White Paper

GAIA and the end states of stellar evolution

Author list

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Chapter 1

Introduction

1.1 General remarks

Gaia is a satellite mission of the ESA, aiming at absolute astrometric measurements of about one billion stars ($V < 20$) with unprecedented accuracy (see e.g. Jordan, 2008, and references therein). Additionally, magnitudes and colors will be obtained for all these stars. Additionally, near infrared ($8470 – 8740 \text{ Å}$) medium resolution spectra will be taken with a resolution of $R = \lambda/\Delta\lambda = 11 500$, aiming at the determination of radial velocities for bright objects ($V < 17.5$).

The orbit of the Gaia mission has been chosen to be a controlled Lissajous orbit around the Lagrangian point L2 of the Sun-Earth system in order to have a quiet environment for the payload in terms of mechanical and thermo-mechanical stability. Another advantage of this position is the possibility of uninterrupted observations, since the Earth, Moon and Sun all lay within Gaia’s orbit. The aim of Gaia is to perform absolute astrometry rather than differential measurements in a small field of view. For this reason, Gaia – like HIPPARCOS – (i) simultaneously observes in two fields of view (FoVs) separated by a large basic angle of $106.5^\circ$, (ii) roughly scans along a great circle leading to strong mathematical closure conditions, (iii)
performing mainly one-dimensional measurements, and (iv) scanning the same area of sky many times during the mission under varying orientations.

These conditions are fulfilled by Gaia’s nominal scanning law: The satellite will spin around its axis with a constant rotational period of 6 hours. The spin axis will precess around the solar direction with a fixed aspect angle of 45° in 63.12 days. On average, each object in the sky is transiting the focal plane about 70 times during the 5 year nominal mission duration. Most of the times, an object transiting through one FoV is measured again after 106.5 or 253.5 minutes (according to the basic angle of 106.5°) in the other FoV.

The Gaia payload consists of three instruments mounted on a single optical bench: The astrometric instrument, the photometers, and a spectrograph to measure radial velocities.

The astrometric field consists of 62 CCDs and a star is measured on 8-9 CCDs during one transit. The accumulated charges of the CCD are transported across the CCD in time delay integration mode in synchrony with the images. In order to reduce the data rate and the read-out noise only small windows around each target star, additionally binned in across-scan direction depending on the object’s magnitude, are read out and transmitted to the ground.

Multi-colour photometry is provided by two low-resolution fused-silica prisms dispersing all the light entering the field of view in the along-scan direction prior to detection. The Blue Photometer (BP) operates in the wavelength range 3300–6800 Å; the Red Photometer (RP) covers the wavelength range 6400–10500 Å.

The RVS is a near infrared (8470 – 8740 Å), medium resolution spectrograph: \( R = \frac{\lambda}{\Delta \lambda} = 11500 \). It is illuminated by the same two telescopes as the astrometric and photometric instruments.

The astrometric core solution will be based on about \( 10^8 \) primary stars which means to solve for some \( 5 \times 10^8 \) astrometric parameters (positions, proper motions, and parallaxes). However, the attitude of the satellite (parameterized into \( \sim 10^8 \) attitude parameters over five years) can also only be determined with high accuracy from the measurements itself. Additionally, a few
million calibrational parameters describe the geometry of the instruments.

The current official launch date of Gaia is in May 2013. The launch vehicle is a Soyuz-Fregat rocket which will lift-off from Sinnamary in French Guyana. After a several-month commissioning phase Gaia will start its five year period of nominal measurements which can be extended by another year. About two to three years after the mission the final Gaia catalogue will be published. However, it is foreseen that several intermediate catalogues will be produced well before. After about 18 months of the measurements, a first astrometric solution will be possible which can solve for positions, proper motions and parallaxes of almost all stars with reduced accuracy.

The accuracy of the astrometric measurements depend on the brightness and spectral type of the stars. At \( G = 15 \) mag (Gaia magnitude, approximately equivalent to the \( V \) magnitude) the final accuracy in position, proper motion per year and the parallax will be 25 micro arcsecond. A somewhat larger accuracy is reached for red stars. At \( G = 20 \) mag the final precision drops to about 300 \( \mu \)as.

