RUNAWAY AND HYPERVELOCITY STARS IN THE GALACTIC HALO: BINARY REJUVENATION AND TRIPLE DISRUPTION

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ABSTRACT

Young stars observed in the distant Galactic halo are usually thought to have formed elsewhere, either in the Galactic disk or perhaps the Galactic center (GC), and subsequently ejected at high velocities to their current position. However, some of these stars have apparent lifetimes shorter than the required flight time from the Galactic disk/GC. We suggest that such stars have evolved in close runaway or hypervelocity binaries. Stellar evolution of such binaries can drive them into mass transfer configurations and even mergers. Such evolution could then rejuvenate them (e.g., blue stragglers) and extend their lifetime after their ejection. The extended lifetimes of such stars could then be reconciled with their flight times to the Galactic halo. We study the possibilities of binary runaway and hypervelocity stars (HVSs) and show that such binaries could have been ejected in triple disruptions and other dynamical interactions with stars or with massive black holes (MBHs). We show that currently observed “too young” star in the halo could have been ejected from the Galactic disk or the GC and be observable in their current position if they were ejected as binaries. Specifically, it is shown that the HVS HE 0437−5439 could be such a rejuvenated star. Other suggestions for its ejection from the Large Magellanic Cloud are found to be highly unlikely. Moreover, it is shown that its observed metallicity is most consistent with a Galactic origin and a GC origin cannot currently be ruled out. In addition, we suggest that triple disruptions by the MBH in the GC could also capture binaries in close orbits near the MBH, some of which may later evolve to become more massive rejuvenated stars.

Key words: black hole physics – galaxies: nuclei – stars: kinematics

Online-only material: color figures

1. INTRODUCTION

Young massive OB stars are usually observed close to their birthplace in young stellar clusters or associations (e.g., Hoogerwerf et al. 2000). Some of them, however, are observed in isolation, far from any star-forming region. Observations of such stars in the Galactic halo are especially puzzling given the unfavorable conditions for regular star formation in such regions. Formation of massive stars usually requires special conditions such as the existence of molecular clouds with dense cores that could collapse to form massive stars. Such gas reservoirs do not exist at large distances in the Galactic halo (Savage & de Boer 1981; Sembach & Danks 1994). Nevertheless, young OB stars are observed there. These halo young stars are usually observed to have high peculiar velocities (>40 km s$^{-1}$), and are thought to have been ejected from their birthplace and acquire their high velocity through some dynamical process. Due to their high velocities they could propagate to their currently observed remote location, even during their short lifetimes. Such high-velocity stars are thought to be dynamically ejected in stellar binary interactions or through a binary supernova (SN) explosions (so-called runaway stars, e.g., Blaauw 1961; Poveda et al. 1967; Martin 2006, and references therein). Young stars with even higher velocities, the so-called hypervelocity stars (HVSs; with velocities >300 km s$^{-1}$; Hills 1988; Brown et al. 2005, 2007b; Hirsch et al. 2005, and references therein), are mostly likely ejected from the Galactic center (GC) through some interaction with the massive black hole (MBH) known to exist there (Hills 1988; Yu & Tremaine 2003). However, in some cases even the high velocities of these runaway/HVSs are not sufficient to explain their remote locations, so far from any star-forming region. In those cases, it appears that flight times of these young stars from their birthplace in the Galactic disk (or the GC) to their current location is longer than their main-sequence (MS) lifetimes.

In the following, we suggest that such discrepancy could be solved if these stars were ejected as runaway or hypervelocity binaries. A combination of dynamical and evolutionary processes could then explain the existence of these “too young” halo stars. Following their ejection and propagation in the Galaxy, the ejected runaway/hypervelocity binaries could evolve and rejuvenate through mass between (or merger of) the binary stellar components. Such rejuvenation could extend the MS lifetime of these stars and resolve the discrepancy between their apparent lifetimes and estimated flight times. We first shortly overview the observations of Galactic halo young stars in Section 2. We then discuss the possible dynamical scenarios for the ejection of runaway and hypervelocity binaries that can serve as progenitors of rejuvenated halo stars (Section 3). The rejuvenation scenario is presented in Section 4, followed by the discussion (Section 5) and summary.

2. YOUNG STARS IN THE GALACTIC HALO

In many cases dynamical processes can eject massive stars from their original birthplace at high velocities. These so-called runaway stars (Blaauw 1961; for a short overview see Hoogerwerf et al. 2001) constitute a considerable fraction of the early O and B star population in the Galaxy; ~30%−40% of the O stars and 5%−10% of the B stars (Stone 1991, and references within). Such stars have large peculiar velocities of 40 ≤ $v_{pec}$ ≤ 200 km s$^{-1}$ (Gies 1987; Hoogerwerf et al. 2001) or even higher (Martin 2006). Besides their relatively high velocities, runaway stars are also distinguished from the normal early-type stars by their much lower (less than 10%) multiplicity compared with the binary fraction of normal early-type stars.
Table 1

Too Young” Stars in the Galactic Halo

| Name          | Mass ($M_\odot$) | $T_{\text{evol}}$ (Myr) | $T_{\text{ej}}$ (Myr) | References                  |
|---------------|-----------------|--------------------------|------------------------|-----------------------------|
| HE 0437−5439  | 9               | 29                       | 90 ± 10                | Edelmann et al. (2005)      |
| Runaway stars |                 |                          |                        |                             |
| BD +38 2182   | 6.6             | 60                       | 53 ± 8                 | Martin (2006)               |
| BD +36 2268   | 6.9             | 51                       | 50 ± 2                 | "                           |
| HD 140543     | 22              | 8                        | 23 ± 3                 | "                           |
| HD 188618     | 9.7             | 26                       | 38 ± 8                 | "                           |
| HD 206144     | 9.7             | 26                       | 25 ± 2                 | "                           |
| PG 0122+214   | 6.7             | 35 ± 6                   | 51 ± 24                | Ramspeck et al. (2001)      |
| PG 1610+239   | 5.8             | 54 ± 10                  | >62                    | "                           |
| PHL 159       | 8               | 28 ± 2                   | 31                     | "                           |
| PHL 346       | 9.9             | 19 ± 2                   | 27 ± 7                 | "                           |
| SB 357        | 7.4             | 26 ± 4                   | 61                     | "                           |
| HS 1914+7139  | 6.2             | 39 ± 6                   | 91                     | "                           |
| PG 0914+001a  | 5.8 (4.7)       | 79 (116)                 | 199 (109)              | Lynn et al. (2004)          |
| PG 1209+263a  | 6.3 (5)         | 62 (91)                  | 272 (170)              | "                           |
| PG 2214+509c  | 7.5 (6.5)       | 41 (53)                  | 53 (52)                | "                           |
| PG 2229+509a  | 5.8 (5.4)       | 49 (63)                  | 63 (58)                | "                           |

