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 and **??**).

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

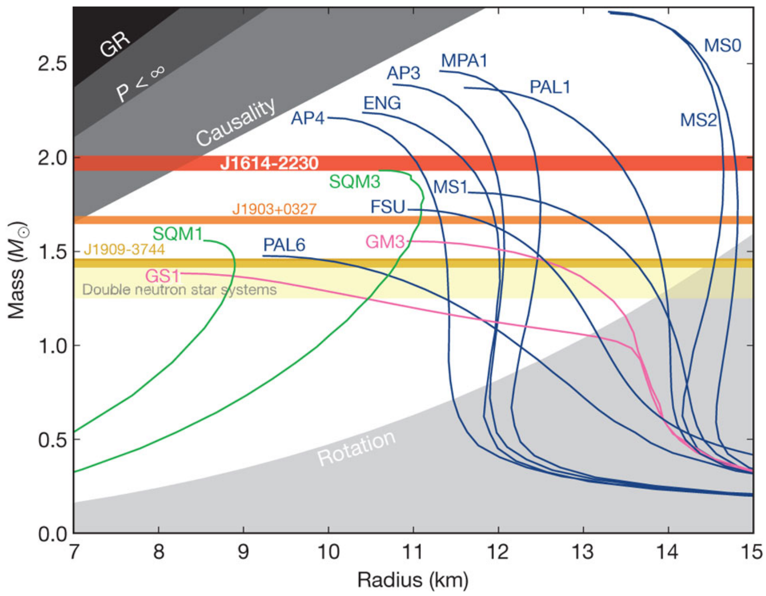

Figure 1.1: The plot shows non-rotating mass versus physical radius for several typical equation of states. Blue, nucleons; pink, nucleons plus exotic matter; green, strange quark matter from (doi:10.1038/nature09466)

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:

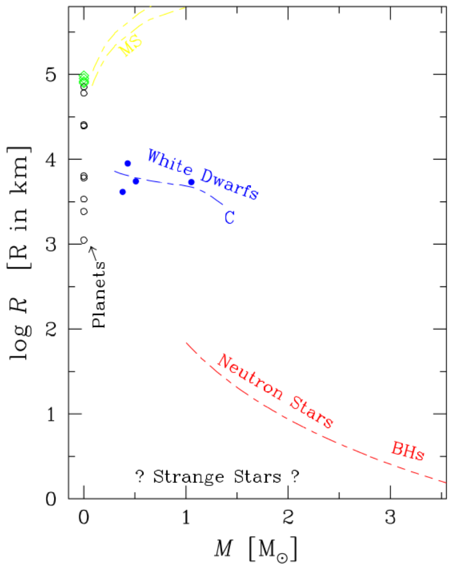

Figure 1.2: Mass-radius relation for different objects (de Boer & Seggewiss, 2008).

$$\Psi = -G\frac{M_1}{\sqrt{x^2+y^2+z^2}} - G\frac{M_2}{\sqrt{(R-x)^2+y^2+z^2}} - \frac{\omega^2}{2}\left[(x-\mu R)^2+y^2\right] \tag{1.2}$$

where G is the gravitational constant, R represents the separation between the point masses, and $\mu = M_2/(M_1+M_2)$. We further assume that the binary orbit is Keplerian, thus the orbital frequency is given by:

$$\omega^2 = G\frac{M_1+M_2}{R^3} \tag{1.3}$$

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)

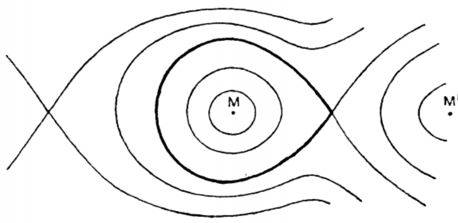

Figure 1.3: Geometry of the Roche surfaces. The Roche lobe is mark in bold font (Kopal, 1959).

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 $L/L_\odot = (M/M_\odot)^\alpha$, 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. The scenario described above was first studied by Kippenhahn et al. (1967) and then in De Loore & Doom (1992). It represents the evolution of a binary system starting with a 2 $M_\odot$ and a 1 $M_\odot$ star. For more details on the evolution of close binaries see Paczynski (1971) and Postnov & Yungelson (2014).

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 $\omega = (2\pi)/\text{Period}$ 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. As their name suggest this are very variable systems. These are due either by instability of the accretion flow, referred to as dwarf nova (Osaki, 1974), or unstable burning of hydrogen at their surface, called nova (Starrfield et al., 2016). We will discuss in some detail the outburst caused by these instabilities by presenting the classification of CVs and exploring the bast taxonomy of these objects.

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 accreation in a CV goes back to the year 1956 by Crawford & Kraft. In the paper Crawford & Kraft

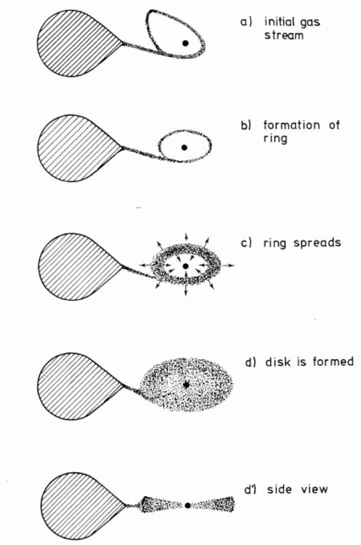

Figure 1.4: Schematic illustraion of the formation of an accretion disk around a compact binary (Verbunt, 1982).

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.

1.3.4.1 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.

1.3.4.2 Polars

Polars are a type of CV where the magnetic field is strong enough to control de 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 somethings referred as AM Her-like system.

1.3.4.3 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 know member of this class is DQ Her. DQ Her is somethings refer 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).

1.3.4.4 Non-Magnetic

As opposed to the magnetic CVs, the magnetism doesn't interfere significantly with the accretion from the secondary stars. These 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.

1.3.4.5 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.

1.3.4.6 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 seeShara (1989) and a very recent one from 2016 by Starrfield et al..

1.3.4.7 Novae-like (NL)

Another classification of white dwarfs that I haven't mentioned is the novale-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.

1.3.5 X-Ray binaries

1.3.5.1 Low-mass X-Ray Binaries

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 **??**.

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 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. Prendergast & Burbidge (1968) concluded 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 onto 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 X-Ray emmisions 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. **??** 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.

1.3.5.2 High-mass X-Ray Binaries

1.3.5.3 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 [4] is $0.77 M_{\odot}$ (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.

1.3.5.4 K stars

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

1.3.5.5 M stars

Search for good reference for info. Include specta?

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:

[4]the 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.

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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