies are more challenging and limited in number but provide tantalizing clues about the impact of environment on BS production. The population of halo BMP stars was studied by Preston & Sneden (2000). Some stars of their sample and additional BMP candidates were later investigated by Carney et al. (2001, 2005) and Sneden et al. (2003). BMP stars may be distinguished from normal halo counterparts in color/color or color/metallicity diagrams. In addition to blue colors, BMP stars were found to be different from normal halo populations in a few aspects.

There is a very high fraction of binaries with orbital period below 4000 days. Of 62 stars in the Preston & Sneden (2000) sample, 42 are probable spectroscopic single-line binaries, which gives a fraction of $\epsilon \approx 0.68$. Carney et al. (2001) reanalyzed this sample and found 29 spectroscopic binaries, corresponding to $\epsilon \approx 0.47$. In any case, this fraction is much larger than that predicted by the Duquennoy & Mayor (1991) period distribution for normal field stars.

If the total binary fraction of the BMP stars were the typical solar neighborhood value of 0.5, the fraction of binaries with $P < 4000$ days would be $\epsilon \approx 0.15$, which is considerably lower than that measured for BMP stars. Post-MS mass transfer, however, would produce an excess of binaries if BSs formed by this mechanism were a significant component of the BMP population. This fact was used to argue that BSs produced in binaries contributed to the BMP sample considerably.

The average eccentricity of binaries in the BMP sample is also low. In a small sample of BMP stars studied by Carney et al. (2001), 6 of 10 stars were binaries with an average eccentricity $\langle e \rangle = 0.11$. This may serve as an additional argument for the model advocated in that paper, namely, one where the majority of the BSs in this population form through accretion during the post-MS evolution of the primary.

Stellar abundances can also be used as a test for field BS candidates. In the Carney et al. (2001) sample, 5 of 6 BMP stars found in binaries were Li deficient, and one was also Be deficient. Both of these elements are fragile and might be depleted in mergers. In comparison, 2 of 3 single BMP stars had normal lithium abundances. No data were presented on the lithium abundance of the last star, which was found to be in a very long period binary. This suggests that mixing is important for binary BMP stars but less so for the single stars.

We now proceed with the argument made by Preston & Sneden (2000) and calculate the fraction of BSs in the halo relative to the number of HB stars. BMP stars are speculated by the authors to be a mix of BSs and stars accreted from Galactic satellites such as the Carina dwarf spheroidal galaxy. Let $n_{\text{BMP}}$, $n_{\text{BS}}$, and $n_A$ be the space density of BMP stars, BSs, and accreted stars in the BMP sample, respectively. In addition, let $e_{\text{BMP}}$, $e_{\text{BS}}$, and $e_A$ be the binary fractions of those subsamples. Then we have two equations, one for the total number of BMP stars and another for the number of binaries:

$$n_{\text{BMP}} = n_{\text{BS}} + n_A,$$

$$e_{\text{BMP}} n_{\text{BMP}} = e_{\text{BS}} n_{\text{BS}} + e_A n_A.$$

These may be written as

$$\frac{n_{\text{BS}}}{n_{\text{BMP}}} = \frac{e_{\text{BMP}} - e_A}{e_{\text{BS}} - e_A}.$$

We now have one measured quantity, $e_{\text{BS}}$, and two assumed ones, $e_{\text{BMP}}$ and $e_A$, to derive the fraction of BSs in the BMP sample, and we must also normalize them to the number of HB stars.

The uncertainty for the measured quantity is large (compare the Preston & Sneden [2000] estimate $e_{\text{BS}} \approx 0.68$ with the value $e_{\text{BS}} \approx 0.47$ if Carney et al. [2001] are correct). Preston & Sneden (2000) used $e_{\text{BS}} = 0.87$ and $e_A = 0.15$, which is consistent with the fraction of F and G disk binaries with orbital periods less than 4000 days. While the latter seems to be a reasonable estimate, the former needs refinement. The well-studied cluster M67 serves us as a useful reference point once again. Hurley et al. (2001) had 28 BS candidates. If we exclude the highly eccentric binary, a binary with a period greater than 4000 days, a triple system, and two subgiants, we are left with 23 systems. Eight of them are single stars, eight are spectroscopic binaries, and seven are possibly RS CVn systems (a close binary
with one star being a subgiant). Thus, we can place an upper limit on the BS binary fraction of \( f_{\text{BS}} = 15/23 \approx 0.65 \). Given these numbers, we recalculate the expected number of BSs in the halo population relative to HB stars. The results are presented in Table 1.

We expect the number of BSs formed through close binary mergers to be comparable to that by post-MS mass transfer events in low-density environments (§ 5). Given this possibility, we need to account for possible single BSs in the BMP sample. We therefore include two populations of BSs: single stars and the ones found in binaries. We apply a binary fraction of 0 to the first type and a binary fraction of 1 to the second type. The system of equations then becomes

\[
N_{\text{BMP}} = n_{\text{BS, sgl}} + n_{\text{BS, bi}} + n_{A},
\]

\[
\epsilon_{\text{BMP}} = n_{\text{BS, sgl}} + \epsilon_A n_{A}.
\]

This system now has the family of solutions

\[
\frac{n_{\text{BS}}}{n_{\text{BMP}}} = \frac{\epsilon_{\text{BMP}} - \epsilon_A}{\mu/(\mu + 1) - \epsilon_A},
\]

where \( \mu = n_{\text{BS, bi}}/n_{\text{BS, sgl}} \).

Two families of solutions for two different assumed values of \( \epsilon_{\text{BMP}} \) can be computed. The lower line corresponds to \( \epsilon_{\text{BS}} = 0.87 \) used by Preston & Sneden (2000) and the upper line to our estimate of \( \epsilon_{\text{BS}} = 0.65 \). The minimum fraction of BSs in the BMP sample must be about 40% to explain the number of binaries in the BMP sample. Adopting our value of \( \epsilon_{\text{BS}} \) would imply that 73% of the BMP population are BSs with a binary fraction of 70% for the BSs.

