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Cataclysmic variables in globular clusters

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Abstract. Every massive globular cluster (GC) is expected to harbour a significant population of cataclysmic variables (CVs). In this review, I first explain why GC CVs matter astrophysically, how many and what types are theoretically predicted to exist and what observational tools we can use to discover, confirm and study them. I then take a look at how theoretical predictions and observed samples actually stack up to date. In the process, I also reconsider the evidence for two widely held ideas about CVs in GCs: (i) that there must be many fewer *dwarf novae* than expected; (ii) that the incidence of magnetic CVs is much higher in GCs than in the Galactic field.

Key words. Stars: novae, cataclysmic variables – Galaxy: globular clusters

1. Introduction

Globular clusters (GCs) are old, gravitationally bound stellar systems that typically contain $\sim 10^6$ stars. Some of these stars are binaries, and some of these binaries are cataclysmic variables (CVs), i.e. systems in which a white dwarf (WD) accretes material from a roughly main sequence (MS) companion. These CV populations in GCs deserve special attention for at least three reasons:

1 The Globular Cluster Perspective: the late dynamical evolution of a GC is thought to be driven largely by its close binary (CB) population (e.g. Hut et al. 1992). However, the dominant non-interacting MS-MS binaries are difficult to detect and study in GCs. CVs can therefore be used as convenient tracers of the underlying CB populations for studies of GC dynamics and evolution.

2 The Cataclysmic Variable Perspective: in principle, GCs can provide us with sizeable samples of CVs at known distance and (to some extent) age. Such samples might allow critical tests of theoretical CV/binary evolution scenarios. An interesting complication is that not all CVs in GCs are likely to have formed and evolved in isolation: many are likely to have been produced, or at least affected, by dynamical interactions (see later).

3 The Supernova Perspective: it has been suggested that GCs might be significant Type Ia Supernova factories (Shara & Hurley 2002), at least in elliptical galaxies (Ivanova et al. 2006). All SN Ia progenitor populations are thought to be close relatives of CVs (e.g. double WD systems, supersoft sources, WD + red giant binaries), so CVs can again serve as a useful tracer population for these progenitors. In fact, it is even still possible that some CVs might be SN Ia progenitors themselves (Thoroughgood et al. 2001; Zorotovic, Schreiber & Gänsicke 2011).

2. Theoretical background

So how many – and what type of – CVs might we expect in a typical massive GC? Let us start with a simple back of the envelope calculation, based solely on the number of stars in a cluster and entirely ignoring stellar dynamics. The space density in the Galactic field is of order $\rho \sim 10^{-5}\mathrm{pc}^{-}3$ (e.g. Pretorius et al. 2007; Pretorius & Knigge 2011). The volume of the Milky Way is of order $V \sim 10^{11}\mathrm{pc}^3$, so the expected number of CVs in the Galaxy is around $N_{CV,MW} \sim 10^7$. Now the fraction of the Milky Way's stellar mass that is bound up in its GC system is roughly $f_{GC} \sim 0.001$ and there are $N_{GC} \sim 100$ GCs in the Galaxy. So, *other things being equal*, the number of CVs that would be expected in a single GC is of order $N_{CV,GC} \sim f_{GC} N_{CV,MW}/N_{GC} \sim 100$.

But *are* other things actually equal? We already noted above that CV populations in GCs might be strongly affected by dynamical encounters. This is actually quite easy to understand: stellar densities in dense cluster cores can reach $10^6\mathrm{pc}^{-3}$. To put things into perspective: the volume occupied by a single nova shell, like that around T Pyx, is $\sim 0.01\mathrm{pc}^3$. So in a dense GC core, this same volume will contain $\sim 10,000$ stars. Close dynamical encounters between cluster members are therefore inevitable.

Fundamentally, there are two types of relevant dynamical encounters: direct collisions and near misses. These can affect CV populations in GCs in three basic ways: (i) they can create new CVs; (ii) they can destroy wide binaries that would have evolved into CVs in the field; (iii) they might alter the binary properties of CVs/CV progenitors. It has been known for a long time that bright, neutron-star-hosting low-mass X-ray binaries are $\simeq 100\times$ over-abundant in GCs, presumably because they are efficiently produced by dynamical formation channels in the dense GC environment (e.g. Clark 1975). At first sight, we might therefore expect dynamical creation to dominate over destruction also for CVs. However, dynamical encounter cross-sections scale with mass, so one cannot simply assume that the same enhancement factor will apply to CVs and LMXBs.

Until recently, estimates of CV formation rates in GCs tended to focus on one channel at a time. For example, Davies (1997) noted that CV progenitors might be destroyed in dense cluster cores, but would likely survive in the outskirts. His estimate for the number of such "primordial" CVs in a given single massive cluster was $N_{CV,p} \sim 100$, not too different from our naive estimate that ignored dynamics entirely. The role of two-body encounters in producing GC CVs was explored by di Stefano & Rappaport (1994). They found that the number of CVs produced via the "tidal capture" (Fabian, Pringle & Rees 1975) of a MS star by a WD might also be $N_{CV,tc} \sim 100$. Finally, Davies (1995) considered 3-body interactions as a source of CVs, such as exchange encounters in which a WD is exchanged into a pre-existing MS-MS binary. He found that this channel again might contribute $N_{CV,3b} \sim 100$ CVs.

