Master ASEP
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MUSE integral field unit observations of the compact objects in the globular cluster NGC 6397

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Abstract

Globular clusters are very old groups of stars. Due to their age and the gravitational interactions dominating the dynamics of the clusters, they are home to a significant fraction of compact binaries. The formation and evolution of these kinds of binaries is still not completely understood. Of special interest is the globular cluster NGC 6397 as it is the closest core collapsed cluster and has therefore been extensively studied with instruments like Chandra, Hubble Space Telescope, and more recently in the optical with the Multi Unit Spectroscopic Explorer (MUSE), installed on the Very Large Telescope (VLT). Integral field spectrographs, like MUSE, have many advantages compared to traditional long slit spectroscopy, as spectra are obtained for every pixel and thus every object in the large field of view ($1'$ x $1'$). Here we present analysis of the compact binary population in NGC 6397 taken with MUSE. The goal is to further understand the characteristics of the proposed bimodal population of cataclysmic variables in the cluster, which have been suggested to be of primordial and dynamically formed origin. Spectral analysis will allow us to examine the origin of these two populations.

Contents

Chapter 1: Introduction

1.1 Location, Location, Location

Important in real estate, but also seems to be an important factor to take into account when studying compact objects in binary systems. It seems that, like with people, where you were born plays a role on your and evolution. This seems to be true for cataclysmic variables (CVs), the kind of compact binary system that we will explore in more detail in the present work. Our goal is to try to understand the formation of these kind of systems when they are formed in a crowded and high density environment (like in a cluster of stars), and when you give them enough time to evolve and interact with other stars (like in a globular cluster).

Now that we have defined our broad goal let's take a step back and explore in more detail what are compact objects, their different types, and the different ways they can interact with each other and other types of stars (Sec. 1.2). That section will lead us to the discussion of where and how we expect to find them, and what can we learn by studying them in the different environment where they form (sections 1.4).

1.2 Compact Objects or Stellar remnants

Compact object, as their name suggest, are very massive and dense objects formed from the remains of a dying stars; hence their other name, 'stellar remnants'. They come in three main flavors, each following a different formation mechanism that is mainly determined by the mass of the progenitor star (ref.). The different types are neutron stars (NS), black holes (BH), and white dwarfs (WD). Besides these three, other possible exotic types of stars have been proposed; including quark stars, boson stars, and Thorne-Zytkow objects. These will not be discussed in this work as there is still a lack of observational evidence concerning their existence. The reader is refer to the following references to discover more about these particular kind of proposed stars. (Find references for exotic stars).

On the three confirmed compact objects (neutron stars, white dwarfs and black holes), we will focus on the first two (NS and WD). They below to a class of object called "degenerate objects". These are object for which the supporting force comes from the degeneracy pressure of fermions[1]. In the case of a white dwarf the pressure is provided by the degenerate electron gas (Fowler, 1926), and for a neutron stars, clearly, the neutrons cause the repulsive pressure (ref).

The next subsection will list some of the characteristic for NS, and WD (both when they are found in isolation (sec 1.2.1 and 1.2.2) or in a binary system sec 1.3). Black holes will be briefly discussed for the sake of completeness.

1.2.1 White Dwarfs

White dwarfs are the most common end product in the evolution of stars. Around 90% will evolve to become one (Koester & Weidermann, 1980). This includes all main sequence stars [2] (MS) with a

[1]Fermions are particles with half-integer spin. They follow the Fermi-Dirac statistics, thus obey the Pauli exclusion principle. The consequence of the exclusion principle is that two fermions cannot occupy the same quantum state. This is the origin of the degeneracy pressure.

[2]Main sequence stars are those that are burning hydrogen in their cores.

