Explaining the absence of symbiotic stars in globular clusters and observational prospects for their identification

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ABSTRACT

Even though plenty of symbiotic stars (SySts) have been found in the Galactic field and nearby galaxies, not a single one has ever been confirmed in a Galactic globular cluster (GC). We investigate the lack of such systems in GCs for the first time by analysing 144 GC models evolved with the \textsc{MOCCA} code, which have different initial properties and are roughly representative of the Galactic GC population. We focus here on SySts formed through the wind-accretion channel, which can be consistently modelled in binary population synthesis codes. We found that the orbital periods of the majority of such SySts are sufficiently long (≥10\textsuperscript{3} days) so that, for very dense GC models, dynamical interactions play an important role in destroying their progenitors before the present day (∼11–12 Gyr). In less dense GC models, some SySts are still predicted to exist. However, these systems tend to have relatively low white dwarf luminosities (≤100 L\odot), are located far from the central parts (>70 per cent are far beyond the half-light radius) and are sufficiently rare (≤1 per GC per Myr), which makes their identification rather difficult in current observational campaigns. We propose that future searches for SySts in GCs should be performed with either high-quality spectroscopy or photometry (using narrow-band filters centred on either He\textsc{ii} and H\alpha or Raman scattered O\textsc{vi} emission lines), in the outskirts of nearby low-density GCs with sufficiently large Galactocentric distances. Finally, we obtained spectra of the candidate proposed in ω Cen (SOPS IV e-94) and showed that this object is not a SySt.

Key words: binaries: symbiotic – globular clusters: general – methods: numerical – stars: evolution – stars: individual: SOPS IV e-94.

1 INTRODUCTION

Symbiotic Stars (SySts) are interacting binaries in which, usually, a white dwarf (WD) accretes matter from an evolved red giant (see Mikołajewska 2012, for a review). They are characterized by high accretion rates (greater than a few 10\textsuperscript{-9} M\odot yr\textsuperscript{-1}), which are needed to detect the WD beside an evolved red giant donor (e.g. Kenyon 1986) and sufficiently long orbital periods, which are needed to accommodate the evolved giant. In many SySts, the accretion rate is high enough (greater than a few 10\textsuperscript{-8} M\odot yr\textsuperscript{-1}) to trigger and support quasi-steady thermonuclear burning. The composition of SySts makes them very important luminous tracers of the late phases of low- and medium-mass binary star evolution and, in turn, excellent laboratories to test models of close binary evolution. In particular, their studies have important implications for, e.g. understanding mass transfer in wide binaries, the interaction of novae with their interstellar surroundings, or the formation of astrophysical jets. Last but not least, SySts are also promising nurseries for type 1a supernovae, regardless of whether the path to the thermonuclear explosion of a Chandrasekhar-mass carbon-oxygen WD is through accretion, the so-called single degenerate scenario, or through coalescence of double WD systems, the so-called double degenerate scenario (e.g. Di Stefano 2010; Mikołajewska 2013; Ilkiewicz et al. 2019).

As in the case of other WD binaries, such as cataclysmic variables and AM CVn, SySt are usually defined by spectroscopic properties (Kenyon 1986), i.e. (i) a red continuum with absorp-
tion features of a late-type red giant; (ii) a blue continuum with bright strong H i and He i emission lines; (iii) either additional lines with an ionizational potential of at least 30 eV (e.g. He II 2, D. Belloni et al. bright strong H i) (e.g. He II), [O III], [Ne V], [Fe VII]) with an equivalent width of at least 1 Å or an A- or F-type continuum with additional absorption lines from H i and He i and singly ionized metals. This definition seems quite convenient for Galactic SySts, since there is no contamination from the interstellar medium.

Depending on the red giant nature, SySts are divided into two main classes. The S-type SySts host normal red giants and have orbital periods of the order of a few years. The D-type SySts harbour Mira variables (e.g. Gromadzki et al. 2009) usually surrounded by a warm dust shell and are expected to have orbital periods of decades or longer (Whitelock 1987), despite only one such system having a determined orbital period (R Aquarii: 43.6 years, Gromadzki & Mikolajewska 2009). Even though S-type SySts correspond to the majority of known systems (~ 80 per cent), the pathways leading to their formation is far from being understood, since their orbital period distribution cannot be accounted for by current binary population models (e.g. Webbink 1988; Mikolajewska 2012).

Up to now, the most detailed study of SySts using binary population modelling was performed by Lü et al. (2006). These authors predicted that the orbital period distribution of SySts should peak at ~ 1500 days and that only ~ 20 per cent SySts should have orbital periods shorter than ~ 1000 days. Lü et al. (2006) explained the discrepancy between their result and the observed orbital period distribution, which peaks around 600 days, by an observational incompleteness of the sample. These authors argued that the observations were biased towards bright SySts with small orbital periods. At that time, only 30 SySts had known orbital periods (Mikolajewska 2003). That sample included SySts with orbital periods shorter than ~ 200 days, which were hardly predicted to exist in their binary population models. However, since then, the orbital periods of over 100 known SySts in the Milky Way and Magellanic Clouds have been measured and the main characteristics of their distribution remain practically unchanged (Mikolajewska 2012; Gromadzki et al. 2013).

At the moment, it seems there is a general problem with binary population models that predict a bi-modal final orbital period distribution for binaries that have evolved off the giant branch and the asymptotic giant branch, in which the common-envelope channel results in a rich variety of short-period (~ 1 day) binaries and the wind-accretion channel results in plenty of systems with orbital periods longer than ~ 1000 days (Nie et al. 2012, see their fig. 13). The most peculiar result of the adopted evolutionary scenario is that there are virtually no binaries predicted with orbital periods of ~ 100 – 1000 days, especially because we know they do exist from observations of both SySts and Galactic post-AGB binaries (e.g., van Winckel et al. 2009; Oomen et al. 2018). All these accentuate the need for more advanced models for mass transfer in binaries with red giant donors (e.g., Podsiadlowski & Mohamed 2007; Chen et al. 2010; Ilickiewicz et al. 2019).

SySts have been found since the beginning of the last century in several different environments, and more than 200 such systems exist in the Milky Way (e.g., Belczyński et al. 2000; Miszalski et al. 2013; Miszalski & Mikolajewska 2014; Rodríguez-Flores et al. 2014; Merc et al. 2019). In addition, there are plenty discovered in nearby galaxies, such as the Magellanic Clouds (Ilickiewicz et al. 2018), M31 (Mikolajewska et al. 2014), M33 (Mikolajewska et al. 2017) as well as single SySts in NGC 6822 (Kniazev et al. 2009) and NGC 205 (Gonçalves et al. 2015). Despite the frequency of SySts in several different environments, not a single one has ever been detected in a Galactic globular cluster (GC). GCs are one of the most important objects for investigating the formation and the physical nature of exotic systems such as X-ray binaries, degenerate binaries, black holes, blue straggler stars, cataclysmic variables, millisecond pulsars, etc (e.g. Benacquista & Downing 2013). Such studies provide tools that can help to understand the formation and evolution processes of star clusters, galaxies and, in general, the young Universe. Therefore, understanding the absence of SySts in GCs might lead to important astrophysical implications.

We concentrate here on SySts formed through the wind-accretion channel, i.e. without Roche-lobe overflow in the WD formation channel. We notice that most SySts are S-type and, in most of them, the WD likely formed in an episode of Roche-lobe overflow. However, their formation channels are clearly not understood, which makes the modelling of these systems difficult, not only in isolation, but also in GCs. Therefore, we leave these systems for follow-up works, in which we will first try to explain their orbital period distribution, and subsequently investigate the role of dynamics in shaping their properties in GCs.

