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Cataclysmic variables in globular clusters

First results on the analysis of the MOCCA simulations database

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Abstract. In this first investigation of the MOCCA database with respect to cataclysmic variables, we found that for models with Kroupa initial distributions, considering the standard value of the efficiency of the common-envelope phase adopted in BSE, no single cataclysmic variable was formed only via binary stellar evolution, i. e., in order to form them, strong dynamical interactions have to take place. Our results also indicate that the population of cataclysmic variables in globular clusters are, mainly, in the last stage of their evolution and observational selection effects can change drastically the expected number and properties of observed cataclysmic variables.

Key words. Stars: cataclysmic variables – Globular cluster: general – Methods: numerical

1. Introduction

Cataclysmic variables (CVs) are among the most interesting objects in globular clusters (GCs). They are interacting binaries composed of a white dwarf (WD) that accretes matter stably from a main sequence (MS) star or a brown dwarf (BD) (e. g., Knigge et al. 2011, for a comprehensive review). CVs are subdivided according to their photometric behaviours as well as the WD magnetic field strength, being, mainly, magnetic CVs (where the accretion is partially or directly via magnetic field lines) and non-magnetic CVs (where the accretion is via an accretion disk). Among the non-magnetic CVs, the most prominent subgroup is that composed of dwarf novae (DNe) which exhibit repetitive outbursts due to the thermal instability in the accretion disk.

In this initial investigation, we analysed six GC models: three (called S models) with "Standard" distributions of the initial binary properties (uniform distribution for the mass ratio, uniform in log or log-normal distribution for the semi-major axis and thermal distribution of eccentricities), and three with the Kroupa initial binary population (Kroupa 2008) (called Kroupa models). In what follows, we will present the main results achieved so far.

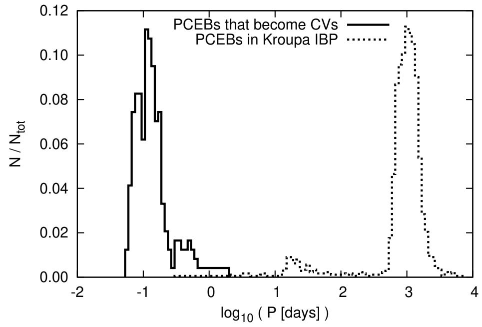

Fig. 1. Distribution of the orbital period of the post-common-envelope binaries (PCEBs). Solid line concerns the PCEBs that become CVs when evolving the "Standard" initial binary population with BSE. Dashed line is related to the PCEBs that emerge from one of the Kroupa models. Notice the long periods of most PCEBs in the Kroupa model.

2. Absence of non-dynamical CVs in Kroupa models

One of the most important results of this initial investigation is that in the three Kroupa models, there is no CVs produced via only binary stellar evolution. In other words, in order to form CVs in such models, strong dynamical interactions have to take place. This is a strong hint toward an inconsistency between observations and theoretical predictions, because we do observe CVs in the field and regions where dynamics could not have played any role.

There could be two reasons for that. Either the mass feeding algorithm that increases the mass ratio of the binaries that would be potential CV progenitors might require adjustments, or the efficiency of the common-envelope phase (CEP) in BSE (Hurley et al. 2002) should be much smaller. The adopted value is $\alpha = 3.0$.

The mass ratios associated with the CV progenitor binaries are small ($q \lesssim 0.2$) and they are short-period binaries. Since the mass feeding procedure tends to increase the secondary mass due to accretion of gas from the circumbinary material, the secondary mass increases while the primary mass remains constant (Kroupa 2008). This implies that the initial mass ratio of short-period binaries increases toward the unity. This way, it might be that the feeding procedure generates initial binaries that are inappropriate for evolving into CVs.

On the other hand, if the CEP efficiency decreases significantly, then a great deal of orbital energy would be needed in order to eject the common-envelope, since the orbital energy loss in the process would be large. This would bring the long-period binaries (with low q) to shorter periods, and consecutively turn them into potential CVs.

Fig. 1 illustrates the situation. Note that the post-common-envelope binaries (PCEBs) in the Kroupa models have quite long periods, since the binaries with appropriate q to become CVs are long-period ones. Although, by decreasing the efficiency of the CEP, such periods at the end of the process would be smaller and then, potential CVs.

3. Probability of detecting DNe during outburst

The searches for DNe in GCs so far have been leading to the conclusion that DNe are rare in GC (e. g. Pietrukowicz et al. 2008). Nevertheless, such observational findings do not corroborate theoretical predictions. Firstly, around 100-200 CVs should be present in massive GC (Ivanova et al. 2006). Secondly, most CVs should be DNe (e. g., Knigge et al. 2011).

This corresponds to a rather strong inconsistency between theory and observation and the most popular hypothesis that attempts to explain the so-called absence of DNe in GC is based on the mass transfer rate and the WD magnetic field. Dobrotka et al. (2006) proposed, using the disk instability model (DIM), that low mass transfer rate combined with moderately strong WD magnetic field can disrupt the inner part of the accretion disk, preventing, in turn, the outburst in such CVs.

The probability of detecting a DN during its outburst can be estimated as follows. Given a GC distance and a limiting magnitude: if the DN can be detected only during outburst; then, the probability of detecting it during one night of observation within the DN cycle is its duty cycle. If the DN can be detected during qui-

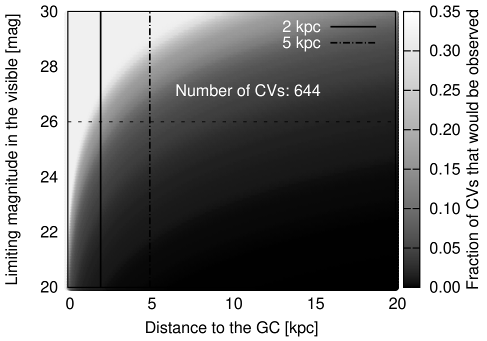

Fig. 2. Dwarf nova detection rate a function of the limiting magnitude and the distance of the cluster, considering all CVs in the six models. The colour bar represents the fraction of CVs that would be observed based on a probability-weighted 2D normalised histogram in each cell of size 0.005x0.1.

escence and during outburst; then, we add 1/3 to the previous probability, which corresponds to the probability of the DN be an eclipsing binary. Finally, if the CV cannot be detected even during outburst; thus, the probability is null.

