

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 ($1' \times 1'$). 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.

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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 formation 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 details 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 and 1.5).

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 different flavors, each following a different formation mechanism that is mainly determined by the mass of the progenitor star (do I need a reference for this?). The different types are neutron stars, black holes, and white dwarfs. 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 lack of physical observational evidence on there existence. The reader is refer to the following references if so inclined to know more about these particular kind of proposed stars. (Find references for exotic stars).

1.2.1 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 supernova produced by this collapse, lefts behind a dense and massive core. A core of a couple of kilometers in radius (exact number?), but sustaining possible up to ~ 2 Solar mas (ref for max observed NS or Oppenhiemr limit). They are mainly composed of neutrons and a thin atmosphere of a few cm of Hydrogen and other heavier elements (ref for NS atmosphere models). We have come a long way since the first proposition of their existence, but there still a lot of uncertainty on their interiors and a lot of existing conflicting models. Since we have had observational evidence on their existence (ref first observational evidence, maybe first pulsar PSR B1919+21?) efforts have been done to constraint the different physical models. Figure 1.1 shows a visual summary of the

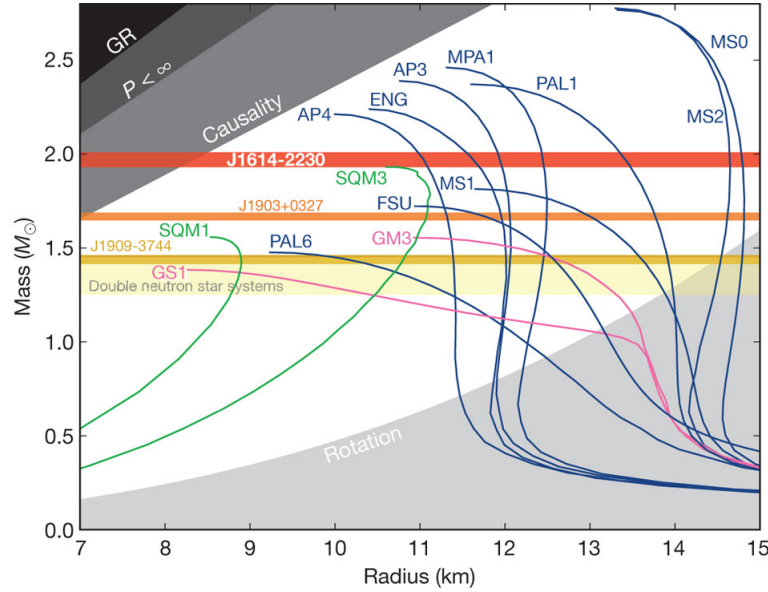


Figure 1.1: The plot shows non-rotating mass versus physical radius for several typical equation of states. Blue, nucleons; pink, nucleons plus exotic matter; green, strange quark matter from (doi:10.1038/nature09466)

different models proposed. There are many ways that we can observationally constraint these models, spectroscopy being one of them. Spectroscopy is still the gold standard for observational astronomy of the electromagnetic spectrum. The advantages of using spectroscopy to study compact objects is discussed later in section 1.5. The focus of that section is on the advantages of spectroscopy for the study of white dwarfs, but the same applies to systems with a neutron star object. The details on the future plans on how to use MUSE data to constraint such models of a neutron stars are left for the future work section (??).

It is important to note that these dense objects are expected to be formed as isolated objects, but are also known to be found in binary system. They can interact with other compact objects and main sequence (MS) stars ¹. The impatience reader can skip to sec 1.3 for more details on the kind of binary systems in which we expect to find a neutron star. We now continue with our discussion of other types of compact object. The next in line being probably the one who gets more attention out of all the compact objects: black holes.

1.2.2 Black Holes

The term was coined by John Wheeler in 1968 (reference for the term), but the idea about an object so massive that don't even light could escape have been around for centuries (Ref. for Laplace 1700s). Like neutron stars they are the fate of really massive stars. In this case even more massive objects were no known force can fight gravitational attraction.