mass between 0.6 and 8 $M_\odot$ (Koester & Chanmugam, 1990). The resulting white dwarf will have a mass between 0.3 and 1.4 $M_\odot$ (Prada Moroni & Straniero, 2009; Chandrasekhar, 1931), the average mass being ~ 0.7 $M_\odot$ (Koester & Chanmugam, 1990). All this mass is contained in a radius of about ~ 0.01 $R_\odot$ (Kepler & Bradley, 1995). These values give a mean density of 10^9 kg/m^3 . Fig 1.2 shows the mass-radius relation of compact objects. This relation will be composition dependent and will depend, for example, on the atmosphere dominating element (Hamada & Salpeter, 1961). About 80% of all white dwarfs have hydrogen-dominated atmospheres (spectral type DA), but there exists a second class where helium dominates the atmosphere composition (spectral types D0, DB, DC, DZ and DQ)(Wickramasinghe & Ferrario, 2000; Koester & Chanmugam, 1990). White dwarfs are also known to be magnetic. Surface magnetism ranges from about 10^5 to 10^9 G (Suh & Mathews, 2000). Isolated magnetic whit dwarfs represent $\sim 5\%$ of all WDs. See Wickramasinghe & Ferrario (2000) for a review on magnetism in WDs and for more details on the physics of white dwarfs the reader is referred to Koester & Chanmugam (1990) and Kepler & Bradley (1995).

1.2.2 Neutron Stars

Neutron stars, first proposed in 1934 by Baade and Zwicky, are stars where the sustaining force against gravity comes from the degeneracy pressure between neutrons (Baade & Zwicky, 1934). These stars are produced from the gravitational collapse of a massive star (> 8 $M_\odot$)(ref for mass range) at the end of its life. The type II supernova produced by this collapse, leaves behind a dense and massive core. A core of ~ 12 kilometers in radius (ref), but up to ~ 2 $M_\odot$ (this limit being model dependent. See Lattimer & Prakash (2007). For comparison with white dwarf a sample mass-radius relation for a NS (red) is plotted along with that of a white dwarf (blue) in fig 1.2. Like WDs, neutron stars are also know to show magnetism. They have an average magnetic field strength of $< B > \sim 10^{14}$ G (Beskin et al., 2015). There also exist some neutron stars with unusually high strong magnetic fields (B $\sim 10^{14} - 10^{15}$ G) and are called "magnetars" (Duncan & Thompson, 1992). For a review on magnetic fields in neutron stars see Reisenegger (2005).

Neutron stars are mainly composed of neutrons and a thin atmosphere of a few cm of hydrogen or helium (ref for NS atmosphere models). We have come a long way since the first proposition of their existence, but there is still a lot of uncertainty concerning their interiors and a lot of existing conflicting models (Lattimer & Prakash, 2007). Since we have had observational evidence on their existence (ref PSR B1919+21) efforts have been done to constrain the different models. Figure 1.1 shows a visual summary of some of the different models proposed. There are many ways that we can observationally constrain these models, spectroscopy being one of them.

1.2.3 Black Holes

Black holes are the fate of collapsing matter when no force, including the degeneracy pressure of neutrons, is not enough to repel gravitational attraction. Black holes, like neutron stars and white dwarfs, can be the result of the collapse of a single main sequence star. Stars with an initial mass $\gtrsim 20$ can end up as a black hole (Heger et al., 2003), but the initial mass is not the only factor that comes into play. For example, the formation of the black hole will depend also on the metallicity of the star as well as the initial mass. See Heger et al. (2003) and (Brown et al., 2000) for details on the evolution of high mass stars and the different formation path leading to a black hole from a single collapse star.

To compare the physical characteristic of a black hole to other compact objects we can define the gravitational radius or Schwarzschild radius of a black hole. This is the radius to which a given mass

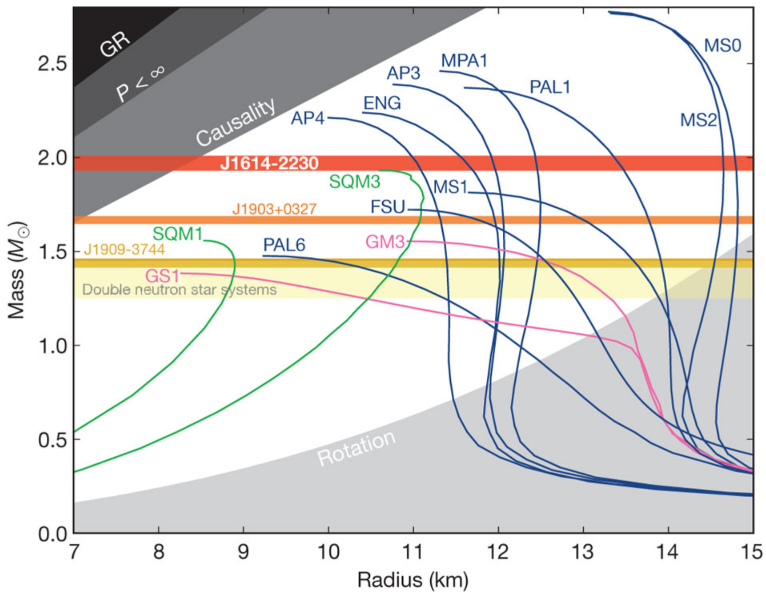

Figure 1.1: The plot shows non-rotating mass versus physical radius for several typical equation of states. Blue, nucleons; pink, nucleons plus exotic matter; green, strange quark matter from (doi:10.1038/nature09466)