Note. *Numbers in parentheses show lower/upper limits on the timescales that could minimize the time discrepancies (from Lynn et al. 2004).*

3. DYNAMICAL EJECTION OF RUNAWAY AND HYPERVELOCITY BINARIES

3.1. Runaway Binaries

Two mechanisms are thought to contribute to the ejection of runaway stars, both involve binarity (or higher multiplicity). In the binary SN scenario (Blauw 1961) a runaway star receives its velocity when the primary component of a massive binary system explodes as an SN. When the SN shell passes the secondary, the gravitational attraction of the primary reduces considerably, and the secondary starts to move through space with a velocity comparable to its original orbital velocity. In the dynamical ejection scenario (Poveda et al. 1967) runaway stars are formed through gravitational interactions between stars in dense, compact clusters. Simulations show that such encounters may produce runaways with velocities up to 200 km s$^{-1}$ (Mikkola 1983; Leonard & Duncan 1990; Leonard 1991; Gualandris et al. 2004). These scenarios suggest that many of the early OB stars formed in young clusters could be ejected from their birthplace and leave the cluster at high velocity.

Theoretical studies suggest that binary stars could also be ejected at high velocities, although at smaller fraction of $\sim$0.1 of all the runaway stars (Leonard & Duncan 1988, 1990; Portegies Zwart 2000). Such runaway binaries have indeed been observed (Gies & Bolton 1986; Mason et al. 1998; Martin 2006; Lockman et al. 2007; McSwain et al. 2007a, 2007b), with fractions of $\sim$0.1 in the runaway stars samples. The periods of the runaway binaries were found to be typically short (<5 days; Gies & Bolton 1986; Mason et al. 1998; Martin 2003) as expected from the dynamical ejection scenario. Some of the binaries were found to be with larger period ($\sim$20 days) and relatively eccentric orbits ($>$0.4) and are thought to be ejected due to an SN explosion (Lockman et al. 2007; McSwain et al. 2007a, 2007b), in which case rejuvenation is not possible.

3.2. Hypervelocity Binaries

Extreme velocities as found for HVSs most likely suggest a different dynamical origin than that of runaway stars. Several scenarios have been suggested for ejection of HVSs, all of them require an interaction with the MBH. These include a disruption of a stellar binary by an MBH (Hills 1988; Yu & Tremaine 2003; Ginsburg & Loeb 2006; Perets et al. 2007), an interaction of a single star with an intermediate mass black hole (IMBH) which inspirals to the GC (Hansen & Milosavljević 2003; Yu & Tremaine 2003; Levin 2006; Baumgardt et al. 2006; L¨ockmann & Baumgardt 2008; Sesana et al. 2008), or interaction with stellar black holes (SBHs) in the GC (Yu & Tremaine 2003; Miralda-Escudé & Gould 2000; O’Leary & Loeb 2008). In such scenarios stars could be ejected from the GC with velocities of hundreds and even a few thousands km s$^{-1}$, possibly extending much beyond the escape velocity from the Galaxy.

Recently, it was suggested that binary stars could also be ejected as hypervelocity binaries during the inspiral of an IMBH (Lu et al. 2007; Sesana et al. 2009), and could serve as evidence for the binary MBH ejection scenario. It was noted that the other scenarios for hypervelocity ejection are not likely to eject hypervelocity binaries. Specifically, the probability for a binary ejection in a triple disruption by an MBH is negligibly small. The later claim may well be correct for the low-mass HVSs discussed in Lu et al. (2007), however, as we show in the following, a nonnegligible number of massive hypervelocity binaries could be ejected through a triple disruption by the MBH in the GC.
Young massive binaries may also be ejected by an inspiraling IMBH as suggested by Lu et al. for low-mass binaries. However, the fraction of surviving binaries close to the MBH, where they could be ejected as HVSs by an inspiraling IMBH, is small because most would be disrupted through dynamical interactions with other stars in this hostile environment (see Perets 2009 for detailed discussion). Moreover, it is likely that the most if not all of the observed young HVSs in the Galactic halo were not ejected in such a scenario, given the observational constrains on the number of young stars observed close to the MBH in the GC (Perets 2009). In the following, we discuss the triple disruption scenario.

### 3.2.1. Triple Disruption by an MBH

A close pass of a binary star near an MBH results in an exchange interaction, in which one star is ejected at high velocity, while its companion is captured by the MBH and is left bound to it. Such interaction occurs because of the tidal forces exerted by the MBH on the binary components. Typically, a binary (with mass, $M_{\text{bin}} = M_e + M_c$; semimajor axis, $a_{\text{bin}}$), is disrupted when it crosses the tidal radius of the MBH (with mass $M_{\text{BH}}$), given by

$$ r_t = \left( \frac{M_{\text{BH}}}{M_{\text{bin}}} \right)^{1/3} a_{\text{bin}}, \quad (1) $$

and one of the stars (with mass $M_e$) is captured close to the MBH and the other (with mass $M_c$) is ejected at high velocity of about (Hills 1991; Bromley et al. 2006)

$$ v_{\text{BH}} = 1800 \, \text{km s}^{-1} \times \left( \frac{a_{\text{bin}}}{0.1 \, \text{AU}} \right)^{-1/2} \left( \frac{M_e + M_c}{2 \, M_\odot} \right)^{1/3} \left( \frac{M_{\text{BH}}}{4 \times 10^6 \, M_\odot} \right)^{1/6} \times \left( \frac{2 M_c}{M_e + M_c} \right)^{(1/2)}. \quad (2) $$

The same scenario could be extended to a triple disruption by an MBH. Triple stars have a stable configuration if the semimajor axis of the outer binary, $a_0$ is much larger than the semimajor axis of the inner binary, $a_i$ (i.e., $a_i \ll a_0$). In such hierarchical triples, the outer binary could be disrupted by the MBH while the inner closer binary is kept bound. In this case a triple disruption could produce a hypervelocity binary, or alternatively a captured binary star near the MBH. The ejection velocity in Equation (2) is strongly dependent on the semimajor axis of the binary (the outer binary in the triple case) and on the mass of the stellar binary (triple in this case). Both of these parameters vary by much between the population of low-mass stars and high-mass stars.

