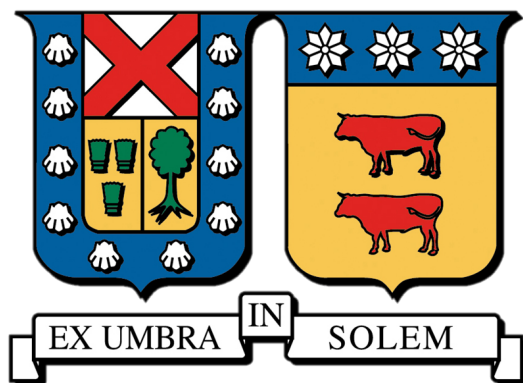


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Measuring the spin period of (cool) magnetic white dwarfs to constrain
the crystallization-rotation driven dynamo model

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PROYECTO PARA OPTAR AL GRADO DE LICENCIADO EN CIENCIAS, MENCIÓN

FÍSICA

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Abstract

Context: Understanding the formation of magnetic white dwarfs has been a long-time problem. Recently, it has been proposed that the magnetic fields of some white dwarfs are generated due to the interplay of crystallization and fast rotation in white dwarfs. These magnetic white dwarfs should meet two conditions: (1) they should have a low effective temperatures such that they have crystallised cores (2) they should have short spin periods gained by accretion of material.

Aim: I aim to measure the spin period of cool DZ magnetic white dwarfs to prove the prediction that they possess a shorter spin period than their non magnetic counterparts.

Method: I obtained photometric data of five cool magnetic white dwarf with SPECULOOS, reduced the data with a free python-based software, PROSE, and searched for periodicities using the Lomb-Scargle periodogram implemented in PERIOD04

Results: I measured the rotation period of two out of five magnetic white dwarfs (6.34 ± 0.10 hr and 4.84 ± 0.02 hr for WD 2138-332 and LSPM J0107+2650, respectively). I found complications for the other three systems: SDSS J003708.42-052532.8 has too few data points for a reliable estimate, WD 0322-019 has probably a magnetic field too low to form the dark spots ($B=0.120$ MG), and WD 0315-293 could either have a spin period shorter than the time resolution of the data or the magnetic field produces a spot configuration that does not lead to significant photometric variability.

Conclusions: The short periods measured for WD 2138-332 and LSPM J0107+2650 are consistent with the rotation-crystallization dynamo driven model, which predicts shorter periods for magnetic white dwarfs than for non-magnetic white dwarfs.

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Chapter 1

Introduction

In the universe we can find a countless number of objects, which all have their own characteristics and we can separate them in groups depending on their origin or properties.

Stellar remnants are the product of the death of a star and we can find three types of these objects: white dwarfs, neutron stars and black holes. The most common stellar remnants are white dwarfs. This is because nature prefers to form low mass stars over massive stars and white dwarfs are the end product of the evolution of low - intermediate mass stars, meanwhile neutron stars and black holes are born from massive stars.

In this thesis, I will be analysing data of white dwarfs which present magnetic fields of $B \simeq 0.1 - 0.5 \text{ MG}$, in order to test the crystallization driven dynamo model (see section 1.4.4) proposed by Isern et al. (2017). Based on this model it is predicted that cool DZ white dwarfs are expected to rotate faster than non-magnetic white dwarfs (Schreiber et al., 2021a).

1.1 Formation of white dwarfs

White dwarfs are born when a star of intermediate mass ($M \simeq 1 - 9 M_{\odot}$) reaches a state where it can no longer produce energy through nuclear fusion. The evolution from a star to a white dwarf takes several stages during the life of the star. The first step is the pre-main sequence phase, that occurs before the star's life. At the very beginning of star formation, there is nothing but a big molecular cloud. Depending on the quantity of stars that lived and died before, we can find different kinds of metals in these clouds. A star is born from a molecular cloud when this cloud begins to collapse. This collapse will produce the fragmentation of the cloud. The biggest fragments of this collapse form protostars. Depending on how much material falls into the protostar it will be a low mass star or a massive one. When the temperature in the center of the protostar is sufficient to fuse hydrogen into helium, a main sequence star is born. At the very onset of hydrogen burning, the star has reached the zero age main sequence. Stars spend most of their lifetime on the main sequence (See Figure 1.1). At the beginning of its life, the star will be composed mostly of hydrogen. But, during the main sequence the star consumes the hydrogen due to nuclear processes and creates helium in the center of the star.

Depending on the mass of the star it can follow three paths to its final stage of life. The first one is for low mass stars ($< 0.8 M_{\odot}$). At the end of the main sequence, these stars will expand and later they expel their external layers and will form a white dwarf composed almost only by

helium, but we will not be able to find one, because the time that these stars need to form a white dwarf is longer than the age of the universe.

Meanwhile, intermediate mass stars ($M \simeq 0.8 - 8 M_{\odot}$) will have a very different fate when the main sequence phase ends. When the hydrogen in the core runs out, the star begins to expand and it turns into a red giant. The core of the giant branch is composed only by helium and this core is made by degenerated matter due the gravitational pull that squeezes the atoms. When the red giant stop its expansion the star stabilizes for a short period of time and contracts. The burning of helium, what makes the core to expand and this cause the contraction. When the helium in the core runs out, the star enters in a new phase of expansion known as the asymptotic giant branch.

After their last phase of expansion, the asymptotic giant branch, the star divides into two visible parts: the envelope and the core. The envelope escapes from the core by solar winds and thermal pulses. When the envelope reaches a large size it is known as a planetary nebula (from point 11 until point 12 in Figure 1.1). On the other hand, we have the hot degenerate core that is left behind. The elements in the core are separated into different layers because of the strong gravity of this core. In the center are the heaviest elements such as oxygen and carbon. A thin layer of helium coats the carbon-oxygen core. The last layer is the thinnest of all and is made of hydrogen that was not used during fusion. Such stellar remnants are known as white dwarfs (from point 12 to point 13 in Figure 1.1; [Carrol and Ostlie 2017](#)).

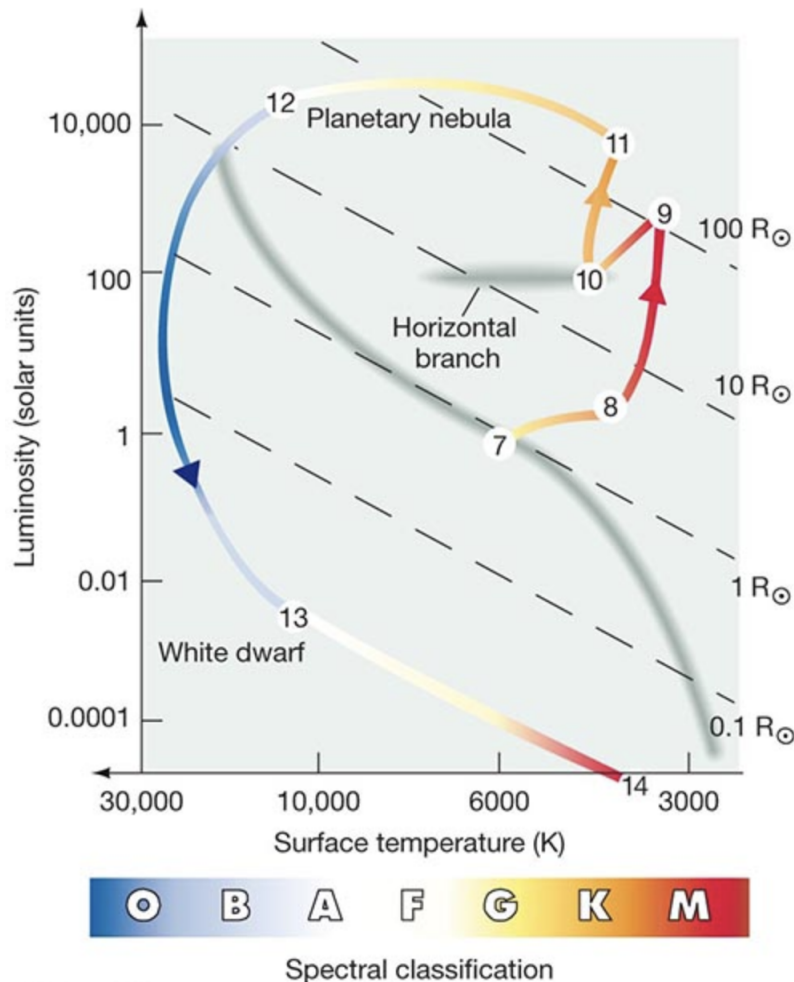
At last, the massive stars ($M \gtrsim 8 M_{\odot}$) follow a similar path as the stars with intermediate mass. At the end of the main sequence massive stars enter into the Hertzsprung gap. The Hertzsprung gap is similar to the sub-giant branch but it occurs on a shorter period of time. And at the end of the asymptotic giant branch, the stars reach temperatures in their cores sufficient to start carbon burning and even the fusion of more massive nuclei. These stars end their lives in supernova explosions when their core collapses to form either a neutron star or a black hole.

1.2 White dwarfs properties

White dwarfs do not produce energy by nuclear reactions. The energy produced by contraction goes to increase the internal energy of the star to compensate the Fermi energy. This happens because white dwarfs are made up of degenerate matter. If it was not made of degenerate matter, the energy of contraction would increase the temperature of the white dwarf and it could start the process of fusion in the core again. Instead, white dwarfs simply start slowly to cool down. The older a white dwarf is, the cooler it will be. By observing the luminosity and mass of the stellar remnant, it is possible to determine its age and, in consequence, the oldest white dwarfs provide constraints on the age of the galaxy.

As expected, white dwarfs possess a small fraction of the mass of their progenitor star. Their mean mass is around $0.663 \pm 0.136 M_{\odot}$ ([Ferrario et al., 2015](#), See right panel in Figure 1.2;). The masses of white dwarfs are obtained by fitting their spectra (in particular the hydrogen Balmer absorption lines) to obtain their effective temperatures and surfaces gravities which can then be combined with cooling models or it can be calculated combining effective temperature, a theoretical mass-radius relation, and parallaxes (e.g. [Kepler et al., 2007, 2016](#)).

