Exotic Stars as Challenges to Evolution
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Star Clusters as Exotic Star Factories

Jarrod R. Hurley, Michael M. Shara

American Museum of Natural History, Department of Astrophysics, Central Park West at 79th Street, New York, NY 10024, USA

Christopher A. Tout

Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, UK

Abstract. In light of recent N-body simulations performed using the GRAPE-6 special-purpose hardware we discuss the role of the star cluster environment in producing unusual stellar populations and the possibility that stars labelled *exotic* in the solar neighbourhood may be commonplace within star clusters.

1. Introduction

There are a number of reasons to expect that globular clusters should be efficient at producing stars that do not follow the standard stellar evolution path for the duration of their lives. First, and foremost, these are crowded stellar environments where, especially in the central regions, the number density of stars is high enough that the timescale for a star to collide with another cluster star is comparable to the age of the system. Fold into this the fact that globular clusters are observed to have sizeable binary populations (Richer et al. 1997, for example), that binaries present a much larger cross-section for collision than a single star, and that exchange interactions involving a binary and a third star are likely, and already you see the possibilities. Furthermore, the relaxation timescale for a globular cluster is also less than its age and it is on this timescale that important dynamical processes such as mass-segregation and core-collapse occur. Mass-segregation is driven by weak two-body gravitational encounters that cause the binaries and heavier stars to sink into the inner regions as the cluster tends toward a state of equipartition of energy. The result of core-collapse would be a point of infinite density if it were not for the energy generated by encounters between binaries and single stars in the core. These vital 3-body interactions increase the binding energy of the binary while giving a velocity kick to the third star.

All of these factors enhance the likelihood of stellar interactions but when considered together it comes as no surprise to find that globular clusters are hotbeds of stellar activity, and hence ideal factories for producing exotic stars. Blue stragglers are being found in increasingly large numbers in globular clusters (Ferraro et al. 1999, for example) and the fact that they are concentrated toward the cores of these clusters is taken as strong evidence of a dynamical

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origin. However, blue stragglers can probably no longer be claimed as *exotic* stars simply because improved observational resources have rendered them common. This makes understanding their origin and morphology no less important and the same is true for all types of star that are identified as interesting via their occupying a non-standard position in a cluster colour-magnitude diagram (CMD) – sdB stars (Moehler, Heber, & Durell 1997) being another example. X-ray binaries are more likely to be considered exotic and these are found to be at least 1 000 times more abundant in globular clusters than in the Galactic field. Even these are becoming common with the advent of the Chandra X-ray observatory (Grindlay et al. 2001).

Simply because open clusters contain less stars and operate at lower stellar density than their globular counterparts we would expect them to be less likely to produce exotic objects. However, owing to computational constraints with the N-body method we have been forced to model open clusters and no-one has yet to complete a direct N-body model of a Galactic globular cluster. If we could have jumped straight to modelling globulars then most likely we would have but in a way it has been fortunate that we did not. Our models of open clusters have produced plenty of interesting cases of dynamical modification of stellar populations (Hurley et al. 2001; Shara & Hurley 2002) and shown that these are active environments full of promiscuous stars (Hurley & Shara 2002). Open clusters are also interesting because they disperse on timescales of a few Gyr, or less, and hence provide an avenue for producing exotic stars observed in the Galactic field.

2. The Simulation Method

The Aarseth `NBODY4` code (Aarseth 1999) has been developed to investigate the detailed evolution of star clusters using the N-body method. This is the ideal method for following the evolution of a dynamical system dominated by gravity but it is computationally expensive – the cost scales approximately as $O(N^3)$ per relaxation time for N-bodies. The production of the GRAPE family of special-purpose hardware (Makino & Taiji 1998) provided a major boost for the suitability of the N-body method. This hardware basically operates as a Newtonian force accelerator and the latest incarnation, the GRAPE-6, performs at Tflops speed, making direct simulations of small globular clusters a reality for the first time.

Importantly `NBODY4` incorporates algorithms for the detailed treatment of stellar evolution and the full range of possible interactions within binary stars (Hurley et al. 2001, and references within). It follows all external perturbations to binary orbits, weak or strong, and allows for chaotic orbits, exchange interactions, tidal capture, collisions and mergers (see Aarseth 1999 for a complete description).