For low-mass stars ($M_{\text{triple}} \sim 3 \, M_\odot$, for equal-mass stars) such as those studied by Lu et al. (2007), one requires $a_{\text{bin}} \approx 0.4$ AU for ejection of a hypervelocity binary at $\sim 900 \, \text{km s}^{-1}$. Such close binaries are infrequent (only a few percent of the binary population; Duquennoy & Mayor 1991), and the fraction of low-mass triples with such close outer binaries is negligibly small (Tokovinin et al. 2006). For higher mass stars such as the observed young B-type HVSs in the Galactic halo, $m_* \sim 2-4 \, M_\odot$, corresponding to a triple mass of $M_{\text{triple}} \sim 6-12 \, M_\odot$ (assuming equal-mass stars). In this case even a semimajor axis of $a_0 \sim 0.6-1 \, \text{AU}$ is sufficient for the ejection of a hypervelocity binary. High-mass binary stars are known to have higher binary fraction (probably $f_{\text{bin}} > 0.8$, e.g.; Abt et al. 1990; Mason et al. 1998; Kobulnicky & Fryer 2007) and different semimajor axis distribution than low-mass stars, with a large fraction of them ($f_{\text{bin}} \sim 0.4$) in close binaries ($a_{\text{bin}} < 1 \, \text{AU}$, e.g., Abt 1983; Morrell & Levato 1991). The triple fraction and distribution of massive stars is still uncertain, but it is strongly suggestive of a high triple fraction among binaries. Evans et al. (2005) find that most if not all of the massive binaries they observed (in Cepheids) are likely to be triple systems. Some $f_{\text{triple}} \sim 0.8$ of the wide visual binaries in stellar associations are in fact hierarchical triple systems, where typically the more massive of the binary components is itself a spectroscopic or even eclipsing binary pair (Zinnecker 2005). Fekel (1981) compared the properties of close multiple stars. He finds a fraction $f_{\frac{1}{2} \, \text{yr}} \sim 0.2$ of the more massive systems (we choose systems with total mass of $> 6 \, M_\odot$) to have outer binary periods shorter than half a year, corresponding to $a_0 \lesssim 1 \, \text{AU}$, i.e., with characteristics allowing for the ejection of hypervelocity binary if they were disrupted by an MBH. The fraction of close triples (such as those in Fekel 1981) out of the total triple population is unknown. Lacking a better estimate, we assume this fraction to follow the fraction of close binaries; i.e., we take the fraction of close triples out of the full triple population to be $f_{\text{triple}} = f_{\text{bin}} \cdot f_{\frac{1}{2} \, \text{yr}} = 0.4 \times 0.2 = 0.08$ (note that the fraction of close triples might in fact be higher, since $f_{\text{bin}}$ is taken for binaries with $a_{\text{bin}} < 1 \, \text{AU}$ where as Fekel’s sample also contain triples with wider outer binaries). Taken together we can estimate the triple fraction of hypervelocity binary potential progenitors to be $f_{\text{prog}} = f_{\text{bin}} \cdot f_{\text{triple}} \cdot f_{\frac{1}{2} \, \text{yr}} \simeq 0.05$ (taking a binary fraction of 0.8 of which 0.8 are triples, and 0.08 of those have outer binaries with period $< 0.5$ yr). We note that there is some weak trend for more massive stars to have higher multiplicity, however, more observational data are required for a better resolution of the mass dependence of the multiplicity, and the quoted values are assumed to represent all MS B stars.

Note that very few studies on observed massive triples have been done, and therefore we also try to estimate the appropriate triple fraction differently, based only on the better known characteristics of massive binaries, where we follow the method used by Fabrycky & Tremaine (2007). Again, we assume that the orbital and stellar characteristics of the third component in a given triple could be chosen from the same distributions of the binaries\(^1\). We pick a sample of randomly chosen triple systems taken from the appropriate binary distributions. For our sample we choose many triples with initial orbital distributions such that both their inner and outer binaries are taken from the best-fit observed distributions of Kobulnicky & Fryer (2007). Each given triple has an inner binary with semimajor axis $a_0$ and masses $m_1$ and $m_2$; and an outer companion with mass $m_3$ in an orbit with semimajor axis $a_0$. The period is chosen from a distribution of orbital separations which is flat in log space, $f(\log p) \propto \text{const}$, corresponding to $f(r) \propto 1/r$ (i.e., Öpik’s law). The minimum value for the appropriate semimajor axis is taken to be twice the radii of the binary stars, i.e., separation of a contact binary which does not immediately merge. The maximal value is taken to be $1000 \, \text{AU}$.

\(^1\) This is a reasonable assumption since the difference in the dynamics of a star due to the interaction with a companion single mass or a very close binary (i.e., the inner binary) are very small, especially when discussing the surviving triples that are hierarchical. Nevertheless, we emphasize that this is an assumption. Future observations of triple systems, when available, should be used to produce more accurate and not assumption-dependent estimates of triples distributions.
following the best-fit distribution found by Kobulnicky & Fryer (2007). The mass ratio, $q$, is chosen from a power-law distribution ($f(q) \propto q^{-0.4}$); we also tried other distributions suggested in the literature and found only minor effects on the final calculated fraction. The mass of the tertiary companion, $m_3$, was determined by choosing $q = m_3/m_1 + m_2$ from the same mass ratio distribution. This approach implies that the mass of the third star was correlated with the mass of the inner binary, but we do not believe that this correlation has any significant effect on our results. Two periods and eccentricities were picked in the same manner discussed in Fabrycky & Tremaine (2007). The smaller (larger) period was assigned to the inner (outer) orbit. The semimajor axes were computed from these masses and periods assuming noninteracting Keplerian orbits. The mutual inclination distribution of the tertiary is assumed to be isotropic with respect to the inner binary. After these parameters were selected, we used the empirical stability criterion used in Fabrycky & Tremaine (2007; see their Equation (37), originally formulated in Mardling & Aarseth 2001) to determine whether the system is hierarchical or if it will disrupt in a small number of dynamical times. If the semimajor axes obeyed this criterion then we accepted the triple as stable, otherwise, we assumed it disrupted. We then found the fraction of stable triples, such that their disruption by the MBH in the GC could eject a hypervelocity binary, i.e., have outer semimajor axis small enough for the ejection velocity to be high.

From a large sample of triples ($10^5$) we find that about 0.03 of potentially formed triples are stable triples that could serve as hypervelocity binaries progenitors, where these results are not very sensitive to the prime mass $m_1$ of the inner binary component. This is generally consistent with the observation based estimates given before. We conclude that $\sim 0.03$–0.05 of all massive HVSs could have been ejected with a binary companion or have left a close binary captured in an orbit very close to the MBH.