When we spectroscopically observe them, not all white dwarfs look the same. They can be differentiated by the type of atmosphere they have as this determines their spectroscopic appearance. In other words, we can categorize white dwarfs depending on the absorption lines that we see



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Figure 1.1: Schematic representation of the Hertzsprung-Russell diagram that shows the evolution from the zero age main sequence (point 7) of a solar-like star. When the star leaves the main sequence it enters the first giant branch (start of point 8), when helium burning starts (point 9) it becomes a red clump or horizontal branch star and when no helium is left in the core, it enters the asymptotic giant branch (AGB, point 10). At the end of the AGB phase, the envelope is expelled (11) and the white dwarf corresponds to the central object in a planetary nebula. From point 12 on, the white dwarf gradually cools and its luminosity decreases. Figure taken from http://www.khadley.com/courses/astronomy/ph_206/topics/starevolution/h-r-diagram.html

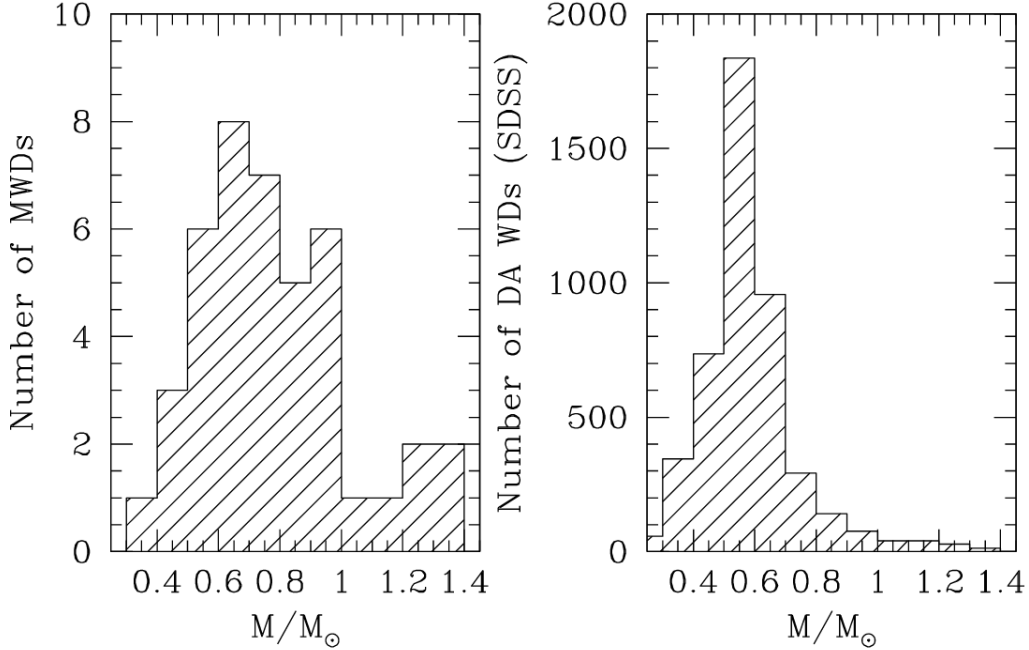


Figure 1.2: White dwarf mass distribution *right*: derived from spectra of the Sloan Digital Sky survey (data release 4) of 7167 DA non-magnetic white dwarfs (Kepler et al., 2007), and *left*: masses measured from the magnetic white dwarf sample of Ferrario and Wickramasinghe (2010).

(which are produced in the white dwarf atmospheres). When one observes that the atmosphere only produces hydrogen absorption lines, the white dwarf is known as DA white dwarf. A DB white dwarf is a remnant where in the atmosphere one can see only absorption lines of helium. Finally, when one can see metal absorption lines, it is called DZ. However, when we find white dwarfs that have absorption lines from different elements, it receives the acronyms of the absorption lines found. For example a white dwarf with more hydrogen absorption lines than helium is named DA(B) white dwarf, but in the opposite case, more helium absorption lines, is called DB(A). Those white dwarfs that are magnetic are labelled with an “H” at the end, e.g. a magnetic DA white dwarf would be DAH (Kepler et al. (2007)).

But why can we see metal absorption lines in the spectra of white dwarfs? The theory says that the strong gravity in the surface of the white dwarf will sink all heavy elements. This explains why most of white dwarfs are DA or DB, but it should not be possible to see the absorption lines of metals. However, we can see the absorption lines in some white dwarfs and there is even a category for the white dwarfs with metal absorption lines (e.g. DQ or DO but these types are beyond the scope of this work). There are three theories that explain the presence of metals in the spectra. The first case is called radiative levitation. When the radiation field in a white dwarf is strong, i.e. when the white dwarf is hot and young, radiation pressure can keep heavy elements in the atmosphere despite their larger mass. The problem with this theory is that it only explains the scenario of metal absorption lines in hot white dwarfs (effective temperatures above 35 000 K), thus this phenomenon can not explain the metals seen in cooler white dwarfs. The second theory says that, due the deep convective zones in the exterior layers of the white dwarf, deeper material is dredged-up to the surface and thus one can see metals absorption lines. But, like the first theory,

it only works for a small range of white dwarf effective temperatures (convection starts to deepen for white dwarfs cooler than $\sim 10\,000\text{ K}$). The gap left in the effective temperature by combining both processes can not be explained by any intrinsic process. The last theory is that white dwarfs accrete lower mass planets or asteroids. When the remnant absorbs these objects, the elements of the chemical composition of the accreted objects can be observed as metal absorption lines in the spectra of white dwarfs. In [Köster et al. \(2014\)](#) they made a survey for metal pollution in DA white dwarfs. They found that a 56% of the studied white dwarfs present metal absorption lines, and half of these white dwarfs are currently accreting. The white dwarfs that accrete matter are known as polluted white dwarfs. The accretion theory can explain why we can see metal line absorption in the middle range of effective temperatures of white dwarfs and could also explain one of the topics that I will discuss later: the short rotation periods for these accreting white dwarfs.

Another characteristic of white dwarfs is their spin period. As the outer layers of the star are expelled in the later stages of its life, the core begins to gain angular velocity. This causes the stellar remnant to have a short rotation period. The resulting rotation period may depend on a number of factors, including: the spin period of the progenitor, if the white dwarf is accreting matter and potentially the strength of the magnetic field.

When the remnant reaches a certain temperature the ions of the center are arranged in a crystalline structure. When crystallisation begins, the interior of the white dwarf suffers a big change. The core of the white dwarf, where the crystallisation occurs, is richer in oxygen. While in the liquid envelope, the concentration of carbon is higher. This separation between the elements in the center of the remnant produces convection zones in the carbon rich outer layers. Also the mass of the white dwarf has a direct impact on the crystallisation. The more massive the white dwarf, the higher the temperature at which it will start to crystallize ([Isern et al. \(2017\)](#)).

An additional interesting characteristic of some white dwarfs is that they have a very strong magnetic field, but there are other white dwarfs with no or very weak magnetic fields. Why is there such a difference? What characteristics do white dwarfs with magnetic fields have in common? These is the big question that motivated the research presented in this work.

1.3 Magnetic white dwarfs

One of the properties of white dwarfs is that some of them have a strong magnetic field. To put the field strength into perspective, white dwarfs typically have sizes similar to the Earth but can host magnetic fields a billion times stronger than the Earth’s magnetic field.

But there’s a big difference in the strength of the magnetic field between white dwarfs. For example, the strength of these fields from isolated white dwarfs goes from 10^3 G to 10^9 G ([Ferrario et al., 2015](#)). In the case of magnetic white dwarfs in binary systems, where the white dwarf accretes matter from its partner, specifically a low mass star, the range of the magnetic fields are between 10^6 - 10^8 G . The binary systems described before are known as a Cataclysmic Variables (CVs) and about 35% of CVs contain a magnetic white dwarf (e.g. [Pala et al., 2020](#)).

The structure of the field is not simple. Highly magnetic white dwarfs present non-bipolar field structure. So far, no evidence has been found to indicate that the magnetic fields decay over time. This is consistent with the Ohmic decay time scales, that are about 10^{11} yrs .

The mass distribution of magnetic white dwarfs indicates that magnetic white dwarfs are more massive. The mean mass for white dwarfs with a field strength above 1 [MG] is $0.784 \pm 0.047 M_{\odot}$

(see left panel in Figure 1.2), meanwhile, as mentioned above, the mean mass of non-magnetic DA white dwarfs is $0.633 \pm 0.136 M_{\odot}$ (the process of how the masses are obtained is explained in Ferrario et al. 2015).

Cool white dwarfs with a strong magnetic field have a convective atmosphere. Convection along the atmosphere is not homogeneous, this leads to the appearance of star spots. The star spots are areas where the convection is reduced, this leads to a cooler and darker zone than the rest of the atmosphere. These star spots allow us to measure the rotation rate of magnetic white dwarfs.

There are several theories to explain the existence of magnetic white dwarfs. In the next section, I will briefly explain the different theories, that aimed at explaining why there are white dwarfs with magnetic fields as strong as ~ 1000 MG, while there are others with undetectable magnetic fields (smaller than a few kG).

1.4 Theories of formation of magnetic white dwarfs

It is a question of several years in stellar astrophysics why a considerable number, approximately 25% of the observable white dwarfs, have a strong magnetic field (more than 1 MG) and others don't have a detectable magnetic field. There are four theories that try to explain this behavior of some white dwarfs: fossil magnetic field, double white dwarf merger remnant, a magnetic dynamo produced during common envelope and a crystallisation and rotation driven dynamo.

1.4.1 Fossil fields

The first theory says that the magnetic field of the white dwarfs is the field that survived from the main sequence star (Ap and Bp stars). Once the star expels the envelope, the core starts to rotate faster, because the radius of the sphere is reduced. This shrinkage of the surface is what causes the magnetic field to increase, due the magnetic flux conservation.

The problem of this theory is that we should find an equal proportion of magnetic white dwarfs in binary systems as in isolated white dwarfs, but this is not the case. The fraction of magnetic white dwarfs is higher in binary systems than in isolated remnants. In addition, the number of strongly magnetic main sequence stars is not sufficient to explain the fraction of strongly magnetic white dwarfs (Kawka, 2018).

An additional argument against this theory is that the magnetic field may not survive the life of the star. According to the observations and to Braithwaite and Spruit (2004) the magnetic fields from magnetic white dwarfs should arise from unstable magnetic fields which might be difficult to maintain throughout the main sequence.

1.4.2 Dynamo produced during common envelope

There are two origins on magnetic white dwarfs that are based on what happens at the end of the life of binary systems. Possible progenitors are binary systems where the core of the initially more massive star and the secondary star survive a common envelope phase or where the two cores merge (Kawka, 2018; Tout et al., 2008a; Potter and Tout, 2010; Wickramasinghe et al., 2014).

According to the first scenario, the magnetic fields are generated during common envelope evolution. Common envelope evolution starts when the initially more massive star fills its Roche-

lobe as a giant star and dynamically unstable mass transfer leads to the formation of a gaseous envelope around the core of the giant (the future white dwarf) and the companion.

During common envelope evolution, a magnetic field might be generated due to the different speeds of rotation between the common envelope and the binary star system which can generate a differentially rotating and convective envelope. The difference in rotational speed between the envelope and the binary star increases when the white dwarfs gets closer, so the magnetic field becomes stronger. More details are in [Tout et al. \(2008b\)](#).