These are fascinating objects and a lot can be said about them. They have been extensively studied and indirectly observed across the electromagnetic spectrum, and most recently with gravitational waves observatories (LIGO ref ?). But we won't discussed them anymore in here. They will be briefly

¹Main sequence stars are those that for millions of years spend their time burning hydrogen at their cores.

mentioned again when discussing the population of compact objects expected to be found in the dense regions of our galaxy halo (globular clusters sec 1.4.2).

Now we pass to the last type of known compact object: white dwarfs. They will be the subject of most of the rest of this report.

1.2.3 White Dwarfs: The poor star's fate

White dwarfs are by far the most common type of compact objects. It is the fate of most main sequence stars when they burn all the available hydrogen in their cores (give percentage and citation ?). This will also be the ending of our own Sun several billions years from now. Something so common, yet so unknown. It is true that thanks to the development of quantum mechanics and multi-wavelength observation of these objects (gravitational waves observation of these objects will have to wait until the eLISA mission (ref. to eLISA?)) we have learned a great deal about them, but still a lot of uncertainty surrounds them. Specially on their formation and evolution when in a binary system. That is the main motivation behind this work. But now lets take a step back and defined precisely what are white dwarfs and briefly discussed what we do know about them.

White dwarfs, like neutron stars, are supported by the degeneracy pressure. In the case of a white dwarfs this pressure is due to the electrons and not the neutrons. But unlike neutron stars the progenitor star (a MS star of $> 8 M_{\odot}$? Ref. Needed) has a more complex history leading to the formation of the compact object. A qualitatively picture of the evolution of the progenitor star as it "moves" around the Hertzsprung-Russell (HR) diagram² is shown in figure 1.2. The field of stellar evolution is an active and complex area of research and the reader is invited to read Koester & Chanmugam (1990) for a more detail review of the physics and evolution of white dwarfs. For now the details of the evolution of the progenitor star of the white dwarf is not so important, but it is a good way to introduce the HR diagram. The HR diagram is an useful tool and the names of the different regions indicated in the HR diagram presented in figure 1.2 is something to bear in mind for the rest of this report.

Continuing our comparison between the different compact objects, it only left to say that white dwarfs are too expected to be found in binary systems. These binary systems formed from a compact object are the topic of the next section.

1.3 Compact Binaries: Nature's "Death Stars"

Here we will explore a small part of the vast compact binary zoo. In doing so we will be studying some of the most powerful events in the universe. These powerful events are the result of the interactions between a massive and extended object (main sequence star e.g. our Sun), an even more massive and dense object (neutron star or white dwarf). These interactions can result in flashes of light capable of competing in brightness with their host galaxy. In fact, these objects have only been discovered relatively recently when humans have been able to observed the sky in high energy electromagnetic radiation, X-Rays. The first discrete X-Ray source in the universe was discovered in 1962 by Giacconi et al, named Sco X-1. The results were published in a landmark paper titled "Evidence for X-Rays from sources outside the solar system". These sources are now known to be several orders of magnitudes brighter in X-Ray than our Sun ($\sim 1 \times 10^{38}$ ergs s^{-1} (Bradshaw et al., 1999) vs $\sim 1 \times 10^{28}$ ergs s^{-1}

² The Hertzsprung-Russell or HR diagram is basically a log-log plot of luminosity L vs. effective temperature. This is widely use in astronomy.