In this paper, we search for the physical reasons behind the absence of SySts in GCs. In particular, we check whether dynamics could play a significantly important role in destroying their progenitors during the GC evolution. In addition, for those GC SySt that are not destroyed, we predict their properties and correlations with their host GCs, by providing relevant information that might help future theoretical and observational efforts.

### 2 NUMERICAL SIMULATIONS

In what follows, we briefly describe the GC models and the MOCCA code (Hypki & Giersz 2013; Giersz et al. 2013, and references therein) used to simulate them. More details about the modelling/models can be found in Belloni et al. (2019).

#### 2.1 Globular Clusters

MOCCA includes the FEWBODY code (Fregeau et al. 2004) to perform numerical scattering experiments of small-number gravitational interactions and the BSE code (Hurley et al. 2000, 2002), with the upgrades described in Belloni et al. (2018b) and Giacobbo et al. (2018), to deal with stellar and binary evolution. This version of the MOCCA code includes up-to-date prescriptions for metallicity-dependent stellar winds, which are based on Belczynski et al. (2010), but with the inclusion of the Eddington factor from Chen et al. (2015).

| Property                      | Values          |
|-------------------------------|-----------------|
| Number of objects (×10⁵)      | 4, 7, 12        |
| Mass (×10^5 M_☉)              | 4.72, 8.26, 14.2|
| King model parameter          | 6, 9            |
| Tidal radius (pc)              | 60, 120         |
| Half-mass radius (pc)          | 1.2, 2.4, 4.8   |
| Fallback                       | yes, no         |
| Common-envelope efficiency    | 0.25, 0.50, 1.00|

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Table 1. Initial GC conditions and binary evolution parameters. For all models, we adopted a low metallicity (Z = 0.001), the canonical Kroupa (2001) initial mass function, with masses between 0.08 M_☉ and 150 M_☉, and a high binary fraction (95 per cent).
MOCCA assumes a point-mass Galactic potential with total mass equal to the enclosed Galaxy mass inside a circular orbit at the specified Galactocentric radius, and uses the description of escape processes in tidally limited clusters follows the procedure derived by Fukushige & Heggie (2000). We stress that MOCCA has been extensively tested against N-body codes and reproduces N-body results with good precision, including detailed distributions of mass and binding energy of binaries (e.g. Giersz et al. 2008; Wang et al. 2016; Madrid et al. 2017). Most importantly, MOCCA is faster than N-body codes, which allows us to simulate several hundreds of real GC models that permit more powerful statistical analyses for constraining the overall population of particular types of binaries in GCs.

In all models, we assume that all stars are on the zero-age main sequence when the simulation begins and that any residual gas from the star formation process has already been removed from the cluster. Additionally, all models have low metallicity ($Z = 0.001$), are initially at virial equilibrium, and have neither rotation nor mass segregation. With respect to the density profile, all models follow a King (1966) model, and we adopted two values for the King parameter $W_0$, 6 and 9. Regarding the tidal radius, we assumed two values, namely 60 and 120 pc. Finally, we have three different half-mass radii: 1.2, 2.4 and 4.8 pc.

The initial binary population adopted here for all models corresponds to models constructed based on the distributions derived by Kroupa (1995, 2001) and Kroupa et al. (2013), with the modifications described in Belloni et al. (2017). We simulated models with three different numbers of objects (single stars + binaries), namely 400k, 700k, and 1200k, which have masses of approximately $4.72 \times 10^7$, $8.26 \times 10^7$ and $1.42 \times 10^8 M_\odot$, respectively. All of them have very high initial binary fraction (nearly 100 per cent, e.g. Kroupa 2008), which is needed to resolve the angular momentum problem in star formation and consistent with the fact that triples and higher order systems are rarely the outcome of star formation (e.g. Goodwin & Kroupa 2005). In all models, we have used the Kroupa (2001) canonical initial mass function, with star masses in the range between 0.08 $M_\odot$ and 150 $M_\odot$ (Weidner et al. 2013).

For each initial cluster configuration, we simulated models with three values for the common-envelope efficiency, namely 0.25, 0.5 and 1.0. In addition, we assumed that none of the recombinination energy helps in the common-envelope ejection and that the binding energy parameter is automatically determined based on the giant properties (Claeys et al. 2014, appendix A). Even though we focus on SySts in which the WDs are formed without Roche-lobe overflow, several other types of binaries inside the cluster are affected by the choice of the CE efficiency. This choice thus influences the amount of particular types of GC binaries (see Belloni et al. 2019, for the case of cataclysmic variables). In this way, even though this has never been thoroughly checked, the choice of the CE efficiency may play a role in the global GC evolution.

For massive stars, we assumed the delayed core-collapse supernova model (Fryer et al. 2012). We also included pair-instability supernovae and pair-instability pulsation supernovae, as described in Spera & Mapelli (2017). Supernova natal kicks for neutron stars are distributed according to the Maxwellian distribution suggested by Hobbs et al. (2005). In the case of black holes, we have two options: either kicks are distributed according to Hobbs et al. (2005) and no fallback prescription is adopted; or kicks follow Hobbs et al. (2005) and are reduced according to mass fallback description given by Fryer et al. (2012), for the delayed core-collapse model.

As part of the upgrades to the BSE code, we included in our modellling the possibility of neutron star formation through electron-capture supernova (e.g. Kiel et al. 2008) and accretion induced collapse (e.g. Michel 1987). In both cases, we assume no kick associated with the neutron star formation. All other binary evolution parameters are set as in Hurley et al. (2002).

All the parameters and initial GC conditions discussed above are summarized in Table 1. As shown by Belloni et al. (2019), by comparing the simulated and observed distributions of core to half-light radii, V-band absolute magnitude, average surface brightness inside the half-light radius and central surface brightness, our models are very close to massive and intermediate-mass real GCs, and we only miss the low-mass GCs in our analysis. Additionally, our present-day GC models cover a reasonable range of concentrations, central surface brightness and half-mass relaxation times (see also Askar et al. 2017). Therefore, our models are consistent with a substantial fraction of the real GCs, and are in turn roughly representative of the Galactic GC population.

2.2 Symbiotic Stars

Our principal goal here is to investigate the properties of SySts formed through the wind-accretion channel in our simulations. For that end, we define SySts as WD + red giant binaries, in which the WDs are formed avoiding Roche-lobe overflow. In addition, those binaries are SySts only if their accretion-powered WD luminosities are at least $10 L_\odot$ (e.g. Mikołajewska & Kenyon 1992; Lü et al. 2006). This is the luminosity resulting from the release of gravitational energy due to accretion and is given by

$$\frac{L_{WD}}{L_\odot} \approx 3.14 \times 10^7 \left( \frac{M_{WD}}{M_\odot} \right) \left( \frac{R_{WD}}{R_\odot} \right)^{-1} \left( \frac{M_\text{orb}}{M_\odot} \right)^{-1} \left( \frac{v_{\text{orb}}}{v_w} \right)^{-3/2},$$

where $M_{WD}$ is the WD mass, $R_{WD}$ is the WD radius and $M_\text{orb}$ is the accretion rate onto the WD. Given such high accretion luminosities, red giants in SySts are usually located towards the top of either the first giant branch or the asymptotic giant branch (e.g. Mikołajewska 2007).

In the BSE code, the accretion rate efficiency of mass loss through winds is estimated according to the Bondi & Hoyle (1944) mechanism, given by

$$\beta_{\text{BH}} = \frac{\alpha_{\text{BH}}}{2\sqrt{1 - e^2}} \left( \frac{GM_{WD}}{a v_w} \right)^2 \left[ 1 + \left( \frac{v_{\text{orb}}}{v_w} \right)^2 \right]^{-3/2},$$

where $G$ is the gravitational constant, $v_w$ and $v_{\text{orb}}$ are the wind and orbital velocities, respectively, $a$ is the semi-major axis, $e$ is the eccentricity, and $\alpha_{\text{BH}} = 1.5$.