The end-of-mission photometric performance is of the order of 5-15 mmag, again depending on the brightness and spectral type.

### 1.2 Gaia’s performance for white dwarfs

Torres et al. (2005) have performed intensive Monte-Carlo simulations and arrived at about 400,000 white dwarfs down to \( G \approx V = 20 \) that will be detected by Gaia. For disk white dwarfs Gaia will be practically complete up to 100 pc and will observe about half of all white dwarfs within 300 pc, decreasing to one third at distances of 400 pc. Disk white dwarfs at the cut-off of the luminosity function \( (M_{\text{bol}} \approx 15.3, M_V \approx 16) \) can be detected up to distances of 100 pc, considerably improving the age determination of the solar neighborhood to about \( \pm 0.3 \) Gyr. Moreover, a detailed check of white dwarf cooling theory is possible by a careful analysis of the Gaia white dwarf luminosity function.
Additionally to the astrometric information mentioned above, the analysis of the BP/RP low-resolution spectra will be essential. If we add up all BP spectra for a give white dwarf for the entire mission, Balmer lines can be detected down to about $G = 18$ in hydrogen-rich (DA) white dwarfs close to the maximum of the Balmer line strength ($T_{\text{eff}} \approx 12,000$ K. For other atmospheric parameters the shape of the BP and RP spectra can be used to determine approximate effective temperatures. This information can be used to select the white dwarfs from the whole sample of observed stars.

However, a detailed analysis of white dwarfs will need follow-up spectroscopy (see Sect. ??) in order to determine their precise atmospheric parameters. Only with this information the scientific programmes described in this white book can fully exploit the valuable data from the Gaia satellite.

One of the major advantages of the Gaia sample of white dwarfs is that it constitutes an all-sky survey with very clear selection criteria. Biases introduced by unclear selection effects are certainly one of the major obstacles of statistical investigations of white dwarfs (Jordan, 2007). One can clearly conclude that white dwarf research will tremendously benefit from the Gaia data.

This white paper will provide an overview on the scientific exploitation of the Gaia data of white dwarfs. We will show which broad range of topics is connected to this research, from exoplanet research to a better understanding of our galaxy, from the improvement of our knowledge of the late phases of stellar evolution to test of physical theories.

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Chapter 2

Science

Some discussion of the science goals of GAIA and our goals in general; furthering WD science etc...

2.1 Mass-Radius relation

Two of the most important physical parameters that can be measured for any star are the mass (M) and radius (R). They determine the surface gravity (g) by the relation given in equation 2.1

\[ g = \frac{GM}{R^2}, \]  

where G is the gravitational constant. Hence, if \( \log g \) is measured the mass can be calculated provided the stellar radius is known. One outcome of Chandrasekhar’s original work on the structure of white dwarfs was the relationship between mass and radius, arising from the physical properties of degenerate matter. Further theoretical work yielded the Hamada-Salpeter zero-temperature mass-radius relation (Hamada & Salpeter, 1961). However, white dwarfs do not have zero temperature, indeed many are very hot. Hence, the Hamada-Salpeter relation is only a limiting case and the effects of finite temperature need to be taken into account. Several
authors have carried out evolutionary calculations, where the radius of a white dwarf of given mass decreases as the star cools. Those of Wood (1990, 1995), have a semi arbitrary starting point for the hottest models while the Blöcker et al. (1997) models are full evolutionary calculations from the AGB. Other calculations are available from Althaus & Benvenuto (1997, 1998) and Fontaine, Brassard & Bergeron (2001).