The problem that this theory has is that can only explain the behavior of the magnetic white dwarfs that are found in binary systems. Besides, this theory implies that all the binary systems have a magnetic white dwarf, but in [\(Belloni and Schreiber \(2020\)\)](#) shows that not all binary systems posses a strong magnetic field. The last argument against the theory is that, when the envelope is ejected, the magnetic field disappears ([García-Berro et al. \(2012\)](#)).

1.4.3 Merger of two white dwarfs

An alternative scenario that has been proposed is that the magnetic field of the white dwarfs comes from the collision of two white dwarfs. When a binary system loses enough angular momentum the two objects of the binary collide and create a new object. In [García-Berro et al. \(2012\)](#) it is explained how the merger of the remnants produces a “hot, differentially rotating and convective corona”. This corona can produce a strong magnetic field, that does not decay in a very long time. The argument for this is that the corona acts like a magnetic liquid, so it produces the effect of a dynamo in the merger.

A variation of the merger scenario is that one of the white dwarfs is destroyed by its partner due tidal forces. The leftovers of the destroyed partner form an accretion disk, where the remaining white dwarf accretes the mass of the disk.

As with the previous theories, the merger of two white dwarfs have a few difficulties to explain the behavior of all magnetic white dwarfs. First of all this theory only can explain white dwarfs born from a merger of white dwarfs. This new white dwarfs are more massive than the average magnetic white dwarfs and there are not so many mergers to cover the number of M_{WD} .

1.4.4 Dynamo by crystallisation and fast rotation

The idea of a dynamo based on crystallization and fast rotation was originally developed to explain the existence of strong magnetic fields in white dwarfs that are part of a certain type of binary stars ([Schreiber et al. \(2021b\)](#)). The theory stems from the idea from [Isern et al. \(2017\)](#) that, perhaps, the magnetic field of white dwarfs is generated in a analogous way to the magnetic fields generated in low mass main sequence stars and planets like our Earth. This means, that the magnetic field is generated using by a dynamo.

For this idea to work, two requirements must be met. The first is that the nucleus must be crystallizing (process explained above). The second relevant aspect for strongly magnetic white dwarfs is that they should have shorter spin periods compared to the white dwarfs without magnetic field (or with very weak magnetic fields). The latter is very important in the context of this research since it is a quantity that can be measured.

The theory originated from the observation and analysis of close binary systems. When the binary meets certain conditions, begins the transfer of mass from one star to the other. In theory,

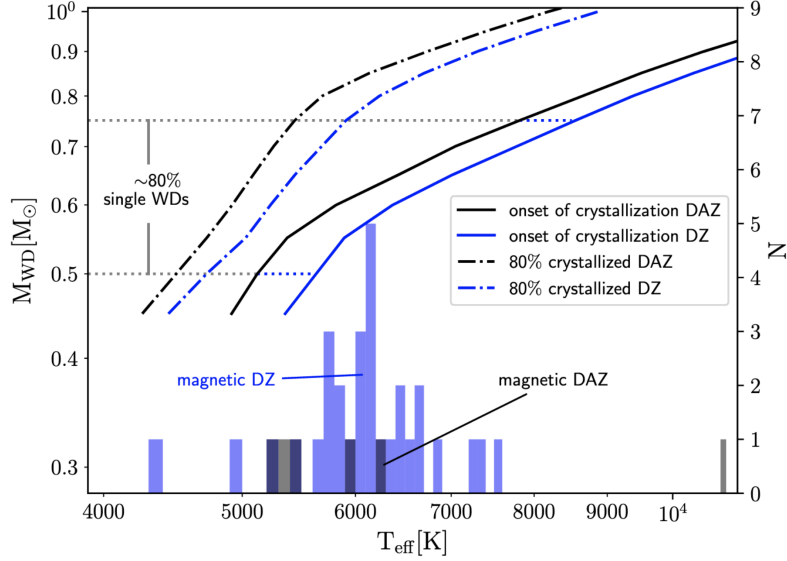


Figure 1.3: The crystallization process is shown for 80% completion (dotted-dashed lines) and the onset (solid lines). The models account for white dwarfs with thin (blue) and thick (black) hydrogen atmospheres. The crystallization starts at slightly higher temperatures in white dwarf with thin atmospheres. Magnetic white dwarfs presenting metals (i.e. DZ and DAZ; histogram) have effective temperatures in the range 5 000 – 9 000 K, which coincides that the core starts to crystallize for white dwarf masses corresponding to typical white dwarf masses

this accretion of mass should increase the angular velocity and, in consequence, shortening the rotation period (Schreiber et al., 2021b). It should be easier to find white dwarfs with shorter periods in binary systems that are Roche-lobe filling, but what happens with the single white dwarfs that are in the cosmos?

Single white dwarfs with strong magnetic fields are found among the coolest white dwarfs, therefore, they are the oldest white dwarfs. The temperature of crystallisation depends on the mass of the star. Most of the magnetic white dwarfs have a mass between 0.5 and 0.75 $M_{\odot}$, this means that almost all white dwarfs start to crystallize at a temperature around 8000 K (see figure 1.3). Analyzing the data of magnetic white dwarfs one can notice that all the magnetic white dwarfs with metals in the atmosphere (DZ) have an effective temperature under the 7500[K].

In Schreiber et al. (2021a) it is proposed that, since the single DZ white dwarfs can't accrete from a companion star (because they are single), the star gain mass by trapping in its gravitational field and eventually absorbing planets and asteroids. When a planetesimal or an asteroid are too close to the white dwarf, they are disrupted by the tidal force that the dwarf applies. The disruption this rocky material creates a circumstellar debris disk, from where the white dwarf accretes.

If this idea is correct, magnetic and crystallizing DZ white dwarfs should rotate faster than non-magnetic single white dwarfs. In this thesis I test this idea by measuring the rotational periods of magnetic white dwarfs using photometric observations.

Chapter 2

SPECULOOS

The first step was to take images of a sample of magnetic white dwarfs that are candidates to have short spin periods. For that purpose we use the telescope SPECULOOS. The SPECULOOS Southern Observatory (Delrez et al., 2018) is located in the region of Antofagasta, at the ESO Paranal observatory. The original aim of SPECULOOS was to detect extra solar planets, specifically planets orbiting ultracool dwarfs. SPECULOOS consists in an array of four telescopes, which each have two mirrors. The primary mirror has a diameter of one meter, meanwhile the coupled mirror has a diameter of 28 cm, and is located at a distance of 1.6 m. The mirrors are covered with a thin layer of aluminium which increases the reflectance.

The design of the telescopes provides a good aerodynamic and low resistance to wind, which is essential to facilitate the motion of the telescopes. The telescopes use “direct drive torque motors” (Delrez et al., 2018), which allows a very fast slewing and tracking without many errors. The control of the observatory can be done remotely, since the observatory is fully robotic. The only requirement is to have a good and stable connection to the internet.

Each telescope has a built-in thermoelectrically-cooled camera. This camera has a detector which provides a good sensitivity from ~ 350 nm to ~ 950 nm. Also the camera is optimized in the near Infrared spectrum. The camera’s field of view of the sky is $12' \times 12'$, and a pixel scale of $0.35''/\text{pixel}$. The camera has a very low-fringing in the near infrared. The camera is equipped with four readout speeds. Using the 1 MHz readout mode with a pre-amplifier gain of 2 electrons/ADU, provides a low readout noise of 6.2 electrons. The gain is 1.04 electrons/ADU with these settings. Also, each camera is provided with a filter wheel. This wheel allows ten 5×5 cm different filters. The filters that SPECULOOS uses are Sloan- $g', -r', -i', -z', I + z$ and blue-blocking (see Figure 2.1).

Also the complex is equipped with a Boltwood Cloud Sensor II, a weather station that allows to monitor the cloud cover, wind speed, humidity, dew point (temperature where the water vapor starts to condensate into liquid) and the amount of light that comes from the Sun. Finally, the telescopes are equipped with an uninterruptible power supply.

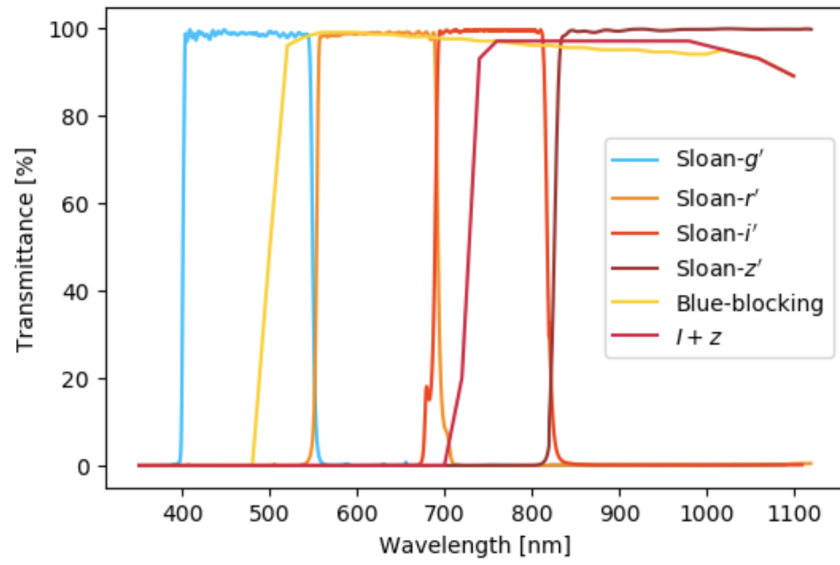


Figure 2.1: Transmission curves of the broad-band filters that are available in the SPECULOOS Southern Observatory. Figure taken from [Delrez et al. 2018](#)

Chapter 3

Photometry

Photometry is the science of measuring light, specifically the flux or intensity of light. The photometry technique uses the different spectral regions of light as main source. In photometry, the brightness of an object is not measured over the whole spectrum, instead one typically uses different types of filters (e.g. see Figure 2.1), which help us to derive information about the stars. The filters limit the wavelength range of the photons that are detected. For example, if we use different types of filters, we can know the effective temperature of the star. That's possible because T_{eff} determines in which filter it is brighter.

When we detect and observe a star, we are measuring the light at a given moment. But, the amount of light that we detect from a star varies in time. The reason of this change of the amount of light has different origins, but we can classify them into two categories: intrinsic and extrinsic.

The intrinsic changes are produced by the emitting objects. Some types of stars that exhibit these intrinsic changes are pulsators, where the shape, size and temperature of a single star can change in time or binary star systems in which one star accretes material from a companion and physical processes around the star can make rapid changes in the light emission. The variability I expect to identify in this work, is produced by the rotation of white dwarfs that have dark spots produced by their magnetic fields. The time scales of all these different variations cover a wide range, from second to days, from days to years (Beck et al., 2015).

