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Are most Cataclysmic Variables in Globular Clusters dynamically formed?

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Abstract. We have been investigating populations of cataclysmic variables (CVs) in a set of more than 300 globular cluster (GC) models evolved with the MOCCA code. One of the main questions we have intended to answer is whether *most CVs in GCs are dynamically formed or not*. Contrary to what has been argued for a long time, we found that dynamical destruction of primordial CV progenitors is much stronger in GCs than dynamical formation of CVs. In particular, we found that, on average, the detectable CV population is predominantly composed of CVs formed via a typical common envelope phase ($\gtrsim 70$ per cent). However, core-collapsed models tend to have higher fractions of bright CVs than non-core-collapsed ones, which suggests then that the formation of CVs is indeed slightly favoured through strong dynamical interactions in core-collapsed GCs, due to the high stellar densities in their cores.

Keywords. methods: numerical, novae, cataclysmic variables, globular clusters: general, binaries: general

1. Motivation and Approach

Cataclysmic variables (CVs) are interacting binaries harbouring a white dwarf (WD) undergoing dynamically and thermally stable mass transfer from a low-mass companion, usually a main-sequence (MS) star (e.g. Warner 1995). They are expected to exist in non-negligible numbers in globular clusters (GCs), which are natural laboratories for testing theories of stellar dynamics and evolution.

Due to the high stellar crowding in GCs and and the CV intrinsic faintness, CVs are difficult to identify in such environments. Until now the best-studied GCs with respect to CV populations are NGC 6397 (Cohn *et al.* 2010), NGC 6752 (Lugger *et al.* 2017), ω Cen (Cool *et al.* 2013; Henleywillis *et al.* 2018) and 47 Tuc (e.g. Rivera Sandoval *et al.* 2018). The identification of CVs in these GCs has been carried out by identifying the *Hubble Space Telescope* (*HST*) optical counterparts to *Chandra* X-ray sources. Usually these counterparts show an Hα excess (suggesting the presence of an accretion disc), they are bluer than the MS stars and several also show photometric variability in different bands.

In the core-collapsed clusters NGC 6397 and NGC 6752, CVs can be divided into two populations, a bright and a faint one. On their optical colour-magnitude diagrams (CMDs), *bright* CVs lie close to the MS and *faint* CVs close to (or on) the WD cooling sequence, R $\approx$ 21.5 mag being the cut-off between both populations. Interestingly, in the non-core-collapsed clusters 47 Tuc and ω Cen, only one CV population is observed, that being mainly composed of faint CVs. In addition, the observed number of bright CVs per cluster mass in core-collapsed clusters is so far much higher than in non-core-collapsed clusters.

In the series of papers by Belloni *et al.* (2016, 2017a,b, 2019), we have analysed a large set of $\sim$300 GC models with a focus on the properties of their present-day CV populations, CV progenitors, and how CV properties are affected by dynamics in dense environments. The prime goal in this series of papers is to explain the observed properties and to answer the following questions: i) *Are most CVs in GCs dynamically formed?* ii) *Do we need to invoke dynamics to explain main properties of bright and faint CVs?* We summarize here the main findings in this series with focus on the influence of dynamics on CV progenitor destruction and CV formation.

In order to simulate the GC models, we used the MOnte Carlo Cluster simulAtor (MOCCA) code developed by Giersz *et al.* (2013) and Hypki & Giersz (2013, and references therein), which includes the FEWBODY code (Fregeau *et al.* 2004) to perform numerical integrations of three- or four-body gravitational interactions and the Binary Stellar Evolution (BSE) code (Hurley *et al.* 2002), with the upgrades described in Belloni *et al.* (2018b) to deal with CV evolution. Amongst our models, we have a variety of different initial conditions spanning different values of the mass, size, King concentration parameter, initial binary population (e.g. Belloni *et al.* 2017c, 2018a), binary fraction, and Galactocentric distances. In addition, we also explored two parameters of stellar/binary evolution, namely inclusion or not of mass fallback for BH formation (Belczynski, Kalogera & Bulik 2002) and three different common envelope phase (CEP) efficiencies. All variables in our modelling (i.e. binary evolution parameters, initial binary populations, and initial cluster conditions) are summarized in table 1 in Belloni *et al.* (2019).

2. Dynamical Destruction versus Dynamical Formation

We start discussing the rate of destruction of primordial CV progenitors with respect to the initial stellar encounter rate given by $\Gamma = \rho_0^2 R_c^3 \sigma_0^{-1}$ (e.g. Pooley & Hut 2006; Hong *et al.* 2017), where ρ_0, R_c and σ_0 are the central density, the core radius and the mass-weighted central velocity dispersion, respectively. We quantify the fraction of primordial CV progenitors that are destroyed in dynamical interactions before becoming CVs ($N_{\rm CV,dest}/N_{\rm CV,progen}$). This is illustrated in the left-hand panel of Fig. 1, where we show such a fraction versus Γ for all models. Note that the greater the Γ, the higher the fraction of destroyed primordial CV progenitors (i.e. the stronger the influence of dynamical interactions on destroying these progenitors). In terms of the soft-hard boundary, the greater the Γ, the shorter the period that defines the boundary between soft and hard binaries. We carried out Pearson's rank correlation tests, and we found strong correlation with more than 99.9 per cent confidence, being $r \approx 0.78$.