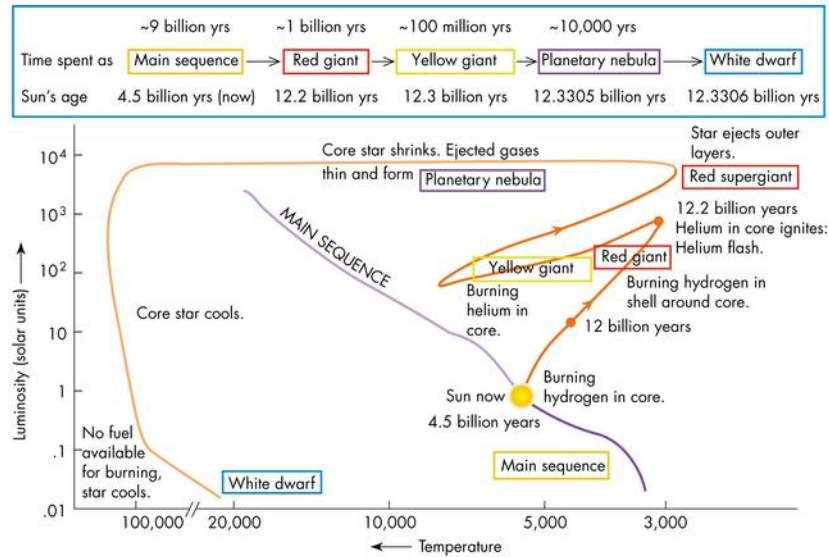


Figure 1.2: Evolution Sun-like star to white dwarf. Source: The Sloan Digital Sky Survey data <http://skyserver.sdss.org/dr1/en/astro/stars/stars.asp>

(Peres et al., 2000)). This first X-ray source, Sco X-1, has been widely studied for more than 50 years in all wavelengths and it represents the prototype low-mass X-ray binary (LMXB). So let's talk next about what is a LMXB and how they are related to compact objects.

1.3.1 Low-Mass X-Ray Binary

A low-mass X-ray binary is composed of a neutron star and a low-mass late-type star (sometimes referred as the secondary or companion star). What is important in this scenario is that the companion star fills what is called the Roche lobe. The Roche lobe represents the area of influence of a star in a binary system. Inside the Roche lobe of an object the material will be gravitationally bound to that object. If the secondary star fills its Roche lobe, material can be transferred to the compact object (in the case of a LMXB a neutron star). This mass transfer is called "Accretion". If the accreting material has some initial angular momentum it cannot fall radially into the more compact object but it will slowly fall into the compact object and form what it is called an "accretion disk". A sketch of how this happens can be seen in Fig 1.3.

The specific accretion scenario described above was first proposed by Prendergast & Burbidge (1968). This was not the first model to explain the X-ray emissions from these objects. The first attempts were done by Shklovskii (1967) and even before by Hayakawa & Matsuoka (1964). The models all proposed high-temperature infalling gas into a very massive and dense object. But Prendergast & Burbidge (1968) model takes into account the angular momentum of the infalling plasma, and thus the formation of a disk. Concluding that "the optical radiation will be emitted from the outer parts of the disk and the X-Rays from the inner part." (Prendergast & Burbidge, 1968). The model was developed for accretion in white dwarfs but it also extends to neutron stars. The first accretion disk model for neutron star accretors came in 1972 from Pringle & Rees. This model mentioned the fact that around the neutron star the magnetic field controls the gas dynamics. This would mean that the