needs to be reduced to get a escape velocity equal to the speed of light. This translates to:

$$r = \frac{2MG}{c^2} \tag{1.1}$$

The maximum possible mass for a neutron star is $\sim 3\mathrm{M}_\odot$ (Rhoades & Ruffini, 1974). Above this mass we expect to find black holes. A mass of 3 $\mathrm{M}_\odot$ gives an equivalent Schwarzschild radius of about 9 km.

1.3 Compact Binaries

Compact binaries are those binaries where at least one of their components is a compact objects (WD, NS or BH). In this section we will start by discussing some of the basic concepts of binary evolution, follow by a discussion on mass exchange between binaries, and finished by looking in more detail some specific examples of compact binaries that are relevant to this study.

1.3.1 The Gravitational Potential

The total potential of a binary system is the sum of the gravitational and the rotational potential. To get an analytical solution we can assume a model in which the resulting disturbing potential is due to the presence of two point masses, M_1 (or the primary) and M_2 (also called the secondary). Moreover, we assume a co-rotating Cartesian reference frame (x,y,z) with origin at the primary M_1; whose x-axis is is in the direction joining the two point masses; and the z-axis is perpendicular to the orbital plane. The total potential at an arbitrary point P(x,y,z) then reads:

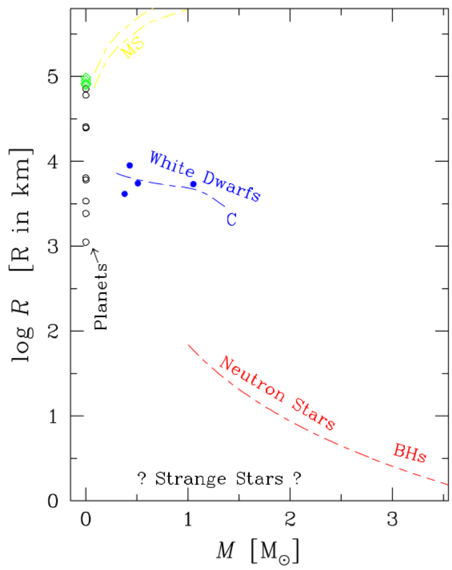

Figure 1.2: Mass-radius relation for different objects (de Boer & Seggewiss, 2008).

$$\Psi = -G\frac{\mathrm{M}_1}{\sqrt{x^2+y^2+z^2}} - G\frac{\mathrm{M}_2}{\sqrt{(R-x)^2+y^2+z^2}} - \frac{\omega^2}{2}\left[(x-\mu R)^2+y^2\right] \tag{1.2}$$

where G is the gravitational constant, R represents the separation between the point masses, and $\mu = \mathrm{M}_2/(\mathrm{M}_1+\mathrm{M}_2)$. We further assume that the binary orbit is Keplerian, thus the orbital frequency is given by:

$$\omega^2 = G\frac{\mathrm{M}_1+\mathrm{M}_2}{R^3} \tag{1.3}$$

Taking into the account the assumptions the surfaces generated by eq 1.2 are called *Roche Equipotential*[3]. Fig 1.4 such such equipotential surfaces (x,y plane). Of special interest are two regions on the graph:

- The inner Lagrangian point $\mathbf{L}_1$. This is where all the forces cancel out.
- Critical or **Roche lobe**. The surface that have the potential equal to the L_1 potential.

The Roche lobe has the property that inside the lobe of an object, any material will be gravitationally bound to that object. With these knowldege we can classify binary systems in three groups:

1. **Detached systems**. If the volumes of both components are significantly smaller than their Roche lobe.
2. **Semi-detached systems**. Where one of the components fills its Roche lobe.
3. **Contact systems**. Where both components appear to fill their respective Roche lobes.