4. REJUVENATION AND EVOLUTION IN HIGH-VELOCITY CLOSE BINARIES

Binaries ejected at high velocities are relatively close binaries. For both runaway and hypervelocity binaries the closer the binary is, the higher is its probability to be ejected at high velocity (see, e.g., Equation (2)). In the case of binaries evolving in triples (e.g., hypervelocity binaries from triple disruptions), dynamical evolution could be very efficient in producing very close inner binaries. A large fraction of such triples evolve through Kozai oscillations (Kozai 1962), in which the inner binary is periodically driven into high eccentricities. When the eccentricity of the inner binaries is high enough, the binary components tidally interact and dissipate the orbital energy. This mechanism of Kozai cycles and tidal friction (KCTF) was shown to drive the inner binary into close configuration and circularization at periods of a few days (Kiseleva et al. 1998; Eggleton & Kiseleva-Eggleton 2001; Fabrycky & Tremaine 2007), at relatively short times ($\sim$Myr), much shorter than the MS lifetime of the stars (D. Fabrycky 2007, private communication). In fact it is quite plausible that most of the observed contact binaries are produced through evolution in triple stars (D’Angelo et al. 2006; Pribulla & Rucinski 2006; Fabrycky & Tremaine 2007). We conclude that most if not all runaway and hypervelocity binaries should be ejected as close (period of up to a few tens of days) or even contact binaries.

During the evolution of close binaries in the triples they can closely interact through mass transfer and even mergers (citeper+09). Such interaction could lead to rejuvenation of one of the binary components (see, e.g., Dray & Tout 2007; Vanbeveren et al. 1998), and even to its “reincarnation” as higher mass star. Such rejuvenated stars, also known as blue stragglers (although this term usually refers to low-mass rejuvenated stars) could appear much younger than their real age (Vanbeveren et al. 1998). For high-velocity stars such extended lifetimes could potentially be translated into much larger propagation distances from their birthplace. Consequently, such high-velocity massive blue stragglers could be observed to have flight times longer than their apparent lifetime (see Table 1).

We used the population synthesis program SeBa, as described in detail in Portegies Zwart & Verbunt (1996) and Portegies Zwart & Yungelson (1998), to study the possible outcomes from the evolution of close runaway and hypervelocity binaries. In this module, stars are evolved via the time-dependent mass–radius relations for solar metallicities given by Eggleton et al. (1989) with corrections by Eggleton et al. (1990) and Tout et al. (1996). These equations give the radius of a star as a function of time and the initial mass of the star (on the zero age MS). The mass of the stellar core and the rate of mass loss via a stellar wind (not specified in this prescription) were included using the prescriptions of Portegies Zwart & Verbunt (1996).

We have focused on the evolution of the possible binary progenitors of the rejuvenated OB stars, such as currently observed in the Galactic halo (Table 1). For this purpose we generated a grid of initial conditions for the periods (in the range 1–100 days) and eccentricities (0–0.99) of the binaries. Observations of massive binaries show that the components mass ratios are usually large (Kobulnicky & Fryer 2007). We have studied binaries with different masses and/or mass ratios. For each possibility we followed the binaries evolution for any initial condition in our grids, until both the binary components (or single component in case of a merger) have finished their evolution on the MS. We then recorded the total evolution time and the binary characteristics (component masses, period, and eccentricity). Here, we show the results of two representative masses for the prime binary component (4.8 and 9.6 $\odot$) and two possible mass ratios ($q = 0.9, 0.5$). Similar results have been found for other masses and mass ratios.

The binary evolution scenarios in our grid which produce rejuvenated stars correspond to different types of mass transfer scenarios, namely, type A and type B mass transfer (Paczynski 1971). We find three main outcomes for the evolution of such close binaries; merger, strong mass transfer, and weak mass transfer (see Figure 1). When the two components are very close (i.e., small periods of a few days for circular orbits, or longer period binaries with higher eccentricities), the binary components merge to form a single star containing almost all of the total initial binary mass. These mass transfer scenarios are all basically subtypes of type A mass transfer (see Nelson & Eggleton 2001 for detailed description). The time until merger varies between almost immediate merger up to the MS lifetime of the more massive component. A mass transfer and/or merger evolution may lead to some observational signatures, such as possibly high rotational velocity (Leonard 1995, and references therein); or chemical anomalies, such as CNO abundances anomalies citepsar+96, che+04, fer+06. For our rejuvenated stars candidate sample we find that high

2 http://www.ids.ias.edu/~starlab/seba/
rotational velocities are possibly observed in PG 1209+263, HS 1914+7139, PG 0914+001 (Ramspeck et al. 2001). Large rotational velocities are possibly observed in PG 1209+263, HS 1914+7139, and PG 0914+001 (Ramspeck et al. 2001). Large chemical anomalies are observed in HS 1914+7139 (Lynn et al. 1992). However, such peculiarities are not likely to be strong signatures, since they do not necessarily arise only due to mass transfer processes, and may not even be produced in the majority of rejuvenated stars to begin with. We conclude that given the weak observational signature of the rejuvenation process on the appearance of the rejuvenated stars, observations of the chemical or rotational properties cannot serve to directly trace their binary origin.

In longer period binaries (and/or smaller eccentricities), strong mass transfer occurs when the more massive binary components leave the MS. The massive component then shed most of its mass to its companion. This scenario usually produces a massive MS star containing 0.8–0.8 of the initial total binary mass with a low-mass companion. Such scenario corresponds to type B mass transfer (see, e.g., Paczyński 1971 for details). These binaries have typical periods of few × 10–200 days. The timescale for the production of the accreting massive components is typically the MS lifetime of the initial prime component of the binary. In a smaller part of the phase space explored in our grids, a weak mass transfer occurs where only a small fraction of the mass from the prime component is accreted by its companion. In these cases, the rejuvenation of the companion is negligible.

5. DISCUSSION

Young stars have been observed in the Galactic halo since the 1970s (e.g., Greenstein & Sargent 1974). Such stars are found well away from any star-forming region and are remote from any high-density interstellar gas pockets where they could have potentially formed. The origin of these young stars in the Galactic halo have been extensively studied (see Keenan 1992 for a review), and many of them could be understood in terms of ejection mechanisms. They could have formed in the Galactic disk and then be ejected at high velocities due to dynamical interactions, and travel to their current position in the halo. However, some of these young halo stars have apparent evolutionary age shorter than the flight time from any star-forming region in the Galactic disk or the GC (e.g., Table 1).