This prescription is known to underestimate the efficiency of wind mass transfer in binaries, especially in the case of red giants in the asymptotic giant branch, which have slow and dense winds. Thus, to properly identify the SySts in our simulations, we implemented into the BSE code the wind Roche-lobe overflow mechanism, as described in Abate et al. (2013) and Ilkiewicz et al. (2019). Briefly, the enhanced accretion efficiency is given by (Abate et al. 2013)

$$\beta_{\text{WRLOF}} = \frac{25}{9} q^2 \left[ -0.284 \left( \frac{R_\odot}{R_{\text{RL}}} \right)^2 + 0.918 \frac{R_d}{R_{\text{RL}}} - 0.234 \right],$$

where $q$ is the mass ratio of the WD and the red giant, $R_\odot$ is the solar radius, $R_{\text{RL}}$ is the Roche-lobe radius of the WD, $R_d$ is the orbital radius. In the case of a black hole, the denominator of the $\beta_{\text{WRLOF}}$ expression is $R_d$.
where $q = M_{\text{WD}}/M_{\text{giant}}$, $M_{\text{giant}}$ is the red giant mass, $R_{\text{RL}}$ is the red giant Roche-lobe radius and $R_d$ is the dust condensation radius given by (Höfner 2007)

$$R_d = \left( \frac{R_{\text{giant}}}{2} \right) \left( \frac{T_d}{T_{\text{eff, giant}}} \right)^{(4+p)/2},$$  

(4)

where $R_{\text{giant}}$ is the giant radius, $T_{\text{eff, giant}}$ is the giant effective temperature, $T_d$ is the dust condensation temperature and $p$ is a parameter characterising wavelength dependence of the dust opacity.

The WD cannot accrete more mass than is lost by the red giant, which might happen for highly eccentric systems with Eq. 2. To avoid this, as in Hurley et al. (2002), we enforced that $\beta_{\text{Hill}} \leq 0.8$. In addition, as in Abate et al. (2013), we imposed that $\beta_{\text{WDLOF}} \leq 0.5$ to be consistent with results from hydro-dynamical simulations. Moreover, we assumed dust condensation of amorphous carbon grains, which gives $T_d \approx 1500$ K and $p \approx 1$ (Höfner 2007). Finally, as in Ilić et al. (2019), in our simulations, having calculated both wind Roche-lobe overflow (Eq. 3) and Bondi-Hoyle (Eq. 2) accretion rate efficiencies, we took the higher to be the accretion rate efficiency.

3 SYMBIOTIC STAR PROPERTIES

We start the presentation of our results by focusing on the initial and present-day properties of the simulated SySts in GCs and in isolated binary evolution, i.e. without dynamics. The initial time corresponds to the beginning of the simulation, i.e. roughly when the cluster is born, while the present-day time is assumed here to be $\sim 11 - 12$ Gyr, which is consistent with the measured ages of Galactic GCs (VandenBerg et al. 2013). In order to obtain the properties of SySts in a non-crowded environment, we selected all the initial binary populations (composed of zero-age main-sequence binaries), which follow the same distributions (Belloni et al. 2017c) in all models, and evolved them with the bse code till the present day.

3.1 Orbital Period

In Fig. 1 we show the initial and present-day orbital period distribution of simulated SySts without dynamics. The present-day orbital periods are those in which, during the SySt phase, the accretion-powered WD luminosity is highest. The orbital periods are sufficiently long to put SySts amongst the largest interacting binaries. Differences in the initial and present-day distributions are due to mass and angular momentum losses from the systems during binary evolution. Present-day orbital periods range from $\sim 10^3$ to $\sim 10^6$ days, with the distribution peaking at $\sim 10^5$ days. Interestingly, systems having the shortest orbital periods ($\lesssim 10^3$ days) have initial WD progenitor masses $\lesssim 1 M_\odot$, which allows them to evolve into WDs without filling their Roche lobe during the asymptotic giant phase. Moreover, our predicted orbital periods more likely resemble those of D-type SySts, than S-type SySts.

In the same figure, we also show the average initial hard-soft boundary ($P_{h/s}$) in our GC models ($\sim 10^3$ days), and that of the sparsest model ($\sim 10^5$ days). This boundary is set when the average binary binding energy equals to the average cluster kinetic energy. This separation is thus intrinsically related to the interplay between the binary binding energies with respect to host GC properties. Pragmatically, it corresponds to the orbital period separating hard ($P_{\text{obs}} < P_{h/s}$) and soft ($P_{\text{obs}} > P_{h/s}$) binaries (e.g. Heggie & Hut 2003). Hard binaries are very strongly bound and are not expected to go through disruptive encounters. Soft binaries, on the other hand, are very weakly bound and tend to be destroyed in dynamical interactions. Some binaries have orbital periods comparable to the hard-soft boundary and can sometimes be destroyed or only significantly altered. Most binaries, on average, evolve according to the Heggie–Hills law: hard binaries get harder, while soft binaries get softer, after dynamical interactions (Heggie 1975; Hills 1975), which implies that soft binaries tend to be eventually disrupted.

The orbital period defining the hard-soft boundary, based on average properties, in a particular GC is given by

$$P_{h/s} \text{ yr} = \left( \frac{a_{h/s}}{a_{\text{major}}} \right)^3 \left( \frac{2 (m)}{M_{\odot}} \right)^{-1},$$  

(5)

where $(m)$ is the average mass, given by $M_{\text{GC}}/N$, where $N$ is the number of objects (single + binaries), $M_{\text{GC}}$ is the total mass, and $a_{h/s}$ is the semi-major axis that defines the hard-soft boundary and is given by $R_{\text{half mass}}/0.4N$, where $R_{\text{half mass}}$ is the half-mass radius (Spitzer 1987). We can safely apply Eq. 5 since SySts are not much more massive than an average star-binary in a cluster. More specifically, they are probably about 2 – 3 times more massive (red giants about 1.5 times and WD about 1.5 times). Thus, the time-scale for SySts being mass segregating is not extremely short. They
need more than the half-mass relaxation time to sink to the center from the GC halo (farther than the half-mass radius).

For clusters with similar N, Eq. 5 says that the denser the cluster (i.e. the smaller the half-mass radius), the smaller the semi-major axis (or the shorter the orbital period) that defines the hard-soft boundary. Thus, at a particular density, the hard-soft boundary will penetrate the region occupied by SySt progenitors, as illustrated in Fig. 1. Therefore, beyond this density, more and more SySt progenitors are potentially destroyed, as the density increases. As mentioned before, the fate of SySt progenitors with orbital periods comparable to the orbital period defining the hard-soft boundary is not so easy to predict. Therefore, even though we expect many of them to be destroyed before the present-day, some might potentially survive the GC dynamical evolution. Indeed, those binaries with the shortest periods ($\lesssim 10^4$ days) in the distribution might survive in less crowded regions inside the clusters, as the probability for interaction in such regions is much smaller than in the central parts. This is especially true for clusters with sufficiently long initial half-mass relaxation times, since in these clusters mass segregation is not very efficient.