Meanwhile, the extrinsic changes are caused by factors outside the star or the system. The most common factor is the Earth's atmosphere. The distortion produced by the atmosphere is called seeing. The seeing produces smearing in the point spread function (PSF; which will be explained below) and some nights can it is not constant. This means that the intensity of the light is not the same in time and the star light covers a range of pixels. Another source of external variation of light is the sky glow. Other factor that produces extrinsic changes occurs in a binary stars and/or stars surrounded by exoplanets. One object can eclipse the other one thereby reducing the flux that we detect.

The most frequently used detectors are charge-coupled device (CCD) cameras. These cameras are photometers, so they can measure and record the photons that come to the CCD. It is important to know that the CCD can't exceed a certain amount of light (i.e. it saturates). The reason is that, when you go above the "full well depth", the image that the camera takes will be contaminated.

If saturation can be avoided, the light that comes to the CCD produces a shape in the image. The function describing this shape is called point spread function (PSF). The shape of the PSF can be approximated by Gaussian or Moffat functions. The core value in this function is the full

width at half maximum (FWHM), which is “the diameter where the flux falls to half its central value” (Romanishin, 2002).

To counteract the noise that occurs when taking pictures of celestial bodies, other types of “frames” are taken and a different type of analysis is needed. These frames and procedures allow us to detect the location and intensity of the noise. With that information one can obtain a better picture of the object of study. These images which help us to quantify and correct the noise are called support frames. This type of pictures are known as bias, dark, and flats.

3.1 Bias

Bias frames or Offset is one of the most common calibration frames or “support frames”. A bias consists in taking a picture with no exposure time in the dark by covering the lens. It is a common practice to take several biases, then they are stacked all the pictures together into a single master (see section 3.4) and, with a program, we eliminate calibrate the camera.

Every CCD has a dark fixed-pattern noise, a pattern that is the result of the manufacturing process and every image taken with this detector records this faint pattern. Bias frames are taken to correct for this noise by subtracting them from the science image.

3.2 Dark

The dark frames works in a similar way as the bias, but with one big difference and that’s that the dark frames need the same exposure time as the images. The difference between this two type of frames lies in the origin of the calibration that is needed. While the calibration in the bias frames has a electronic origin, in the scenario of the dark the origin of the noise is thermal.

Due the thermal energy, the CCD camera release a certain number of electrons. This released electrons are added to the photo and will affect the quality of this. This effect is known as dark current. The reason of why the exposure time of the darks must be equal to the exposure time of the images is that, with a longer exposure time, higher is the effect of the dark current.

3.3 Flats

Flats are another very common method of calibration frames. The flat frames are used to detect the sensitivity of the pixels in the CCD camera. This allows the pixels to be calibrated so that they respond equally to light sources with the same photon flux.

There exist two type of flats the dome flats and the sky flats. Although the way to take flats is different, the goal is the same: detect which pixel has a higher sensibility. The importance of this is that, if there are photograms with a higher sensibility than others, this can induce noise in the image.

Unlike the bias or darks, in the dome flats the input of the camera has to be illuminated with a uniform white light, with the idea of taking images to a uniformly illuminated background that locates somewhere inside the dome (sometimes a white wall, or a white cloth). Flats are combined with a statistical function, making a masterflat (section 3.4).

Instead of Dome-flats, one can also take sky flats which are taken just when the sun hides at the horizon. The telescope points to the sky and take the flat frames. The advantage of the sky flats is that the light comes uniformly to the telescope. Since the flat dome is illuminated by a flashlight or a projector, the light that reaches the camera has some maximum and minimum intensity. But in the sky flat this doesn't happen. Another difference is that one must move the telescope between each flat frame. The reason is that, as you're pointing at the sky, stars appear in the pictures and the stars create a zone where the pixels receive a great number of photons. For that reason one must move the telescope, so this way, when one combine the flats, the areas of star light can be removed.

To remove the pixel-to pixel variations in sensitivity (e.g. through dust) the science image is divided by the master flat frame.

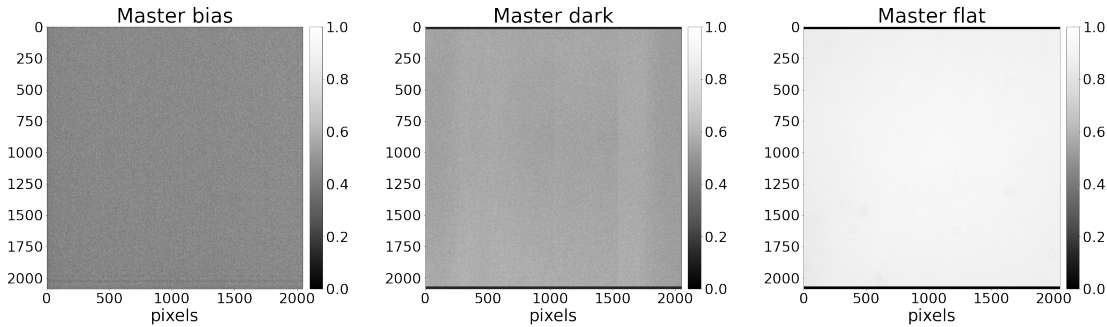


Figure 3.1: From left to right are shown the masterbias, masterdark, and masterflat of the brightest system observed with SPECULOOS: WD 2138-332. The masterbias and masterdark have 300.755 ± 2.683 and 0.315 ± 0.101 counts, respectively. The masterflat is built by median-combining 6 skyflats which each has a much higher count level, and each skyflat is normalised using the mean of each individual skyflat before they are combined. The count rate is 1.000 ± 0.142 .

3.4 Masters

Once all the images and support frames have been taken, the process of reducing the image begins. The first step is to create what we call Masters. The masters are the result of processing each type of support frame. Therefore, exist a masterdark, a masterbias and a masterflat. Once one obtain the masters, begins process of noise elimination. Each light frame is corrected by these three Masters. And depending on the instrument and purpose of the science the way of how the masters are created (e.g. what formula is used). Given that in this work I used SPECULOOS photometric data, I will explain in more details in the method section how these masters are created. Examples of these masters are shown in Figure 3.1

3.5 Aperture Photometry

Once the light images have been reduced and corrected, the flux for each of the stars in the field can be extracted. And if the corrected images are stacked as a function of time, we can identify flux fluctuations (either intrinsic or extrinsic) in time. There is when the term aperture photometry

plays a role to measure the flux of the stars. There are several ways to do photometry like circular, elliptical or rectangular. The simplest one is the circular aperture.

The circular aperture consists of enclosing in a circle the chosen star, in this way, the flux of the star is obtained. But how can we fix the extra flux that comes from the background? To solve this problem around the aperture a concentric annulus is defined for which also its flux is measured, which allows us to determine the average flux of the background (see figure 3.2). In a nutshell, the measurement aperture measures the total counts of light and the sky annulus measures the sky signal per pixel.

As it can be seen, it is important to set right the values of both variables, because, a very small aperture will not detect all the flux of the star, but a very big one will not detect the object, because it's signal is too little. On the other hand a very big sky annulus will detect more light than the background have, because it can detect light from other stars (Romanishin, 2002).

Once the fluxes of the stars are extracted they can be compared in order to determine the type of variability of certain stars in the field.

3.5.1 Differential photometry

As I mentioned above, there are different origins of why the luminosity of the star its not the same all the time. That is why two methods were created to help eliminate the variation of light that is not intrinsic to the star. These two types of photometry for variables stars are known as differential photometry and relative photometry. The first one measures the brightness of the target and a nearby star in the field simultaneously. The other one compares the target with a star that has a known fixed magnitude. The one that I used in this project is differential photometry.

In differential photometry one must choose a certain number of objects to use as references. It is important that the chosen objects must be stars. It is better if the star selected as a reference presents low flux variation. Once it has been verified that the objects are stars, the process of the differential photometry begins. One takes the data on the luminous intensity of the body under study and the reference stars. A comparison is made between the reference stars and the object of study. Then, a detailed search can be made to identify at which times of the night the object of interest and the comparison stars present variations in their fluxes. If these variations coincide in time, it means that this change is not intrinsic from the star. In other words, one can see the effect of the atmosphere over the intensity of the light that comes to the telescope. This is very relevant because the difference between the object of interest and the comparison stars can greatly diminish the fluctuations of Earth's atmosphere in the dataset of the object of interest.

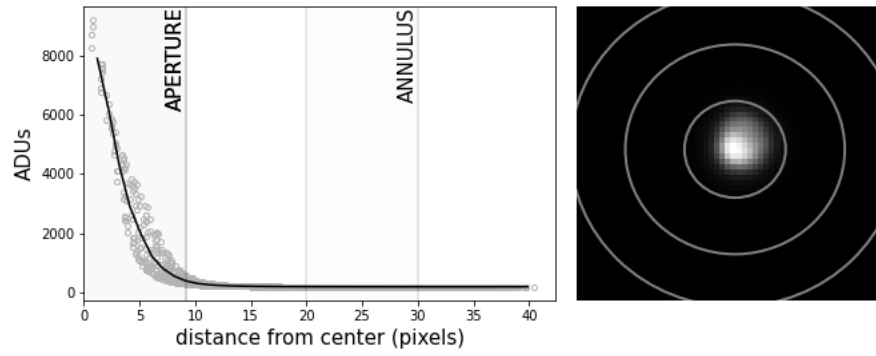


Figure 3.2: Aperture photometry performed on one of the magnetic white dwarfs: WD 2138-332. *left*: The curve that it is observed corresponds to the amount of light as a function of the CCD pixels measured from the center of the target to the void. The aperture and the annulus radii can be defined quantitatively. *right*: Correspond to the graphic representation of the aperture and the annulus over the selected target.

Chapter 4

Methods

To test the predictions of the crystallisation and rotation driven dynamo, I studied metal polluted white dwarfs which are candidates to have short spin periods, since they are accreting planetary debris. Thus, I analyse photometric data of the brightest magnetic white dwarf sample listed in Table 1 in [Schreiber et al. \(2021a\)](#) (See Table 4.1). The white dwarfs that are visible from the south were observed with SPECULOOS South under the programs 0107.A-9010(A/B/C/D) and 0107.A-9011(A/B/C/D).

Table 4.1: Log of the observations. In general, all the observations have use the SDSS g' filter. The target SDSSJ003708.42-052532.8 (in bold) provides a spin period measurement which is not reliable given the small number of images. The detection algorithm of PROSE was not able to identify the target LSPM J0107+2650 given the low quality of the images (i.e. clouds were present during these observations on 18-10-2021). The last three images in the target WD 0315-293 were taken when the sky was very bright at the end of the night, and thus they were removed during the analysis.