In situ star formation in the Galactic halo could potentially explain the existence of young halo stars. However, the very low gas density in the halo (e.g., Savage & de Boer 1981; Sembach & Danks 1994) make this possibility seem difficult. Dyson & Hartquist (1983) suggested that star formation could occur during collisions between cloudlets within high-velocity clouds at high-galactic latitudes, but Christodoulou et al. (1997) have shown that such events are much too rare. Martos et al. (1999) suggested that spiral density waves in the disk could trigger star formation above the Galactic plane up to a kiloparsec, but this seems unlikely for higher distances, where many of the...
young halo stars are observed. Both of these mechanisms would produce a few or up to tens of young stars with correlated velocities whereas formation of isolated stars is unlikely. In one case, Lynn et al. (2002) have studied the environment of the halo young star PHL 346, but found no evidence for similarly young stars in its vicinity.

Rejuvenation scenarios of runaway stars have been discussed in the literature, but in a different context, dealing with mass accretion onto a star following an SN explosion (Martin 2003), and the possible formation of a Thorne–Zytkow object (Leonard et al. 1993). These scenarios dealt either with a specific observed runaway (Martin 2003), or with more rare cases than the scenario discussed here. They also discussed interaction of a compact object with its companion rather than the rejuvenation due to mass transfer in the post-MS evolution stages of binaries.

In the following we discuss the status of the candidate runaway and HVSs in the Galactic halo and the implications of the binary rejuvenation and the triple disruption scenarios for the young stellar population in the GC. We suggest that all of the currently observed young Halo stars could have been ejected from the Galactic disk or the GC, when the binary rejuvenation scenario is taken into account. We also expand our discussion on the origin of the HVS HE 0437−5439, which was recently discussed in the literature. We show that an ejection origin by an IMBH or through interactions in a massive cluster in the Large Magellanic Cloud (LMC; Gualandris & Portegies Zwart 2008; Gvaramadze et al. 2008) are highly unlikely to be the origin of this star and suggest this HVS as a candidate rejuvenated HVS ejected as a binary from the GC, which later on merged to form a more massive HVS. We also show that its observed low metallicity is consistent with a Galactic origin and a GC origin cannot be ruled out.

5.1. Rejuvenated Runaway Stars

In Table 1, we have listed young stars observed in the Galactic halo that have estimated propagation times which could potentially be larger than their evolutionary time, given the uncertainties. As we have shown in Section 4, the rejuvenation in binaries can extend the travel time of the runaway stars as MS stars. Following the rejuvenation, in both the full merger and the strong mass transfer cases discuss above, we find that the newly rejuvenated massive star, with mass $m_{\text{rej}}$, contains most of the mass of the initial binary. The typical formation timescale is of the order of the MS lifetime of the prime binary component, $t_{\text{m}}$. If such binaries are ejected as runaway or HVSs they could propagate for as long as $t_{\text{m}}$ before producing the newly formed massive star. The MS lifetime of this rejuvenated star, $t_{\text{m rej}}$, could then be much smaller then the propagation time, $t_{\text{m rej}} < t_{\text{prop}} \leq t_{\text{m}}$, thus producing an apparent discrepancy between the flight time and the lifetime of this star.

Such rejuvenation scenarios provide a maximal flight time for a given star of $t_{\text{prop}} = t_{\text{m}} + t_{\text{m rej}}$. Since the mass of the prime component in the binary progenitor is at least half the mass of the rejuvenated star we find the maximal propagation time to be $t_{\text{prop max}} = t_{\text{m rej}} + t_{\text{m rej}}$, where $t_{\text{m rej}}$ is the MS lifetime of a star with half the mass of the observed halo star. We find that all of the candidate stars in Table 1 have $t_{\text{flight}} < t_{\text{prop max}}$ and could be rejuvenated stars.

5.2. Rejuvenated Hypervelocity Stars and the Case for HE 0437−5439 and US 708

Currently, ~20 HVSs have been observed in the Galactic halo (Brown et al. 2005, 2007a, 2007b; Hirsch et al. 2005; Edelmann et al. 2005). The kinematics and ages of most of these stars are consistent with their possible origin from the GC. A discrepancy between the kinematics and the ages of a few of the bound HVSs might exist (Brown et al. 2007a), making them possible candidate rejuvenated stars. However, more observations are required to confirm that these stars are truly early B-type stars, and not halo extreme horizontal branch stars.

The HVS HE 0437−5439 was spectroscopically identified to be a genuinely young B2 III−IV halo star with mass of $\sim 9.0 \pm 0.8$ $M_{\odot}$ (Edelmann et al. 2005; Bonanos et al. 2008; Przybilla et al. 2008). Its apparently short lifetime and the large distances from the GC and the Galactic disk make it too young to have traveled from these regions during its lifetime, even with its very high velocity (723 km s$^{-1}$; Edelmann et al. 2005). It was therefore suggested to be either ejected from the LMC or rejuvenated in a binary ejected by an IMBH inspiral to the GC (Edelmann et al. 2005). In the following we discuss the possible evidence for the origin of this star (metallicity), and its dynamical history. We show that the suggested dynamical origins of this star from the LMC require improbable dynamical scenarios, and as an alternative we suggest it is a rejuvenated star ejected as a hypervelocity binary in a triple disruption by the MBH in the GC. We also show that the chemical abundances of HE 0437−5439 suggested as evidence for an LMC origin of the HVS, do not rule out its possible GC origin, and could be consistent with such a scenario. In addition, we shortly discuss the possible rejuvenation origin of the low-mass old HVS US 708.

5.2.1. Ruling Out Some Possible Dynamical Origins of HE 0437−5439 from the LMC

Given the observed high velocity of HE 0437−5439, a dynamical scenario for this star would most likely require an interaction with an MBH, Gualandris & Portegies Zwart (2007) have suggested that a tidal disruption of a binary by an IMBH in a young stellar cluster in the LMC could produce HVS such as HE 0437−5439 at a rate of $5 \times 10^{-5}$ yr$^{-1}$. We note that such IMBH have not yet been observed in the LMC (or elsewhere). Moreover, Gualandris & Portegies Zwart (2007) have not taken into account a few important considerations. (1) The travel time from the LMC to our Galaxy for such an HVS is about 20 Myr, very close to the ages of the clusters they suggested as possible hosts of an IMBH. For these clusters the HVS should have been ejected immediately after the formation of the IMBH (assuming that the IMBH have formed quickly enough in the cluster to begin with), probably during less than 1 Myr, in order to achieve its current position. Given the calculated ejection rates, only $N_{\text{ej}} \sim 10^6 \times 5 \times 10^{-8} = 0.05$ HVSs could have been ejected, on average, in the relevant time. (2) The stellar mass function has not been taken into account by Gualandris & Portegies Zwart (2007). The fraction of stars as massive as $8.5 M_{\odot}$ or more (the estimated mass of HE 0437−5439) is very small, only a fraction of $f_{\text{IMF}} \sim 0.01$ of the stellar population is in such massive stars (and likely even smaller, as most of these more massive stars were likely to fuel the growth of the IMBH). (3) The ejection of HVSs is isotropic, and therefore only a fraction of them $f_{\text{MW}} < 0.1$ would be directed to the Milky Way. Taking together the average number of observable massive ($> 8.5 M_{\odot}$) HVSs from the LMC (similar to HE 0437−5439).
should be about $N_{\text{eject}} \times f_{\text{typ}} \times f_{\text{MW}} = 5 \times 10^{-5}$, making this possibility highly unlikely.