For the largest group of white dwarfs, the H-rich DA stars, there is a very powerful technique to determine log g and effective temperature ($T_{\text{eff}}$) based on fitting synthetic stellar spectra to the hydrogen Balmer absorption line profiles. However, the resulting estimates of the mass and radius have generally relied on using the theoretical mass-radius relation to remove the inter-dependence of M and R on g. While, the basic stellar models and white dwarf mass-radius relation are not in serious doubt, there are uncertainties that arise from the detailed input physics and higher-level refinements that take into account the finite stellar temperature and details of the core/envelope structure. Varying the assumed input parameters in these models can lead to quite subtle, but important differences in the model predictions as illustrated in Figure 2.1 which shows several different theoretical mass-radius relations along with the observed masses and radii of the white dwarfs in four well studied astrometric binaries.

### 2.1.1 Testing the mass-radius relation and stellar models

Direct observational tests are difficult. To break the reliance of mass and radius determinations on the theoretical models requires additional independent information on at least one of M or R. For example, accurate photometry of the stellar flux ($F_\lambda$) allows determination of R, provided we know the distance (D) as shown in equation 2.2

$$F_\lambda = 4\pi \left( \frac{R^2}{D^2} \right) H_\lambda,$$

where $H$ is the Eddington flux. Alternatively, if we can determine the gravitational redshift ($V_{\text{gr}}$) of a white dwarf we get a second relation between M and R, allowing us to solve for
Figure 2.1: Left: Fontaine et al. (2001) models “thick” (solid) and “thin” (dashed) hydrogen envelopes. Right: Models from Wood (1990, solid) and Althaus & Benvenuto (1998, dashed). The data for 40 Eri B, Procyon B, V471 Tau and Sirius B are respectively from Provencal et al. (1998, 2002), Bond et al. (2011; private comm), Girard et al. (2000), O’Brien et al. (2001) and Barstow et al. (2005).

Their values as shown in equation 2.3

\[ V_{gr} = 0.636 \frac{M}{R} , \]  

where M and R are in Solar units and \( V_{gr} \) is in km/s.

However, \( V_{gr} \) can only usually be measured independently if the white dwarf is in a binary system as its space velocity needs to be known.

Figure 2.1 represents the state of the art in the accuracy of M and R measurements based on available data. All four examples shown an accurate distance was obtained from the Hipparcos parallax of the main sequence companion. While parallaxes were measured for a handful of white dwarfs, these stars were very close to the magnitude limit for the mission and have consequently large measurement errors.
Gaia can potentially contribute to dramatic improvements in measurements of the mass and radius or white dwarfs, through much improved accuracy of parallax measurements for both isolated white dwarfs and white dwarfs in binary systems coupled with accurate photometry. However, these data will be insufficient on their own to distinguish between different evolutionary models. We will still require improved accuracy in the determination of $g$ and/or $V_{gr}$. Therefore, an extensive programme of supplementary ground or space-based spectroscopic observations will be needed to realise the full potential of the Gaia observations of white dwarfs.

2.1.2 Calibration and the Mass-Radius Relation

White dwarf stars and in particular pure hydrogen DA white dwarfs have long been used as ground-based and space-based photometric calibrators. With Gaia parallaxes it will be possible to do two things. First, as shown by Holberg & Bergeron (2006) and Holberg, Bergeron & Gianninas (2008) it is presently possible, using existing parallaxes, to establish a one-to-one correlation between observed absolute magnitudes and synthetic absolute magnitudes for DA white dwarfs. The synthetic magnitudes are calculated from the spectroscopic effective temperatures and gravities and need only be normalised at a single observed magnitude, say $V$-band. The photometric scale is that presently used is that established for the Hubble Space Telescope, which has an absolute accuracy of 1\% at visual wavelengths. The existing correlation between observed fluxes and synthetic fluxes in well characterised bands is also at the 1\% level (see Figs. 1 and 2 of Holberg et al. 2008). At present the largest source of uncertainty in these correlations are the existing parallaxes. Gaia parallaxes will virtually eliminate this source of uncertainty allowing the enhanced correlations to be extended to thousands of stars. In this way accurate absolute fluxes can be established for a large ensemble of standard stars that can be reliably used for space-based and ground-based calibrations.