Name	Date (DD-MM-YYY)	RA	Dec	G (mag)	exp. time (s)	number of images
WD 2138-332	10-09-2021	21 41 57.56	-33 00 29.80	14.4638 ± 0.0005	60	376
WD 0322-019	10-09-2021	03 25 11.05	-01 49 15.05	15.9166 ± 0.0028	150	66
LSPM J0107+2650	16-10-2021	01 07 28.61	+26 34 28.29	18.9277 ± 0.0037	1000	18
	17-10-2021				1000	18
	18-10-2021				1000	12
WD 0315-293	03-11-2021	03 17 12.09	-29 11 34.21	17.228 ± 0.003	360	43
SDSSJ003708.42-052532.8	01-09-2021	00 37 08.42	-05 25 32.80	19.749 ± 0.004	600	8

4.1 Photometric data with SPECULOOS

During the observations, the setup of SPECULOOS/Y4KCam was the same: i.e. the SDSS g' filter was used and 2×2 binning was set in order to reduce overheads. The filter g' fully covers the Balmer lines (β and γ) and several of the strongest helium lines usually present in white dwarfs.

The standard calibration was used which consists of 9 biases, 14 darks and 6 skyflats. The exposure times for darks and skyflats are [60-1000] [s] and [6-15][s], respectively. Due to the different brightness of the targets the exposure time of the science images varies where the brightest have the shorter exposure times (see Table 4.1).

4.2 Process of reduction and calibration

To make this analysis of reduction and calibration of the images I used the program PROSE (Garcia et al., 2022). PROSE is a Python framework that allows us to work with the images through processing pipelines. PROSE utilize three key words to work: Images, Blocks and Sequences. The images encapsulates the data of a single frame. The Blocks command acts on the images and they are single processing units (in simple words it is the task that is applied to the images). Lastly, a Sequence is a series of Blocks. So with these keywords we can say that PROSE is an assemble of sequences. Some of the blocks that I used during the reduction, calibration and processing of the images were: Calibration, SegmentedPeaks, Gaussian2D, DAOFindStars, PhotutilsAperturePhotometry, XArray, among others. The role of each will be explained below.

PROSE consists in four sequences for photometric reduction. The first sequence consists in detecting the N brightest stars from one image. Then, these stars will be used as a reference for the rest of the images during the stacking process in sequence 2. During the second sequence each image goes through bias, dark and flat calibration (more details on the corrections applied to the images in section 4.2.1). Once the calibration process is completed, the position of the stars detected in Sequence 1 are used to align the images. On each image the pipeline attempts to detect the same N stars and compare their position to the references. When the images are aligned, the program builds a stacked image, and saves the *affine* transformation that each image needed to the reference image. In sequence 3, PROSE detects the stars in the stacked file and characterize the profile of the detected stars. Finally, in sequence 4 the flux of the detected stars are extracted using circular aperture photometry in each calibrated frame, however as the images are misaligned, the inverse transformation matrix previously computed and stored for each exposure is applied to the apertures.

The Blocks mentioned before act during the sequences and perform the following functions: *Calibration* block performs the Bias, Darks and flat calibration; the *SegmentedPeaks* performs the detection of the position of the stars; *Gaussian2D* characterised the effective point spread function; *DAOFindStars* detects the references stars in the images; *PhotutilsAperturePhotometry* performs the aperture photometry; and *XArray* saves the fluxes and other measurements.

4.2.1 Reduction process within PROSE

Once the different frames where taken, I combined the different support frames to get their masters. The equations that models the masters are:

$$masterbias = \text{median}[bias_i] \quad (4.1)$$

$$masterdark = \text{median}[(dark_i - masterbias)/t_{\text{exp}}] \quad (4.2)$$

$$masterflat = \text{median}[flat_i - masterbias - masterdark \times t_{\text{exp}}] \quad (4.3)$$

where t_{exp} is the exposure time. It is worth to note that the median was used and not the mean value for creang the masterflat. The reason is that, the skyflat frames contain different other astronomical objects and these objects produced that some pixels of the camera receive

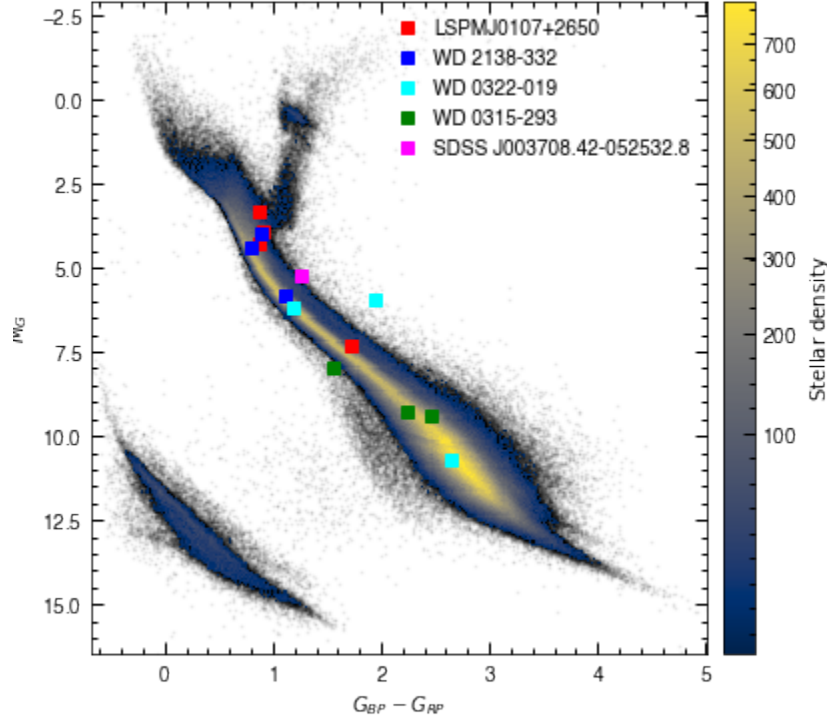


Figure 4.1: *Gaia* color-magnitude diagram built from the objects within <200 pc, (additional filters taken from section 2.1 in [Gaia Collaboration et al. \(2018\)](#) were applied). Overplotted are the comparison stars which fall on the main sequence

more photons than others. So, if I use the mean value these objects will introduce noise in the masterflat. Figure 3.1 shows the master files obtained for the white dwarf WD 2138-332.

Based on these files the images are corrected as:

$$\frac{image_i - (masterdark \times t_{exp} + masterbias)}{masterflat} \quad (4.4)$$

4.2.2 Aperture Photometry

Once the images are corrected, it is necessary to identify the object of study. For this purpose I search the object using the finding charts in the astronomical database SIMBAD. To do that I made a crossmatch with *Gaia* and use the *Gaia* ID to ensure I found the target. Once the white dwarf has been found I select three or four stars that act as reference stars for differential photometry. I use three criteria to determine if the object in the field of view of the image corresponds to a main sequence star: (1) I look in the SIMBAD database if the candidate correspond to a star, (2) I look

Table 4.2: Values of the parameters used in the aperture photometry

Name	FWHM (Pixels)	Aperture radius (Pixels)	Inner radius (Pixels)	Outer radius (Pixels)
WD 2138-332	7.01	8.67	20	30
LPSM J0107+2650 ^a	5.44	7.5	20	30
LPSM J0107+2650 ^b	5.97	7.5	20	30
WD 0322-019	3.83	10	20	30
SDSS J003708.42-052532.8	3.23	7.5	20	30
WD 0315-293	4.24	6.5	20	30

in the *Gaia* database for its effective temperature and (3) I determined their position in the *Gaia* color-magnitude diagram (see Figure 4.1). Several of the stars in the images were not entries in the SIMBAD database, making my first criterion very unsuccessful. The combination of the latter two criteria provided the majority of the comparison stars. All those stars in which their temperatures are available and in the range 5000 – 6500 K. The fluxes of the objects can have big variations. In this case, I select the best two to four main sequence (candidates) stars as comparison stars, in order to mitigate any intrinsic variation of the reference stars (their lightcurves are shown in grey in the left panel in Figure 4.2).

Once my object and the reference stars are selected (see Figure 4.3) the next step comes i.e. measure the light intensity. The intensity of the white dwarf is measured using the aperture photometry. In this case I used the simplest aperture: the circular aperture. I used the Moffat2D function as the point spread function. The values that I chose for the aperture, inner radius and outer radius and the FWHM obtained are listed in Table 4.2. As you can see in the charts, the values for the aperture radii are not equal. This is due to the number of pixels used by each object in the image.

Figure 3.2 shows the aperture and the annulus chosen for the white dwarf WD 2138-332. The next step is to subtract the background flux measured in the annulus to the flux within the aperture. Finally, I perform the differential photometry.

4.3 Extracting the differential lightcurves

Once the noise has been corrected in the images and the aperture photometry has been performed, I can obtain the differential light curves of the white dwarfs. These light curves allow us to see real flux variations of the white dwarf, which must be produced due to internal processes of the star. As it can be seen on the top curve in Figure 4.2, the data can be approximated by a sinusoidal function (in the next section I will explain how I get this solution) and it clearly shows that the flux of the white dwarfs vary over the time.

When I am calculating the light curves, several factors must be taken into account, one are the systematics. Figure 4.2 (right panel) show systematics for the white dwarf WD 2138-332, where parameters have the following meanings:

- dx and dy : correspond to the shift produced when the images are aligned. These parameters are used when doing the affine transformation of the images during the photometry.

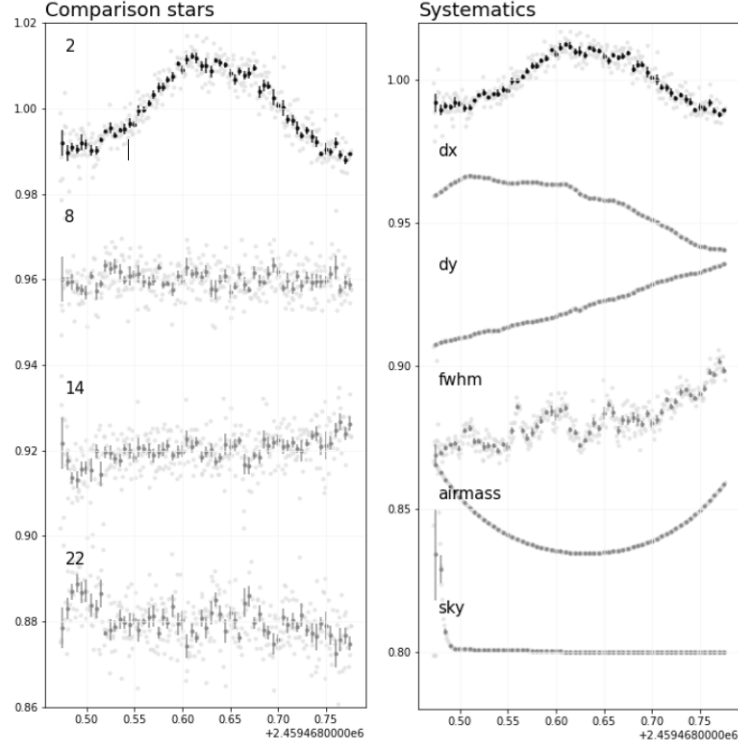


Figure 4.2: The *left* image correspond to the light curves of WD2138-332 and the comparison stars used to extract the differential photometry. They can be found enclosed in a blue circle (WD2138-332) and yellow circle (comparison stars) in Figure 4.3, while the *right* panel shows the systematics that can affect the process of differential photometry.