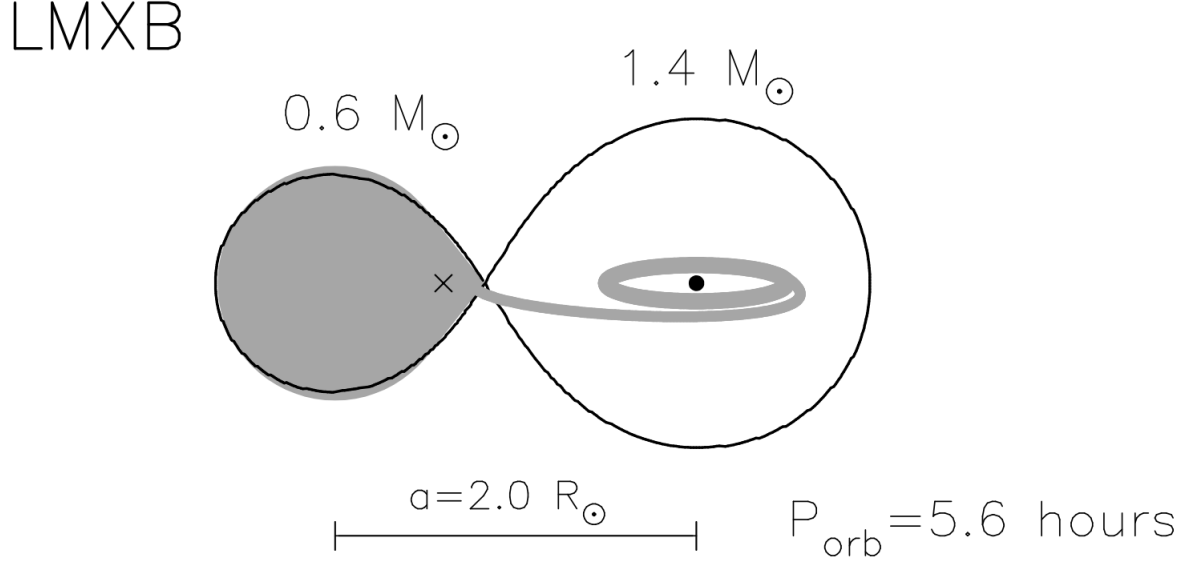


Figure 1.3: The plot shows a cartoon representation of a LMXB from Tauris & van den Heuvel (2006). The black lines represents the Roche lobe. In this picture the companion star fills its Roche lobe and so material is transfer into the neutron star. The material from the star forms what is called an accretion disk due to the initial angular momentum of the accreting material from the star.

X-Ray emissions also come from the regions on the stellar regions near the poles.

Here we only touch the basics on the accretion phenomena that are present in some compact binary systems. A more detail look into the physics can be found in Pringle (1981) and a more recent book is Frank et al. (2002). We will revisit the subject of accretion disks in sec. 1.5 when we see why we need spectroscopy to better understand the nature of the compact binaries and their accretion disks.

Now that we have seen in what kind of binary system neutron stars can be found, we can turn the page and study white dwarfs in binary systems.

1.3.2 Cataclysmic Variables

Like with the neutron star we start by examining what happens when a compact object (in this case a white dwarf) accretes from a main sequence star due Roche lobe overflow. In this case the name is not as descriptive as for the LMXBs, they are called Cataclysmic Variables (CVs). They, like LMXB, are sources of X-Ray and optical radiation coming mainly from the accretion disk surrounding the white dwarf.

CVs might be formed from the most common compact object (white dwarfs), but by no means this lower their ranking in the compact binaries group. Like LMXB they have been studied since the dawn of X-ray astronomy, and even further back with optical observation. In fact the first discussion of accretion in a CV goes back to the year 1956 by Crawford & Kraft. In the paper Crawford & Kraft proposed a model for AE Aqr that involved gas transfer from the primary to the white dwarf. This was done a mere 18 years after the discovery of AE Aqr as a rapid variable star in 1938 by Zinner.

These are fascinating objects with a rich range of behaviours, including really energetic outburst

that give rise to the name cataclysmic variables. They are the main subject of study of this work, but before we can say anything more about them we need to explore the vast taxonomy of these objects.

Magnetic CVs

Easy enough these are CVs for which the magnetic field is strong. The actual definition is a bit more complex involving synchronization of orbit and rotation, and modulation of X-rays; but we don't need to know the details now. The main idea is that in the presence of a strong magnetic field the accretion flow can be disrupted. This disruption can be partial or complete. This then gives rise to a subdivision of these objects: Polars and Intermediate Polars. They both share some characteristics. In both type of systems seem to be very variables (other of magnitudes and ref for this). They also share some spectral properties, the most noticeable one being the presence of Helium II. This is due to the ionized accreting plasma.

Polars

Polars are a type of CV where the magnetic field is strong enough to control the flow of the material near the white dwarf. The term was first coined by Krzeminski & Serkowski (1977) due to the high degree of polarization (both circular and linear) found in these type of systems. 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)). In fact Polar systems are sometimes referred as AM Her-like system.

Intermediate Polars (IPs)

The second kind of magnetic CVs are those where the magnetic field is not negligible but also it is not strong enough to completely dominate the accretion flow. They are called Intermediate Polars. The first two classified members are TV Col and AP Psc. They showed AM Her-like spectra, but no sign of strong polarization (Ref. needed ?). Another very well known member of this class is DQ Her. DQ Her is sometimes referred as a subclass of IPs, or even as a synonym for IP. A 30 pages review, a bit outdated, dedicated solely to the topic of DQ Her stars and IPs is Patterson (1994).

