

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).

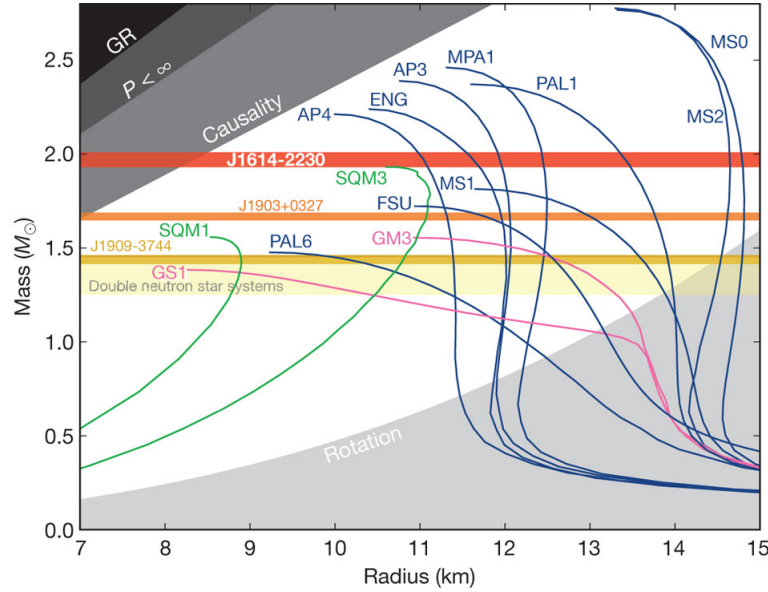
Now that we have defined our broad goal let's take a step back and explore in more details what are compact objects, their different types, and the different ways they can interact with each other and other types of stars (Sec. 1.2). That section will lead us to the discussion of where and how we expect to find them, and what can we learn by studying them in the different environment where they form (sections 1.3 and 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 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  $\sim 2$  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 different models proposed.



**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)

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 1.4. 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 <sup>1</sup>. The impatience reader can skip to sec 1.2.4 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 1795). 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

<sup>1</sup>Main 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 1.3.2).

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  $> 8 M_{\odot}$ ) 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) diagram<sup>2</sup> 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.

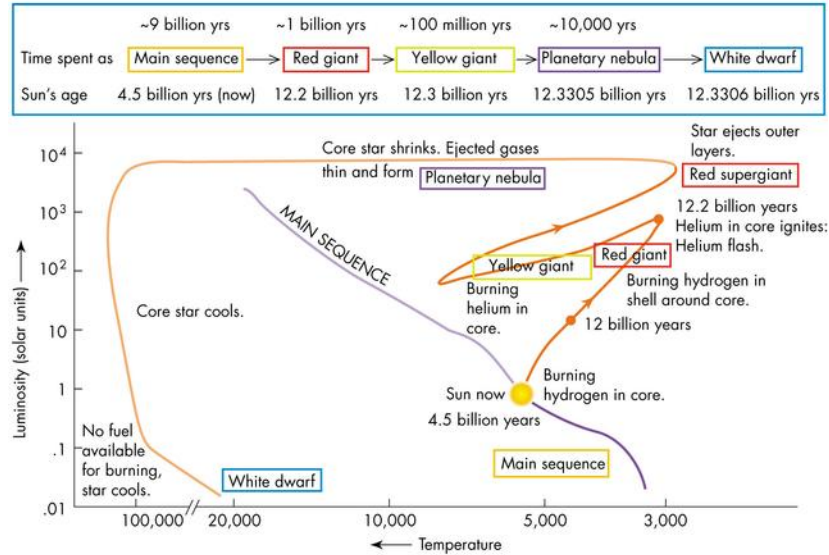
Continuing our comparison between the different compact objects, it only left to say that white dwarfs too are expected to be found in binary systems. This is the topic of the next section.

### 1.2.4 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<sup>-1</sup> (Bradshaw et al., 1999) vs  $\sim 1 \times 10^{28}$  ergs s<sup>-1</sup> (Peres et al., 2000)). This first X-ray source, Sco X-1, have been widely studied for more than 50 year 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.

<sup>2</sup> 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 server data <http://skyserver.sdss.org/dr1/en/astro/stars/stars.asp>