Recently, it was suggested that HVSs might be produced through binary–binary dynamical interactions of massive binaries in a dense cluster (Gvaramadze et al. 2008). Leonard (1991) has studied such encounters. He found that the lowest mass star participating in the interaction could attain the highest velocity. Such velocity would be comparable to the escape velocity from the most massive star participating in the encounter. If HE 0437–5439 was ejected from the LMC, it would require an ejection velocity of $>900$ km s$^{-1}$ in order to acquire its current position during its lifetime (Gualandris & Portegies Zwart 2007; Przybilla et al. 2008). For this to happen HE 0437–5439 would need to encounter stars more massive than itself. Even then the fraction of encounters where such velocity could be attained by this star is $f_{\text{high}} \sim 10^{-4} (4 \times 10^{-4}, 2 \times 10^{-3};$ see Leonard 1991) for encounters where the masses of the other stars are larger than $15 M_\odot$ ($30 M_\odot$, 60 $M_\odot$, respectively). Since binary–binary encounters usually lead to the disruption of one of the binaries, one would require $\sim 1/f_{\text{high}}$ such binaries to exist in order for one of them to potentially be ejected at such high velocity. Such conditions, i.e., the existence of hundreds (thousands) of $>30 M_\odot$ (greater than $15 M_\odot$) stars in a super dense cluster core are not known to exist in any young cluster in the Galaxy or in the LMC. We conclude that the scenario for ejection of HE 0437–5439 through a dynamical interaction with massive stars in a cluster is highly unlikely.

5.2.2. The Metallicity of HE 0437–5439 Does Not Rule Out a Galactic Center Origin

Recently, Bonanos et al. (2008) and Przybilla et al. (2008) have found the metallicity of the HVS HE 0437–5439 to be low relative to solar metallicity. They suggested this as a possible evidence for an LMC origin of this star rather than a Galactic origin. However, an LMC origin would be difficult to explain dynamically, as discussed above. Moreover, in the following we show that the current metallicity measurements do not rule out a Galactic (and GC) origin for HE 0437–5439.

It is known that the observed abundances of some elements in Galactic B stars are depressed relative to the established solar values (see, e.g., Martin 2004; 2006; and the Appendix). Therefore, one should compare the metallicity of B-type stars such as HE 0437–5439 with large surveys of similar B-type stars. Przybilla et al. (2008) made a comparison with a single galactic B star and a single LMC B star that may not representative of the large scatter in the abundances shown in larger samples. Bonanos et al. (2008) made a comparison with a large B stars survey in the LMC, but for the comparison with the Galactic abundances they took the solar abundances rather than Galactic B stars surveys. Figure 2 shows the spread in the measured chemical abundances for different samples of stars (LMC, Milky Way and the GC stars) found in the literature (see caption of Figure 2). For small samples (with 10 stars or less) the data for each of the stars are shown rather than the mean abundance, since given the very small samples the mean may not be a good representative of the underlying distribution of abundances. For the larger samples the 1$\sigma$ spread around the mean (i.e., where 68% of the measured values are found) is shown. We can use these data samples and compare them with the chemical abundances of HE 0437–5439. The results by Przybilla et al. (2008) have systematically smaller error bars, and also contain the abundances for more elements (C, N, O, Mg, Si, and Fe) compared with the results obtained by Bonanos et al. (2008; which do not show the Fe abundance), and are therefore used in the comparison. Nevertheless, given the large differences that exist between the chemical abundances obtained by Przybilla et al. (2008) and those found by Bonanos et al. (2008), the latter results are also shown in Figure 2 for completeness.

Comparison of the chemical abundances of HE 0437–5439 as found by Przybilla et al. (2008) to those found in surveys of B-type stars throughout the Galaxy (Daffon et al. 2001) show that its metallicity is highly consistent with their metallicities.$^5$ Most (greater than 50%) of the stars in the sample have more extreme elemental abundances than that of HE 0437–5439 (for each of the elemental abundances observed; see Figure 2, bottom panel), showing that the elemental abundances of HE 0437–5439 are quite typical of the Milky Way chemical abundances.

Although a galactic origin is most consistent with the metallicities of HE 0437–5439, its high velocity would require an interaction with an MBH, currently known to exist only in the LMC.

$^5$ Even in such surveys large uncertainties exist; in the Appendix we show the chemical abundances of B stars found both in the Galaxy and the LMC in several different surveys, enabling a more detailed comparison. Figure 2 shows only the results from the survey of Daffon et al. (2001), nevertheless, this survey includes B stars from different regions in the Galaxy, and it is generally consistent with the other samples (see the Appendix). One could also compare the values obtained for HE 0437–5439 to those of other young halo stars showing that its metallicities are not unusual for such objects.
GC. Therefore, its metallicities should be compared with the metallicities of similar unevolved B stars in the GC. Unfortunately, metallicity measurements of stars in the GC region exist only for a small number of stars, none of which are similar to HE 0437−5439 (although some of these GC stars have similar masses, they are at a very different evolutionary stage: Cunha et al. 2007). Therefore, given the current data, drawing conclusions on the origin of HE 0437−5439 based on metallicity comparisons with GC stars is premature. Nevertheless, we briefly discuss such metallicity comparison, but caution that this should not be taken as evidence for the origin of HE 0437−5439, but at most as a possible clue until further measurements of the metallicity of GC stars are available.

The chemical abundances of stars in the GC are known mostly for cool evolved stars (Cunha et al. 2007). Data on two additional highly massive (∼150 M⊙) LBV stars exist (Najarro et al. 2009), but given their very different stellar type and evolution, comparing their abundances with that of HE 0437−5439 is not justified, and we do not use their data. The number of data points (stars) for each element are 10, 7, 6, and 5 for the elements Fe, O, C, and N, respectively. The C, O, and Fe abundances of HE 0437−5439 are found to be consistent with GC values (see Figure 28), but the N abundance is not (with all five stars in the GC sample have higher abundances than those found for HE 0437−5439). We note that better agreement is observed for those elements for which more data exist. The N abundance of HE 0437−5439 is lower than those of the GC stars. However, since CNO cycle mixing can convert these elements in the GC stars (see, e.g., Carr et al. 2000; Cunha et al. 2007) and in HE 0437−5439, one should be careful and also check the sum of these elements and not only compare each of these elements by itself. We find that the sum of these elements is consistent with that of the GC sample stars, i.e., not even the N abundance of HE 0437−5439 could be interpreted as an evidence against a GC origin. Moreover, given the low statistics of the GC sample, the lower N abundance is not statistically significant, even by itself. Given the wide range of abundances found in different Galactic B-type stars surveys (see the Appendix), it is possible that this specific HVS B star may have lower abundances of these specific element.