Simulations performed to date with `NBODY4` on the GRAPE-6 have generally started with N in the range of 20 000-30 000 stars and a binary fraction somewhere between 10-50%. Stellar masses are drawn from a realistic initial mass function, typically between the limits of $0.1 - 50\,M_\odot$, and all stars are assumed to be on the zero-age main-sequence at the start of the simulation, with no residual gas remaining from the star formation process. The model cluster is

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evolved within the Galactic potential and stars are removed from the simulation when their distance from the cluster centre exceeds twice the tidal radius defined by this potential.

3. Exotic Stars

Fig. 1 illustrates how the proportion of *interesting* stellar populations within a cluster increases as the system evolves. Here we have highlighted blue stragglers (BSs), giants, and double-white dwarf binaries (DWDs), but other populations also exist. By interesting we mean that either the population occupies a non-standard position in the CMD (BSs), has been modified to some extent by dynamical interactions (BSs, DWDs), or is likely to be involved in future events producing non-standard stars (giants). The objects in each of these three example populations are more massive than the average stellar mass for the cluster so it is no surprise that they have been affected by mass-segregation and reside primarily in the cluster core.

Fig. 2 shows a CMD constructed from the snapshot of a simulation at 4.0 Gyr. Clearly evident is a substantial number of BSs and that some of these are in binary systems. Hurley et al. (2001) used N-body simulations to model the diverse BS population observed in M67 and showed that not only was the cluster environment effective at increasing the number of BSs present but that it opened up formation paths for all the various known types. This includes BSs in short-period binaries, either circular or eccentric, and in long-period binaries, with the latter predominantly the result of 3-body exchange interactions. Also contained in Fig. 2 is a large number of DWDs. Shara & Hurley (2002) have shown that this population contains a number of short-period supra-Chandrasekhar mass systems that will merge within the age of the Galaxy, i.e. possible Type Ia supernova progenitors. Remarkably, production of these Type Ia progenitors is enhanced in star clusters by a factor of 10 relative to the field (when normalized to the same number of primordial binaries). This enhancement is the result of dynamical encounters between binaries and other cluster stars: orbital perturbations that harden primordial binaries, orbital perturbations that harden existing DWDs and reduce their merger timescale, and/or exchange interactions that produce new close binaries while increasing the average binary mass. In both of these papers a number of interesting individual cases of stellar interaction have been highlighted (see also Hurley & Shara 2002).

We now turn our attention to some of the *exotic* stars presented at this conference and address the possibility of producing these, or stars of the same type, in star clusters. V652 Her is a pulsating helium star with a mass of 0.6 $M_{\odot}$ whose properties can be readily explained by assuming it results from the merger of two helium WDs (see Jeffery on page 53 of these proceedings). Hurley & Shara (2002) detailed the formation of a double-helium-WD binary that involved two exchange interactions and two common-envelope events. The mass of the helium WDs was 0.3 and 0.4 $M_{\odot}$ and the orbital period at formation was 0.7 d, meaning that angular momentum loss from the system owing to gravitational radiation would cause the WDs to merge in less than 12 Gyr. Such mergers occur at a rate of one or two per 20 000 star simulation - including 0.6 $M_{\odot}$ merger products.