Non-Magnetic

As opposed to the magnetic CVs, the magnetism doesn't interfere significantly with the accretion from the secondary stars. This doesn't mean that these CVs are "well-behaved" and less variable than the magnetic ones. Au contraire, these kind of CVs are known to display an eruptive behaviour. In fact, they were the first kind of CVs to be detected and the reason they carry the infamous name, cataclysmic variables. Non-magnetic CVs (for the most part. Some exceptions are known e.g. ? I think DQ Her but have to check and V1500 Cyg from Pagnotta et al 20016) are the source of very powerful outbursts. There are the two kind of eruptions observed in CVs and they define the different types of non-magnetic CVs.

Classical Novae (CN)

When the surface of an accreting white dwarf becomes hot enough, nuclear fusion can take place and a thermonuclear runaway happens. This creates a violent explosion capable of ejecting material at high

velocities. These outburst are fairly easy to detect since they cause a substantial increase in brightness (6-19 magnitudes ? Find reference). A CV observed erupting in such a way is classified as a *classical novae*. By definition a CN have been seen to erupt only one. If a previously recognized CN erupts again as a CN they are called recurrent novae.

Classical novae are the most violent non-destructive eruption observed from a CV, but not the only one. Another kind of instability can cause violent outburst in a CV and gives the name to the second type of non-magnetic CVs, dwarf novae.

Dwarf Novae (DN)

An dwarf novae outburst in an eruption caused by instabilities in the accretion disk. This is predicted to happened in non-magnetic CVs with low accretion rates. They usually not happen in magnetic CVs because as stated in Shara et al. (2005): "Magnetic fields in CVs are usually expected to prevent the disk instability that leads to dwarf nova eruptions". There are some few exceptions like EX Hya (ref for this ?). CVs that show dwarf novae outburst 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 (? get ref for this), and no material is ejected. They also, unlike classical novae, are periodic in nature with a well defined time scale depending mainly on the accretion rate.

For the details on the nuclear physics governing DN see Shara (1989) and a very recent one from 2016 by Starrfield et al..

Novae-like (NL)

Another classification of white dwarfs that I haven't mentioned is the novae-like one. These are a bit ambiguous as both magnetic or non-magnetic systems can be classified as NLs. They are basically CVs that seem to have stable accretion, thus not undergoing dwarf novae outburst and having a bright stable disk. So even if you would guess from the name, this represent the 'non-eruptive' CVs.

A lot of new terms have been defined here I apologize for that, but this also shows how rich variety of behaviours present in CVs. So far we have focused our discussion of CVs based on the nature of only the white dwarf, after all these are the main driver of systems. But before we can pass to another topic we have to discuss a bit the nature of the secondary stars in CVs.

The Secondary stars

The detailed study of the secondary stars in CVs can be on its own the sole topic of a thesis. Here we limit the discussion for late-type stars. This is justified by the fact that we will be studying CVs in globular clusters. Globular clusters, as we will see in the next section, are very old clusters of stars, so the most common stars in the cluster are expected to have relatively small mass (Do i need to cite this). In fact for NGC 6397, the globular cluster studied in this work, the turnoff mass ³ is $0.77M_{\odot}$ (De Marco et al., 2005).

Late-type stars can be a term a bit ambiguous, but in this report the term will exclusively refer to K and M type stars. Let's look at them in more detail.

³the turn off mass is the maximum mass on the main sequence. This can serve as a rough estimate of the maximum mass of main sequence stars in a globular clusters.

K stars

Search for good reference for info. They are discussed in Natalie's thesis. Include spectra?

M stars

Search for good reference for info. Include spectra?