We show in Fig. 2 the initial and present-day predicted orbital period distributions of GC SySts. Notice that most systems have initial and present-day orbital periods of $\sim 10^3 - 10^5$ and $\sim 10^3 - 10^5$ days, respectively. While comparing with outcomes of isolated binary evolution (Fig. 1), we can see the role played by dynamics in shaping the parameter space of GC SySts and their progenitors. In isolation, initial orbital periods extend up to $\sim 10^6$ days. However, due to dynamical interactions, there is a cut-off in such a distribution limiting the orbital periods from being very long. This in turn also reflects in the present-day orbital period distribution, which also exhibits a similar cut-off in the distribution.

3.2 Other Properties

In Fig. 3 we show other present-day SySt properties (eccentricity, semi-major axis, WD and red giant masses, accretion rate and accretion-powered WD luminosity) and compare the distributions obtained in isolated binary evolution (i.e. without dynamics) and inside our GC models. As some of these properties might change during the SySt life-time, we show the properties at the moment the accretion-powered WD luminosity is maximum.

With respect to the main orbital elements, we can clearly see that differences with respect to SySts formed in isolation and those in GCs. In particular, GCs host relatively more systems with circular orbits and smaller semi-major axis. This is another illustration of the above-mentioned role played by dynamics in shaping the SySt properties. Additionally, we can see that the eccentricity distribution is roughly bimodal, in which we see the binaries that managed to circularize and the wider binaries that peak near $\sim 0.4 - 0.6$. Moreover, most SySts have semi-major axis ranging from a few au up to $\sim 100$ au.

Concerning the component masses, not surprisingly, all WDs are carbon-oxygen, as they are formed similarly to single stars, i.e. without Roche-lobe overfilling. Additionally, most of them have masses between $\sim 0.55$ and $\sim 0.9 M_\odot$, but a few are more massive than the Sun. The red giant masses are mostly concentrated between $\sim 0.7$ and $\sim 0.9 M_\odot$, which is directly connected with the main-sequence turn-off for the metallicity and present-day time assumed here. However, some have masses smaller than $\sim 0.6 M_\odot$, which is due to the strong mass loss through winds before reaching the SySt phase of maximum accretion-powered WD luminosity. Regarding the evolutionary status of the red giant donor, we found that most ($\gtrsim 80$ per cent) belong to the first giant branch, while the remaining are mostly thermally-pulsing asymptotic giant branch stars.

The accretion rates onto the WD range from $\sim 10^{-8} M_\odot$ yr$^{-1}$ to $10^{-7} M_\odot$ yr$^{-1}$, but most concentrate around $10^{-7.5} M_\odot$ yr$^{-1}$. Such rates are high enough so that thermonuclear burning of the accreted material on the WD surface occurs, either steadily or unstably. According to the Nomoto et al. (2007) criterion, $\sim 25$ per cent of the systems reached the phase of stable hydrogen burning, while the remaining are likely symbiotic (recurrent) novae. Concerning the accretion-powered WD luminosity, the distribution is much broader than the accretion rate one, but limited to values between 10 and $\sim 300 L_\odot$. The lower limit comes from our definition of SySt and the upper limit is a direct consequence of the accretion rates coupled with the WD properties. We would like to stress that such WD luminosities are basically lower limits, as we do not include in our modelling computations of nuclear-powered luminosities, i.e. luminosities powered by thermonuclear hydrogen burning, which provides WD luminosities greater than $\sim 10^3 L_\odot$ (e.g. Nomoto et al. 2007). Indeed, most known SySts have WD luminosities $\gtrsim 10^3 L_\odot$, which cannot be explained solely by accretion (Mikołajewska 2010).

The last property we discuss is the SySt life-times. Most systems spend $\sim 0.5 - 2$ Myr in the SySt phase. These SySt life-times are likely due to their age (they are $\sim 11 - 12$ Gyr old), coupled with their red giant masses (they are close to the turn-off mass, which is $\sim 0.8 - 0.9 M_\odot$) and the low mass loss rate (due to the low metallicity). The red giant phase in these systems is much longer, but only in a fraction of the red giant life the accretion-powered WD luminosity is $\gtrsim 10 L_\odot$, which is our condition for the occurrence of the symbiotic phenomenon.

While taking into account all properties together, we can see...
that properties of GC SySts and of those formed in isolation are rather similar, with the exception of the orbital period, semi-major axis and eccentricity. In the parameter space comprised by these properties, the region from which GC SySts come is considerably smaller than that from which isolated SySts come. This is due to the role played by dynamics in destroying SySt progenitors and reducing in turn the region in the parameter space. Interestingly, this is quite the opposite of what happens with cataclysmic variables in GCs, in which dynamics extend the region in the initial parameter space from where they come (e.g. Belloni et al. 2016, 2017a,b, 2019).

4 WHY NOT A SINGLE SYMBIOTIC STAR HAS EVER BEEN CONFIRMED?

We have just seen that SySt formed through the wind-accretion channel have very long orbital periods ($P \gtrsim 10^3\text{ days}$) and most have initial orbital periods longer than those defining the initial hard-soft boundaries in our models (see Figs. 1 and 2). Therefore, we do expect that most SySt would be destroyed during the GC evolution. However, binaries with such long orbital periods could in principle still survive in less dense GCs, especially if they are beyond the half-mass radius, residing in the GC outskirts. In this...
Fraction of destroyed SySt progenitors as a function of the initial GC stellar encounter rate ($\Gamma$). Filled stars correspond to more realistic models, according to the radius–mass relation found by Marks & Kroupa (2012), while open stars to the remaining models. Notice the clear correlation between these two quantities and the extremely high fractions found among our models, especially for those very dense.

In the left-hand panel of Fig. 5, we can see that SySts are more centrally concentrated in the dense clusters than in the very dense ones. This is because SySts and their progenitors are more massive than the average stars inside the GCs. Thus, due to mass segregation, they sink, on a time-scale proportional (shorter by the ratio between the average mass and the SySt mass) to the half-mass relaxation time, towards the central parts. Moreover, in these less dense clusters, the probability for dynamical interaction, and in turn for binary (SySt progenitors) dynamical disruption, is smaller than in the very dense models. This provides better chances for the SySts to survive the mass segregation process and disruptive dynamical interactions. Indeed, long relaxation time means small density and, then, low number of dynamical interactions.

4.1 Dynamical Destruction

In Fig. 4, we show the fraction of destroyed SySt progenitors as a function of the initial GC stellar encounter rate, given by $\Gamma = \rho_0 r_c^3 \sigma_0^{-3}$ (Pooley & Hut 2006), where $\rho_0$, $r_c$, and $\sigma_0$ are the central density, the core radius and the mass-weighted central velocity dispersion, respectively. We note that $\Gamma$ is a somewhat better indicator of the strength of dynamics one would expect during the GC evolution than individual quantities, e.g. the initial central density, initial concentration, etc. In the figure, we separate the clusters according to their concentration. Very dense models roughly follow the Marks & Kroupa (2012) radius–mass relation, i.e. models with initial half-mass radii of $\approx 1.2$ pc, which are likely more realistic models. This is because this relation is in good agreement with the observed density of molecular cloud clumps, star-forming regions and globular clusters, and provides dynamical evolutionary time-scales for embedded clusters consistent with the life-time of ultra-compact H II regions and the time-scale needed for gas expulsion to be active in observed very young clusters, as based on their dynamical modelling (e.g. Belloni et al. 2018a, and references therein). Dense models comprise the remaining clusters, which are still dense, but somewhat less dense.

Figure 4. Fraction of destroyed SySt progenitors as a function of the initial GC stellar encounter rate ($\Gamma$). Filled stars correspond to more realistic models, according to the radius–mass relation found by Marks & Kroupa (2012), while open stars to the remaining models. Notice the clear correlation between these two quantities and the extremely high fractions found among our models, especially for those very dense.