In recent years, our ability to model GC dynamics and their connection to binary evolution has improved significantly. We therefore now have more comprehensive predictions for the number and type of CVs we might expect to find in GCs (Ivanova et al. 2006). Figure 2 shows the "flowchart" of the various CV production channels in a particular GC model – real life is clearly more complex than back-of-the-envelope single-channel estimates. Despite this, the predicted numbers – $N_{CV,GC} \sim 200$ for a typical massive cluster – are not far off the earlier estimates and indicate a mild, $\sim \times 2$ enhancement of CV numbers over the Galactic field. Nevertheless, the *properties* of the CVs in these models can be quite strange. For exmaple, the survival rate of primordial CVs is only about 25%, so the majority of GC CVs are dynamically formed. Also, a full 60% of GC CVs did not form via a common envelope phase, and 50% formed via some form of binary encounter.

3. Detecting CVs in GCs

So how should we go about detecting the hundreds of CVs that are predicted to lurk in any

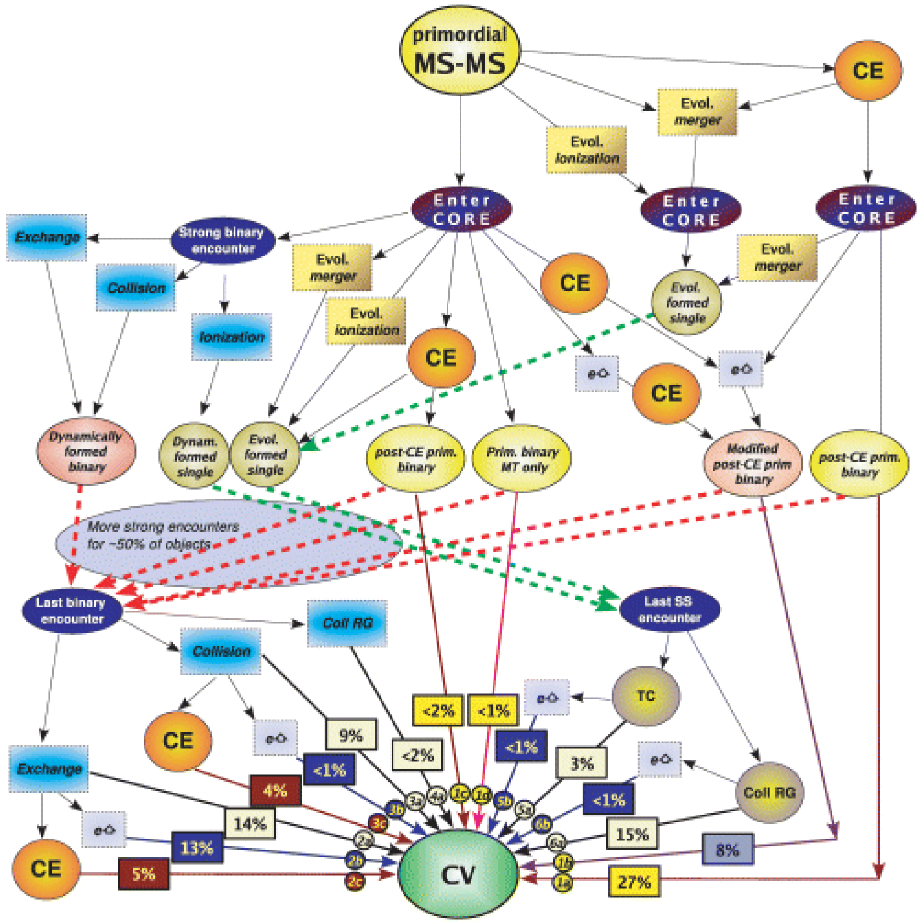

Fig. 1. The main CV formation channels in GCs in the simulation carried out by Ivanova et al. (2006), to which the reader is referred for details. Figure reproduced by permission from Ivanova et al. (2006).

given massive GC? The answer is pretty much in the same way we find them in the rest of the galaxy: via their variability, their emission lines, their excessively blue colour and/or their X-ray emission. The GC setting does not exactly make our life easier though, since (i) GC CVs are typically 10 – 100 times more distant and hence 100 – 10, 000 times fainter than nearby field CVs, and (ii) GCs are crowded places, with surface densities that can easily reach or exceed 10 stars per square arcsecond. Nevertheless, all four of these methods have been used to locate CVs in GCs, so let us briefly look at each of them in turn.

3.1. Variabilty

CVs exhibit many different types of variability on all sorts of time scales, from flickering and oscillations on time scales of seconds, to nova eruptions that are thought to recur every $\sim 10^4$yrs. However, the most obvious type of CV variability to exploit for locating CVs in GCs is that related to dwarf nova (DN) outbursts. DNe typically brighten by ¿3 magnitudes during eruption and standard CV evolution theory predicts that *most* CVs should be DNe (e.g. Knigge, Baraffe & Patterson 2011). So multi-epoch imaging would seem to be a