The empirical relations between observed and synthetic absolute fluxes described above leads to the second way that Gaia parallaxes can be used investigate fundamental stellar astrophysics; observationally testing the degenerate mass-radius relation. Basically, Gaia paral-
laxes can be used to produce accurate estimates of white dwarf radii through the stellar solid angle and Eddington fluxes. Using such radii in binary systems containing white dwarfs, where the gravitational redshift can accurately be determined, represents a powerful opportunity to critically test basic temperature dependent mass-radius relations. Unless eclipsing systems are available, white dwarf radii are most easily estimated from absolute photometry and accurate parallaxes. If such radii are coupled with independent constraints on M and R from spectroscopic determinations of temperature and gravity and gravitational redshifts, then three independent measures of M and R are possible. Using these constraints and the associated uncertainties in M and R it is possible to construct contours of equal likelihood in the mass-radius plane; see Fig. 4 of Farihi et al. (2011) for an example of this type of analysis.

The particular programme advocated here is to prepare for the arrival of Gaia parallaxes by identifying a large sample of up to 100 binary systems containing DA white dwarfs where accurate photometric fluxes and spectroscopic, temperatures, gravities and redshifts can be obtained (a few suitable systems and observations already exist). These DA stars would be selected to densely and uniformly sample a range of masses between 0.5 Solar masses up to near the Chandrasekhar limit. The goal would be to systematically obtain the necessary ground-based observations, so that when Gaia parallaxes are available, independent mass and radius estimates can be promptly compared with theoretical mass-radius relations at the few percent level. This should allow robust statistical tests at the one percent level.

2.1.3 Eclipsing white dwarf / main-sequence binaries and the M-R relation

White dwarf plus main-sequence binaries are numerous throughout our Galaxy. Post common envelope binaries (PCEBs) are a type of close white dwarf / main-sequence binary with periods $\leq$ 1 day. A small number of these systems are inclined in such a way that, as viewed from Earth, they exhibit deep eclipses, as the main sequence secondary star passes in front of the white dwarf. These deep eclipses allow us to measure extremely precise radii which, combined
Figure 2.2: **Left:** Primary eclipse of the PCEB NN Ser from Parsons et al. (2010) with model fit over-plotted. The total eclipse duration is 12 minutes. In this case the radii of the two stars were measured to a precision of 1%. **Centre:** Light curve of the PCEB QS Vir from Parsons et al. (2010) showing out-of-eclipse variations due to the tidal distortion of the main-sequence star by the white dwarf. These effects can be used to determine the period of the system even in the absence of an eclipse. **Right:** Mass-radius relation for white dwarfs. The red point represents the mass and radius of the white dwarf in the PCEB NN Ser. It is the most precise model-independent measurement of a white dwarfs mass and radius to date.

with spectroscopic observations that yield the component masses, enable us to test mass-radius relations for both the white dwarf and its, often low-mass, main-sequence companion. A typical eclipse of a PCEB is shown in the left hand panel of Figure 2.2. The sharp ingress and egress features allow us to measure radii to a precision of $\sim 1\%$ in a way that is almost entirely independent of model atmosphere calculations.

We currently know of over 2000 white dwarf / main-sequence binaries (Rebassa-Mansergas et al., 2011). Of these there are 34 confirmed eclipsing systems. Gaia is expected to discover around 1000 more, giving us a large population with well understood selection effects. It will also provide orbital periods; this will be achieved by detecting multiple eclipses, but also by providing high S/N photometry out of eclipse. Eclipsing PCEBs often show large ($\sim 0.1 - 0.3$ mag) variations out of eclipse due to irradiation or tidal distortion of the main-sequence star as shown in the centre panel of Figure 2.2. These variations can even be used to determine the orbital periods of non-eclipsing systems. Gaia will also provide radial velocity data on the main sequence star for the brighter systems (around the calcium infrared triplet). Spectral
features from the main-sequence companion are likely to be visible in this window providing some constraints to the masses of the two stars.