### 4.3. Subturnoff Mergers

If the sum of the masses in a binary merger is below the turnoff mass, then the product will not be a blue straggler; such objects are more difficult to detect as a result. There are two potential observational diagnostics of such objects. Because of the strong mass-luminosity relationship, a subturnoff merger will be significantly less chemically evolved than a single star of the same mass and age. In practice, this is a difficult test to apply because the magnitude of the difference is a function of the initial mass ratio and the epoch where the merger occurred, which makes quantitative predictions of the number of detectable systems difficult. In addition, distinguishing such stars from nonmembers is not trivial.

The surface abundances of merger products may also differ from those of their unmerged counterparts, and this does provide a potential test of the population of such objects. The potentially observable species most likely to be affected are the light elements LiBeB, which are destroyed by proton capture reactions at relatively low stellar interior temperatures (approximately 2.5, 3.5, and 5 MK, respectively). Lithium abundances in stars are particularly important because lithium is a sensitive diagnostic of stellar mixing and the lithium abundance is relatively easy to measure. Severe lithium depletion is the norm in most BSs (Hobbs & Mathieu 1991) but not in all candidates (Ryan et al. 2001a, 2001b; Carney et al. 2001, 2005). In addition, the abundance of \(^7\)Li in old metal-poor stars can be used to test the theory of big bang nucleosynthesis (e.g., Boesgaard & Steigman 1985). The relative surface abundances of \(^{12}\)C, \(^{13}\)C, and N could also be affected if matter in CN cycle nuclear equilibrium is mixed to the surface.

There is a substantial body of literature on stellar lithium depletion (see, e.g., Pinsonneault 1997); here we summarize some of the main features relevant to using lithium depletion as a diagnostic of mergers. Lithium is destroyed in the outer convection zone of open cluster stars with effective temperatures below 5000 K (Iben 1965), and there is an efficient mixing process that destroys LiBeB in mid-F stars with effective temperature between 6250 and 6750 K (Boesgaard & Tripicco 1986; Boesgaard et al. 2005). Lithium is usually not observable in normal stars much hotter than 7000 K because it is fully ionized. For open cluster stars with effective temperatures below 6200 K there is evidence for a slow mixing process occurring on the main sequence that can produce dispersion in lithium abundances among open cluster stars of the same effective temperature (e.g., Jones et al. 1999).

The observational situation for halo stars is less chaotic. There is a well-defined lithium plateau originally discovered by Spite & Spite (1982). There is a lively debate in the literature about the possible existence of a small dispersion in lithium abundances among halo stars (Thorburn 1994; Ryan et al. 1999; Pinsonneault et al. 1999); however, any such dispersion is clearly much smaller than that observed in the open cluster case. However, there is a small minority of stars that have upper limits well below the typical values for halo stars; 4% of the Thorburn (1994) hot halo star sample, for example, had upper limits more than an order of magnitude below the plateau. If a less stringent criterion of a factor of 5 is adopted, the fraction of highly lithium depleted stars is approximately 7% (Ryan et al. 2001, 2002). Ryan et al. (2002) found that three of the four highly lithium depleted stars that they observed had detectable rotation, in marked contrast to typical field stars. Although this result is strongly suggestive of an unusual history for these objects, some care must be taken in interpreting this as direct evidence that all highly lithium depleted stars below the turnoff must be objects that have experienced mass transfer. The three rapid rotators lie very close to the field turnoff for their metallicity and may in fact be bona fide blue stragglers. These three systems are also binaries with orbits consistent with mass transfer from an evolved companion.

Given the sheer complexity of the observational database, we therefore do not believe that lithium alone can serve as a diagnostic of the population of stellar mergers. A theoretical calculation of the frequency of such mergers, however, could aid in understanding the observed pattern; we therefore present calculations for the subturnoff merger fraction in § 5.

### 5. RESULTS

Both MS and post-MS binary interactions can lead to mass transfer or even mergers, and in the case in which the final mass is greater than the TO mass of a cluster, a BS can be produced. We begin by estimating the maximum number of mass exchanges that could be produced from mergers on the main sequence or mass transfer on the RGB or asymptotic giant branch (AGB). We find that the three channels have comparable efficiencies; a variety of factors combine to yield total populations significantly lower than the upper limits set by this process.

Binaries with a small initial orbital period (below approximately 5 days) and sufficiently low masses (at least one of the

| Table 1 Results |   |   |   |   |
|-----------------|---|---|---|---|
| N               | e_{\text{BMP}} | e_A | e_{\text{BS}} | n_{\text{BS}}/n_{\text{BMP}} | n_{\text{BS}}/n_{\text{BMP}} |
| 1               | 0.60          | 0.15 | 0.87          | 0.63         | 4.0         |
| 2               | 0.47          | 0.15 | 0.87          | 0.44         | 2.8         |
| 3               | 0.60          | 0.15 | 0.65          | 0.90         | 5.7         |
| 4               | 0.47          | 0.15 | 0.65          | 0.64         | 4.1         |
components smaller than 1.2 \( M_\odot \) may spiral in to form a contact system in less than a Hubble time and eventually merge to form a single main-sequence star. Although the orbital period phase space for MS mergers is relatively small, even stars well below the turnoff can merge; this increases their number relative to interactions that occur after the turnoff.