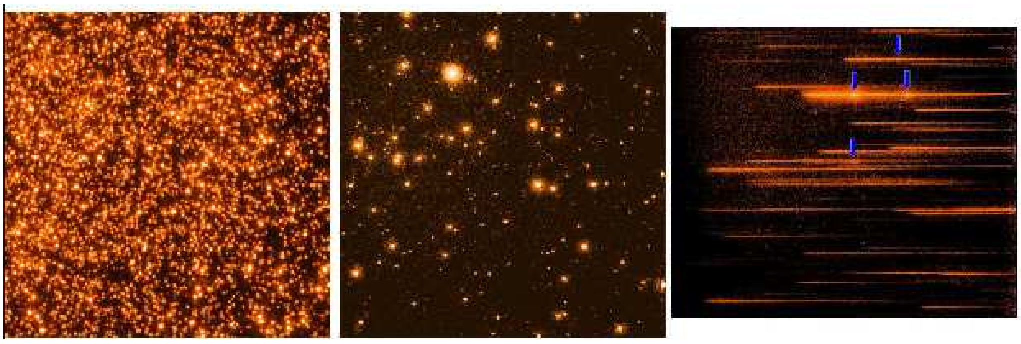

Fig. 2. *Left panel:* A U-band image of part of the core of 47 Tuc. *Middle panel:* The same region observed in the far-ultraviolet. *Right panel:* A 2-D spectral image of roughly the same region again, obtained via slitless FUV spectroscopy. Each horizontal trail is the spectrum of a FUV source. Three CVs that exhibit emission line are marked (see Figure 4). All images span roughly 25″× 25″, were obtained with HST and have been described and analyzed fully in Knigge et al. (2002, 2003, 2008).

good way to search for CVs in GCs, although we need to know the characteristic duty cycles of DNe in order to interpret such observations – a critical point to which we will return.

The first concerted effort to use this strategy was undertaken by Shara et al. (1996), who analysed 12 epochs of HST observations GC 47 Tuc (although only 3 epochs covered more than a fraction of the cluster core). The recovered only a single – previously known – DN and therefore concluded that *"there are probably no more than three DNe in the core of 47 Tuc, in significant disagreement with the standard model of tidal capture, unless the properties of DNe in globulars differ (e.g. in outburst frequency) from those in the field."* Several other DNe in GCs have been discovered since then, including two in M80 (Shara, Hinkley & Zurek 2005), two in NGC 6397 (Shara et al. 2005), at least one more in 47 Tuc (Knigge et al. 2002, 2003); one in M22 (Hourihane et al. 2011) and one in M13 (Servillat et al. 2011). However, the most recent *systematic* study (Pietrukowicz et al. 2008) found *"only 12 confirmed DNe in a substantial fraction of all Galactic GCs"* and thus concluded that "the results of our extensive survey provide new evidence...that ordinary DNe are indeed very rare in GCs". Taken at face value, these conclusions are obviously in serious conflict with theory, which predicts hundreds of CVs in a single massive cluster, most of which should be DNe. We will return to this apparent conflict in Section 5.5.

3.2. Emission lines

The second obvious way of finding CVs in GCs is via their emission lines. In practice, such searches have usually been implemented as narrow-band Hα imaging surveys, with crowding still necessitating the use of HST (e.g. Bailyn et al. 1996; Carson, Cool & Grindlay 2000). Typical CV hauls with this method have been a handful of CV candidates per cluster, i.e. still a long way from the $\sim$ 200 predicted. However, an obvious question is whether such searches reached deep enough uncover the dominant (faint) part of the CV population. We will come back to this question also; for the moment, we will merely note that the absolute magnitudes of the CVs recovered were typically around $M_V \simeq 7 - 8$.

3.3. Blue colour

The third way of finding CVs (or at least CV candidates) in GCs is via their colours. The luminosity of most CVs is dominated by accre-

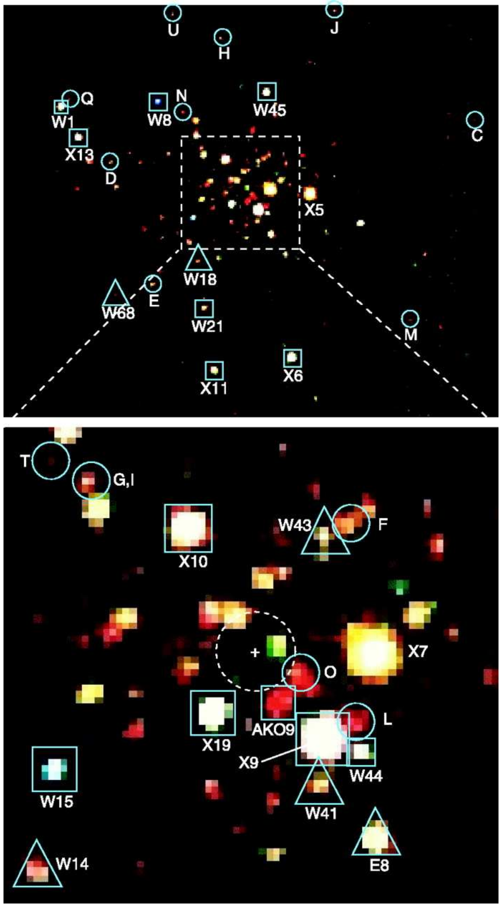

Fig. 3. X-ray color image obtained with Chandra of the central 2′× 2.5′of 47 Tuc. The zoom-in on the core in the bottom panel spans 35″square and is thus comparable in size to the optical and FUV images in Figure 2. CVs are marked with squares. Figure reproduced by permission from Grindlay et al. (2001), to which the reader is referred to for details.

tion power, and most of the energy released by accretion is generated close to the W. These regions are much hotter than the most massive MS stars in an old GC, so CVs are exceptionally blue compared to normal stars in a GC. This can already be exploited in the optical region, where CVs should stand out in, for example, U-B colour-magnitude diagrams (e.g. Cool et al. 1998), but is also a good reason to search for GC CVs in the far-ultraviolet (FUV) band with HST (e.g. Knigge et al. 2002; Dieball et al. 2005, 2007, 2010). The latter offers the nice additional advantage that crowding ceases to be a problem entirely, since most ordinary MS stars are effectively invisible in the FUV (Figure 2). On the downside, the field of view of HST's FUV detectors is very small, and often covers only (part of) the cluster core. Such searches typically yielded about 1-50 CV candidates per cluster, but, as before, one needs to keep their limited completeness in mind.