4.2 Spatial Distribution

In Fig. 5, we depict the cumulative radial distribution function for present-day SySts in all our models, with respect to the cluster core radii (left-hand panel) and half-light radii (right-hand panel). As before, models are separated according to the initial concentration, very dense models being those closer to the Marks & Kroupa (2012) radius–mass relation. From the SySt spatial distribution, we can clearly see that the overwhelming majority of systems are far from the central parts. Additionally, given their long initial orbital periods, it is not surprising that they only managed to survive in (very) dense GC environments because of that.

Considering all models, we found that most ($\gtrsim 70$ per cent) are beyond the half-light radii and nearly all ($\gtrsim 90$ per cent) are beyond the core radii. Those models in which SySts survive inside (or nearly) the GC cores are characterized by large cores ($\gtrsim 3$ pc), which provides that, albeit rare, the core relaxation time might be still sufficiently long, preventing in turn very frequent and strong dynamical disruptive interactions. Indeed, long relaxation time means small density and, then, low number of dynamical interactions.

Therefore, should GCs be born as dense as proposed by Marks & Kroupa (2012), our results provide a natural explanation for the lack of SySts in GCs, which is due to dynamics playing an extremely important role in destroying their progenitors. However, if GCs are not that dense initially, then dynamical destruction of SySts alone would not explain their absence in GCs. If so, we could still expect non-negligible numbers of SySts in GCs and there should be additional reasons for the fact that not a single one has been discovered so far.
4.3 Expected Number

We have shown previously that dynamics play a significantly important role in destroying SySt progenitors, especially in very dense clusters. Despite that, we also showed that some SySts are still expected to exist in GCs at the present day, which are not destroyed because the less crowded region to which they belong. This is intrinsically connected with the half-mass relaxation time, which should be long enough so that SySts from the cluster halo will not have time to mass segregate and be destroyed in dynamical interactions. Provided these two facts, one might still wonder why we fail to observationally detect these systems. We provide in what follows additional arguments for that, which are based on the expected number of SySts in GCs.

4.3.1 From the GC numerical simulations

We have considered that the present day is somewhere between 11 and 12 Gyr, which corresponds to the expected cluster ages in the Galactic GC population. Within these time interval, we found that the SySt formation rate is roughly uniform when taking into account all our 144 GC models. This provides, on average, a SySt formation rate given by \( \sim 4.22 \pm 0.63 \) SySt per Myr in the whole sample of GC models. Given such a uniform formation rate and the total number of GC models, we have, on average, a birth rate of \( \sim 0.0293 \pm 0.0014 \) SySt per Myr per GC. If we optimistically assume that the SySt life-time is one Myr, then we would expect to be able to observe this amount of SySt in a GC within a Myr. This then provides that we would expect a probability of detection, in observations taken in the past \( \sim 100 \) years, to be \( 10^{-4} \) times the formation rate in Myr\(^{-1} \), which gives \( \sim 2.9 \times 10^{-6} \)

We would like to stress that this estimate is based on ideal situations in which we would be able to detect the SySt with 100 per cent confidence, which in reality is not the case. In addition, the SySt life-time could be shorter than a Myr in a significant fraction (or even most systems) of the population. Thus, this probability of \( \sim 2.9 \times 10^{-6} \) should be interpreted as an upper limit, and a more realistic detection probability would be smaller than this. Therefore, albeit not impossible, it is rather unlikely that we would be able to detect any SySt in the Galactic GC population, provided the low occurrence of SySts in these stellar systems.

4.3.2 From the expected amount of symbiotic stars in the whole Milky Way

We should compare this estimate with what we expect in the Milky Way, based on the SySt progenitor properties. The expected number of SySts in the whole Galaxy can be estimated following an approach similar to Kenyon et al. (1993), which does not request any nuclear burning on the WD, using the following expression

\[
N_{\text{SySt}} \sim F_{\text{SySt}} \times \tau_{\text{SySt}},
\]

where \( \tau_{\text{SySt}} \) is the typical SySt life-time and \( F_{\text{SySt}} \) is the SySt birth rate in the Milky Way, given by

\[
F_{\text{SySt}} \sim F_{\text{SySt,prog}} \times f_{\text{SySt}},
\]

where \( F_{\text{SySt,prog}} \) is the birth rate of SySt progenitors in the Milky Way and \( f_{\text{SySt}} \) is the fraction of SySt progenitors that effectively become SySts.

The birth rate of SySt progenitors can be estimated with the following expression

\[
F_{\text{SySt,prog}} \sim F_{\text{PNe}} \times \sigma \times R_{\text{disc}}^2 \times H_{\text{SySt}} \times f_{\text{bin}},
\]

where \( F_{\text{PNe}} \sim 3 \times 10^{-3} \text{ kpc}^{-3} \text{ yr}^{-1} \) (e.g. González-Santamaría et al. 2019) is the planetary nebula birth rate, \( R_{\text{disc}} \sim 15 \text{ kpc} \) is the Galactic disc radius, \( H_{\text{SySt}} \sim 0.4 \text{ kpc} \) is the Galactic scale.
height, consistent with the observed location of SySts in the Milky Way (Mikolajewska et al. 1997), and \( f_{\text{spin}} \sim 0.5 \) is the binary fraction consistent with that of WD progenitors (e.g. Patience et al. 2002; Moe & Di Stefano 2017). Then, we find a birth rate of \( F_{\text{SySt, prog}} \sim 0.424 \text{ yr}^{-1} \) for the Galactic SySt progenitors.

The fraction of SySt progenitors that effectively become SySts can be estimated as

\[
f_{\text{SySt}} \sim f_1 \times f_2 \times f_3, \tag{9}
\]

where \( f_1 \) represents the fraction of SySt in a given period range, \( f_2 \) is the fraction of systems that survive the WD formation process, and \( f_3 \) is the fraction of those systems with secondaries massive enough to become red giants within the Hubble time. Since we are interested only in SySts formed via the wind-accretion channel, with orbital periods \( \sim 10^3 - 10^5 \) days, we can assume that \( f_1 \sim 0.3, f_2 \sim 1.0, f_3 \sim 0.5 \) (Duquennoy & Mayor 1991; Kenyon et al. 1993), which implies that \( f_{\text{SySt}} \sim 15 \text{ per cent} \) of the progenitors are expected to become SySts.

Replacing the values of \( F_{\text{SySt, prog}} \) and \( f_{\text{SySt}} \) in Eq. 7, we found that the birth rate of SySts in the Milky Way is given by \( F_{\text{SySt}} \sim 6.3 \times 10^{-2} \text{ yr}^{-1} \). Regarding the SySt life-times in our simulation, \( \tau_{\text{SySt}} \) ranges from 0.001 to a few Myr and, on average, is \( \sim 1.6 \pm 0.8 \) Myr. Replacing the values of \( F_{\text{SySt}} \) and \( \tau_{\text{SySt}} \) in Eq. 6 provides that \( N_{\text{SySt}} \sim 100000 \pm 50000 \) SySts should be expected in the whole Milky Way.

If the total number of SySts in the Milky Way is \( \sim 500000 - 1500000 \), then we would expect a mass density of \( \sim 0.5 - 1.5 \times 10^{-7} \) SySts \( M_\odot^{-1} \), assuming a Milky Way mass of \( \sim 10^{12} M_\odot \) (Watkins et al. 2019). A better estimate for the mass density would come naturally from the space density, but this does not seem possible in the case of SySts, due to poor constraints on distances. Interestingly, this does not seem possible even with Gaia, because large orbits, such as those of SySts, cause the center-of-light to wobble with a shift comparable to the parallaxes (Sion et al. 2019). The total mass of the Milky Way stellar halo is estimated to be \( 4 - 7 \times 10^{10} M_\odot \), so the Milky Way GC population currently accounts for about 2 – 3 per cent of the Milky Way stellar halo mass (Forbes et al. 2018). Thus, an optimistic estimate of the entire Milky Way GC population mass is \( \sim 10^{7} M_\odot \). From the mass density of SySts in the Milky Way and the mass expected in the GC population, we expect \( 0.5 - 1.5 \) SySts in the whole GC population. As we have about 150 GCs in the Milky Way, we would expect \( 0.003 - 0.01 \) SySt per GC, which is roughly consistent with our estimate from the GC models.