With the discussion of the secondary stars we end our discussion on compact objects and binaries. In this section we learned what compact objects are and explored two specific types of accreting binaries, LMXB and CVs. We briefly mentioned the characteristics of an LMXB, and then focused on the CVs. We studied the rich nomenclature of CVs, and the different types of CVs based on their outburst and magnetic properties. But I must say that I have only touch the surface of this ample topic. The following references are valuable sources for the avid reader that wish to know more about the subject. The first good source of information is Warner's book *Cataclysmic Variable Stars* (Warner, 2003), an essential reference for this topic. Another good reference at a lower level and easier to read is Hellier (2001).

A review that deals with the evolution of LMXB and CVs (the two only binaries mentioned here) is Patterson (1984). Another one that don't limit the discussion to white dwarfs and neutron star is the book Frank et al. (2002). The book extends the discussion to all the compact objects (including black holes) and discussed the physics of the different models of accretion besides Roche overflow.

Now that we have a better idea about compacts objects, specially about CVs, the next sections will be about where can search for compact binaries, and how.

1.4 Globular Clusters: A stellar nursing home

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?

1.5 Spectroscopy: The golden standard

The advances in spectroscopy have been tied with our understanding of compact binaries. This was recognized as early as 1966 by Zeldovich & Guseynov. In this letter they wanted to "draw attention" to the study of "collapsed stars" and call to the find X-Rays from single-line spectroscopic binaries as "unambiguous proof of the existence of a collapsed star". For CVs this have also been the case.

For example the idea that lead to the correct interpretation of accretion as an important agent in the variable systems like AE Aquarii only was possible after the its classification as a spectroscopic binary ⁴ (Joy, 1954). Also spectroscopy have been an amazing tool used to prove and confirmed the presence of accretion disk in compact binaries. This is because emission lines bring key information about binaries, and specially about accreting binaries. They provide kinematic signature of accretion phenomena, and allow for the tracing of the accretion flow. This accretion disk is the dominating light at optical wavelength. The emitted lines from the accretion are highly structured and even time-dependent, in some cases. The most prominent features being the so called Balmer series (Hydrogen emission lines) and Helium lines (Helium I and Helium II). The Balmer lines from an accretion disk in a CV have been first studied by Williams (1980). The expected characteristic double-peak hydrogen emissions were model already in the 1981 by Smak and expanded by Horne & Marsh (1986). Spectroscopy have also been a valuable tool to explore the physical properties of the compact objects, and not only of the accretion flow. For example presence of He II have been suggested to indicate "accretion 'curtains' along the magnetic field lines of the WD." (Edmonds et al., 1999).

In recent times with the advent of space exploration and construction of bigger telescopes. High resolution slit spectroscopy (both from space and from the ground) have allow us to improve our knowledge of the compact binaries. We pay special attention to the advancement in the study of CVs in globular clusters. The first of such studies was for the globular cluster M5 by Margon et al. (1981). Then 18 years after only three studies followed in two other globular clusters (Deutsch et al. (1999); Edmonds et al. (1999); Grindlay et al. (1995)).

After 1999 the next spectroscopic study of compact objects in globular clusters had to wait until de development of the technique called *slitless spectroscopy*. This was proposed to be done for the GC 47 Tuc using slitless spectroscopy with the Hubble Space Telescope. The original proposal estimated to "spectroscopically confirm 25 [CVs]." According to the prediction of the tidal capture theory at the time Knigge (1999). The obtained results were not quite as high, but nonetheless they were able to get three simultaneous spectra of CVs (Knigge et al., 2008, 2003).

These six studies done in total (one ground-base and five from space) leaves us with only nine spectroscopically confirmed CVs in just four GCs. The need for more data is obvious. In this work we hope to achieve this by using yet another advancement in the field of spectroscopy, the development of 3D spectroscopy. 3D spectroscopy, or integral field spectroscopy, will be the subject of the last section of this chapter. We will focus on a particular integral field spectrograph installed at the VLT called MUSE.

1.5.1 The Multi Unit Spectroscopic Explorer (MUSE)

MUSE is a "second generation instrument installed on the Nasmyth focus of UT4 at the Very Large Telescope (VLT) of the European Southern Observatory (ESO)." (Bacon et al., 2010, 2014)

⁴A spectroscopic binary is a binary where we see the periodic doppler shift of a line due to the orbit of the object.

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