3.4. X-rays

The fourth and final CV detection route we will consider is X-ray emission. In principle, X-rays are a great way of searching for compact objects, but, until recently, X-ray observatories suffered from a combination of poor spatial resolution and limited sensitivity. Heroic efforts to survey GCs were made nonetheless (e.g. Hasinger, Johnston & Verbunt 1994), but even the identification of individual sources – especially in the critical cluster cores – was often impossible.

However, the current generation of X-ray telescopes – XMM and, especially, Chandra – has completely revolutionized this field. Chandra, for example, offers excellent sensitivity, a 15′ radius field of view and a spatial resolution of $\simeq$ 1″ – characteristics that are perfectly matched to the requirements of GC surveys. And, sure enough, the very first survey of a GC with Chandra (Grindlay et al. 2001; Figure 2) immediately revealed a population of $\simeq$ 30 CVs in 47 Tuc, a considerably larger number than had been known before. Since then, $\simeq$ 60 clusters have been surveyed with Chandra down to $L_x = 10^{31}$ergs^{-1} (Pooley 2010). For quite a few of these, the limiting L_x is actually considerably deeper than this, though very few have been searched down to $L_x \leq 10^{30}$ergs^{-1}. These searches typically uncovered 10-100 CV candidates in any given high-density, massive cluster. This represents a significant fraction of the predicted population, but is still some way below the theoretical predictions.

4. Confirming CVs in GCs

An object uncovered by any one of the methods described in the previous section is obviously just a CV *candidate* whose status as a genuine CV requires confirmation. As in the field, *spectroscopic* confirmation tends to define the gold standard here. However, the faintness of CVs in GCs, coupled with the crowded nature of the GC environment, make this a difficult proposition. In the optical band, ground-based spectroscopy is only possible in the outskirts of clusters, and long-slit spectroscopy with HST is an expensive way of confirming individual CVs. A sneaky and efficient way around this problem is to exploit the absence of crowding in the FUV by carrying out *slitless*, multi-object FUV spectroscopy (Knigge et al. 2003, 2008; Figure 2). In 47 Tuc, this allowed us to confirm 3 CVs simultaneously, via the detection of the C IV 1550 Åemission line in objects already displaying a clear FUV excess (Figure 4).

However, on the whole, the gold standard has been rarely achieved to date. In fact, only 6 studies have so far succeeded in spectroscopically confirming one or more new GC CVs, and the combined total adds up to *only 9 spectroscopically confirmed CVs in just 4 GCs* (Table 1).

So what is the silver standard? Usually, it is confirmation by multiple methods. For example, an object exhibiting a 3-magnitude outburst that is also an X-ray source and abnormally blue in the optical is pretty much guaranteed to be a DN-type CV. In practice, part of such confirmations can come almost for free. For example, Cohn et al. (2010) use $H\alpha$ imaging with HST to confirm Chandra X-ray sources in NGC 6397 as CVs. But since broad-band exposures are much shorter than $H\alpha$, they can be obtained at essentially no extra cost. Moreover, the $H\alpha$ imaging can be split into short sub-exposures, allowing a search for short time-scale variability (e.g. flickering). Thus Cohn et al. (2010) are able to confirm X-ray CV candidates very effectively through a combination of $H\alpha$ excess, blue colours and variability.

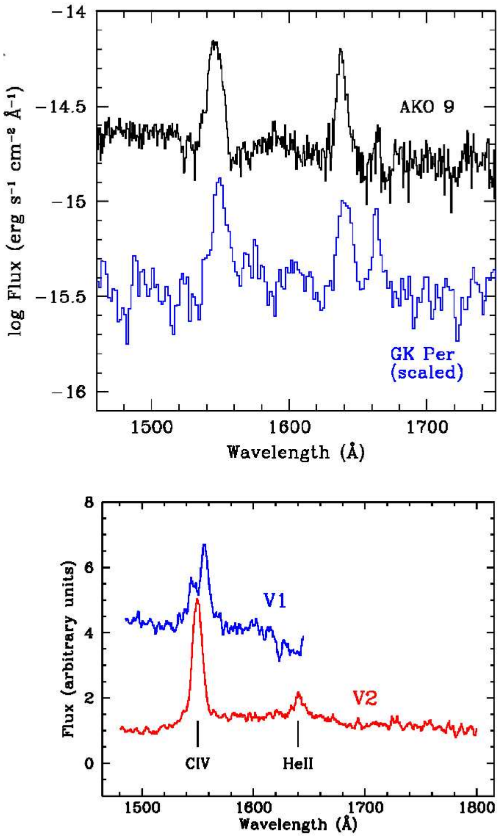

Fig. 4. FUV spectra for 3 CVs extracted from the 2-D spectral image in the right panel of Figure 2. The top panel shows the spectrum of the brightest source (AKO 9), compared to a scaled version of the long-period field CV GK Per. The bottom panel shows the other two objects highlighted with arrows in Figure 2. All three CVs clearly show emission associated with C IV 1550 Å; AKO 9 and V2 additionally display He II 1640 Å. The top panel is reproduced from Knigge et al. (2003).

