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Massive binary stars and self-enrichment of globular clusters

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Abstract. Globular clusters contain many stars with surface abundance patterns indicating contributions from hydrogen burning products, as seen in the anti-correlated elemental abundances of e.g. sodium and oxygen, and magnesium and aluminium. Multiple generations of stars can explain this phenomenon, with the second generation forming from a mixture of pristine gas and ejecta from the first generation. We show that massive binary stars may be a source of much of the material that makes this second generation of stars. Mass transfer in binaries is often non-conservative and the ejected matter moves slowly enough that it can remain inside a globular cluster and remain available for subsequent star formation. Recent studies show that there are more short-period massive binaries than previously thought, hence also more stars that interact and eject nuclear-processed material.

1. Introduction

The abundance correlations and helium enrichment observed in globular cluster stars imply that proton-burning reactions are responsible (Prantzos et al. 2007, and many contributions to this volume). Hot hydrogen burning makes helium, nitrogen and aluminium, while destroying oxygen, carbon and magnesium, as required in models of self-enrichment in globular clusters. However, the number of stars in a second, or further, generation is often similar to or exceeds the number in the first generation (Carretta et al. 2009), and the amount of nuclear-processed material currently in their atmospheres is similar to, or larger than, that present in the atmospheres of the first stellar generation. It is not clear how so much nuclear-processed mass can end up in the second generation of stars. Four main channels have been investigated to date:

1. *Massive Asymptotic Giant Branch (AGB) stars* are the canonically accepted prime candidates for self-enrichment (Ventura et al. 2001). During their thermally-pulsing AGB (TPAGB) phase, hot-bottom burning effectively cycles the whole stellar envelope through a hot hydrogen burning shell. A star of mass $4\,\mathrm{M}_\odot \lesssim M \lesssim 10\,\mathrm{M}_\odot$ ejects about $(M-1)\,\mathrm{M}_\odot$ of nuclear-processed material, which is about 10% of the mass of the whole stellar generation. This does not take into account binary interaction which reduces the nuclear-processed TPAGB mass yield (Izzard 2004) while allowing for significant helium enrichment (Vanbeveren et al. 2012).

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2. *Rapidly rotating massive stars* also eject hydrogen-burned material if they spin fast enough (Decressin et al. 2007). Rotational mixing transports material from the hot stellar core to the surface where it is ejected if the star exceeds its critical rotation rate. This is predicted to happen in some stars (de Mink et al. 2013) although the number of rapidly rotating stars is such that only 3% of the mass of all massive stars is ejected in this manner (de Mink et al. 2009b).

3. *Stellar mergers* in dense cores of globular clusters may also contribute to the reservoir of nuclear processed material (Glebbeek et al. 2009) although this channel probably does not contribute enough mass to make the second generation of stars (Sills & Glebbeek 2010).

4. *Massive binary stars* are another source of nuclear processed material, as we explore in the following.

2. Massive binary stars

While there is some doubt about whether most stars are in multiple stellar systems, we can be sure that most stars with masses exceeding about $2\,\mathrm{M}_\odot$ live with a companion star (Kouwenhoven et al. 2007; Raghavan et al. 2010; Fuhrmann & Chini 2012). Just as importantly, the latest estimate of the O-type binary-period distribution in young, open clusters shows that more of them are close, i.e. liable to interact by mass transfer, than previously thought (Sana et al. 2012). Only about 29% of O-type stars evolve as single stars: the rest either have their envelope stripped (33%), merge (24%) or accrete mass (14%).

Because stars expand as they age, in a close binary the initially more massive (primary) star overflows its Roche lobe first, transferring mass onto the (initially less massive) secondary (Fig. 1). Material flows through the first Lagrange point onto the companion, carrying with it both the chemical signature of the primary star and angular momentum. The transferred mass settles onto the surface of the secondary, spinning it up, but – at least initially – not greatly altering its chemical abundance because material near the surface of the primary is never hot enough for nuclear reactions to be efficient.

Accretion and spin up continues until the mass of the secondary increases by about 10%, at which point it rotates so fast that material at its equator is unbound (Packet 1981). Any further mass transferred by Roche-lobe overflow is ejected from the binary system at a velocity which is low compared to the proto-globular cluster ejection speed. This material may be retained in the cluster for further star formation. As the primary continues to transfer mass, it loses its unburned envelope and material originally deep inside the star, which has undergone nuclear burning, is exposed at the stellar surface. First, layers burned by the CN cycle, then CNO, and later NeNa and MgAl cycles, are transferred through the Lagrange point and ejected from the binary system. Detailed binary evolution models suggest that about three quarters of the transferred mass is ejected from a close binary system, i.e. an accretion efficiency less than about 0.25 (de Mink et al. 2009b), the binary-star physics remains highly uncertain and its study continues (e.g. van Rensbergen et al. 2011; de Mink et al. 2013).

While the binary-star scenario has not yet been explored in detail, it is observed in nature. The binary star RY Scuti is ejecting material rich in helium and nitrogen, and poor in oxygen and carbon, at a velocity of about $50\,\mathrm{km\,s^{-1}}$ (Smith, Gehrz, & Goss 2001) i.e. more slowly than a stellar wind or the escape speed of a young globular cluster. Further examples of binary mass transfer include the Algol systems (van Rensbergen et al. 2011), X-ray binaries (Flannery & Ulrich 1977) and Wolf-Rayet binaries (Petrovic et al. 2005) which must also be products of non-conservative mass transfer.

It is clear that a copious amount of material is ejected from interacting binary stars, much of which has been processed by nuclear burning. We estimate that as much as 13% of the mass of a generation of stars can be ejected in massive binaries, an amount similar to that ejected from rapidly rotating massive stars and AGB stars combined (de Mink et al. 2009b).