The middle panel of Figure 2 shows the comparison of the elements abundances of HE 0437−5439 to those found in the LMC. The metallicities of B stars in the LMC were found by several groups (the largest samples by Korn et al. 2002; Hunter et al. 2007), where we show the values obtained by Hunter et al., for which a large sample exists (30), whereas the sample by Korn et al. contains only four stars. The comparison shows much poorer agreement with LMC abundances than with the Milky Way abundances. The N, Fe, and the Si abundances of HE 0437−5439 are found to be consistent with LMC values, but the C, O, and Mg abundances are not (all 30 stars in the LMC samples have higher abundances than those found for HE 0437−5439 for these elements). We do note, however, that the metallicities of HE 0437−5439 obtained by Bonanos et al. (2008) are consistent with those of the LMC for all elements. In addition the results of Przybilla et al. (2008) are better consistent with LMC values found by Korn et al., which are systematically higher.

These comparisons show that the metallicities obtained by Przybilla et al. (2008) are more consistent with the GC abundances than the LMC abundances shown here (and best consistent with a Galactic origin). However, we caution again that the small statistics and the different type of stars included in the GC sample of stars, the large differences inferred for the metallicities of HE 0437−5439 by different authors (Bonanos et al. 2008; Przybilla et al. 2008); and the different analysis methods used by different groups, suggest that it is still to early to draw conclusions from such metallicity comparisons. It is clear from the above discussion, however, that none of the suggested origins for HE 0437−5439, including the Galactic disk, the LMC, and the GC can be ruled out based upon current metallicity data.

5.2.3. The Possibility of HE 0437−5439 as a Rejuvenated Star from the Galactic Center

As discussed in the previous sections, young halo stars such as HE 0437−5439 could have evolved from two lower mass members of ejected hypervelocity binaries. The binary components either merge completely, or may evolve through a strong mass transfer from the more massive binary component to its initially lower mass companion, which becomes a rejuvenated massive star. The later possibility would give a strong observable signature in the form of a high mass ratio binary with a period of tens of days. The observations of Przybilla et al. (2008) and Bonanos et al. (2008) rule out the possibility of such a binary, and therefore if this HVS is a rejuvenated star its binary progenitor fully merged. As can be seen in Figure 1, a binary progenitor with 4.8 and 4.3 M⊙ components, for example, could have propagated for more than 60–80 Myr and then merge to form a 9 M⊙ star, consistent with the required travel time from the GC (Edelmann et al. 2005). We note that binaries with other high mass ratio components (not shown here), but with a total binary mass of ∼0.5 M⊙ could also produce such a merged star with the appropriate evolutionary timescales. Given the tendency of massive binaries to have high mass ratios, it is likely that most ejected binaries should have mass ratios in the relevant parameter space as to produce a merged star similar to HE 0437−5439. All the hypervelocity binaries have initial semimajor axis smaller than ∼0.2 AU (4−5 R⊙), since they were originally part of the inner binaries in close stable triples. In addition, the KCTF mechanism in triples (see Section 4) could evolve such inner binaries into even closer contact configuration at a very short timescale (Myr). It is therefore expected that most hypervelocity binaries would be at very tight orbits or a few R⊙ separations, such as those required to eventually form a merged starlike HE 0437−5439 (see Figure 1). In other words the rejuvenation scenario is a likely scenario for the formation and ejection of HE 0437−5439. The estimate in Section 3.2.1 suggests fprop = 3%−5% of the HVSs could be ejected as close hypervelocity binaries or leave a binary star close to the MBH. The fraction of rejuvenated HVSs is therefore fEj = fprop · finner · fmerged · ftime where fprop is the fraction of disrupted triples that eject the inner binary, fmerged is the probability the binary merges, ftime is the fractional lifetime of the merger remnant to the original stars lifetime. Simulations of binary disruptions by an MBH (Miller et al. 2005; Bromley et al. 2006) suggest that there is no preference for the primary or the secondary in the binary to be ejected, i.e., they have equal ejection probability; I therefore take ftime = 0.5. Estimating the probability of binary merger is very uncertain. Taking the observed triples sample of Fekel (1981), I find that the inner binaries in the HVSs binaries possible progenitors have periods of a few days, which together with
the binary stellar evolution simulations (see Figure 1) suggest that >0.75 of them would merge due to stellar evolution. I therefore take \( f_{\text{merger}} = 0.75 \). The question of \( f_{\text{lifetime}} \) is more complicated. The merger remnant has a lifetime of \( t_{\text{merg}} \) as discussed in Section 5.1, and the maximal lifetime of its progenitor is at most \( t_{\text{merg}}/f_{\text{prop}} \). A rejuvenated star therefore has a fractional lifetime to the original stars of \( t_{\text{merg}}/t_{\text{merg}} \). Taking the stellar evolution MS lifetimes from the Geneva stellar evolution tracks (Schaller et al. 1992), I find this to be approximately 0.2. However, on average, the HVSs are ejected after half their lifetime. In addition, the ejected stars are observed only after their propagation for \( t_{\text{prop}} = 10^{-6}\,\text{yr} \) (the flight time to distances of 10–100 kpc from the GC where they are currently observed), the fraction of the merger remnant lifetime to the time spent by the progenitor at observable regions is \( t_{\text{merg}}/(0.5\,\times\,t_{\text{merg}} + t_{\text{prop}}) > 0.4 \).

A reasonable estimate is therefore \( f_{\text{lifetime}} = 0.2–0.6 \). Taken together, we find \( f_{\text{rej}} \approx 0.003–0.012 \). Given the current estimate of \( N_{\text{HVS}} \sim 100–650 \) B-type HVSs in the galactic halo Brown et al. (2007b); Perets et al. (2009b), we may expect to find \( N_{\text{HVS}} = f_{\text{rej}} \times 0.25–8 \) rejuvenated (more) massive HVSs in a full sky survey (compare with the value of \( 5 \times 10^{-3} \) massive stars expected to originate from the LMC in the IMBH scenario, if such IMBH indeed exist there in a young massive cluster).