Additional data are required to determine precise masses and radii. No spectral features from the white dwarf will be visible in the Gaia radial velocity spectrum, therefore, in order to measure the radial velocity of the white dwarf (and thus the masses) follow-up phase-resolved spectroscopy around the hydrogen Balmer lines will be needed. For the most part, Gaia data will not be adequate for precision analysis of eclipses and follow-up high-speed photometery will be required to measure precise radii. This combination of spectroscopic and photometric data can lead to masses and radii of the order of precision of those shown in the right hand panel of Figure 2.2, good enough to test white dwarf mass-radius relations. These eclipsing systems can also be used to test mass-radius relations of low-mass stars down to brown dwarf masses.

**Bibliography**


2.2 Initial mass-final mass relation (IFMR)

The initial mass-final mass relation (IFMR) is a theoretically predicted positive correlation between the main sequence mass of a star with $M < 10 \, M_\odot$ and the mass of the white dwarf remnant left behind after it has expired (e.g. Iben Jr. & Renzini 1983). This relation is of paramount importance for several fields in astrophysics (e.g. ages and distances of globular clusters, chemical evolution of galaxies, white dwarf population...) and understanding its form provides a handle on the total amount of gas enriched with He, N and other metals that 95% of all stars, return to the interstellar medium at the end of their lifecycles (e.g. Carigi, Colín & Peimbert 1999). Moreover, the form of the upper end of the IFMR is relevant to studies of Type II supernovae as it can provide a constraint on the minimum mass of star that will experience this fate. For example, with robust constraints on this mass, the observed diffuse neutrino background can serve better as an empirical normalisation check on estimates of the star formation history of the universe (e.g. Hopkins & Beacom 2006).

The form of the IFMR is extremely difficult to predict from theory alone due to the many
complex processes occurring during the final phases of stellar evolution (e.g. Iben Jr. & Renzini 1983). There have been several attempts to produce a theoretical IFMR (Dominguez et al. 1999; Marigo 2001; Marigo & Girardi 2007, but differences in evolutionary codes can lead to very different results (see Weidemann 2000 for a review). The IFMR is generally supposed to be a linear relation over the range $1.16 M_\odot < M_{\text{init}} < 6.5 M_\odot$ (Kalirai et al., 2008; Catalán et al., 2008a; Casewell et al., 2009; Dobbie et al., 2009), but there is some evidence that the IFMR is steeper between $3 M_\odot$ and $4 M_\odot$ than for initial masses either side of this value (see Figure 2.7; Dobbie et al. 2009). There is a problem with fitting a linear IFMR to the current data, and that is that the fit is affected by the high mass white dwarfs which tend to have large error bars on their mass determinations (driven by the steep change in the relationship between stellar mass and lifetime at these young ages; Williams, Bolte & Koester 2009) and the dearth of data in the low mass regime (Catalán et al., 2008b; Dobbie et al., 2009; Salaris et al., 2009).
The first attempt to empirically map the IFMR was made by Weidemann (1977) who obtained the masses of the white dwarfs in the Hyades and Pleiades from fitting synthetic profiles to the Balmer lines. Open cluster white dwarfs were used because the total age of a white dwarf can be expressed as the sum of its cooling time and the main-sequence lifetime of its progenitor. This latter parameter depends on the metallicity of the progenitor of the white dwarf, information which is lost once the star becomes a white dwarf. Since this method combines observational data and the use of models, the obtained relationship is, in effect semi-empirical. Using cluster white dwarfs is the most traditional way to define the IFMR (e.g. Figure 2.7; Weidemann 1987, 2000; Ferrario et al. 2005; Dobbie et al. 2006a; Williams & Bolte 2007; Kalirai et al. 2008; Rubin et al. 2008; Casewell et al. 2009; Dobbie et al. 2009), nonetheless, until relatively recently, rather few white dwarf members of open star clusters had been identified: 61 white dwarfs from 12 open star clusters (Williams et al., 2009). The uncertainties in membership status, cluster ages and the relatively large distances involved resulted in large scatter in the IFMR (Claver et al., 2001; Ferrario et al., 2005). Another problem with this method is that nearby open star clusters have to be sufficiently rich and old enough to harbour detectable white dwarfs. This means that the semi-empirical IFMR is relatively well populated only between 2.5 and 7.0M_☉.