If binaries are sufficiently wide \((P \geq 5 \text{ days})\), the timescale for orbital decay becomes too large for a main-sequence merger. In this case mass transfer can occur only when the primary leaves the MS. If the separation between stars is relatively small \((a \leq 0.5 \text{ AU})\), the primary will overfill its Roche lobe and accretion onto the secondary will occur on the RGB. Binaries that are even wider \((0.5 \text{ AU} \leq a \leq 3 \text{ AU})\) can also go through a similar accretion process when the primary is on the AGB (the red giant is not sufficiently large to overfill its Roche lobe), or they can accrete a small amount of the substantial mass lost in the AGB wind phase. Mass transfer in such wider binaries has been studied by a number of investigators (e.g., de Kool 1990; Iben & Livio 1993). The picture of BMP stars provided by Preston & Sneden (2000) and Carney et al. (2001) would be consistent with accretion happening during the AGB phase of the primary. In this case we would expect BMP stars to be accompanied by carbon-oxygen white dwarfs, which have mass 0.55–0.65\( M_\odot \). Mass transfer in post–main-sequence systems therefore involves a much wider range of orbital phase space than MS mergers but a much more restricted range of primary masses.

Given the initial period distribution by the empirical law of Duquennoy & Mayor (1991), the fraction of binaries with periods shorter than 5 days is 11%. The fraction of binaries that may experience mass transfer on the RGB (with assumed limiting separation of 0.5 AU) is 8.4% given the same initial distribution. Binaries with initial separation between about 0.5 and 3 AU will interact when the primary is on the AGB; their fraction is about 11%.

For a quantitative upper bound for these channels we chose an age of 4 Gyr, appropriate for an old open cluster. We estimate that about 18.4% of all binaries would have had a primary more massive than the current turnoff mass for a main-sequence mass function. Conversely, about 81.6% had primaries less massive than the TO mass and can potentially interact while both stars are on the MS. However, only about 7.6% of these systems will have a total binary mass higher than the TO mass.

The total fraction of binaries that experience mass transfer during the AGB phase of the primary is therefore about 2% of all binaries, while the total fraction of the binaries that may interact while both stars are on the MS and produce something more massive than the turnoff is about 0.8%. This order-of-magnitude calculation shows that both channels have comparable importance and may contribute to the production of BSs. It is worth noting that this would be an upper limit for both mechanisms. The finite lifetime of blue stragglers will reduce the number of BSs that survive to be observed at any given time. Accounting for finite lifetime effects will reduce the observed BS population from both channels. In addition, there are dynamical effects that could suppress post-MS mass transfer relative to MS mergers in some environments. Not all MS binaries that could merge will do so because of inefficient angular momentum loss for low-mass binaries. The merger of the secondary and the core of the primary may not be possible if the initial binding energy is too low to expel the envelope of a giant, which can be important for post-MS interactions. We now discuss each of these effects in turn.

In cluster environment with a moderate collision rate, systems likely to interact during the post-MS are much wider binaries that have larger cross sections for dynamical interactions than systems likely to merge on the MS. So to a first approximation we can expect the reduction of efficiency of BS formation by post-MS interactions relative to the MS mergers in such environments. The rate of MS mergers could even get amplified because, as a result of dynamical interactions, tight binaries get tighter. Therefore, more binaries with period less than 5 days may be produced, and such binaries could then merge on the MS.

For main-sequence mergers the orbital decay time is a strong function of mass with modern angular momentum loss rates, in the sense that lower mass stars experience substantially lower torques than would be expected in a simple Skumanich (1972) braking law. For example, from Figure 2 the orbital period of a binary with primary and secondary masses of 0.6 \( M_\odot \) and an initial period of 4 days will decay to only 3.5 days in 10 Gyr. Such a system would not reach contact, coalesce, and create a merger in a Hubble time. In general, orbital decay for binaries with masses lower than \( \approx 0.6 M_\odot \) is very inefficient.

Binaries that interact in the post-MS phase may form common-envelope systems rather than simply transferring mass; furthermore, not all of the mass of the primary star will be donated to the secondary. A common-envelope phase occurs if the accretion is unstable (e.g., the Roche lobe shrinks faster than the star losing mass does); possible sources of instability are discussed in detail by Hjellming & Webbink (1987). The outcome of this phase may therefore (see de Kool & Ritter 1993) also be a secondary with a mass higher than its initial value, accompanied by a He white dwarf in the case of RGB accretion or a CO white dwarf in the case of AGB accretion. Some of these post–common-envelope systems are the precursors of cataclysmic variables.

With these estimates in mind, we now turn to computing the rates of MS mergers and comparisons of the models to the data. We begin in § 5.1 with a summary of the model results and parameter variations. We compare our data to open clusters, globular clusters, and subturnoff mergers in § 5.2.

5.1. Model Properties and Parameter Variations

There are a substantial number of ingredients that enter even into the restricted problem that we are examining (main-sequence mergers). Furthermore, many of the uncertainties are systematic in nature. We therefore begin with an analysis of the sensitivity of our model results to the theoretical selection criterion and then examine the variations caused by changes in the physical model in the predicted frequency of blue stragglers. We conclude by estimating the resulting theoretical errors, which are typically about a factor of 2.

We define a reference model using what we view as the most reasonable physical choices and then follow with a discussion of the impact of changes in the ingredients. For the baseline model we used a Miller & Scalo MF for primaries and single stars. A flat MF for secondaries was used. The binary fraction was assumed to be 0.5, and a saturated magnetic braking prescription with \( m_{\text{crit}}=1.2 \) and \( q_{\text{lock}}=0.2 \) was adopted. The product in our reference model was supposed to be mixed with ZAMS hydrogen abundance. A merger was counted if it was hotter than the turnoff point of a cluster. All input parameters and their possible range are summarized in Table 2.

5.1.1. Selection Criteria

In order to test theoretical models, we need to be able to define which mergers would be observed as BSs. In different data sets, the BSs are found using different selection criteria, which lead to different and sometimes controversial conclusions.
about their properties. In theory, the predicted number of mergers also depends on what we count as mergers. To understand how much this selection affects our results we ran models with three different selection rules that are relevant for the observational data sets that we are employing. The results are displayed in Figure 5. The underlined model is the same in all panels and constitutes our standard case (§ 5.1.5).