Similar studies – though not usually based on the same combination of methods – have been carried out in a few GCs. Among these, that by Edmonds et al. (2003ab) deserves particular comment, since it also yielded orbital periods for several X-ray-detected CVs in 47 Tuc (see Section 5.1). However, there is a significant downside to the use of all of these different methods for confirming CVs: it leaves us with an overall sample of CVs that suffers

Table 1. Spectroscopically confirmed GC CVs

Cluster	Object	Method	Location	Reference
NGC 6397	CV 1	HST, opt	core	(1)
NGC 6397	CV 2	HST, opt	core	(1)
NGC 6397	CV 3	HST, opt	core	(1)
NGC 6397	CV 4	HST, opt	core	(2)
NGC 6624	CV	HST, FUV	core	(3)
47 Tuc	AKO 9	HST, FUV, slitless	core	(4)
47 Tuc	V1	HST, FUV, slitless	core	(5)
47 Tuc	V2	HST, FUV, slitless	core	(5)
M 5	V101	ground-based, opt	outskirts	(6)

References: (1) Grindlay et al. 1995; (2) Edmonds et al. 1999; (3) Deutsch et al. 1999; (4) Knigge et al.(2003); (5) Knigge et al. 2008; (6) Margon, Downes & Gunn 1981

from strong, multiple and ill-defined selection effects.

5. Population properties

Having discussed how CVs in GCs are found and confirmed, let us now consider what we have learned about their global properties. We need to be clear from the outset, however, that the statistical properties of observational CV samples in GCs are severely distorted by the selection biases we have just discussed.

5.1. Orbital periods

The orbital period distribution of CVs has arguably been the most powerful observational tool for studying CV formation and evolution in the Galactic field. The famous "period gap" – the dearth of CVs with 2hr $\lesssim P_{orb} \lesssim$ 3hr – as well as the existence of a minimum period $P_{min} \simeq$ 80min have been the key properties that led to the development of the "standard model" for CV evolution. In this model, magnetic braking moves CVs from long to short P_{orb} above the period gap, while gravitational radiation drives the evolution below the gap (see Knigge, Baraffe & Patterson 2011 for a comprehensive overview of CV evolution).

Unfortunately, orbital periods are known for only 15 CVs in 6 GCs (see Table 2). Nine of these CVs are located in 47 Tuc, mostly due to the excellent work by Edmonds et al. (2003ab). Such a small and biased sample is not particularly well suited to statistical analyses, but let us throw caution to the wind and compare the P_{orb} distribution of CVs in GCs to that observed in the Galactic field (Figure 5.1). This comparison reveals that the existing GC CV sample shows no sign of the period gap, and indeed only 2 GC CVs ($\simeq$ 13% of the sample) have short periods below the gap. Both of these properties stand in stark contrast to the field population.

The obvious and naive interpretation of this comparison is that the properties of GC CVs are fundamentally different from those of CVs in the Galactic field. This is entirely plausible, given that most GC CVs are expected to have been produced or affected by dynamical encounters (see Section 2). Indeed, some theoretically predicted period distributions for GC CVs look superficially quite similar to the observed distributions (Shara & Hurley 2006; Ivanova et al. 2006; but note that in both cases, the predicted distributions are still affected by technical/computational issues).

All of this sounds quite promising, but we should remember a hard lesson learned from field CVs. Here, we have known for a long time that predicted and observed period distributions tend to disagree quite badly. For example, theoretical binary population synthesis models predict that a full $\simeq$ 99% of Galactic CVs in the field should be short-period systems below the gap (e.g. Kolb 1993) and that

Table 2. GC CVs with Orbital Periods

Cluster	Object	P_{orb} (hr)	Type	Method	References	Comments
47 Tuc	AKO 9	26.6	DN	Ecl,Opt	1,2,3	similar to GK Per
47 Tuc	V3,W27?	4.7	polar?	Var,X-ray	4,5	qLMXB?
47 Tuc	W1	5.8		Var,Opt	6,7	$P_{orb} = 5.8/2$ hr?
47 Tuc	W2	6.3		Var,Opt	6,7	no opt signal
47 Tuc	W8	2.9		Ecl,Opt	6,7	
47 Tuc	W15	4.2		Ecl,Opt	6,7	
47 Tuc	W21	1.7		Var,Opt	6,7	
47 Tuc	W71?	2.4		Var,Opt	6,7	really a CV?
47 Tuc	W120	5.3?		Var,Opt	6,7	
NGC 6397	CV1	11.3		Ecl,Opt	8,9	
NGC 6397	CV6	5.6		Ecl,Opt	8,9	
M 5	V101	5.8	DN	RV,Opt	10	
NGC 6752	V1	5.1		Var,Opt	11	
NGC 6752	V2	3.7?		Var,Opt	11	
M 22	CV 2	2.1	DN	SH,Opt	12	P_{orb} est. from superhumps