[3]We are neglecting here the radiation pressure from the stars. For more details on Roche Potentials Including Radiation Effects see Schuerman (1972)

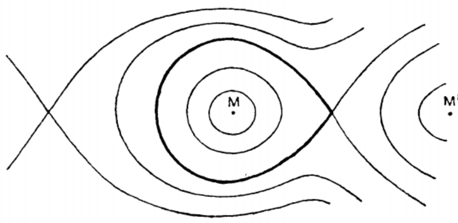

Figure 1.3: Geometry of the Roche surfaces. The Roche lobe is mark in bold font (Kopal, 1959).

This classification scheme was first suggested by (Kopal, 1955) and developed in detail in a comprehensive monograph in 1959 (Kopal, 1959).

1.3.2 Binary Evolution

In this work we are mostly interested in the formation of semi-detached compact binary systems. In this section we briefly explore a possible scenario for its formation.

These kind of systems can be formed from two previously detached MS stars binaries that evolve in different timescales due to their different mass. This can be seen noticing that the luminosity, L, indicates the rate of consumption of nuclear fuel; and the nuclear fuel repository is proportional to the mass, M. This gives us a rough estimates of the nuclear timescale of a star given by:

$$\tau \propto \frac{M 6\times 10^{18}\text{ergs g}^{-1}}{L} \tag{1.4}$$

Where L is the luminosity, M is the mass, and 6×10^{18}ergs g^{-1} is the energy release fusing a gram of hydrogen to helium. Moreover, with the mass-luminosity relation $\mathrm{L}/\mathrm{L}_\odot = (M/\mathrm{M}_\odot)^\alpha$, where $\alpha \gtrsim 3$ (ref. missing), we can conclude that in a system starting with two detached main sequence stars, the more massive one will leave faster the main sequence and finished as a compact object (depending on its mass). This will leave a binary system with a compact object and a evolved main sequence star. The old main sequence star in the binary as it continues evolves will expand and fill its Roche lobe, allowing for accretion into the compact object to happen. The process is, of course, more complex and depend on the initial mass of both stars and initial binary separation. For example, a binary system starting with a 2 $\mathrm{M}_\odot$ and a 1 $\mathrm{M}_\odot$ star will produce a white dwarf accreating from a late-type main sequence star (Kippenhahn et al., 1967; De Loore & Doom, 1992). A system starting with a 15 $\mathrm{M}_\odot$ and 2 $\mathrm{M}_\odot$ will become a neutron star accreting from a low mass main sequence star (Heuvel & J, 1976). In the case of starting masses of 20 $M_\odot$ + 8 $M_\odot$ this can produce a neutron star (or black hole) accreting from a high mass main sequence star (Heuvel & J, 1976). The details on the evolution of close binaries can be found in Postnov & Yungelson (2014).and (de Boer & Seggewiss, 2008)

In the next section we will see in some detail how the accretion can take place once the compact binary is formed due to stellar evolution of their constituents.

1.3.3 Accretion

As mentioned before if one of the binaries fills its Roche lobe, material can flow via the L_1 point to the other star. This is what constitutes a semi-detached binary system. It would be a semi-detached compact binary if at least one is a compact object. Here we look in more detail the nature of the accretion in such a system where a compact object (primary) accreates from a main sequence star via Roche lobe overflow.

In the Roche overflow scenario we have incoming gas from the secondary star. After it passes thought the L_1 point we assume a ballistic behaviour completely governed by the gravitational potential of the compact object. This is justified by the fact showed by (Lubow & Shu, 1975) that the stream is supersonic and we can ignore pressure. We can also assume that the incoming speed must be small. This is safe to assume if the accretion is due solely to overflow of the lobe and thus the velocity is in the order of the sound speed at the atmosphere of the secondary star. This speed ($\sim$ 10km/s reference missin) is much slower than the orbital speed of the binaries, and lower than the velocities acquire during the fall. This simplification means that we can treat the Roche lobe as a zero velocity surface. Meaning that the motion of the gas can be approximated as the trajectory of a test particle release from rest with an initial angular momentum from L_1. This creates an elliptical orbit of the stream around the primary star (fig 1.4 a). As the gas flow continues it will impact itself. This causes the flow to modify its orbit to that of the lowest energy at an specific angular momentum (we assume angular momentum is conserve). Of course the orbit of lowest energy at a given angular momentum is a circular one (see fig 1.4 b). We can estimate the radius of this orbit by again invoking the assumption that no angular momentum is loss. The angular momentum at L_1 would be given by R_{L1} V_{orbit} (where R_{L1} is the distance from the secondary to L_1). Knowing that $\omega = (2\pi)$/Period and equating the angular momentum at L_1 to the angular momentum of a Keplerian orbit at R_{ring} we get:

$$\frac{R_{ring}}{R} = \left(\frac{\mathrm{R}_{L1}}{R}\right)^{\frac{1}{4}} (1+q) \tag{1.5}$$

where I used eq 1.3 to simply the answer by canceling some constants. This is called the *circulation radius*. After a ring is formed (fig 1.4 b), as first indicated in Lynden-Bell & Pringle (1974), any viscous processes will cause the ring to spreads to conserve angular momentum (fig 1.4 d) The nature of these viscous torque won't be discussed here. For a review on the topic see Frank et al. (2002) and Verbunt (1982). It is only left to say that Roche lobe overflow is not the only type of accretion, for example wind accretion. In this work, unless otherwise stated, accretion will mean accretion by Roche lobe overflow. See the references cited above for more detail on other type of accretion.

Now that we studied briefly accretion and see how it can happen in semi-attached binaries, in the next section we will discuss two specific examples of this happening. One where the accretion is onto a white dwarf (Cataclysmic Variable), and the other where the accretion is onto a neutron star or a black hole (X-Ray binaries).

1.3.4 Cataclysmic Variables (CVs)

Cataclysmic variables are semi-detached binary system comprised of a white dwarf (primary star) and typically a low mass main sequence star with a typical period in the range of 1-10 hrs (ref for period). CVs are generally classified into two groups. Magnetic CVs and nonmagnetic CVs (B $<$ 0.01 MG). Magnetic CVs constitute about 25% of the CV population (Balman, 2012).

CVs can be observed in many wavelengths. This includes radio observation of jets Körding et al. (2008); Coppejans et al. (2015), optical and UV observation of the accretion disks Kinney (1994), and X-rays ($\sim 0.5 - 2.5keV$) from the infalling plasma onto the white dwarfs (Kuulkers et al., 2006). As their name suggest these are very variable systems (specially the nonmagnetic CVS). These variabilities are due either by instability on the accretion disk, referred to as dwarf nova (Osaki, 1974), or unstable

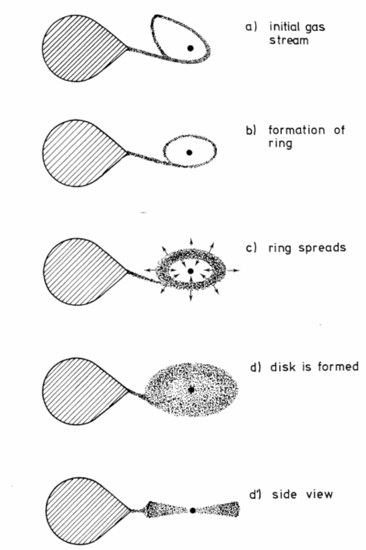

Figure 1.4: Schematic illustration of the formation of an accretion disk around a compact binary (Verbunt, 1982).

burning of hydrogen at their surface, called nova (Starrfield et al., 2016). We will discuss in some detail the outburst caused by these instabilities, and the nature of the magnetic CVs by presenting the classification of CVs and exploring the taxonomy of these objects.

1.3.4.1 Classical Novae (CN)

When the surface of an accreting white dwarf becomes hot enough ($\sim \times 10^8$ K Starrfield et al. (2016)), nuclear fusion can take place and a thermonuclear runaway happens. This creates a violent explosion capable of ejecting material (mean mass of $\sim 2 \times 10^{-4} \mathrm{M}_\odot$) at high velocities ($\sim 10^2 - 10^3$ km s^{-1}) (Gehrz et al., 1998; Shara, 1989). These outburst are fairly easy to detect since they cause a substantial increase in brightness (typically $\sim$ 12 magnitudes Shara (1989)). A CV observed erupting in such a way is classified as a *classical nova (CN)*. Classical novae are seen to erupt only one. If a previously recognized CN erupts again as a CN they are called recurrent novae.