The dotted line denotes the case when all mergers brighter than the turnoff of a cluster are counted. Such a criterion is mathematically precise but observationally problematic; there are numerous effects that can produce spurious candidates close to the TO (see § 3). The dashed line represents the case when we require that a merger product should be at least 0.5 mag brighter than TO to be counted as a BS. This is similar to the selection criteria used in globular cluster studies (e.g., Ferraro et al. 2003). The solid line is the case when a merger product is defined as any object that is hotter than the TO and brighter than 1 mag below the TO. This is chosen to reproduce the selection used by Ahumada & Lapasset (1995) and is used to compare our models with their open cluster data. It is shown that differences provided by the changes in the input theoretical parameters of the model are considerably milder than the changes in the predicted number of BSs associated with the selection criteria themselves.

5.1.2. Uncertainties in the Merger Process

It is straightforward to compute the timescale for binaries to reach contact given the binary masses, initial periods, and angular momentum loss rates. However, the outcome of the merger process is significantly more difficult to predict. One significant assumption, namely, that the timescale of mergers is short compared to the others in the problem, is held fixed in all of our models. Given the complexity of the problem, we have chosen to study limiting cases about the degree of mixing in the final product.

In one class of models we assume that the product is fully mixed; the lifetime of the product will then depend on the degree of nuclear processing in the two components prior to the merger, but the blue straggler will begin anew with a high central hydrogen abundance. We refer to these as mixed models, and our limiting case for our limiting case; for this purpose we ran a set of helium-rich models and calculated the MS lifetime as a function of initial hydrogen abundance. We then accounted for the higher...
luminosity and shorter lifetime of the product in our measurement of the predicted number of BSs. The results are compared with our standard model in Figure 7 (top). Open circles in Figures 7–10 represent data for individual clusters, which are subject to small number statistics. The filled circles with error bars are averages of cluster data in three age bins, and a correction for the fraction of single BSs has been applied (see § 5.2.1 for details). If all merger products were fully evolved, we would expect small changes in the number of merger products for young systems and a reduction in their number of 0.25 dex at the greatest ages.

The histograms in Figure 6, however, indicate that the true distribution is peaked at the higher (unevolved) level and that only a minority of merger products would be expected to be evolved. As a result, the actual reduction in the predicted number of blue stragglers would be well below 0.25 dex, even in older populations.

In the other class of models one star is accreted onto the other; the merger product will then begin its life with a large fraction of its fuel already burnt and will have a shorter lifetime. We refer to these as unmixed models. Such unmixed models will have a shorter lifetime than unevolved models, and the magnitude of the effect depends on which of the progenitors is the core of the merger. In our base unmixed case we assume that the secondary (which has less nuclear evolution) ends up in the core. The effect on the BS luminosity function would be more pronounced, but this is beyond the scope of our paper.

The choice of the distribution of secondary masses relative to primary stars in close binaries and a flat MF for the relative primary and second masses. The impact of changes of the binary fraction and the orbital locking parameter is illustrated in Figure 8, while the impact of changes in the MF is illustrated in Figure 9.

From Figure 8, the effect of change of the binary fraction or orbital locking parameter within reasonable limits is rather mild. Changes in the assumed MF for primaries have only a modest effect (0.16 dex deviation from the standard case at most) because the number of blue stragglers is compared to the number of stars on the upper MS, and the majority of mergers that are counted as BSs occur for primary masses close to the turnover. In the case of a flat mass function for the secondary, the Salpeter MF predicts more mergers because the effect of the decrease in the number of MS stars in the upper MS (to which we normalize our results) is larger than the decrease in the number of binaries with efficient angular momentum loss (which extends farther down the MS).

The choice of the distribution of secondary masses relative to the distribution of primary masses has a larger impact on the models, up to about 0.3 dex in young clusters, with much smaller effect (of the order of 0.1 dex) in old populations. Adoption of a Salpeter MF suppressed the merger rate for two reasons. The secondaries are lower in mass and are less likely to donate sufficient mass to make a BS. In addition, lower mass secondaries experience less efficient angular momentum loss, and the binary systems

Fig. 7.—The (log) predicted fraction of single BSs normalized to the number of stars in the two brightest magnitudes of the MS as a function of age. Predictions of our model for mixed vs. unmixed merger are shown on the upper panel, while evolved and unevolved are compared on the lower panel. [See the electronic edition of the Journal for a color version of this figure.]

Fig. 8.—Predicted number of single BSs normalized to the number of stars in the two brightest magnitudes of the MS as a function of age. The upper panel shows the predictions of our model for different assumed binary fractions, while models with a different parameter for tidal locking are compared in the lower panel. [See the electronic edition of the Journal for a color version of this figure.]
that contain them will have a narrower range of initial periods of binaries that will merge.

5.1.4. Magnetic Braking

The impact of choosing different magnetic braking prescriptions is shown in Figure 10. Saturation effects limit the rate of angular momentum loss in our standard model, resulting in a lack of mergers for young systems. The more efficient unsaturated braking mechanism leads to much more efficient production of mergers early on (at the factor of 5 level) and a corresponding decrease of up to 0.4 dex at greater ages (because the systems in question have already merged and the product has left the MS).

We also incorporate the known absence of a magnetized wind for upper MS stars in our model; the exact mass threshold, however, is somewhat difficult to measure precisely. From Figure 10, an increase of the limiting mass at which stars experience braking from 1.2 to 1.4 $M_\odot$ increases the number of binaries that can spiral in toward contact and also contributes to the production of mergers for systems with turnoff masses greater than 1.2 $M_\odot$. This has little impact on the oldest systems but could increase the predicted number of BSs by up to 0.4 dex in the youngest systems. As we discuss further in §5.2, the current data are much more consistent with a saturated braking law than with unsaturated, when only single BSs are considered.