References: (1) Edmonds et al. 1996; (2) Albrow et al. 2001; (3) Knigge et al. 2003; (4) Shara et al. 1996; (5) Heinke et al. 2005; (6) Edmonds et al. 2003a; (7) Edmonds et al. 2003b; (8) Kaluzny & Thompson 2003; (9) Kaluzny et al. 2006; (10) Neill et al. 2002; (11) Bailyn et al. 1996; (12) Pietrukowicz et al. 2005.
Notation for method is var = photometric variability; ecl = eclipses; RV = radial velocity; SH = superhumps

there should be a pile-up of systems at the minimum period (e.g. Kolb & Baraffe 1999). Until recently, neither of these predictions appeared to be consistent with the properties of observed samples, and there was much debate about whether this meant that the models were wrong or whether the apparent disagreements were all caused by selection effects. This debate is still not fully settled, but what *has* become quite clear is that selection effects are extremely important and must be accounted for in any meaningful comparison of theory and observation (e.g. Pretorius, Knigge & Kolb 2007). In fact, the period spike at P_{min} appears to have been discovered now, thanks entirely to the construction of a CV sample that is deep enough to actually detect these very faint CVs in significant numbers (Gänsicke et al. 2009).

With this cautionary tale in mind, I believe it is too early to draw dramatic conclusions from plots like Figure 5.1. What is clear though is that we desperately need a much larger, and ideally more cleanly selected, sample of GC CVs with orbital periods.

5.2. Scaling with collision rate: do dynamics matter?

There is another way to test if dynamical effects are producing many or most CVs in GCs, which does not require any binary parameter determinations for individual CVs at all. The idea is simple: if most CVs are formed dynamically, then their number in a given cluster should scale with the rate at which dynamical encounters take place in that cluster. This so-called "collision rate" or "encounter frequency" is a function only of cluster (or, rather, cluster core) parameters. The existence of such a scaling for LMXBs in GCs was conclusively established by Pooley et al. (2003), confirming earlier work dating back to at least Verbunt & Hut (1987).

Figure 5.2, from Pooley & Hut (2006), shows how both LMXB and CV numbers in GCs scale with collision rate. Actually, what we have called "CVs" and "LMXBs" here are really X-ray sources with $L_x > 4 \times 10^{31}$erg s^{-1}, divided into these two categories on the basis of an empirical cut in the X-ray colour-

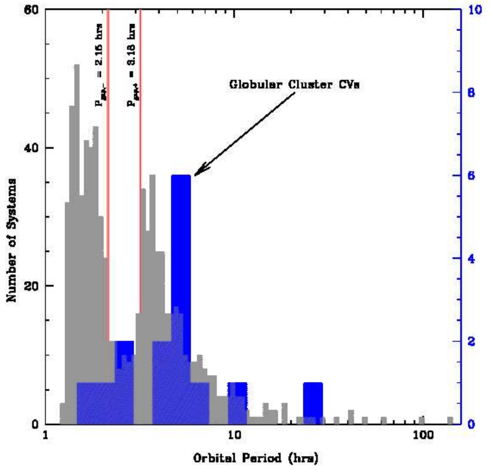

Fig. 5. The observed period distributions of field and GC CVs. The grey histogram shows the distribution for field CVs from a recent edition of the Ritter & Kolb (2003) catalogue. The blue histogram is the (sparse) GC period distribution collated from the literature. The location of the period gap as determined by Knigge (2006) is indicated by the vertical lines.

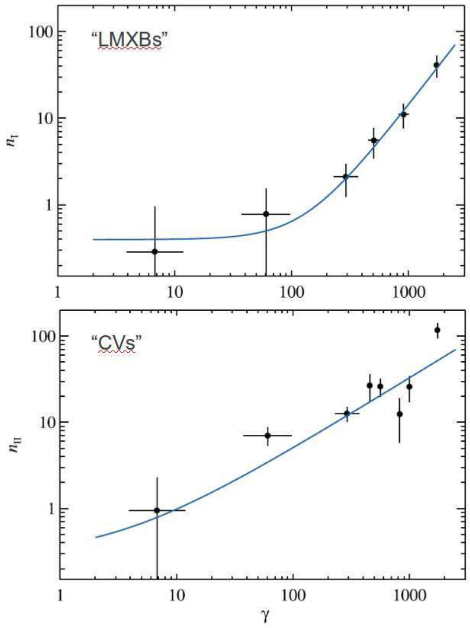

Fig. 6. The specific number of probable LMXBs (top panel) and CVs (bottom panel) in GCs as a function of the specific stellar encounter rate in the cluster. The data were binned for plotting. In both cases, there is a clear correlation, which strongly suggests that both of these compact binary populations are dominated by dynamically formed systems in most GCs. Figure reproduced by permission from Pooley & Hut (2006).

magnitude diagram, but Pooley & Hut (2006) argue convincingly that these populations will be dominated by CVs and LMXBs, respectively. Moreover, the quantities actually plotted in Figure 5.2 the *specific* number of objects (i.e. CVs/LMXBs per $10^6 M_{\odot}$) against the *specific* encounter rate (a measure of the rate at which an individual star undergoes encounters). Ordinary stellar populations should trace a straight line across such a plot, while entirely dynamically-formed ones might be expected to follow a straight line with slope unity (but note that the plots are logarithmic and also that this prediction ignores subtleties like that non-constancy of the collision rate in a given cluster). Figure 5.2 clearly shows that there is a scaling of CV numbers with encounter frequency, which strongly supports the idea that most CVs in GCs are indeed dynamically formed.