1.3.4.2 Dwarf Novae (DN)

A dwarf nova outburst is caused by instabilities in the accretion disk. This is predicted to happened in non-magnetic CVs with low accretion rates (Osaki, 1974). CVs that show these outbursts are classified as dwarf nova. The outburst from a dwarf nova is not as violent as the one from a classical novae. The magnitude change is only of about 2-5 , and no material is ejected. They also, unlike classical novae, are periodic in nature on times scales of weeks to years depending mainly on the accretion rate (Shara, 1989). Probably the best know example of a dwarf nova is the variable star SS Cygni Cannizzo & Mattei (1998).

1.3.4.3 Novae-like (NL)

Another classification of white dwarfs is the novae-like. They are CVs that seem to have stable accretion, thus not undergoing dwarf novae outburst and having a bright stable disk. They represent the 'non-eruptive' CVs.

1.3.4.4 Polars

Polars are CVs with a strong magnetic field. The value of the magnetic field is usually between 20 MG to 230 MG (Balman, 2012). The field in polars is so strong that it couples to the field of the donor and forces the WD to corotate with the binary. The presence of the strong magnetic field also disrupt the accretion disk. In the case of Polars the accretion flow is redicted so it takes place at the magnetic pole guided by the magnetic field lines. This causes X-ray radiation and strongly polarized cyclotron radiation from IR to UV wavelengths (Cropper, 1990). This polarized emmision is the reason for the name Polars (Krzeminski & Serkowski, 1977). The polarization was the first clue on the magnetic nature of these type of systems. It was first discovered for AM Herculis (AM Her), now the prototype polar CV (Tapia (1977)). Polar systems are often referred to as AM Her-like system. This kind of systems represent 63% of the magnetic CV population (Balman, 2012).

1.3.4.5 Intermediate Polars (IPs)

Intermediate polars are the second kind of magnetic CVs. In this type the magnetic field is weaker ($\sim 1-20MG$). The weaker strength of the magnetic fields means that the accretion disk is not entirely dominated by the magnetic field, and the system is asynchronous, so the WD does not corotate with the binary. This kind of systems represent 37% of the magnetic CV population (Balman, 2012). An extensively studied member of this class is DQ Her. DQ Her is somethings refer as a subclass of IPs (IPs with period $\lesssim$ 120 s), or even as a synonym for IP (Patterson, 1994; Warner, 2003).

Should I include AM CVn?

1.3.5 X-Ray binaries

X-Ray binaries are a subclass of compact binaries where the accretor is either a neutron star or a black hole. They can be classified into two regimes depending on the type of the donor star. If the donor or secondary is a late-type star it is called, Low-mass X-ray binary; if it is an early-type star they are called high-mass X-ray binary.

1.3.5.1 Low-mass X-Ray Binaries

Low-mass x-ray binaries (LXMBs) are Roche-lobe overflow binary stars comped of a neutron star or a black holes accreating from a low-mass ($\lesssim 1.5\mathrm{M}_\odot$) donor. The donor can be a main sequence star or even a white dwarf (Tauris & van den Heuvel, 2006).

In the case of a LMXB, since the accretor (NS or BH) has a higher mass than the white dwarf in a CV, the energy release in the accretion process is higher. This means that we get more powerful X-ray radiation from LMXB (up to $\sim 10\mathrm{k}eV$) (Tauris & van den Heuvel, 2006). The period can range from 11 minutes to 17 days, and like CVs they can show magnetism ($\sim 10^9 \sim 10^{11}$G). (Do I use ibid. or cite again?).

1.3.5.2 High-mass X-Ray Binaries

High-mass X-ray binaries (HMXB) are the second class of X-ray binaries. In the case of an HMXB the donor star is a young early-type main sequence star. This usually means a O or B spectral type with a mass $> 10M_{\odot}$ (Tauris & van den Heuvel, 2006). Contrary to the LMXB the accretion is not entirely due to Roche overflow, it can be due to the high velocity winds produced by the donor star. And also unlike the LMXB this systems tend to show stronger magnetic fields and stronger X-ray radiation (ibid.)

1.3.6 The secondary stars

1.4 Globular Clusters

1.4.1 NGC 6397

1.4.2 CVs in Globular clusters

There are three open questions in this field:

1. **Are all CVs in globlular clusters magnetic**
2. **Where are all the primordial CVs?**
3. **What are the periods of these white dwarfs**
4. **Where are all the dwarf and novae?**

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