5.1.5. Standard Model and Theoretical Error Analysis

To calculate the theoretical uncertainties we compared the models described in the previous section with our reference model and calculated the rms. The parameters considered were the primary MF, fraction of binaries, maximum mass of a MS star that experiences magnetic braking, type of merged product (mixed or unmixed), and the minimum mass ratio at which the secondary is tidally synchronized.

For all models a flat mass function for the secondary was used, and we adopted a theoretical selection that resembles the ones used in Ahumada & Lapasset (1995). We did not include evolutionary status within mixed models for two reasons. First, the effect of this parameter is relatively small even for most evolved mergers; second, the number of very evolved mergers is not high (Fig. 6). We decided to disregard unsaturated braking in calculating uncertainties because this model is grossly inconsistent with spin-down studies of single stars. From Terndrup et al. (2000), the uncertainties in the empirical braking law are small enough (20% at the 1 $\sigma$ level) that they should not affect our results. We did not include a model in which secondaries are represented by the same mass function as primaries because we think that such an assumption for close binaries that contribute to merger production (with periods less than 5 days) is physically unmotivated.

In cases where the difference was systematic, we assumed that the difference between the models corresponded to an effective 2 $\sigma$ error. In our models this applies to the cases of the critical threshold for angular momentum loss $q_{lock}$ and mixed compared with unmixed models. We treated binary fractions in the range $\epsilon = 0.3$ and $\epsilon = 0.7$ as plus and minus 1 $\sigma$ cases, as well as differences in the MF between our standard MS MF, the Salpeter MF, and the M35 MF, respectively. Once corrected for binarity and membership, the predictions of our model match the data very well, as described in more detail in the next section.

5.2. Comparison of Model Predictions with Data

5.2.1. Open Clusters

The total blue straggler fraction in the entire sample of open clusters claimed by Ahumada & Lapasset (1995) is substantially higher than our theoretical estimates. However, as discussed previously, the BS fraction is reduced (and more reliably estimated) in the subset of systems with good information about membership. The total BS fraction of this sample is at the high end of (but within) the 2 $\sigma$ theoretical error range. However, there is no a priori reason to expect that all BSs will be produced from MS mergers. In particular, BSs produced by post-MS mass transfer
would still be binaries, while MS mergers would produce single BSs. We should therefore really be comparing the theoretical predictions to the number of single BSs.

In the most comprehensively studied cluster, M67, only eight of 28 BSs are single. If we assume that this proportion is characteristic of all open clusters, then we should reduce the observed BS fraction by this factor. In order to compare with the open cluster data, we therefore proceed as follows. We included the data from the Ahumada & Lapasset (1995) study that had good membership information (from both proper motions and radial velocities) and assumed that the fraction of single BSs was the same in all clusters as in M67. We then divided all clusters into three equal in log (age) bins and calculated the total number of single BSs and the total number of MS stars in the brightest 2 mag.

The results are illustrated in Figure 11. The open circles represent the individual clusters, and the filled points with 1 σ error bars indicate the average results for each bin. The solid line shows the prediction of our base case, while the dashed lines represent the 2 σ theoretical error ranges. The agreement between the number of single blue stragglers observed and the theoretical predictions is extremely good. We interpret this as evidence that approximately one-third of the bona fide BSs in open clusters are produced by the MS merger of primordial close binaries, with an uncertainty of 0.12–0.2 dex at the 1 σ level depending on the age of the cluster. In the next section we address the question of whether this ratio depends on stellar environment.

We find this agreement encouraging and also note that the age trends in the models are qualitatively reproduced in the data. We can also therefore examine the question of what constraints can be imposed on the theoretical model ingredients from the open cluster data set. In order to confidently use the data to discriminate between different classes of theoretical models, it would be helpful to determine whether the binary fraction of BSs in M67 is representative of the open cluster sample as a whole or whether it depends on the cluster age or dynamical properties. In the discussion below we proceed with the assumption that these differential effects are not present.

As can be seen from Figures 7–10, the sensitivity of our model to most of the theoretical ingredients is rather mild. From Figures 7–9, the degree of mixing in the merged product, MF, and values of $\tau$ and $\tau_{\text{break}}$ within reasonable limits does not affect the prediction of our model much. However, there are some cases where the adoption of different theoretical assumptions would significantly degrade the agreement between observations and theory. In particular, adopting an unsaturated (Skumanich type) braking law (see Fig. 10) produces too many mergers for clusters younger than 1 Gyr at a statistically significant level. There is a straightforward physical explanation for this behavior. Saturated and unsaturated loss laws differ only at relatively short orbital periods, and over a Hubble time sufficiently short period systems would be expected to merge for either. As a result the total number of mergers over a Hubble time is comparable, but the timescale for a merger to occur is longer in the unsaturated case. Unless there is a strongly age-dependent change in the binary fraction of BSs, we conclude that the unsaturated braking law is severely disfavored by the data. A more comprehensive study of the binary of BSs, especially in older populations, would permit more stringent tests of the angular momentum loss law in close binaries.

5.2.2. Globular Clusters and Halo Field Stars

Globular clusters provide another natural test of our models, and the sample of Piotto et al. (2004) is well suited to provide a basis for comparison. Compared to the open cluster case, BSs can be more easily disentangled from contaminants. The number of upper MS stars is not a good calibration point for globular clusters, however, because of crowding. As a result we adopt a different normalization for the theoretical calculations that has been widely used in globular cluster studies, namely, the BS population relative to the number of horizontal branch stars. We define a BS as an object merger more than 0.5 mag brighter than the turnoff. This choice resembles the observational selection criteria used in globular clusters (e.g., Ferraro et al. 2003).