Fig. 2 exhibits the fraction of CVs that would be detected (indicated by the grey gradient) as a function the cluster distance and the visible limiting magnitude, including all CVs in our six models. Notice that we have basically three regions in the figure: one dark, one light and one in the middle. The dark region correspond to CVs that could be observed only during outburst, since the probability is small. The light region is associated with the CVs that can be observed also during quiescence, because the probability is $\sim 1/3$ (probability of being eclipsing binary). Finally the middle region (neither so dark nor so light) corresponds to a mix of CVs that can be observed during quiescence and during outburst. This way, smaller the distance and greater the limiting magnitude of the instrument, greater the chances to detect the CV during quiescence.

As an example, in order to compare our results with observations, Cohn et al. (2010, see their Fig. 3) could reach a limiting magnitude around 26 mag in the R filter (similar filter to what we have) in their observations of NGC 6397 (at $\sim$ 2 kpc). In such study, they found 15 CV candidates. This way, as the predicted number of CVs in our average cluster is $\sim$ 100, and our fraction of detectable CVs for such limiting magnitude is around 20 per cent, we should expect that they would have found around 20 CVs in their search. This conclusion comes from the fact that we are considering an ideal situation, i. e., Fig. 2 shows the fraction of detectable CVs in an ideal situation. After including real complications (crowding, heterogeneous observations, etc.), one should expect only a small fraction of the CVs in a GC detected during the observations for a relatively low limiting magnitude as $\sim$ 26 mag.

This result indicates that CVs in GCs are not, a priori, non-DNe ones. In other words, it is not easy to rule out the notion that most of the CVs in GCs are DNe, specially by considering the observational selection effects. Even though the idea that CVs in GCs are preferentially magnetic has been largely accepted and treated as coherent, from our results we cannot discard the possibility that most of them are DNe and due to observational selection effects we are not able to always detect them.

The solution to this problem turns out to be the search for optical counterparts in deep observations ($\gtrsim$ 27 mag) of faint Chandra X-ray sources ($\lesssim 10^{30}$ erg/s), in combination with Hα and FUV imaging with Hubble Space Telescope. Such approach would reveal at least the intrinsic WZ Sge population (brightest faint CVs) in the closest GCs, like M 4 and NGC 6397. As suggested by Knigge (2012), the identification of at least a few WZ Sge systems in GCs might be key to solve this problem.

4. Age-dependence of CV properties

The last key result we found is associated with the age dependence of the CV properties, which can lead to misleading comparisons among models, field and cluster CVs, since cluster CVs are 2-4 times older than field CVs.

Fig. 3 illustrates how the average WD mass in the CVs changes with time during the cluster evolution. Note that for the Kroupa model (having only dynamically formed CVs), the average WD mass is roughly constant with time (~0.8 $M_\odot$). This is because dynamically formed CVs tend to be more massive due to

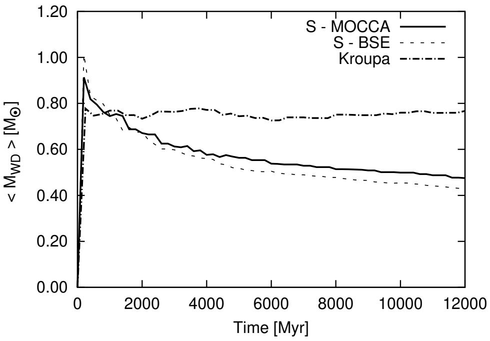

Fig. 3. Evolution of the mean WD mass considering all CVs that are present in three models as a function of time. Notice that the CVs are continually formed during the cluster evolution. The *S–MOCCA* model corresponds to all CVs formed in one "Standard" model evolved with MOCCA, and the *S–BSE* model is associated with all CVs formed in the same model when evolved without dynamics. Finally, the *Kroupa* model is one Kroupa model evolved with MOCCA.

dynamical exchanges/mergers. With respect to the models S–MOCCA and S–BSE, we can see a clear drop in the average WD mass, being the cluster CVs (S–MOCCA) slightly more massive than the field-like ones (S–BSE). This is because only a fraction of the CVs in such an S model is dynamically formed, then we see a small increase in the average WD mass.

5. Conclusions

The study of CVs in GCs with the MOCCA code has just started and we expect more exciting results in future investigations. With the analysis of only six models, we could already find interesting results.

The Kroupa initial binary population might require some adjustments, although more tests with respect to the binary stellar evolution parameters must be done before claiming that. Above all, it seems clearly that the initial binary population can be potentially constrained with specific binary populations (like CVs) in the field and GCs. The search for DNe should be in the direction of deeper observations (optical, Hα and FUV), in order to reach the faint CVs during their quiescence. Additionally, more effort should be put in finding secure optical counterparts of faint X-ray sources down to $\sim 10^{30}$ erg/s.

Finally, the CV population in GCs are intrinsically old, which indicates that cluster CVs are substantially older in comparison with the observed field CVs. This implies that cluster CVs are intrinsically fainter than observed field CVs.

It is worth mentioning that we have been preparing two papers where the results will be presented and discussed with more details.

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