5.3. X-ray and optical properties

An in-depth study of the X-ray and optical properties of GC CVs was carried out by Edmonds et al. (2003ab), who specifically looked at the X-ray selected CV sample in 47 Tuc. One key set of tests they performed was to compare the 47 Tuc CVs to a sample of X-ray-detected field CVs (taken from Verbunt et al. 1997) in terms of the optical magnitudes, X-ray luminosity and X-ray-to-optical ratio. Their maindings were as follows: (i) optically, GC CVs are rather faint and most similar to dwarf novae; (ii) however, their X-ray luminosities are higher than those of non-magnetic field CVs, and most resemble those of intermediate polars (IPs); (iii) unsurprisingly then, their X-ray-to-optical ratios are abnormally high and not really consistent with any field CV sub-population. So does this mean that most GC CVs are somehow physically different from most field CVs? Perhaps. Edmonds at al (2003ab) themselves suggest that their findings may point to GC CVs being peferentially magnetic, low-$\dot{M}_{acc}$ systems. However, we should treat such comparisons of field and GC CV samples with a great deal of caution, since selection effects could easily lead to misjudgments. For example, the GC CV sample studied by Edmonds et al. (2003ab) was entirely X-ray selected (which would always favour the detection of magnetic CVs). Moreover, their field CV sample is a set of objects detected by ROSAT that were *known to be CVs before ROSAT was launched and had known orbital periods* (Verbunt et al. 1997). As such, they form a totally heterogenous sample selected via multiple methods. It would be interesting and worthwhile to repeat the field vs GC CV comparison with an X-ray-selected field CV sample. My own feeling is that the high X-ray-to-optical ratio of the 47 Tuc CV sample is an important clue, but that it is far from clear what it points to.

5.4. Are most GC CVs magnetic?

As noted above, Edmonds et al. (2003ab) argued that the properties of the X-ray-selected CV sample in the famous GC 47 Tuc pointed towards a pre-dominance of magnetic CVs in GCs. This idea actually goes back to at least Grindlay et al. (1995), who obtained spectra of 3 CVs in NGC 6397 with HST (see Section 4 and Table 1) and noted the existence of He II emission in all of them. This line points to the presence of a strong EUV source and is commonly – but by no means exclusively – seen in magnetic CVs, where the polar accretion caps on the WD provide such a source. However, non-magnetic nova-like CVs, in particular, also often show this features.

On its own, the presence of He II lines in a few GC CVs is of course rather weak evidence that most GC CVs are magnetic. Nevertheless, this idea has gained considerable traction over the years. The main reason for this is the hope that it may explain some of the apparent abnormalities of the GC CV population, such as the strange X-ray and optical characteristics (Edmonds et al. 2003ab) and the low discovery rate of DNe in GCs (e.g. Shara et al. 1996; Dobrotka, Lasota & Menou 2006; Pietrukowicz et al. 2008 – see Section 3.1).

From a theoretical point of view, a preference for magnetic CVs in GCs seems unlikely at first sight, but there actually is a possible mechanism that could explain this. As first pointed out by Ivanova et al. (2006), magnetic WDs (in the field) tend to be relatively massive (e.g. Vennes 1999), and since the cross-section for dynamical encounters scales with mass in GCs, this might make magnetic WDs more likely to form CVs dynamically.

So should we accept that GC CVs are preferentially magnetic? Once again, the evidence needs to be evaluated with considerable caution. As discussed in Section 5.3, the X-ray and optical properties of the 47 Tuc CVs do *not* point cleanly to a sample dominated by magnetic systems. In fact, the only property that seemed to match well to that of field CVs (subject to the usual caveats regarding selection effects), was the X-ray luminosity distribution. More recently, Heinke et al. (2008) have shown that the global X-ray *spectral* properties of GC CVs are best matched if the proportion of magnetic CVs is "only" $\simeq 40\%$. This number is still larger than the fraction of magnetic CVs among all known field CVs, which is $\simeq 10\% - 20\%$ (Ritter & Kolb 2003; Downes et al. 2005). However, as already noted by Heinke et al. (2008), one needs to keep in mind that the GC CV sample is X-ray selected, which would favour the detection of magnetic systems (since these are known to be X-ray bright). In fact, a full 64% (29/45) of the CVs found in the Rosat Bright Survey (Schwope et al. 2002; also see Pretorius & Knigge 2011) are magnetic, although this comparison is also unfair, since that survey is flux-limited and not particularly deep (so the volume sampled for X-ray bright magnetic CVs is much larger than that for non-magnetic systems). X-ray surveys of GC that go deep enough to detect *all* non-magnetic CVs would, of course, be unbiased, but few, if any, of these have been carried out.

This still leaves the apparent dearth of DN outbursts in GCs as a possible piece of circumstantial evidence in favour of magnetically-dominated CV population in GCs, so let us take a closer look at this.

5.5. Are DNe abnormally rare in GCs?

As already noted in Section 3.1, both Shara et al. (1996) and Pietrukowicz et al. (2008) concluded that DNe are rarer than expected in GCs if (a) there are really hundreds of CVs in GCs, and (b) cluster DNe have similar properties to known field DNe.

Obviously, what is actually observed these multi-epoch surveys is a particular number of eruptions over a certain time scale. However, in order to interpret these observations, we need to know the completeness of the survey, i.e. the fraction of DNe it is expected to have recovered. Both Shara et al. (1996) and Pietrukowicz et al. (2008) took pains to estimate this via Monte Carlo simulations, using well-known field DNe light curves as templates.