The number of HB stars relative to TO stars is a straightforward function of the relative lifetimes of evolved stars in different phases. The lifetime of the HB phase is well constrained because stars arrive on the HB with a narrow range of helium core masses. In our models the number of HB stars that are single is given by

$$N_{\mathrm{HB}} = \int_{m_{\mathrm{TO}}}^{m_{\mathrm{TO}}(\tau_{\mathrm{HB}} - \tau_{\mathrm{RGB}})} \xi(m) \, dm,$$

where $\xi(m)$ is the mass function used for single stars, $m_{\mathrm{TO}}(\tau)$ is the turnoff mass corresponding to a given age $\tau$, $\tau_{\mathrm{HB}}$ is the lifetime of a star on the HB, and $\tau_{\mathrm{RGB}} = 1$ Gyr is taken as the lifetime on the RGB. The results that follow are not very sensitive to the adopted RGB lifetime. In order to get a sense of the impact of age effects we considered models with cluster ages between 8 and 12 Gyr with solar metallicity.

Intermediate-period binaries will experience interactions on the first ascent RGB, and we do not include stars in this category in our estimates of the HB population. Wide binaries (with orbital separations exceeding 1 AU) will avoid mass transfer and/or common-envelope formation, and stars in wide binaries are thus able to evolve into the HB phase.
For the lifetime of a star on the HB, we took results from Lee & Demarque (1990). Given the range of masses and composition, this lifetime ranges from 85 to 115 Myr; we considered three models with $\tau_{\text{HB}}$ equal to 85, 100, and 115 Myr. The results are shown in Figure 12. Three curves denote models with different assumed HB lifetimes. The shaded region approximately corresponds to the frequency of BSs in globular clusters (Piotto et al. 2004). The prediction of our model traces the upper boundary of the shaded region. No strong correlation with age is expected in this age range, and there is no strong observational evidence for age-related variations in the blue straggler populations of globular clusters. Our predictions trace the upper boundary of BS frequency in globular clusters. This result is in striking contrast with the frequency of BMP stars in the Galactic halo. The excess of observed BMP stars to predicted single BSs is a factor of 4. Significantly, when the sample is restricted to exclude known BS binaries the agreement between theory and observations is dramatically improved; the single blue halo field objects and the single M67 BSs are a factor of 1.7 and about 1.3 greater than our predictions, consistent within the theoretical errors.

A synthesis of the observational data therefore permits the following working hypothesis. In sparse environments such as open clusters or the halo field, approximately one-third of the blue stragglers arise from main-sequence mergers. The remaining systems come from mass transfer involving RGB and AGB stars. In the dense environments of globular clusters wide binaries are destroyed, and the predicted number of BSs from MS mergers is consistent with the measured number of BSs. In this picture we rely heavily on using the binary status of BSs as a proxy for their channel of origin; single stars are ascribed to MS mergers, while binary stars are ascribed to mass transfer on the RGB or AGB. There are two general predictions from such models. BSs in globular clusters should be primarily single stars, and the majority of claimed open cluster BS candidates in the Ahumada & Lapasset (1995) sample are either background contaminants or binary stars.

The preceding comment does not imply that dynamical production of BSs in globular clusters does not occur. The peculiar bimodal radial distribution of BSs in M3 (Guhathakurta et al. 1994) and 47 Tuc (Ferraro et al. 2004) provides clear evidence that there are two distinct mechanisms for formation. In the centers some are probably created by collisions, and in the outer layers by some other mechanism, which should become predominant when the collision rate is low (Mapelli et al. 2004). The best model from that paper does involve a majority of systems in the core produced from dynamical effects, but it also indicates that a pure primordial binary origin cannot be ruled out. Our investigation demonstrates that our model mechanism for mergers is able to produce a sufficient number of BSs even before collisions are accounted for; this implies that main-sequence mergers of primordial short-period binaries must be accounted for in studies of BSs in globular clusters. Sophisticated dynamical models that take into account production of close binaries, destruction of wide binaries, evaporation of low-mass stars, and mass segregation will provide valuable insight into the relative roles of dynamical effects and binary mergers.

In our view it is likely that the net effect of dynamical processes is to lower the blue straggler fraction and that the fraction of collision products in the BSs is likely to be modest. This is consistent with the lower overall frequency of BSs in globular clusters (where dynamical effects can be important) than that found in the field and open clusters.

5.2.3. Under TO Mergers, Possible Connection with Lithium-depleted Stars

The bulk of our discussion has focused on merger products that can appear as blue stragglers. However, a significant fraction of main-sequence mergers will produce objects that are below the cluster turnoff. We illustrate the age dependence of this phenomenon in Figure 13, where the fractional population...
of subturnoff merger products in half-magnitude bins is plotted as a function of bolometric magnitude for ages of 0.6, 4, and 12 Gyr. These can be roughly thought of as being representative of intermediate-aged open clusters (e.g., the Hyades), old open clusters (M67), and the halo field. respectively. The average population in the 2 mag below the TO increases gradually with age, from about 1.5% for the 0.6 Gyr sample to about 4% for the halo TO sample. In all cases this is less than the proportion of highly lithium depleted stars, implying that MS mass transfer alone cannot explain the presence of highly lithium depleted stars.

It should be noted that this is an upper limit; we have chosen the mass function that maximizes this population. An uncorrelated primary/secondary MF would produce much lower mass merger products; a steeper than flat relative MF would make more BSs and fewer subturnoff mass products. It is difficult to provide any quantitative estimates of lithium depletion in the AGB mass transfer scenario and compare it to the amount of depletion expected in MS mergers. The relative depletion of different light species (Li, Be, B) that burn at different temperatures should be investigated, as it could be used to test the underlying cause of the anomalous abundances.

We therefore conclude that a background population at the few percent level should be accounted for in lithium studies but that it would be desirable to establish the presence of a depletion pattern inconsistent with mild mixing before removing such objects from abundance study samples.

6. SUMMARY AND DISCUSSION

We have investigated one channel of the formation of single blue stragglers in low-density stellar systems. It has long been known that the merger of close primordial binaries can be a plausible origin of BSs. Early works on the subject (Vilhu 1982; Stephien 1995) demonstrated that even given the uncertainties associated with the modeling of such wind, this mechanism can explain the observed number of contact systems. Our major results both quantify the importance of main-sequence mergers and clarify the role of environment in BS production. We have also included calculations of the production rate for subturnoff merger products, which are an interesting and surprisingly numerous population.