Regarding the formation channels, Belloni *et al.* (2019) found that the dominant one amongst detectable CVs is typical CEP ($\approx 88^{+12}_{-18}$ per cent, for both core-collapsed and non-core-collapsed clusters). We also found that the average fraction of dynamically formed CVs among only bright CVs is relatively low ($\approx 9^{+24}_{-9}$ per cent, for both core-collapsed and non-core-collapsed clusters). In other words, we found here no (or very weak, if at all) correlation between the number of either detectable CVs or bright CVs with respect to the cluster type (e.g. related to the stellar encounter rate).

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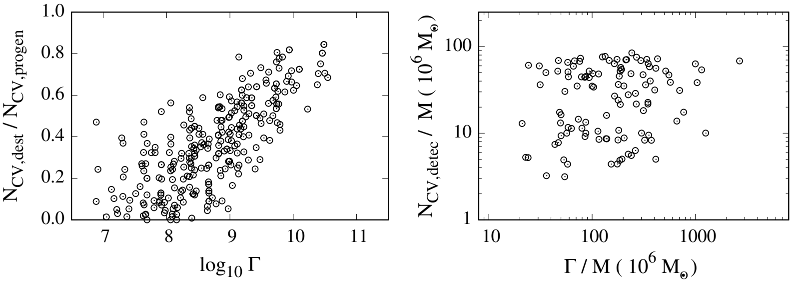

Figure 1. Fraction of dynamical destroyed CV progenitors ($N_{\rm CV,dest}/N_{\rm CV,progen}$) against the initial stellar encounter rate Γ (left-hand panel) and mass-normalized number of detectable CVs (right-hand panel) against the present-day mass-normalized Γ. Note that there is a clear correlation between the fraction of destroyed CV progenitors and the initial Γ. On the other hand, there is no (or very weak, if at all) statistical evidence for a correlation between the detectable CV abundance and the present-day Γ.

Our findings are in agreement with recent studies of *Chandra* X-ray sources in GCs by Cheng *et al.* (2018). Using a sample of 69 GCs and focusing on CVs and chromospherically active binaries, these authors found that there is not a significant correlation between the number of X-ray sources and the mass-normalized stellar encounter rate. These findings disagree with previous results, which considered smaller GC samples (e.g. Pooley & Hut 2006). A correlation would be expected if dynamical interactions largely influence the creation of X-ray sources. However, Cheng *et al.* (2018) have shown that dynamical interactions are less dominant than previously believed, and that the primordial formation has a substantial contribution. In the right-hand panel of Fig. 1 we show the number of detectable CVs normalized by the total cluster mass in units of $10^6\ M_\odot$ as a function of Γ also normalized by the total cluster mass in units of $10^6\ M_\odot$. We found no (or very weak, if at all) statistical evidence for a correlation between the mass-normalized CV abundance and the mass-normalized Γ.

The physical reason for this is associated with the role of dynamics in creating and destroying pre-CVs. We notice that destruction of CV progenitors takes place mainly for MS-MS binaries during the first few hundred Myr of cluster evolution. Later, when WD-MS binaries are created, dynamical interactions are very strongly suppressed, because during the CEP there is a substantial reduction of binary periods. Regarding dynamical pre-CV formation, there are three main possible scenarios: i) *interaction between a low-mass MS-MS binary and a single WD*, ii) *interaction between a low-mass MS-MS binary and a single MS*, and iii) *interaction between a WD-MS binary and a single MS*. We found that the main scenarios previously proposed in the literature for dynamical formation of faint and bright CVs in GCs have a very low probability of occurring, which explains our findings with respect to the influence of dynamics on CV formation (very low fraction of dynamically formed faint and bright CVs) and with respect to the stellar encounter rate (no/extremely weak correlation with the amount of detectable and bright CVs).

With respect to the fraction of bright CVs among detectable ones, we found here that, on average, for non-core-collapsed models, $\sim 5-30$ per cent of the detectable CVs are bright, which is consistent with 47 Tuc and ω Cen. Regarding core-collapsed models, we found that fraction to be $\sim 5-45$ per cent. However, our core-collapsed clusters with the shortest half-mass relaxation times usually have bright CV fractions higher than ~ 50 per cent. This is consistent with observational results of NGC 6397 and NGC 6752, which have fractions of bright CVs in the range of $\sim 40-60$ per cent. Our results suggest then that the formation of CVs is indeed slightly favoured through strong dynamical interactions in core-collapsed GCs, especially those with very short half-mass relaxation times.

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3. Conclusions

We have analysed a relatively large sample of more than 300 GC models, evolved with an up-to-date version of the MOCCA code, with respect to initial binary populations and stellar/binary evolution prescriptions. We found a strong correlation at a significant level between the fraction of destroyed primordial CV progenitors and the initial stellar encounter rate, i.e. we found that the greater the initial stellar encounter rate, the stronger the role of dynamical interactions in destroying primordial CV progenitors. In addition, we showed that dynamical destruction of primordial CV progenitors is much stronger in GCs than dynamical formation of CVs. Moreover, we found that the detectable CV population is predominantly composed of CVs formed via typical CEP ($\gtrsim 70$ per cent). Finally, even though amongst detectable CVs the fractions of bright/faint CVs change from model to model, we found that, on average, non-core-collapsed models tend to have small fractions of bright CVs, while core-collapsed models have higher fractions, so that dynamics play a sufficiently important role to explain the relatively larger fraction of bright CVs observed in core-collapsed clusters.

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