The single most important light curve parameter for determining the completeness of such a survey is the characteristic duty cycle, f_{on}, of DNe, i.e. the fraction of time that a typical DN spends in outburst. Specifically, the completeness of a DN survey that consists of N independent epochs is $\epsilon = 1 - (1 - f_{on})^N$ This is a key point. Both Shara et al. (1996) and Pietrukowicz et al. (2008) based their efficiency estimates on the properties of well-known field DNe. But *that* sample is extremely unlikely to be representative of the underlying CV population even in the Galactic field. More specifically, these systems were probably discovered and well-observed precisely because they are bright, *frequently erupting* long-period systems, i.e. because they have a high duty cycle.

The duty cycles of the DNe templates used by Shara et al. (1996) range from roughly 15% to over 95% with an average of about 50%, while the two control DNe used by Pietrukiwicz et al. (2008) spend roughly 10% and 30% of their lives in eruption. Shara et al. (1996) also presented an analytic efficiency estimate based on an assumed duty cycle of 15%. Given these numbers, let us take $\simeq$ 20% as a rough estimate of the characteristic DN duty cycle assumed in both studies.

How does this number compare to the duty cycle of the most common DNe among the intrinsic CV population. As already noted above, theory predicts that the vast majority of CVs should be short-period systems, and indeed most of them should be ultra-faint CVs at or near the minimum period. (Note that only 5 of the 21 DNe on which the Shara et al. templates were built are short-period systems, and neither of the two control DNe used by Pietrukiwicz et al. are.) These faint, short-period systems are almost certainly still massively under-represented in the known field CV sample, so their characteristic properties are necessarily uncertain.

The best-known example of such a system is probably WZ Sge, so let us take a look at its duty cycle. WZ Sge erupts as a DN roughly once every 30 years, and its main eruption lasts about 1-2 months (Patterson et al. 2002). This amounts to a duty cycle of about 0.4%! If such CVs were to dominate the CV population in GCs, the completeness of existing GC DNe surveys has been seriously overestimated. For the case of N = 3 (the number of epochs covering the full core in Shara et al. 1996), a change from $f_{on} = 0.2$ to $f_{on} = 0.04$ reduces the completeness by a factor of 40.[1] So even if $\sim$ 150 WZ Sge-like CVs were to lurk in the core region of 47 Tuc, only about 2 should have been detected. Indeed, Shara et al. actually detected two DNe in their survey (V2 and V3), although neither is likely to be a WZ Sge-like object. But even the Poisson probability of seeing zero systems when just under 2 are expected is a healthy 15%.

[1] I should note explicitly here that both Shara et al. (1996) and Pietrukowicz et al. (2008) fully acknowledge the low completeness of their surveys for WZ Sge-like systems. What I am stressing here is that such systems might be *expected* to be the dominant CV population.

All of this may be overly pessimistic (or optimistic, depending on one's viewpoint). And the completeness of the survey by Pietrukowicz et al. (2008) for at least some clusters is higher than that of Shara et al. (1996) for 47 Tuc. But it is difficult to be sure. The problem is that we simply do not know the intrinsic outburst properties properties of even the *field* CV/DNe population well enough. What is needed is a survey for DNe in GCs that *guarantees* the detection of at least a few WZ-Sge-like systems, if they exist in large numbers in GCs. This is difficult, but not impossible.

6. Conclusions

I hope to have shown that GC CVs should be of great interest to anybody studying the dynamical evolution of clusters, the binary evolution of CVs or the SN Ia progenitor problem. I also hope I have made it clear that great strides have been taken in recent years in finding and understanding GC CV populations, thanks mainly to the availability of Chandra and HST. Indeed, we are finally discovering significant numbers of CVs in any given massive GC, though still not the hundreds that are theoretically predicted to lurk there. I have also discussed the theoretical and observational hints that field and GC CV populations may differ systematically, although I feel that the jury is still out regarding most of these putative differences.

The next big advances in the field are likely to come from one or both of the following directions. First, if we really wish to test for the presence of the predicted hundreds of CVs per cluster, we have to be sensitive to *faint* CVs. How deep? Ideally, deep enough to discover systems like WZ Sge, at $M_V \sim 13$ in quiescence. This is hard – it requires reaching $m_v \sim 27$ or so. But it is not impossible: Cohn et al. (2010) have essentially done this in NGC 6397 and uncovered two likely WZ-Sge-like CVs, the first such systems in any GC. An interesting short-cut might be to place limits on the number of faint CVs in GCs by considering the *integrated* X-ray luminosity of individually undetected systems (e.g. Haggard, Cool & Davies 2009). Second, we need to obtain orbital periods for a significant sample of GC CVs, so that we can start to make meaningful comparison to theoretically predicted period distributions.

7. Postscript: three topics missing from this review...

There are three topics that I really wanted to cover on in this review, but then I simply ran out of time and space. In the few lines I have left here, let me at least mention them. First, *novae* might both clear (Moore & Bildsten 2011) and enrich (Maccarone & Zurek 2011) GCs; the latter might be key for the multiple stellar populations recently found in some GCs. At least one GC nova has been recovered (Dieball et al. 2010). Second, many *AM CVns* should exist in GCs (Ivanova et al. 2006), yet not a single one is known. Third, *symbiotic stars* in GCs also remain to be found – but we may just have discovered the first one (Zurek et al., in prep.).

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