- *FWHM*: The Full Width at Half Maximum indicates the width of an aperture curve measured at half of the maximum amplitude. They are given in pixels units.
- *airmass*: It correspond to the amount of air that the light of the objects must to pass through to reach the telescope. The function starts in a maximum because the telescope points near the horizon. As the night passes, the mass of air that the light must pass through decreases until the object reaches its zenith. After this the air mass starts to increase again until the objects land on the horizon again.
- *sky*: This parameter correspond to the amount of light present in the night sky at the time of the observation. The reason why the telescope points to the sky with so much light is because the Sky flats were taken using the remaining sunlight after the sunset.

For the case of WD 2138-332 (Figure 4.2) the full width at half maximum presents a lot of fluctuation indicating a very unstable seeing during the observations. The sky was quite bright at the start of the observations.

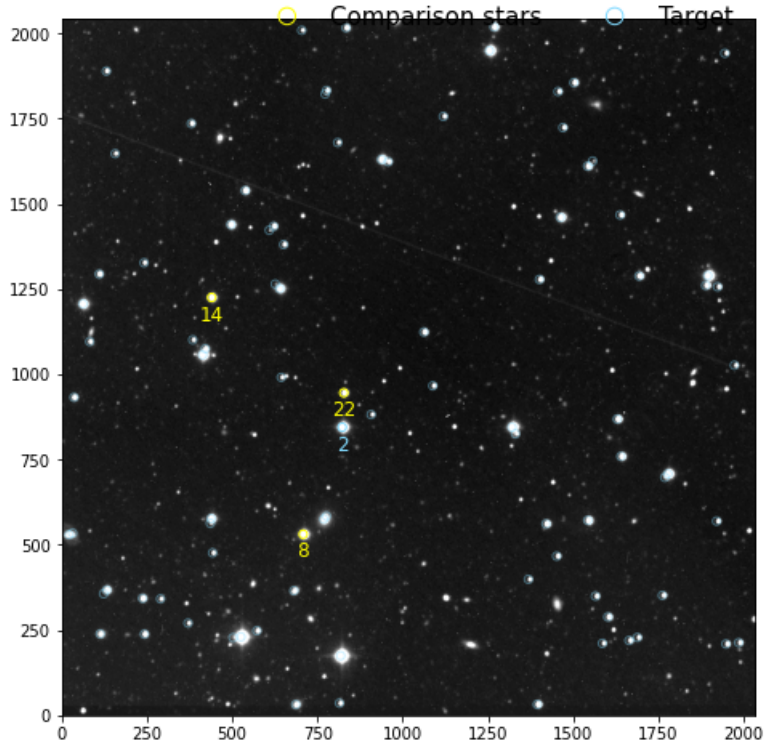


Figure 4.3: Stacked image for the field of the white dwarf WD 2138-332. The white dwarf is enclosed by a blue circle labelled as 2. The other three objects (yellow circles; 8, 14, and 22) are the reference stars used for the differential photometry.

4.4 Periodogram: Lomb-Scargle

The last step in this project was the creation of a periodogram. The periodogram that I selected to work was the Lomb-Scargle periodogram. The Lomb-Scargle periodogram is an algorithm that allows the detection and characterization of periodic signals that present a non-homogeneous distribution. The algorithm can process this type of data by relying on Fourier analysis (VanderPlas, 2018). That's why the Lomb-Scargle periodogram is known as one of the best techniques to calculate the periodicity of unequal spaced data. To make this possible it was necessary to use the software PERIOD04 (<https://www.univie.ac.at/tops/Period04/>).

PERIOD04 is a program created to the statistical analysis of large astronomical time series. This program allows to extract the individual frequency from multiperiodic data. The first step was to import the lightcurve obtained with PROSE, i.e. the times in JD, the differential fluxes and their errors. Then, using the Fourier transform to calculate the power spectrum, the program calculates the frequency and the amplitude of the data. The power spectra for some of my objects are shown in Figure 4.4. The results were introduced into the fitting formula:

$$Z_0 + \sum A_i \times \sin(2\pi(\Omega_i * t + \Phi_i)), \quad (4.5)$$

where Z_0 is the zero point, A the amplitude, Ω the frequency of the data, t the time and Φ the phase that the data have with respect the sinus function. The results obtained from PERIOD04 are shown in Table 4.3:

Table 4.3: Best-fit values obtained from the data by PERIOD04. ^a observation taken on 17-16-2021, ^b observation taken on 18-16-2021, ^c combined data. The fit for SDSS J003708.42-052532.8 is not reliable since the small number of data points

Name	Zero point	Amplitude	Frequency (1/d)	Phase	Nyquist frequency
WD 2138-332	1.0011 ± 0.0002	0.0103 ± 0.0003	3.79 ± 0.06	0.929 ± 0.004	613.189
LSPM J0107+2650 ^a	1.01 ± 0.01	0.15 ± 0.01	4.78 ± 0.05	0.19 ± 0.03	42.7721
LSPM J0107+2650 ^b	1.02 ± 0.04	0.14 ± 0.04	5.3 ± 0.2	0.43 ± 0.05	42.788
LPSM J0107+2650 ^c	1.009 ± 0.009	0.15 ± 0.01	5.0 ± 0.2	0.5 ± 0.1	42.6536
WD 0322-019	1.000 ± 0.001	0.006 ± 0.001	184 ± 5	0.72 ± 0.03	269.883
SDSS J003708.42-052532.8	0.96 ± 0.08	0.10 ± 0.08	8.2 ± 0.6	0.04 ± 0.05	42.6995
WD0315-293	0.9999 ± 0.0009	0.004 ± 0.001	82.5 ± 0.3	0.50 ± 0.03	116.489

My best fit model obtained is overplotted in red on the light curve, which is shown for some of my objects in Figure 4.5, Figure 8.1 and Figure 8.3.

Like all models used in science and as it can be seen, this model presents errors when comparing it with the data. To calculate these errors, PERIOD04 has implemented a Monte Carlo simulation. A Monte Carlo simulation or the Monte Carlo model is based on the creation of models of possible results. In PERIOD04 a dataset is created by using the same time strings, and the fluxes are calculated from the last fit plus Gaussian Noise. This dataset is fitted using least-squares calculation. This process is repeated several times to create a distribution of the best fit parameters. The uncertainties are obtained from these distribution. I choose to repeat this process 10 000 times to obtain a reliable result. The errors are also shown in Table 4.3

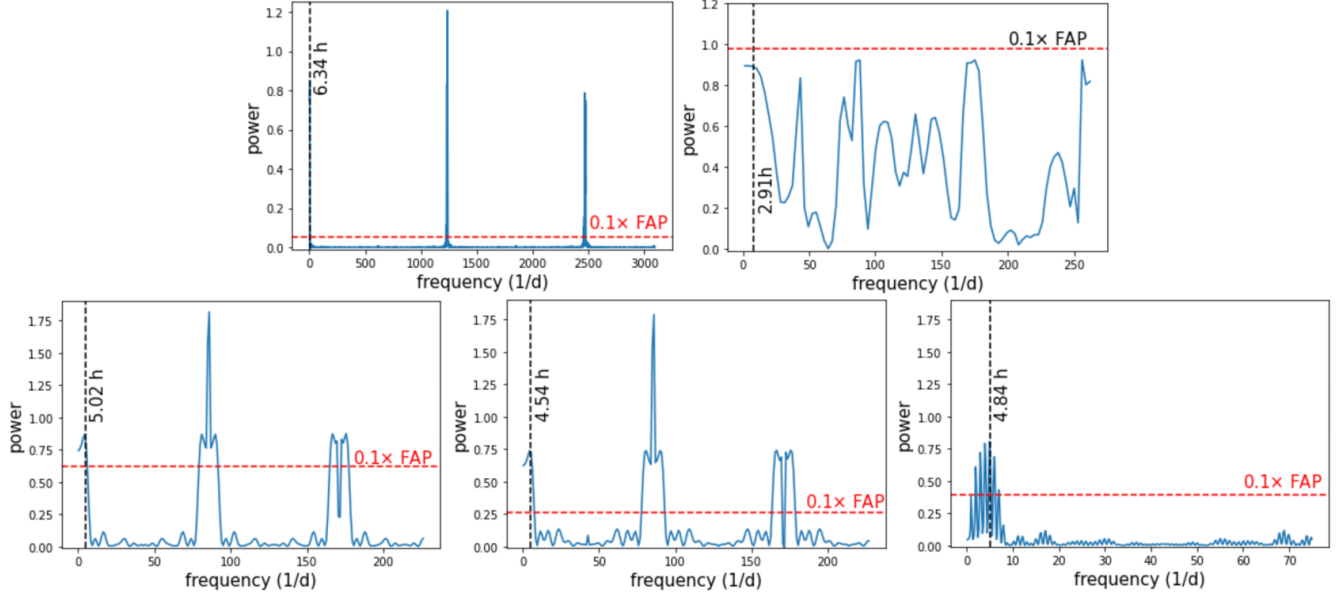


Figure 4.4: Lomb-Scargle periodograms using a 10% false alarm probability. The *top left* panel correspond to WD2138-332. In this panel it is clear that the peaks that one can see correspond to a signal and is not provoked by the noise. This also can be seen on the *bottom* panels, that correspond to LSPM J0107+2650. The *bottom left* panel correspond to the night 16/10/2021, the *bottom middle* panel to the 17/10/2021 and the *bottom right* panel to the combined data of the two nights. On the other hand, the *top right* panel correspond to SDSS J0037-0525, where the fluctuations of the power are below the false alarm probability, which means that the periodicity of the data is pure noise and it is not conclusive to the project.

4.4.1 Peak Significance and False Alarm Probabilities

The Lomb-Scargle periodogram shows us the periodicity of a given dataset. But how can we know that the data have a real periodicity and it is not caused by the noise? To determine when a peak correspond to a signal or it can be considered as noise, I use the false alarm probability.

The false alarm probability consists in identify the probability that the peak occurs within a given data which only contain noise. This means that, the higher the value that the peak reaches, it is a lower probability that the peak will repeat in the periodogram and, therefore, the lower the probability that it will be noise. To estimate this probability a bootstrap simulation is used. The bootstrap simulation is a method where it computes many random resamplings of data. In other words many random Lomb-Scargle periodograms are built by drawing the observed values with replacement but the temporal coordinates remain the same. From these “simulated” periodograms the maxima are extracted. The distribution of these maxima will approximate the true distribution for the case with no periodic signal present. The bootstrap produces the most robust estimate of the false alarm probability because it makes few assumptions about the form of the periodogram distribution ([VanderPlas, 2018](#)).