This estimate naturally assumes that dynamics is not affecting anything. As seen before, not all SySts manage to survive in GCs, which would make this estimate an upper limit in this regard. However, GCs in the Milky Way differ in several ways, which is not taken into account in this estimate. In addition, we adopt rough values for several quantities in this estimate, which could potentially increase the number of expected SySts in the Galactic GC population, if the uncertainties were taken into account. Therefore, it is not too wrong to expect negligible numbers in a large fraction of the Galactic GC population, but at least up to a few SySts in at least some Galactic GCs.

### 4.4 Accretion Luminosity

The final main factor contributing to the observational failure in finding SySts in GCs is likely connected with their WD luminosities. In Fig. 6 we compare observed SySts with those predicted in our GC models, in the plane \( L_{\text{WD}} \) versus \( M_{\text{WD}} \). Predicted accretion-powered luminosities are shown as black open circles, while observed systems in quiescence from Mikolajewska (2010) are depicted as red crosses. The blue solid curve indicates the ‘maximum’ nuclear-powered luminosities, which is related to accreting cold WDs (Iben & Tutukov 1996). The green dot-dashed line corresponds to a constant \( L_{\text{WD}} \) of 100 \( L_\odot \). Expected \( L_{\text{WD}} \) for predicted SySts should lie between values provided by the accretion-powered and maximum nuclear-powered luminosities.

![Figure 6. SySts in the plane WD luminosity (\( L_{\text{WD}} \)) versus WD mass (\( M_{\text{WD}} \)). Predicted accretion-powered luminosities are shown as black open circles, while observed systems in quiescence from Mikolajewska (2010) are depicted as red crosses. The blue solid curve indicates the ‘maximum’ nuclear-powered luminosities, which is related to accreting cold WDs (Iben & Tutukov 1996). The green dot-dashed line corresponds to a constant \( L_{\text{WD}} \) of 100 \( L_\odot \). Expected \( L_{\text{WD}} \) for predicted SySts should lie between values provided by the accretion-powered and maximum nuclear-powered luminosities.](image)

With respect to observed systems, they usually have \( L_{\text{WD}} > 100 \ L_\odot \), which is likely related to intrinsic observational selection effects towards brighter WDs. Indeed, it is very difficult to detect a WD companion beside a red giant, if its luminosity is significantly lower than that of the red giant, and high-quality spectroscopy is necessary in those cases.

Regarding the predicted systems, on average, the red giant luminosity is \( \sim 2300 \pm 500 \ L_\odot \). This suggests that it is rather difficult to identify GC SySts whose WDs are less luminous than \( \sim 10^3 \ L_\odot \). Provided that expected luminosities for steady hydrogen burning are usually higher than that (Nomoto et al. 2007), classical SySts should in principle be recovered. However, not all SySts are expected to be classical. Some/many could be symbiotic (recurrent) novae, which means that their luminosities during quiescence will be likely smaller than \( \sim 10^3 \ L_\odot \), for most of their lives.

The ratio of nuclear-powered and thus luminous (\( L_{\text{WD}} \gtrsim 10^3 \ L_\odot \)) and easy to detect SySt to those only accretion-powered and thus luminous (\( L_{\text{WD}} \lesssim 10^3 \ L_\odot \)) can be estimated as

\[
\frac{L_{\text{WD}}}{L_\odot} \approx 10^{3} \left( \frac{M_{\text{WD}}}{M_\odot} - 0.26 \right). \tag{10}
\]
powered and fainter \( (L_{\text{WD}} \sim 10 \sim 100 \, L_\odot) \) systems is currently unknown. Using only nearby (distance \( \lesssim 1 \, \text{kpc} \)) SySts, it maybe as low as 1.5; albeit this estimate is based on small number statistics (only six SySts are close enough). In our simulation, we found that around 25 per cent SySts should be powered by nuclear burning. This provides an average ratio of 1:4, which, given the uncertainties, is very close to 1:5 found for nearby SySts.

Despite the intrinsic ratio of brighter (nuclear-powered) to fainter (accretion-powered) SySts is uncertain, it seems clear that there should exist more fainter systems than brighter ones. It is simply much easier to observationally identify the brighter systems, which brings a strong bias to the known population. The WD luminosity therefore also imposes difficulties in the identification of SySts in GCs, since high-quality spectroscopy is necessary, which is definitely not easy when considering crowded fields and regions far beyond the solar neighbourhood.

5 PREVIOUS AND CURRENT SYMBIOTIC STAR CANDIDATES IN GLOBULAR CLUSTERS

So far, only a few attempts have been made to identify SySts in Galactic GCs. However, such investigations have not been designed for that purpose and, as pointed out by Zurek et al. (2016), due to their long orbital periods and the dominant contribution of the red giant at longer wavelengths, SySts will usually be missed by optical variability surveys. Spectroscopic surveys are ideal to identity emission lines and, in turn, SySts, but they are very time consuming and, consequently, rare. However, photometric surveys using narrow-band filters centred on either the He \( \text{II} \) and H\( \alpha \) (Ilkiewicz et al. 2018) or the Raman scattered [O \( \text{I} \)] emission lines (Angeloni et al. 2019) are another promising way to look for SySts in GCs.

The first SySt thought to be related to a GC is Pt 1, which was later classified as a Galactic halo SySt (Torres-Peimbert et al. 1980). Pt 1 was discovered as a planetary nebula, possibly associated with the Bulge GC NGC 6401 (Peterson 1977). However, its radial velocity, its distance and the metallicity of the red giant component contradict the association of Pt 1 with NGC 6401 (Munari et al. 1994) and indicate that Pt 1 is a first generation Galactic halo binary.

Zurek et al. (2016) identified a SySt candidate in a Galactic GC: the far-ultraviolet variable source N1851-FUV1 within the core of NGC 1851. This source is likely an accreting WD binary, due to its properties, but its nature is not obviously determined. As this source has likely a WD with an 18-minute periodicity and shows a clear ultraviolet excess, and there is a red giant spatially coincident with this source, it was first classified as a SySt candidate. In order to test this hypothesis, Zurek et al. (2016) carried out optical spectroscopy with \textit{HST} and deep X-ray imaging with \textit{Chandra}. The spectrum spectrum clearly lacks any emission lines, which indicates that the SySt interpretation is probably not right and the presence of a red giant nearby is just a chance superposition of two unrelated objects. This source is now believed to be an AM CVn candidate, based on its X-ray properties, the spectral energy distribution fit and the amplitude of its light curve.