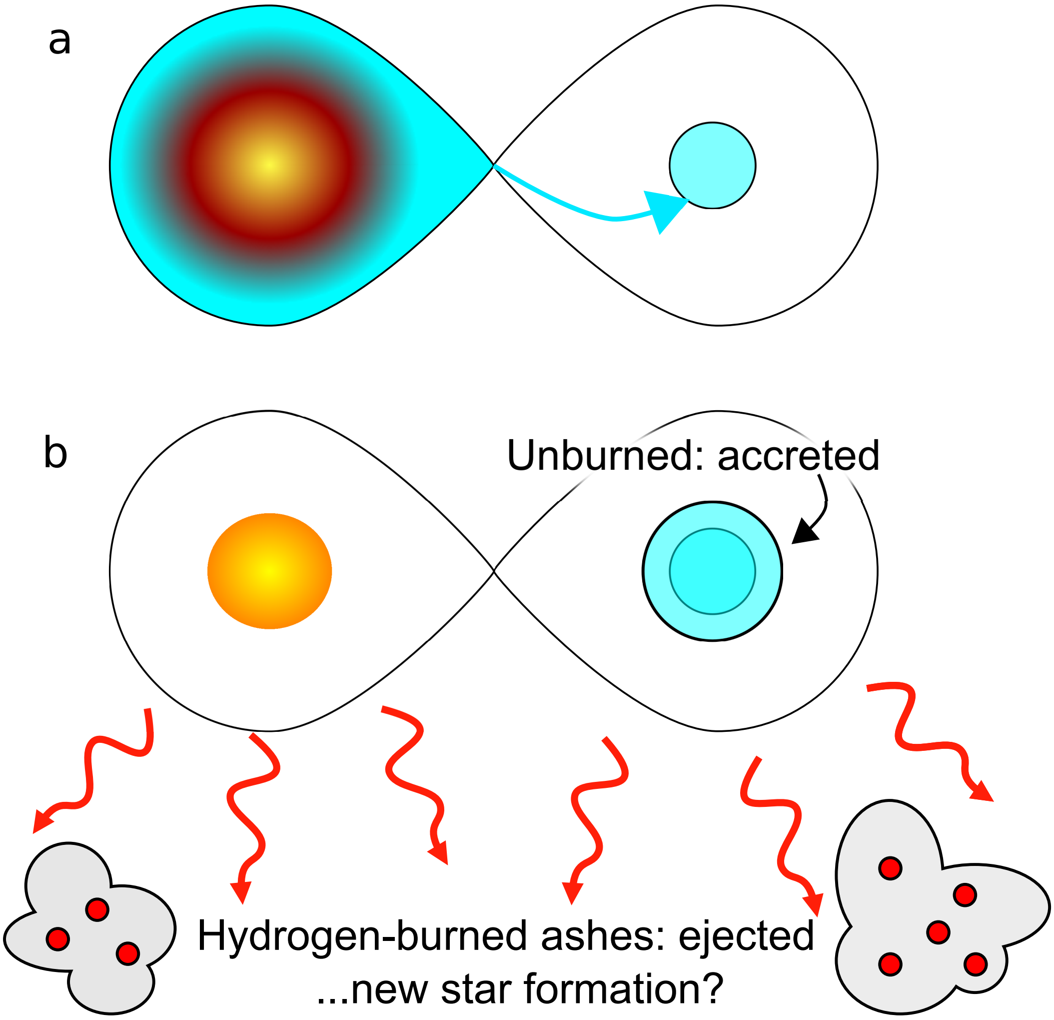

Fig. 1. Schematic view of Roche-lobe overflow in a massive binary system. **(a)** At the start of Roche-lobe overflow, the primary star (left) overflows its Roche lobe and transfers material to the secondary (right). **(b)** By the end of Roche-lobe overflow, the secondary has accreted unburned material while hydrogen-burned material from deep inside the primary has been ejected from the binary system and may mix with other sources of interstellar gas from which a subsequent generation of stars may form.

3. Frascati-fuelled Perspective

It is unlikely that anyone would bet more than a bottle of Frascati's finest white wine on any single one of the proposed scenarios for globular cluster self-pollution being the *only* source of mass for a second generation of stars. Massive AGB stars are generally considered the best candidate because they can process material through hot hydrogen-burning prior to its ejection in a slow wind, although if third dredge up happens in these stars they may not be responsible (although see Yong et al. 2008). The mass range which contributes to clusters is unclear also, are super-AGB stars candidates (D'Ercole et al. 2012)? Rapidly rotating massive stars certainly exist, but their total ejected mass is not enough even assuming – realistically? – that they are all rapid rotators (de Mink et al. 2009b). Binary stars may eject enough mass to satisfy the requirements of a second stellar generation, but quite how conservative is binary mass loss is not clear even after many decades of study (e.g. de Mink et al. 2007, and references therein). The competition between star formation and cluster gas ejection is also relevant because massive stars evolve quickly relative to AGB stars. It may be that massive-star ejecta escapes from the globular cluster before forming any new stars (see e.g. Charbonnel et al. and other contributions to this volume).

Uncertainties in stellar physics, e.g. mass-loss rates, mixing rates and nuclear reaction rates, affect stellar yield predictions considerably (e.g. Ventura & D'Antona 2005; Izzard et al. 2007; Stancliffe & Jeffery 2007; de Mink et al. 2009a; Meynet et al. 2013; and many others). The magnesium-aluminium negative correlation is particularly difficult to reproduce because it requires proton capture at temperatures which massive stars are unable to reach, while such burning is possible in massive AGB stars (Ventura et al. 2011). Still, the massive-binary channel remains relatively unexplored and a serious contributor to the mass that makes the second generation of stars in globular clusters.

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