This function gives us the values that the high peak need to surpass such that they can be considered as significant detections. This means that, given a certain probability, we receive a peak value that marks the limit between noise and signal. In the case of the project I use a 10% false

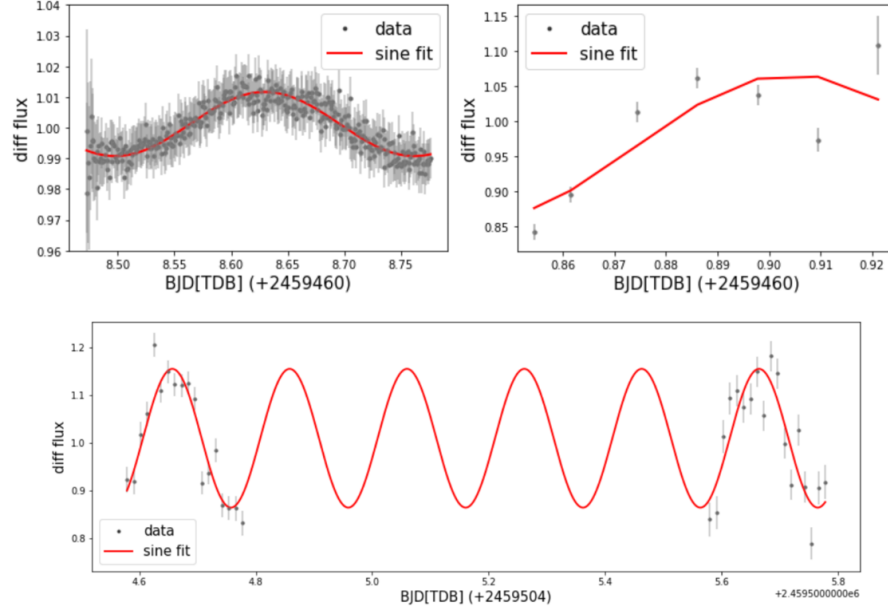


Figure 4.5: The grey points correspond to the data obtained during the observation nights and the grey lines correspond to the error that the flux have, while the red curve correspond to the calculated adjustment. The *top left* panel correspond to the best fit obtained in this project (WD2138-332). On the other hand the *top right* panel correspond to the worst fit due the lack of points (SDSS J0037-0525). The bottom panel correspond to the same object (LSPM J0107+2650) observed in two nights in a row.

alarm probability to test the quality of the Lomb-Scargle periodograms of the targets studied. The false alarm probability is shown with a red dashed line in Figure 4.4, Figure 8.1 and Figure 8.3. The result was that three objects (WD 0322-019, SDSS J0037-0525, and WD 0315-293) don't have value higher enough than the required value. This means that they don't give any information about their period. On the other hand, WD 2138-332 and LSPM J0107+2650 have peaks above the false alarm probability level, this implies that these peaks correspond to signals and that they are not a product of the noise in the dataset.

Chapter 5

Results and Discussion

The SPECULOOS data processed with PROSE program allowed me to extract the light curves which I then searched for periodicities using the Lomb-Scargle periodogram implemented in PERIOD04 (see figure 4.4). I found that two out of five magnetic white dwarfs present a significant period which is 10 per cent above the False Alarm probability (red line in Figure 4.4). I discuss in more detail the systems for which I was not able to measure the spin period in Section 5.2.

For the two targets where I could measure a period, I obtained the Lomb-Scargle periodogram of the targets and fitted the light curves using a sinusoidal function. These systems add two more period estimates to the very small sample of magnetic white dwarfs which are likely to have crystallised cores and their spin periods are known (extracted from Table 3 in Brinkworth et al., 2013). My period estimates along to the ones from the literature (for which their masses are known) are shown in Table 5.1. In addition, also listed are the effective temperatures and masses that have been measured for some of the systems I studied in this work. I have extracted the masses of my objects from the Montreal white dwarfs database. Only the white dwarf SDSS J003708.42-052532.8 has an unknown mass. It is worth to mention, that the estimates of the mass in magnetic white dwarfs are quite debatable given that the Stark broadening affects the Balmer absorption lines, which are key features to be fitted with synthetic white dwarfs models to determine the mass.

5.1 Spin period distribution for magnetic and non magnetic white dwarfs

A key prediction of the dynamo produced according to the crystallisation-rotation theory is that the magnetic white dwarfs formed through this scenario should rotate faster than their non-magnetic counterparts. In order to have an increased sample of magnetic white dwarfs with known spin periods, I also include those from the sample of Brinkworth et al. (2013). However, only five magnetic white dwarfs from their sample have their mass and effective temperature determined (see Table 5.1) in order to evaluate if they have crystallised cores (blue stars in Figure 5.1). The Figure 5.1 shows that three systems have crystallised cores, the other two correspond to white dwarfs which are not crystallizing and therefore their field must have been generated by a different mechanisms, e.g. the merger model (see section 5.1.1).

Therefore, in total there are only five white dwarfs with crystallised cores for which their rotation periods are measured (two in this work plus three from the literature). The period

Table 5.1: Measured parameters from the literature for magnetic white dwarfs. The masses for my objects have been taken from the Montreal white dwarf database.

Name	B (MG)	Period (h)	T_{eff} (K)	Mass $M_{\odot}$	Reference
WD 2138-332	0.4	6.34 ± 0.10	7399	0.70 ± 0.02	1
LSPM J0107+2650 ^a	3.37 ± 0.07	5.02 ± 0.06	6190 ± 140		1
LSPM J0107+2650 ^b	3.37 ± 0.07	4.54 ± 0.14	6190 ± 140		1
LSPM J0107+2650 ^c	3.37 ± 0.07	4.84 ± 0.02	6190 ± 140	0.68-0.88	1
WD 0322-019	0.120	-	5310 ± 100	0.60 ± 0.01	1
SDSS J003708.42-052532.8	7.09 ± 0.04	-	5630 ± 120		1
WD 0315-293	0.519 ± 0.04	-	5200 ± 200	0.58	1
WD 0756+437	300-377	6.68 ± 0.03	8500	1.07	2
WD 1031+234	500-1000	3.53 ± 0.05	15000	0.93	2
WD 1533-057	31	1.890 ± 0.001	20000	0.94	2
WD 0533+053	20	0.45 ± 0.01	5790	0.71	2
WD 2329+267	2.3	2.767	11730	1.18	2

References: (1) This work, (2) [Brinkworth et al. \(2013\)](#).

distribution of this 5-object sample contrast significantly from the period distribution of non-magnetic white dwarfs (I obtained the period distribution for non-magnetic white dwarf using the sample from [Hermes et al. 2017](#)). These period distributions are shown in purple and pink in Figure 5.2 for the magnetic and the non-magnetic samples, respectively. It is clear that the magnetic sample presents shorter rotation periods. However, there are five non-magnetic white dwarf with periods in the range of that of the magnetic ones (periods shorter than seven hours; black dashed line in Figure 5.2)). Then the question arises: Why do these rapidly rotating white dwarfs do not have a strong magnetic field? And the answer is: Simply, because they do not have crystallised cores (black dots in Figure 5.1). In Figure 5.1 the red curve represents the point when white dwarfs start to crystallise. Above this curve, white dwarfs are crystallizing or they have already crystallised cores, while the objects below are not crystallised. The five non-magnetic white dwarfs that have short spin periods are below this curve because their effective temperatures are too high to allow for crystallisation of their cores. This means, that the non-magnetic white dwarfs on the left of the dashed line from Figure 5.2, do not have crystallised cores and for that reason the dynamo theory can not be applied to these objects, resulting in white dwarfs with no magnetic field.

5.1.1 The non-crystallised magnetic white dwarfs: WD 1031+234 and WD 1533-057

Despite the fact that the main idea of this project was to find short spin periods on magnetic DZ white dwarfs to test the crystallisation-rotation driven dynamo idea, there are two objects that can not be understood with this theory. As it can be seen in Figure 5.1 two white dwarfs (WD 1031+234 and WD 1533-057) are below the onset of crystallisation curve (red curve), which implies that they are not crystallising, however, these white dwarfs have a short spin period and

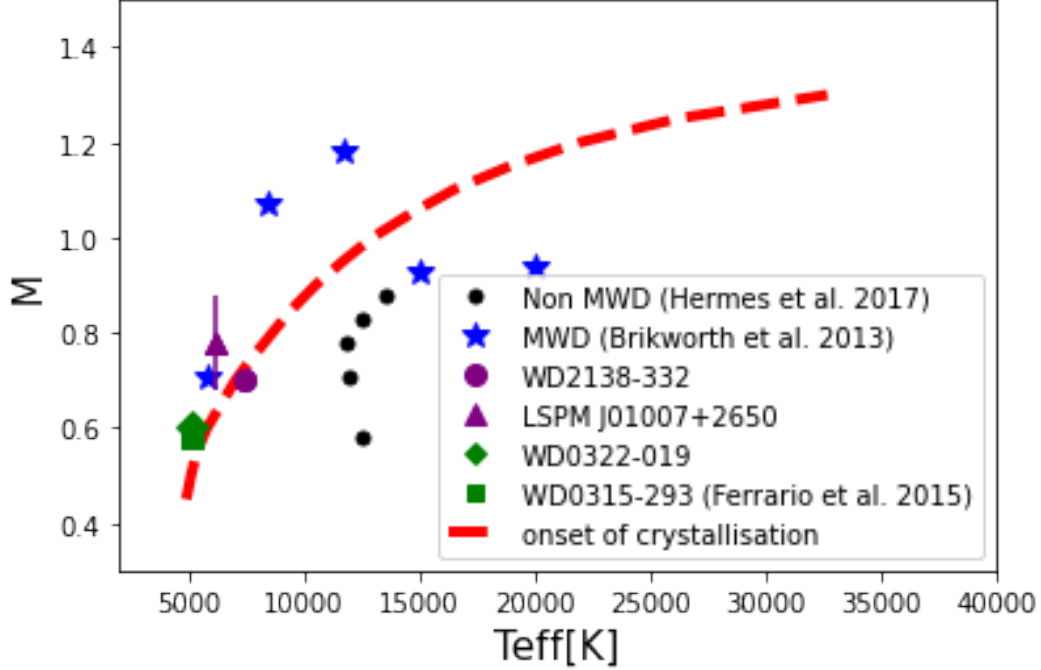


Figure 5.1: The crystallization onset of crystallization (red dashed line) is a function of the effective temperature and the white dwarf mass. More massive white dwarfs are able to start to crystallize at higher effective temperatures. Four out of the five systems studied in this work have their masses and effective temperatures known (green symbols). They all fall at or below the temperature for the onset of crystallization. Also shown are five magnetic white dwarf from [Brinkworth et al. \(2013\)](#) which their spin periods have been measured. In black dots are shown five non-magnetic white dwarfs having non-crystallised cores which present rotation periods shorter than seven hours (See Figure 5.2)

a strong magnetic field.