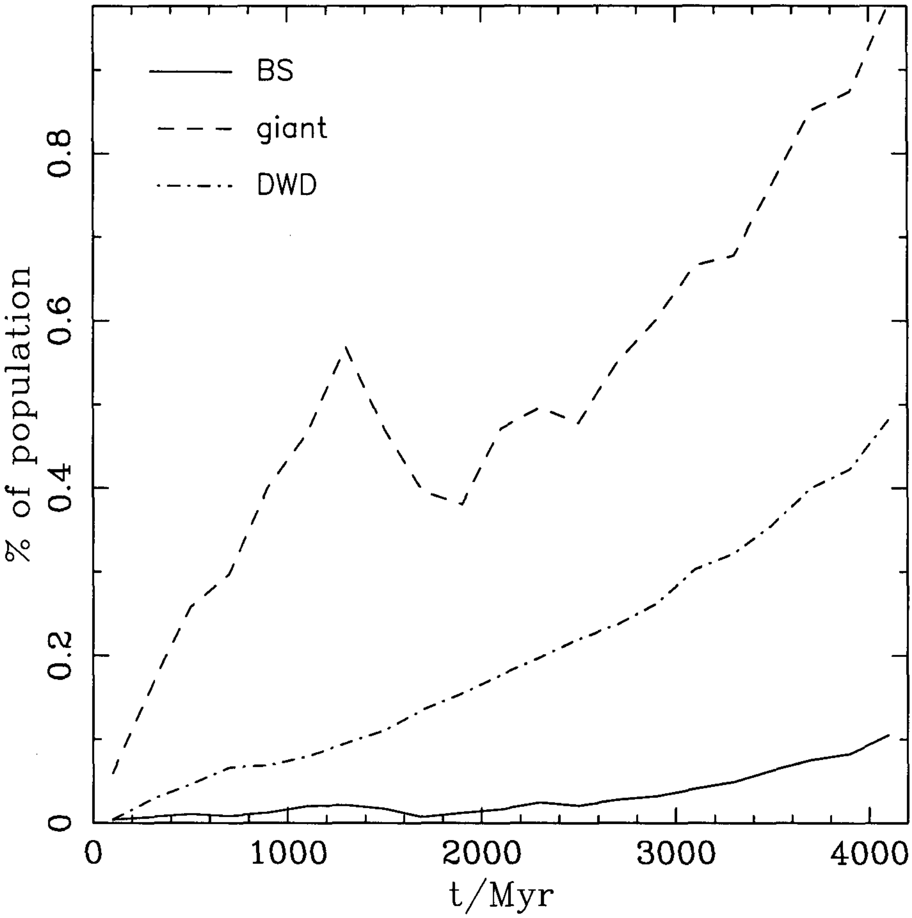

Figure 1. The percentage of blue stragglers (solid line), giants (dashed line), and double-WD binaries (dash-dot line) present in the cluster population, as a function of cluster age. Note that the giant group includes all post-core-hydrogen burning stars up to, and including, stars on the asymptotic giant branch.

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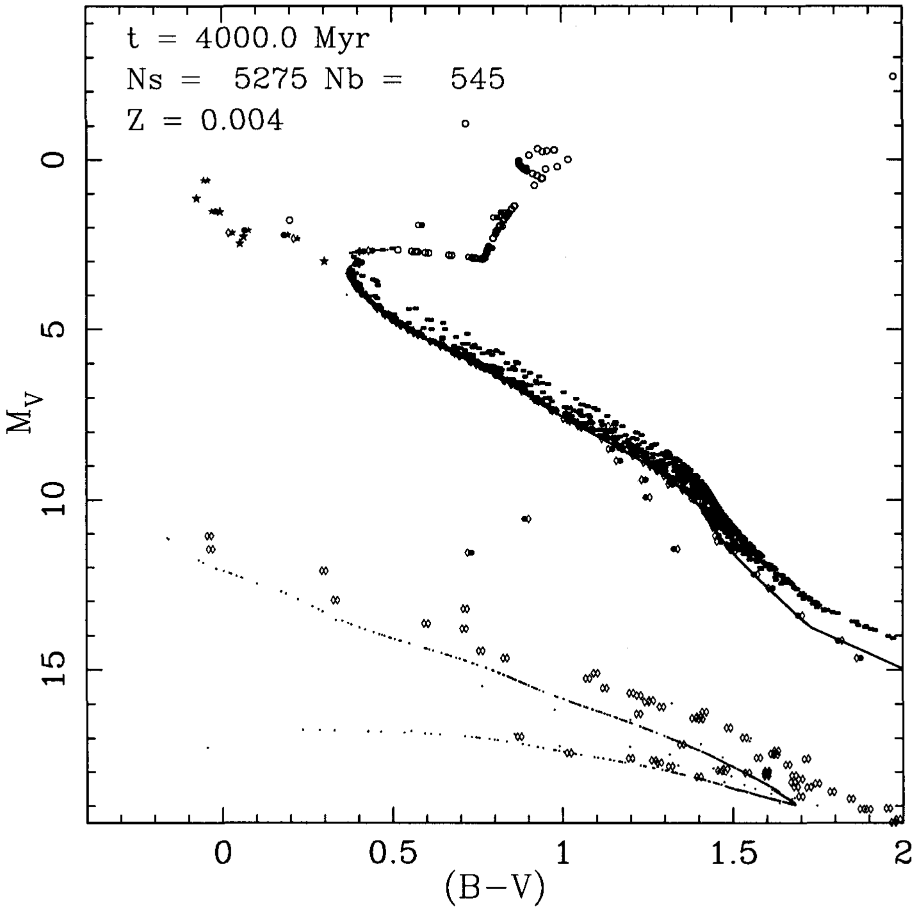