The comparison of theory to observations is significantly complicated by how a BS is observationally defined. In fact, we found that the predicted BS fraction was affected more by the mapping of theory to observations than by changes in any of the parameters in the theoretical models. We conclude that to make quantitative predictions theoretical models must use a definition of a BS close to that used in observational studies as possible. This explains the differing normalization that we used when studying different populations. It is nonetheless possible to define the ratio of predicted to observed systems in different environments, and we believe that differential changes in these ratios will be less sensitive to observational selection effects than the absolute number.

As it stands now, our model predicts about one-third of the number of BSs claimed by Ahumada & Lapasset (1995) for intermediate-age clusters (1–5 Gyr). This number corresponds well to the observed fraction of single blue stragglers in well-studied populations (such as M67) and the inferred fraction of single stars in the BMP population of the Galactic halo. After taking into account only single BSs and correcting the data by the same binary fraction as observed among the population of BSs in M67, the model reproduces the observed number of BSs in open clusters of single BSs by Ahumada & Lapasset (1995) quite well. The tendency for the BS fraction to rise for medium-aged clusters (0.5–3 Gyr) and flatten for older ones (3–10 Gyr) is seen in both the data and the prediction of our model. Data on binarity and membership of BSs in open clusters would permit more stringent tests of our model.

Based on our theoretical error estimates, the overall uncertainty in the predicted number of mergers is at the factor of 2 level. The major ingredient not included in this error budget is the binary period distribution. If we had used the binary period distribution for old field stars, where short-period binaries are relatively rare, we would have predicted a much lower binary fraction. However, because we used the period distribution in young clusters, the presence of a low-period spike in the initial period distribution of close binaries produces a number of mergers close to the observed number of single BSs in open clusters. Our models are consistent with the field star data because mergers remove primordial short-period binaries. As a result the short period spike is absent in the theoretical models for older stars. We believe that this is consistent with the idea that the missing systems have undergone mergers. This conclusion is an indirect one, and it would be helpful to test it in other ways. The strong mass dependence of the merger timescale that is predicted by empirical models of stellar angular momentum loss may provide such an alternate test of the merger hypothesis.

In older models of magnetic braking lower mass stars in close binaries have comparable torques but much lower angular momenta than higher mass binary systems. As a result, there is a tendency for them to merge over comparable, or even shorter, timescales than higher mass binaries. However, the open cluster data for single stars requires a rapid decrease in the loss rate for decreased stellar mass. This implies that the fraction of short-period binaries with masses below 0.6 $M_\odot$ should decline with age much more slowly than the comparable fraction for solar mass stars. If this can be confirmed, it would be a strong piece of evidence that it is mergers that are responsible for the difference between the open cluster and field populations. The origin of this bimodal period distribution for binaries is a separate and interesting theoretical question, and for constructing predictive models of BS populations its dependence on mass and composition should be investigated.

The predicted number of BSs as a function of age can also be used to test magnetic braking prescriptions. We find that an unsaturated magnetic braking prescription is consistent with the age trends in the data. The unsaturated prescription produces too many BSs at low ages; by the time high ages are reached the precursors have all been used up, leading to a deficit in the number of mergers. When this happens, we should necessarily expect a decline in the number of expected BSs (as seen in Fig. 10). The saturated braking law, on the other hand, does predict the correct shape and the number of BSs for all 3 bins. We include a magnetized wind only for low-mass stars; the data suggest that adopting a cutoff at the lower end of the plausible range (1.2 $M_\odot$) is the best current choice. In our view the presence of BSs in young systems (less than 300 Myr) is unlikely to be a binary evolution effect; rotationally mixed models are more physically motivated than invoking a magnetized wind above the break in the Kraft curve.

Our model predicts that MS mergers can account for about one-fourth of BMP stars observed in the Galactic halo, albeit based on limited statistics. According to Preston & Sneden (2000) and Carney et al. (2001) the majority of these systems are members of binaries and, therefore, were probably formed as a result of accretion from a giant on a main-sequence star. If these systems are associated with BSs, then post-MS mass transfer accounts for about $3/4$ of the BMP population. Such systems should
be members of relatively wide (separation of ~1 AU) binaries. The rest—about 1/3 of the BMP stars—should then be single or contact MS binaries and are contributed by the mechanism that we are discussing. Our model looks consistent with the number of single BMP stars in the Galactic halo. However, better statistics and abundance studies would again be desirable.

Even though we realize that dynamical effects may be important for the formation of BSs in globular clusters, we compared our predictions with globular cluster data by Piotto et al. (2004). With appropriate selection criteria imposed on MS mergers, we found that they can account for all of the BSs, even in the richest globular clusters. This MS merger rate is less sensitive to changes due to dynamical processes (collisions) in globular clusters than post-MS mass transfer because close binaries (with periods of 1–5 days) involved in MS mergers have much lower cross sections for encounters than wide binaries and statistically get tighter as a result of collisions, possibly even enhancing the MS merger rate. Wide binaries (with periods of years) have larger cross sections (more encounters) and statistically get wider; this should decrease if not completely eliminate the production of BSs by mass transfer from evolved primaries. We find it extremely intriguing that the predictions of our model trace the upper boundary of the number of BSs in globular clusters.

It is possible that mergers of close binaries may be the primary source of BSs in globular clusters. Detailed dynamical models are required to assess this possibility. Dynamical effects would modify the period distribution of the close binary population. The binaries located in the lower spike of the period distribution will shift to lower periods and therefore produce mergers early on in the lifetime of a cluster. Such mergers would finish their MS life and would not now be observed at the typical age of a globular cluster. This (together with mass segregation) might explain the peculiar radial distribution of BSs in M3 and 47 Tuc by suppressing BS production at intermediate radii. In the outer regions where collisions are not so common, our mechanism should predict the population of BSs relatively well.