The most likely scenario for these two white dwarfs is that they are the result of the merger of two white dwarfs. This theory will also explain the high mass that WD 1031+234 and WD 1533-057 have, which corresponds to $0.93 M_{\odot}$ and $0.92 M_{\odot}$, respectively.

5.2 Non detection of the spin period for WD 0322-019 and WD 0315-293

As mentioned above, it was not possible to measure the spin period for three of the five white dwarfs studied in this work. One of the systems, the white dwarf SDSS J003708.42-052532.8, was discarded because it had too few data points to make a conclusive analysis (only eight images were taken; see Table 4.1). But for the other two white dwarfs (WD 0322-019 and WD 0315-293), the conditions were different. They have a large number of data points, have effective temperatures and masses necessary to start crystallising their cores and have a strong magnetic field, but I could not measure their spin period. What is the explanation for this behavior?

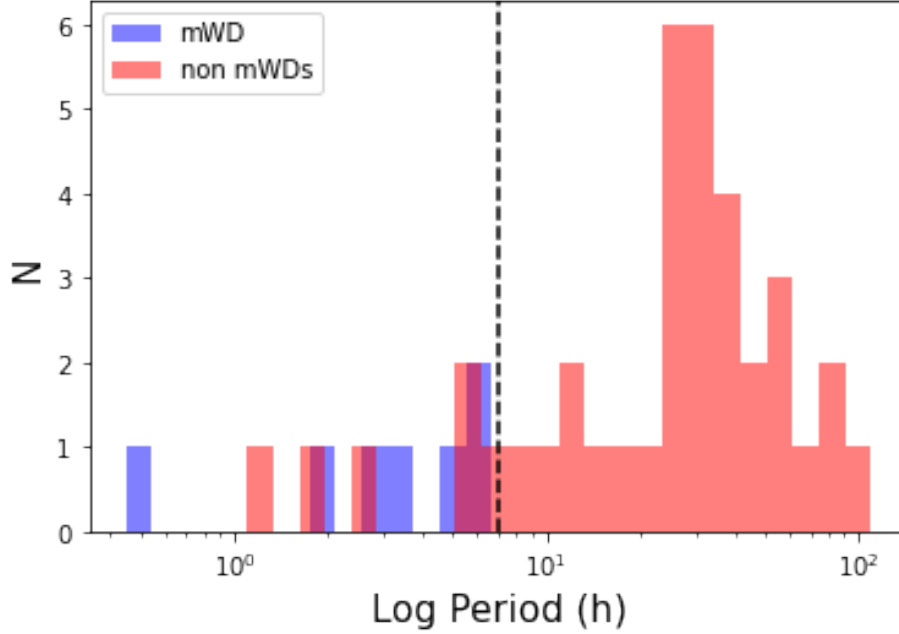


Figure 5.2: Distributions of the spin period of five magnetic white dwarfs with crystallised cores (obtained in this work and from [Brinkworth et al. 2013](#); purple) and non-magnetic white dwarfs (taken from [Hermes et al. 2017](#); pink). The dashed line corresponds to a spin period of seven hours and demarcates the maximum value of spin period that magnetic white dwarfs with crystallised cores have reached in this sample. There exist an overlap of the distribution, but the non-magnetic white dwarfs presenting period shorter than seven hours do not have crystallised cores, and thus they can not generate magnetic fields (see Figure 5.1).

The first argument is that the star spots and rotation do not produce large enough brightness variations. As mentioned before, the star spots are produced in cool magnetic white dwarfs due to a reduction of convection in the atmosphere. Thanks to these spots we are able to determine the white dwarf spin periods. If, however, small spots are more or less evenly distributed over the surface of the white dwarf, any variation in the light curve might have an amplitude that is too small to be detected with SPECULOOS.

As an alternative idea, if the spin period is of the order of a few minutes, the time resolution of my photometric data does not allow to detect the periodicities in the power spectra of the targets. This happens because the exposure times of the white dwarfs is several minutes (see Table 4.1). Obviously, spin periods of the order of the exposure times or shorter cannot be measured as each exposure would provide a brightness averaged over an entire spin period.

Finally, we note that the white dwarf masses from fits to the Balmer lines of magnetic white dwarfs are highly uncertain. At low magnetic fields the dominant broadening comes from the Stark effect which shifts or splits the spectral lines. Unfortunately, the Stark broadening of hydrogen lines in a magnetic field is complex and the problem is essentially unsolved. Therefore, these stars might have lower masses than estimated which could mean that they do not have a crystallizing cores (see diamond and square symbols in Figure 5.1). In this case, the magnetic field must have been generated by a different mechanism.

Chapter 6

Conclusions

The magnetic dynamo based on the interplay of the crystallization in white dwarfs ([Isern et al., 2017](#)) and their fast rotation could help to solve the big question of the origin of the high incidence of magnetism in cool DZ white dwarf. It also can explain the existence of an abysmal difference between the magnetic fields of white dwarfs. This theory, [Schreiber et al. \(2021a\)](#) predicts that magnetic DZ white dwarfs should have a shorter spin rotation period in comparison with non magnetic white dwarfs. This prediction has been the motivation for this project: measure the spin periods of cool magnetic DZ white dwarfs.

We observed five white dwarfs, for two of them we find short spin periods which supports the dynamo idea. In addition, three other objects observed previously by [Brinkworth et al. \(2013\)](#) are consistent with their fields being generated by the dynamo. Having found two new white dwarfs that meet the characteristics of the theory allows me to believe that this theory can be considered as an important channel for producing magnetic white dwarfs. I also found two most likely massive white dwarfs that are fast spinning in the literature which might be explained by the merger channel. Unfortunately, there is currently no database large enough to perform decisive tests of the different channels that have been proposed for the magnetic field generation in white dwarfs. I therefore plan to measure more spin periods in the near future.

Chapter 7

Future work

As discussed above it is very challenging to derive firm conclusions on the crystallization-rotation dynamo driven model based on the small sample of cool DZ white dwarfs I have built. One of my goals for the future is to enlarge this sample to perform a statistically significant study. We have recently been awarded observing time with SPECULOOS to measure spin periods of the bright and nearby white dwarfs in the sample of [Bagnulo and Landstreet \(2021\)](#).

Moreover, [Bagnulo and Landstreet \(2021\)](#) have updated the 20-pc sample of [Hollands et al. \(2018\)](#) using the *Gaia* early data release 3 and compiled all measured parameters of those that are magnetic white dwarfs. This sample contains object that are bright enough for the Transiting Exoplanet Survey Satellite (*TESS*). Hence, I will cross match the [Bagnulo and Landstreet \(2021\)](#) sample with *TESS* and hope to be able to measure their spin periods.

The brightness of this 20-pc sample allows an improved time resolution of photometric data for 1-m size telescopes. Thus, for those objects which did not fall within the footprints of *TESS* I will propose observations with SPECULOOS.

Chapter 8

Supplementary Figures

8.1 WD0315-293

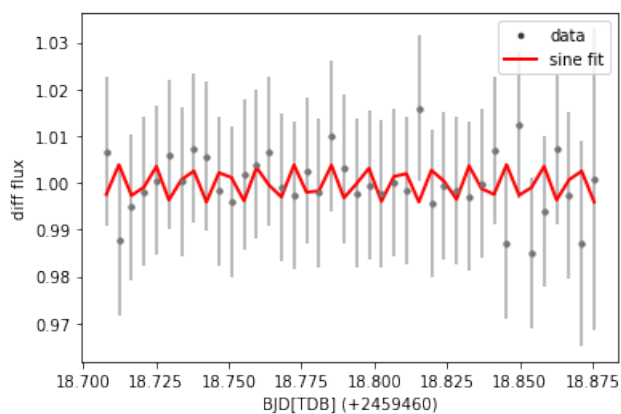


Figure 8.1: Caption

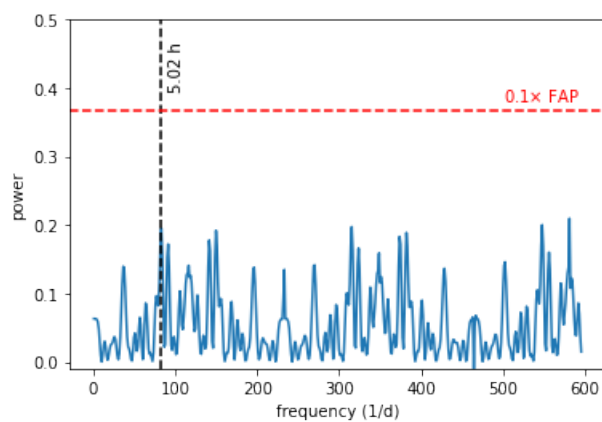


Figure 8.2: Caption

8.2 WD0322-019

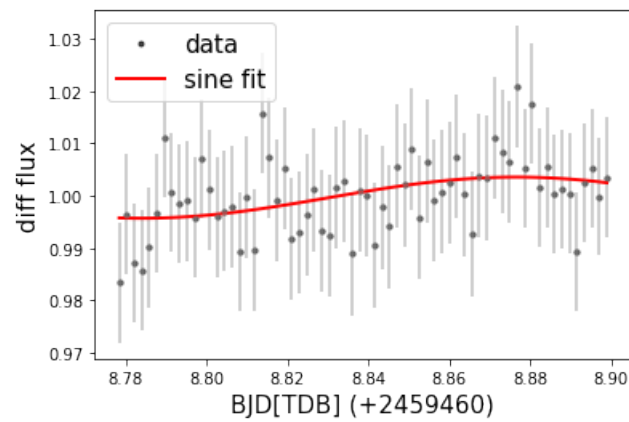


Figure 8.3: Caption

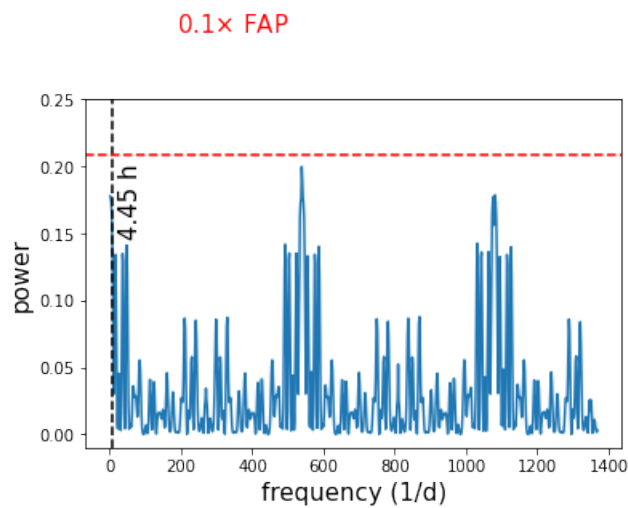


Figure 8.4: Caption

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