Henleywillis et al. (2018) proposed that the second-brightest X-ray source in \( \omega \) Cen, CXOHC D J132601.59-47305.8, is a promising SySt candidate. This source lies at about 8.8 arcmin southwest of the cluster centre, i.e. is located outside the cluster half-mass radius \( \sim 5 \, \text{arcmin} \). The position of this X-ray source coincides closely with that of SOPs IV e-94, which is a Population II carbon star (Harding 1962) and the first such a star identified in a GC. van Loon et al. (2007a) noticed that it is the brightest and reddest carbon star in the cluster, and its very high 12C:13C ratio points at the \( s \)-process in an asymptotic giant branch carbon star to have been responsible for its large carbon overabundance. In addition, this object is at \( \sim 0.34 \, \text{arcsec} \) from the \textit{Chandra} position of CXOHC D J132601.59-47305.8, inside the 95 per cent confidence radius of \( \sim 0.55 \, \text{arcsec} \). Based on the characteristics of carbon stars and the optical and X-ray properties of this source, Henleywillis et al. (2018) proposed that this could be the first SySt ever identified in a Galactic GC. We will refine the nature of SOPs IV e-94 based on published and new data in Sec. 6.

Most recently, Göttgens et al. (2019b) reported a catalogue of emission-line objects in almost 30 GCs observed with the MUSE instrument, which is a second-generation \textit{Very Large Telescope} panoramic integral-field spectrograph and currently one of the most suitable spectrographs for investigating crowded fields (Bacon et al. 2010; Kamann et al. 2013). One illustration of the power of this instrument relates to cataclysmic variables. Before this MUSE survey, only ten cataclysmic variables have been confirmed by spectroscopy in the whole Galactic GC population. Using MUSE, additional five systems have been confirmed and two new systems have been discovered, which almost doubled the previous number (Göttgens et al. 2019b).

With respect to SySts from the MUSE survey, so far there is one potential candidate. Göttgens et al. (2019a) found a nebula within the core of NGC 6656 \( (14^\prime \text{ arcmin}) \) from the cluster centre with spectrum features consistent with those from a nova remnant. The spectrum contains strong H\( \alpha \), H\( \beta \) and [N \( \text{II} \)] emission lines, as well as weaker emission lines from [O \( \text{III} \)], [S \( \text{III} \)], and H\( \alpha \). These authors argued that the ‘guest’ star observed in 48 BCE was a nova that occurred in NGC 6656 and this emission-line source is the remnant of such a nova that has been detected with MUSE.

Even though it is possible that this source is a nova remnant (but see also the arguments by Hoffmann 2019, against this interpretation), whether it corresponds to an eruption on the WD surface of a classical nova (i.e. a cataclysmic variable) or a symbiotic nova is less clear. Göttgens et al. (2019a) discarded that a SySt could be associated with this remnant because they did not find any signature of a cool star in their spectrum. However, this only excludes S-type SySts, whereas most D-type SySts, including RX Pup (Mikolajewska et al. 1999, one of the best studied symbiotic nova), do not show any signatures of a red giant in their optical spectra. Therefore, it is currently not possible to completely rule out the scenario in which this nova remnant could have come from a symbiotic nova.

6 IS SOPS IV E-94 A SYMBIOTIC STAR IN \( \omega \) CEN?

In order to identify SOPs IV e-94 as a SySt, particular features in the spectrum are expected (see Sec. 1) and until these are indeed observed, this object cannot be confidently classified as a SySt. The minimum requirement is the presence of some Balmer emission in the optical spectrum. Whereas the published optical photometry of SOPs IV e-94 \( (U = 14.467, B = 13.301, V = 11.517, R = 10.691, I = 9.917, H = 10.263, \text{Bellini et al. 2009}) \) indicates that there could be some H\( \alpha \) emission \( (H - R - C = -0.428) \), the published spectra (Harding 1962; van Loon et al. 2007b) do not show any emission lines. Instead, the negative H\( \alpha \) – R\( \alpha \) colour could be simply due to strong molecular bands that are present in the optical spectrum and affect the R\( \alpha \) mag. In such a case, SOPs IV e-94 would represent another example of a chance superposition of two unrelated objects – the
X-ray source and the carbon giant – as in the case of N1851-FUV1 in NGC 1851.

To refine the nature of SOPS IV e-94, we obtained a deep optical spectrum with the Robert Stobie Spectrograph (RSS; Burgh et al. 2003; Kobulnicky et al. 2003) mounted on the Southern African Large Telescope (SALT; Buckley et al. 2006; O’Donoghue et al. 2006) under programme 2019-2-SCI-021 (PI: Ilkiewicz). A single RSS configuration was adopted with PG900 grating and a slit width of 1.5" to give wavelength coverage from ∼ 3920 – 6080 Å with resolving power R ∼ 1000. The spectrum, presented in Fig. 7, was made on 14-01-2020 with a 200 s exposure time.

The spectrum of SOPS IV e-94 is dominated by strong C2 and CN molecular bands typical for a carbon star. At the same time, there is no trace of any emission lines, including the strongest Hα emission which is always visible in SySts. None of the features typical for a SySt are present. In particular, the lack of any emission lines in the spectrum of the carbon star indicates that there is no physical association between this star and CX-OHCD J132601.59-473305.8. The X-ray emission most probably originates from another object. Therefore, SOPS IV e-94 cannot be classified as a SySt.

7 BEST CLUSTER TARGETS FOR FUTURE OBSERVATIONS

Provided that some SySts should exist in the Galactic GC population, we can try to answer the following key questions: (i) how do ideal GC targets to search for SySts look? (ii) how far ideal GC targets should be from the Galactic centre and Sun? (iii) what are the best GC targets in the Galaxy to search for SySts? Answering these questions might substantially help future observations aiming to identify SySts in GCs.

7.1 What are the characteristics of ideal globular cluster targets to search for symbiotic stars?

Before proceeding further, we would like to highlight that there is a huge degeneracy regarding GC modelling, in the sense that different initial GC models might evolve to comparable present-day global GC properties. This degeneracy could be broken by modelling properties of particular type of objects (e.g. cataclysmic variables, binary black holes, blue stragglers, among others), which strongly depend on environment properties in which they live. Despite that, we search in what follows, what are the characteristic of GC models harbouring the largest numbers of SySts, based on present-day global properties.

In Fig. 8, we present the expected number of SySts within a Myr against a few present-day GC properties, namely half-mass relaxation time (first panel), core radius (second panel), half-light radius (third panel), and total mass (fourth panel). As before, we separate the models according to its initial concentration, very dense being those closer to the Marks & Kroupa (2012) radius–mass relation. We can see a clear correlation between the expected number of SySts and the half-mass relaxation time, core and half-light radii. Indeed, we carried out Spearman’s rank correlation tests, and found a strong correlation with more than 99.99 per cent confidence, in all cases, being the rank values given by ≈ 0.77, ≈ 0.82 and ≈ 0.71, respectively. On the other hand, there is apparently no (or very weak, if at all) correlation between the expected number of SySts and the total GC mass, which is confirmed by the correlation test that provides a rank value of ≈ 0.26 with at least 99.29 per cent confidence. This suggests that the best GC targets are those relatively extended clusters with relatively long half-mass relaxation times.

Regarding correlations among GC properties, there is a clear correlation between their Galactocentric distances and their half-light radii (van den Bergh et al. 1991; Baumgardt & Hilker 2018), which is likely due to the strong tidal fields in the inner parts of the Milky Way. Moreover, there is a clear observational correlation between the half-mass relaxation times and the half-mass radius (Baumgardt & Hilker 2018), which is not surprising since the half-mass relaxation time is proportional to \( R_{\text{half-mass}} \). These correlations indicate that the best GC targets should also be relatively far from the Milky Way centre and corroborate our finds discussed previously.