In this sense our results are compatible with the dynamical study of BS populations in 47 Tuc by Mapelli et al. (2004). They found that the unusual radial distribution seen in that system could only be explained by dynamical effects if there was a substantial source of BSs arising from primordial binaries. Dynamical studies of this type will be useful for understanding why a peculiar bimodal distribution was found only in a couple of clusters and how much direct collisions of single stars contribute to the production of BSs in the center. Our models are complementary, in the sense that we can provide a plausible theoretical estimate of the BS production rate itself.

We found a predicted population of subturnoff mergers comparable to the ultra–lithium-depleted population in halo field stars. MS mergers could therefore be important in high-precision abundance studies. However, the predicted merger fraction is well below the observed data in open cluster systems. We believe that the best method for determining the contribution of mergers to MS abundance anomalies is to compute the predicted depletion patterns on a case-by-case basis and to compare directly with the data.

We want to conclude this paper by listing observations that we consider important for future progress in this field. More data on BSs in open clusters would be especially useful for comparison with our model. In particular, the binarity of BSs may be the best observational diagnostic of their origin. If the binary fraction can be measured reliably as a function of age, it may be possible to empirically infer the main-sequence merger rate as a function of age and therefore constrain the models much more tightly. The correspondence between our results for open clusters and BMP field stars is interesting, but it relies heavily on data obtained for a small sample. More generally, an empirical constraint of the complete distribution function \(f(m_1, m_2, P)\) in the period range of 1–10 days for binaries in young clusters would provide a valuable ingredient for theoretical modeling; in effect, this would test the assumptions that we have made about the universality of this function. In particular, the difference between the primary star MF and the primary-to-second star mass ratio is important for predicting which mergers will produce BSs and which ones will be subturnoff mergers. In addition to its implications for the problem that we are considering, such data could potentially constrain theories of star formation.

We would like to thank S. M. Rucinski for comments on the astro-ph preprint and an anonymous referee whose suggestions improved the paper.

REFERENCES

Abt, H. A. 1985, ApJ, 294, L103
Abt, H. A., & Willmarth, D. W. 2004, in Rev. Mex. AA Ser. Conf. 21, The Environment and Evolution of Double and Multiple Stars, Proc. IAU Colloq. 191, ed. C. Allen & C. Scarf (México: Inst. Astron., UNAM), 37
Ahumada, J., & Lapasset, E. 1995, A&AS, 109, 375
Andronov, N., & Pinsonneault, M. H. 2004, ApJ, 614, 326
Bailyn, C. D. 1992, ApJ, 391, 298
———. 1995, ARA&A, 33, 333
Bailyn, C. D., & Pinsonneault, M. H. 1995, ApJ, 439, 705
Barrado y Navascués, D., Stauffer, J. R., Bouvier, J., & Martin, E. L. 2001, ApJ, 546, 1006
Boesgaard, A. M., & Steigman, G. 1985, ARA&A, 23, 319
Boesgaard, A. M., & Tripicco, M. J. 1986, ApJ, 303, 724
Carney, B. W., Latham, D. W., & Laird, J. B. 2005, AJ, 129, 466
Carney, B. W., Latham, D. W., Laird, J. B., Grant, C. E., & Morse, J. A. 2001, AJ, 122, 3419
Davies, M. B., Piotto, G., & de Angeli, F. 2004, MNRAS, 349, 129
de Kool, M. 1990, ApJ, 358, 189
Deo, K., & Ritter, H. 1993, A&A, 267, 397
de la Fuente Marcos, R. 1995, A&A, 301, 407
Duquennoy, A., & Mayor, M. 1991, A&A, 248, 485
Durney, B. R., & Latour, J. 1978, Geophys. Astrophys. Fluid Dyn., 9, 241
Eggen, O. J., & Iben, I., Jr. 1989, AJ, 97, 431
Ferraro, F. R., Beccari, G., Rood, R. T., Bellazzini, M., Sills, A., & Sabbi, E. 2004, ApJ, 603, 127
Ferraro, F. R., D’Amico, N., Possenti, A., Mignani, R. P., & Paltrinieri, B. 2001, ApJ, 561, 337
Ferraro, F. R., Fusi Pecci, R., & Cacciari, C. 1993, AJ, 106, 2324
Ferraro, F. R., Sills, A., Rood, R. T., Paltrinieri, B., & Buonanno, R. 2003, ApJ, 588, 464
Griffin, R. G. 1985, in Interacting Binaries, ed. P. P. Eggleton & J. E. Pringle (Dordrecht: Reidel), 1
Guhathakurta, P., Yanny, B., Bahcall, J. N., & Schneider, D. P. 1994, AJ, 108, 1786
Hjelmand, M. S., & Webbink, R. F. 1987, ApJ, 318, 794
Hobbs, L. M., & Mathieu, R. D. 1991, PASP, 103, 431
Hurley, J. R., Pols, O. R., & Tout, C. A. 2000, MNRAS, 315, 543
Hurley, J. R., Tout, C. A., Aarseth, S. J., & Pols, O. R. 2001, MNRAS, 323, 630
Iben, I., Jr. 1965, ApJ, 141, 993
Iben, I., Jr., & Livio, M. 1993, PASP, 105, 1373
Jones, B. F., Fischer, D., & Soderblom, D. R. 1999, AJ, 117, 330
Kafka, S., & Honeycutt, R. K. 2003, AJ, 126, 276
Kaluzny, J., & Krzeminski, W. 1993, MNRAS, 264, 785
Kaluzny, J., & Richtler, T. 1989, Acta Astron., 39, 139
Kassim, M., Janes, K. A., Frield, E. D., & Phelps, R. L. 1997, AJ, 113, 1723
No. 2, 2006 Mergers of Close Primordial Binaries 1177