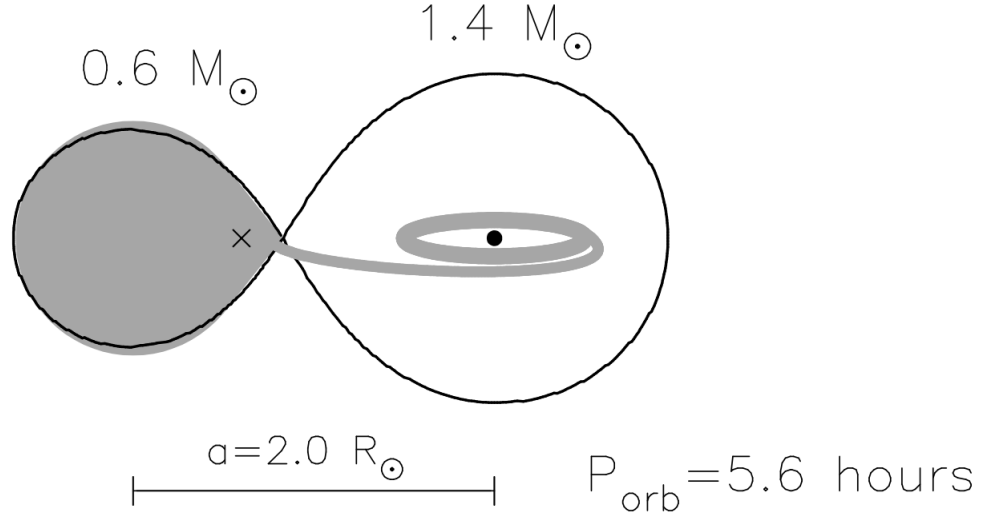
### Low-Mass X-Ray Binary

A low-mass X-ray binary is composed of a neutron star and a low-mass late-type star (sometimes refer 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 transfer to the compact object (in the case of a LMXB a neutron star). This mass transfer is called "Accretion". If the accreting material have 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". An sketch on 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 object. The first attends 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 a white dwarfs but it also extents 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 X-Ray emmissions 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. 1.4 when we see why we need

# LMXB



**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.

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.

## 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 only after 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 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.

### 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)).

### 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. A 30 pages review, a bit outdated, dedicated solely to the topic of DQ Her stars is Patterson (1994).

## Non-Magnetic

As opposed to the magnetic the magnetism doesn't interfere with the accretion from the secondary stars. This means that in this case we have a well . This doesn't mean that

### Dwarf Novae

Dwarf novae belong to the class of nonmagnetic cataclysmic variables in which the magnetic field of the white dwarf is too weak to disrupt the accretion disk, so that the disk can extend close to the surface of the white dwarf

**novae**

**novalike**

### The Secondary stars

Type k and m.

With the discussion of the secondary stars we end our discussion on the nomenclature and classification of CVs. A very long and detailed reference for CVs is Warner's book *Cataclysmic Variable Stars* (Warner, 2003). Another good reference at a lower level and easier to read is Hellier (2001).

In this section on compact objects we have introduced a lot of new terms

Now that we have an idea of what compact objects are and what kind of binaries we can expect to find, we can discuss w

pet's first look at what are globular clusters and see why they are the perfect place to look to study the formation and evolution of binary systems.

## 1.3 Globular Clusters: A stellar nursing home

As we saw. We expect them to form in high density environment. Review  
Know distance for example.

### 1.3.1 NGC 6397

### 1.3.2 CVs in Globular clusters

As usual we will ignore BHs. I can briefly mention that they are expected to be found in GC. Briefly mentioned search for spectet Intermediate BH (reference), but concentrate on CVs For a big review see (big reference of GC natalie old), and relativistic binaries is worth looking (reference mathew benacquista). A great review on CVs is Kiselevich CVs in GC.

I hope I have convinced you by now that compact objects are a class of objects worth studying. Their mass and densities let us probe into physics that is still not possible with modern technology. The violent phenomena happening at the different scales is an open laboratory for high energy physics and their exotic and eccentric cores still presents a challenge for nuclear physicist.

I also hope that I made the point that cataclysmic variables are of special interest, as they represent the fate of our own star and possibly of the vast majority of stars. These are objects that are predicted to be so common, and yet far to be completely understood.

It should also be clear by now after the discussion on globular clusters in the last section why we would expect and search for CVs in them. But what I haven't discussed is what is our current understanding on the issue. What have we learned in years of observation and more importantly what is still to learn about them. In other words what is the motivation

Natasha paper

There are three open questions in this field:

1. Are all CVs in globular 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?

#### Magnetism

The look for He II. (Emission lines) and line ratios.

#### Primordial CVs

Balmer series

Bright vs faint  $H\alpha$ , period ? (We

What hasn't been discussed is what is the current understanding on the topics. We can expect to see emission on absorption maybe

**Period gap: Is it real?**

We need more data and sp. Emission lines can help.

**Where are all the dwarf and novae?**

These two are violent explosion

Optical spectroscopy is the answer

## 1.4 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 (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 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 in a binary system. 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).

Magnetism in Helium II lines is a for magnetism (reference for this ).

. as mentioned above. In white dwarfs for example we can look for the Helium emission lines, both He I and He II, to get more information about the magnetism and temperature of the accretion disk. He II is a sign of magnetism and He I can only be found in neutral accreting matter (ref for magnetism and accretion). And only spectroscopy can help with the correct classification of CVs in their different classes.

In modern times also with the advent of space exploration. High resolution slit spectroscopy from space have allow us to study in more details compact binaries. Specially CVs in globular clusters. This done for NGC 6397 ( and ). And the developend of with slitless far-UV allow to do simultaneously 3 CVs in 47 Tuc (Knigge et al. 2003, 2008).

But still this only leaves us with only 8 spectroscopically confirmed CVs in just 4 GCs. (Only 4 in NGC 6397) thanks to 6 different studies of GCs. With only 6 studies (). Still a lot is to be discovered in the spectra of CVs.

The next advancement is the so called IFUs. This is an active and intense area of research. A review mentioning the different methods and benefits of 3D spectroscopy is given by Bershadsky (2009). There exist many of such instrument but we will focus only on one in particular called MUSE.

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