At this point we are able to answer the question regarding the properties best GCs should have to be considered ideal targets to search for SySts. One should search for SySts in the outskirts of nearby low-density clusters (given their large radii, angular size and brightness) whose half-mass relaxation times are considerably long and their locations are not so close to the Galactic centre. This is consistent with what one would expect, since in low-
density clusters, the probability for interaction is relatively small, which means that SySts have better chances to survive. In addition, the hard-soft boundary is shifted to longer orbital periods in sparse GCs, because the typical velocity dispersion in such clusters is smaller than in denser ones. Moreover, in clusters with long half-mass relaxation times, mass segregation is not effective, hence SySt progenitors do not have time to sink towards the central parts, and consequently have their probability of interactions increased with the higher densities in the central parts. This also provides better chances for the SySts to survive. Furthermore, there are better chances to detect SySts in nearby clusters, which are apparently brighter and better spatially resolved, reducing the crowding. Another disadvantage of clusters far away from the Sun is the increase of the probability of interlopers. Finally, as clusters relatively distant from the Milky Way centre tend to have larger half-light radius, they also have better chances to contain a non-null number of SySts.

This prediction is in a very good place for observations. From an observational point of view, the completeness in spectroscopic surveys mainly depends on the stellar brightness (which depends on the cluster distance to the Sun) and the stellar density (which depends on the star radial distance to the cluster centre), as shown by Göttgens et al. (2019b, their figs. 11 and A1). In this way, the lower the cluster density or the smaller the cluster distance to the Sun, the higher the completeness, for a given star brightness. Therefore, it is reasonable to predict that the best approach to identify SySts is to perform searches in the outskirts of nearby low-density GCs, in which typical difficulties related to crowded fields of high stellar density environments would not be that strong. In addition, surveys in the outskirts could also increase significantly the number of spectroscopically confirmed cataclysmic variables in GCs, since around half of the GC cataclysmic variable population is expected to be located outside the half-mass radii, especially in such low-density clusters (Belloni et al. 2019).

7.2 What are the best globular cluster targets to search for symbiotic stars?

Among all clusters, ω Cen deserves special attention, as it is one of the best studied Galactic GC. Although we showed that the promising candidate SOPS IV e-94 in this cluster is not a SySt (Section 6), ω Cen is still a very good target for searches of SySts. It is an extended and massive low-density cluster, characterized by a long half-mass relaxation time and large half-light and core radii. As discussed in Section 7.1, these features place ω Cen in the sample of clusters that might promisingly harbour SySts.

Another rather important cluster is 47 Tuc, which is another well-studied Galactic GC, together with ω Cen. Among all Galactic GCs, has the largest number of detected X-ray sources (Bhatcharya et al. 2017; Cheng et al. 2019), including plenty of millisecond pulsars, cataclysmic variable candidates (Rivera Sandoval et al. 2018), and many other exotic binaries (Knigge et al. 2008). The core of 47 Tuc is ≈1.5 denser than that of ω Cen and its stellar encounter rate is ~100 times larger (Bahramian et al. 2013). In general, 47 Tuc is one of the Galactic GCs with the largest stellar interaction rates (Bahramian et al. 2013; Cheng et al. 2018). As discussed previously, the destruction of SySts is larger in denser and more dynamically active clusters, thus explaining the lack of SySt detections in the central parts of such a GC, where most of the searches for interacting binaries have been performed so far (e.g. Edmonds et al. 2003a,b; Knigge et al. 2008; Rivera Sandoval et al. 2018; Campos et al. 2018). However, given its relatively long half-mass relaxation time and size, it is a good candidate to look for SySts, especially in its outer parts.

Within the catalogue by Baumgardt & Hilker (2018), nearby low-density clusters with relatively long half-mass relaxation times and relatively large Galactocentric distances are, e.g.: NGC 288, NGC 4372, NGC 4590, NGC 4833, NGC 5897, NGC 6362, NGC 6809 and Pal 11. All these clusters have half-mass relaxation times $\gtrsim 3$ Gyr, central densities $\lesssim 400$ $M_\odot$ pc$^{-3}$, distances $\lesssim 12$ kpc, projected half-light radii $\gtrsim 5$ pc, and Galactocentric distances $\gtrsim 5$ kpc.
The clusters investigated in the MUSE survey are in general relatively dense, many being core-collapsed, and only the central parts have been covered (i.e. up to the half-light radii), which are usually preferred because there is less confusion regarding the GC membership. Only one cluster similar to those listed above was investigated with MUSE, namely NGC 3201 (Kamann et al. 2018; Giesers et al. 2018, 2019; Göttgens et al. 2019b). However, the pointings for this cluster covered basically the central parts, well inside the half-light radius. Despite these authors investigated binaries in detail, by providing the orbital period and eccentricity distributions (mainly for main-sequence binaries) for the first time in a GC, they could not find any cataclysmic variable nor SySt. Perhaps, if there were pointings in regions farther from the central parts, some interesting accreting WD binaries could be recovered, including the long-period ones, such as SySts.

Another interesting cluster investigated with MUSE is NGC 6656, which possibly harbours a nova remnant that could have originated in a symbiotic nova, instead of a classical nova (Göttgens et al. 2019a). This nova remnant lies within the core radius, which provides a rather low probability for long-period systems such as SySts to survive. From our results, ~10 per cent of the predicted SySts are inside the core radii of our models. So, albeit unlikely to find them there, it is not impossible. Additionally, NGC 6656 has one of the largest cores in the Galactic GC population (Harris 1996, 2010 edition), so it is rather consistent with our results that such a type of GC might harbour a SySt within its core. Therefore, it is definitely worthwhile to put more observational efforts on this source to disentangle the possibility that it could be a symbiotic nova remnant.

8 SUMMARY AND CONCLUSIONS

We investigated here symbiotic stars formed through the wind-accretion channel in 144 globular cluster models evolved with the MOCCA code with the aim of explaining why not a single one has ever been identified in a Galactic globular cluster.

We found that most progenitors of these systems are destroyed in dense globular clusters before effectively becoming symbiotic stars at the present day. This happens because the progenitors of these systems have initially orbital periods (~10^5 years) that are comparable to (or even much longer than) the orbital period separating soft from hard binaries in the clusters. This puts them into the group of soft binaries and makes their destruction through dynamical interactions sufficiently easy over the cluster evolution timescale (~11–12 Gyr).

However, in less dense clusters, symbiotic stars should still be present. Most of these symbiotic stars (~70 per cent) are located far from the cluster central parts and beyond the cluster half-light radii (i.e. less dense regions), which is the main reason why they managed to survive in the clusters. This also makes their detection difficult, provided the large areas of the globular cluster outskirts. Additionally, given the typical life-times of symbiotic stars (~1 Myr), their expected numbers are extremely low (~1 per globular cluster per Myr). Coupled with that, it is very difficult to detect a white dwarf companion when its luminosity is not sufficiently high (~100 L☉), e.g. for symbiotic (recurrent) novae in quiescence, which is likely the case for a large fraction of the systems.

Our results provide therefore an explanation for the observed absence of symbiotic stars in Galactic globular clusters, which occurs due to a combination of four important effects: (i) most are destroyed in dynamical interactions and; most that survived (ii) likely have relatively low white dwarf luminosities, (iii) are far from the central parts, and (iv) are sufficiently rare; which makes their discovery in current dedicated observational surveys rather difficult.

Coupling the properties of symbiotic stars and globular clusters, we found that the best chances to identify them are in the outskirts of nearby low-density clusters with relatively long half-mass relaxation times and relatively large Galactocentric distances, by means of either high-quality spectroscopy or photometry using narrow-band filters centred on either the He I and Hα or the Raman scattered O VI emission lines.

Finally, we refined the nature of SOPS IV e-94, the promising SySt candidate in ω Cen, by obtaining a deep SALT optical spectrum and concluded that this object cannot be classified as SySt. This is because none of the features typical for a SySt are present in the spectrum of SOPS IV e-94, e.g. there is no trace of any emission lines, including the strongest Hα emission which is always visible in SySts.

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