Figure 2. Colour-magnitude diagram for an open cluster simulation at 4.0 Gyr. The simulation started with 18 000 single stars, 2 000 binaries, and a metallicity of $Z = 0.004$. After 4.0 Gyr there are 5 275 single stars and 545 binaries remaining. Main-sequence stars (dots), blue stragglers (stars), sub-giants, giants and naked helium stars (open circles) and white dwarfs (dots) are distinguished. Binary stars are denoted by overlapping symbols appropriate to the stellar type of the components, with main-sequence binary components depicted with filled circles and white dwarf binary components as diamonds. Bolometric corrections computed by Kurucz (1992) from synthetic stellar spectra are used to convert theoretical stellar quantities to observed colours.

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V471 Tauri is a short-period (12.5 hr) eclipsing binary comprising a 0.84 $M_\odot$ WD and a 0.93 $M_\odot$ K dwarf (see Bond on page 239 of these proceedings). It is a post-common-envelope and pre-cataclysmic binary and interestingly is a member of the Hyades, a 600 Myr old open cluster. The WD in this system presents a paradox in that it is the most massive WD known in the Hyades but also the hottest and youngest. A suggested formation scenario is that of a progenitor triple system in which the inner binary is a close pair of main-sequence stars that merged to form a BS, and the third star is the K dwarf. The BS subsequently evolves on to the asymptotic giant branch (AGB), fills its Roche-lobe, and a phase of common-envelope evolution produces the current configuration. In our N-body simulations it is not uncommon for BSs to form in this way, i.e. merger of the inner binary of a triple system, and some of these systems do result in a common-envelope phase involving an AGB star and a K dwarf. Unfortunately an exact replica of V471 Tauri has yet to be produced via this channel but surely it is only a matter time (provided enough simulations are performed). We have seen the formation of a binary consisting of a 0.55 $M_\odot$ WD and a 0.93 $M_\odot$ K dwarf with a 12.5 hr period. In this case the K dwarf exchanged itself in to a primordial binary after 380 Myr of cluster evolution. Its new companion was a core-helium burning star which evolved to fill its Roche-lobe, resulting in common-envelope evolution, and the formation of a short-period binary comprising the K dwarf and a naked helium star that subsequently evolved to become a WD. This presents another possible formation path for V471 Tauri.

We hope that this short summary of the exciting, and rapidly developing, field of star cluster simulations has given the reader an insight in to the immense possibilities that exist for manufacturing exotic stars in star clusters.

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References

Aarseth, S. J. 1999, PASP, 111, 1333

Ferraro, F. R., Paltrinieri, B., Rood, R. T., & Dorman, B. 1999, ApJ, 522, 983

Grindlay, J. E., Heinke, C., Edmonds, P. D., & Murray, S. S. 2001, Science, 292, 2290

Hurley, J. R., & Shara, M. M. 2002, ApJ, 570, 184

Hurley, J. R., Tout, C. A., Aarseth, S. J., & Pols, O. R. 2001, MNRAS, 323, 630

Kurucz, R. L. 1992, in IAU Symp. 149, The Stellar Populations of Galaxies, ed. B. Barbuy & A. Renzini (Dordrecht: Kluwer), 225

Makino, J., & Taiji, M. 1998, Scientific Simulations with Special-Purpose Computers – the GRAPE Systems (New York: Wiley)

Moehler, S., Heber, U., & Durell, P. R. 1997, A&A, 317, 83

Richer, H. B., et al. 1997, ApJ, 484, 741

Shara, M. M., & Hurley, J. R. 2002, ApJ, 571, 830