We summarize this section by concluding that current suggestions for the hypervelocity ejection of HE 0437–5439 from the LMC (either by an IMBH or through interactions with other massive stars) are highly unlikely, and suggest that HE 0437–5439 was ejected from our GC (where we stress that this scenario is not ruled out by current metallicity comparisons) in a hypervelocity binary following a triple disruption by the MBH.

5.2.4. The Possibility of US 708 as a Rejuvenated Star from the Galactic Center

We note that the HVS US 708, which is not a young star but an evolved sdO star, was suggested to evolve from a merger of a close binary (Hirsch et al. 2005). In that respect, we find that when the evolution of close binaries such as studied here is followed to later times (not shown here) such white dwarfs are indeed formed in some cases. It is therefore possible that US 708 was also ejected as a binary star from a triple disruption that later on evolved and merged to form an sdO star, in a similar way to the rejuvenated young halo star studied here (as suggested by W. Brown 2007, private communication). However, the unique evolution and a merger of two white dwarfs is only poorly followed in the evolutionary code used here, and further studies should be made to check this possibility.

5.3. Binaries in the S-stars Cluster in the Galactic Center

In recent years high-resolution observations have revealed the existence of many young OB stars in the GC near the MBH. Most of the young stars are observed in the central 0.75 pc around the MBH. The young stars population in the inner 0.04 pc (the “S stars”) contain only young B stars, in apparently isotropic distribution around the MBH (Eisenhauer et al. 2005; Ghez et al. 2005). The young stars outside this region contain many O stars in a disklike structure and were probably formed from the fragmentation of a gaseous disk (Levin & Beloborodov 2003; Paumard et al. 2006). However, the origin of the S stars is difficult to explain by this process. It was suggested that the S stars with their very different properties migrated from the stellar disk through a planetary migrationlike process (Levin 2007, but see Perets et al. 2009a). This interesting possibility has not yet been studied quantitatively. Another possibility is that these stars have a different origin, possibly from the disruption of young binaries and the following capture of one of their components (Gould & Quillen 2003). It was recently shown that such a scenario could be consistent with the current knowledge regarding the number of the observed S stars and their orbital properties (Perets et al. 2007). In case of a triple disruption, a binary could be captured at a close orbit near the MBH. We therefore suggest that some of the observed S stars may be binaries. Such binaries may not survive for long in this environment due to interactions with other stars (see Perets 2009, for a detailed discussion on binaries survival in the GC). Such interactions could also change the orbits of the disrupted binary components near the MBH. Still, the closest binaries could survive for longer times (Perets 2009) and may be observed. Interestingly, observations of wider S-stars binaries would suggest more recent capture; i.e., the binary period may serve to estimate the time a binary spent in the close by regions of the MBH. In addition such S-star binaries could rejuvenate to form more massive S stars, possibly explaining the occurrence of the most massive S stars such as S-2.

6. SUMMARY AND CONCLUSIONS

In this paper, we have studied a possible explanation for the existence of young stars far in the Galactic halo. Such stars are usually thought to have formed elsewhere, either in the Galactic disk or the GC, and later on ejected at high velocities into their current position. However, some of these stars have apparent lifetimes shorter the required flight time from the Galactic disk/GC. Here, we suggested that such stars have evolved in close runaway or hypervelocity binaries. We found that stellar evolution of such binaries can drive them into mass transfer configurations and even mergers. Such evolution could then rejuvenate them (similar to the cases of lower mass blue stragglers) and extend their lifetimes after ejection. The extended lifetimes of such stars could then be reconciled with their flight times to the Galactic halo, and the travel times could be extended up to 3–4 times relative to their apparent lifetimes.

Three typical scenarios were found for the binaries evolution.

1. In case of a full merger of the binary progenitor components, a single halo star would be observed. Unless the binary merger lead to peculiar characteristics of the merged star, such as possibly high rotational velocity, or chemical peculiarities, observation of such stars could not directly trace their binary origin. Nevertheless, we predict that in such cases the calculated propagation time of the star from its birthplace would be limited to approximately the MS lifetime of its binary progenitor components (at most the MS lifetime of a star with half the mass of the observed halo star). (2) In the case of a strong mass transfer, one of the binary progenitor component have accreted most of the mass of its companion. In such a case the evolved binary could be observable as a high mass ratio binary,
with typical periods of 10–200 days. (3) In the case of a weak mass transfer, only a small fraction of the mass of the binary progenitor component is accreted by its companion, leading to negligible or mild rejuvenation. This third evolutionary route would not produce “too young” halo stars, albeit they could produce marginal cases. However, such halo young binaries (that have already been observed) can confirm the scenario of runaway binaries that, for different orbital parameters of the binary, could have produced rejuvenated high-velocity stars.

We studied the possibilities of binary runaway and HVSs and showed that such binaries could have been ejected in triple disruptions and other dynamical interactions with stars or with MBHs. Consequently, currently observed “too young” star in the halo could have been ejected from the Galactic disk or the GC and be observable in their current position if they were ejected as binaries (whereas other suggestions such as ejection from the LMC are shown to be highly unlikely). The calculated propagation times of these stars are indeed consistent with the evolutionary lifetimes in rejuvenated binaries. We suggest to look for binary companions that may exist for some of these stars, thus directly confirming the binary rejuvenation scenario (HD 188618 in Table 1 has already been suggested as binary candidate; Martin 2006). We also specifically discuss the HVS HE 0437−5439 in that respect, and show that it could be a rejuvenated HVS from the GC (where we also discuss its recently observed metallicity, showing that a GC origin cannot be currently ruled out, contrary to recent suggestions).

Finally, we also suggest that triple disruptions by the MBH in the GC could capture binaries in close orbits near the MBH, some of which may later evolve to become more massive rejuvenated stars. Future observations might be able to study these binaries.

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APPENDIX

CHEMICAL ABUNDANCES OF YOUNG B STARS AND HALO STARS

Following Section 5.2.2, we supplement in this appendix a table (Table 2) in which the detailed chemical abundances of B stars found in Galactic and LMC surveys are shown, in order to give better and broader perspective on their scatter and uncertainties. These show the typically lower measured metallicities characterizing B stars, in comparison with the solar abundances. Also shown are the chemical abundances found for HE 0437−5439 by Bonanos et al. (2008) and Przybilla et al. (2008). In addition we detail the metallicities of other candidate rejuvenated halo stars from Table 1 (for which measurements are available), showing that the metallicities of HE 0437−5439 are not unusual. The quoted mean abundances in the surveys have typical 0.1–0.2 dex uncertainties in the measurements. The specific uncertainties for single stars are given specifically for each star.

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