An alternative way to expand the parameter space of the IFMR is to use white dwarfs in binary systems where it can be assumed that the members of a wide binary (common proper motion pair) were born simultaneously and with the same chemical composition (Wegner 1973; Oswalt, Hintzen & Luyten 1988). Since the components are well separated (100 to 1000 AU), it can be considered that they have evolved as isolated stars. Catalán et al. (2008b) used these pairs to provide additional points on the IFMR by obtaining the total age of the white dwarf and the metallicity of its progenitor from the study of the companion star. However, only a small sample of binaries were used to improve the initial-final mass relationship, because a parallax measurement is necessary in order to obtain the luminosity of the companion with accuracy, and from this the total age of the system. These systems are in general, much closer than open star clusters, which means they are brighter and thus much easier to study spectroscopically. Of these 6 additional white dwarfs (+ in Figure 2.7), 3 have masses of less that
There are however, large errors on some of these measurements, and they also show the dispersion that appears in the cluster based IFMR. The reason for this dispersion in both cases is currently unknown (i.e. it is not metallicity based). One other option for the IFMR is to use double degenerate systems such as PG0922+16 (Finley & Koester, 1997), where the difference in cooling times between the two white dwarfs can be used to calculate the stellar lifetimes and hence initial mass. This method is however, limited by the relative scarcity of double degenerate systems.

To better define the IFMR as it is now, we require two things; firstly more information about the white dwarfs we have; e.g. parallax to confirm cluster membership and distances to binaries, and secondly, smaller errors on the ages of these objects. Salaris et al. (2009) observed that the largest source of systematic error in IFMR calculations, is from the uncertainty in the cluster age used to define it. Gaia spectroscopy and parallax will allow much better determination of white dwarf parameters, particularly in southern open clusters that have not been observed by large scale optical photometric surveys such as the SDSS.

To expand the IFMR at both the low and high mass ends, we require more white dwarfs in known age systems. Torres et al. (2005) used Monte Carlo simulations to predict $\sim 400000$ white dwarfs will be detected by Gaia. Of these, 25% are expected to be in binary systems, 6.5% belonging to wide binaries with a K-type or earlier companion (Holberg et al., 2008), though the statistics are not complete. Gaia will provide accurate parallaxes for all these systems which will be essential to obtain their luminosity with precision. If the predictions are correct Gaia will provide thousands of wide binaries useful to improve the semi-empirical initial-final mass relationship. In particular, this will benefit the coverage of the low-mass domain (Figure 2.7) which represents 90% of the stellar population (white dwarfs with masses $\sim 0.6M_\odot$).

Gaia will provide a large range of both parallax and proper motions for the whole sky, allowing us to expand our parameter space by using both clusters and binaries. We will also be able to use the proper motions and parallax with the convergent point method to identify white dwarfs as part of moving groups, and hence obtain an age for them as for GD50 (Dobbie
For every new white dwarf discovered by Gaia we will have a proper motion, photometry and a parallax. Gaia will also provide radial velocities of the primary star for binary systems, and cluster members. We will also require high signal to noise ratio spectroscopy to obtain an effective temperature, gravity and mass, estimate of whether the white dwarf is magnetic, and radial velocity which will confirm association membership (of a cluster or binary). These data will allow us to reject objects that are not true cluster or binary members, resulting in less scatter in the IFMR.

Spectra of the cluster members and primary stars will also be required to give an estimate of metallicity, which along with magnetic objects may cause uncertainties in the IFMR. These data will come from multi-object spectrographs such as UVES+GIRAFFE as part of the ESO Gaia survey, or the spectrographs BigBOSS being proposed for the Kitt Peak 4m, HERMES being proposed for the AAT and WEAVE for the WHT. These instruments will provide accurate chemical abundance measurements for open star clusters, leading to a much cleaner main sequence, due to rejection of outliers/non-members, and hence a more accurate age estimate for the cluster.

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2.3 Luminosity function

2.3.1 Age of the Galaxy

The field of white dwarf (WD) cosmochronometry (e.g. Wood & Oswalt, 1998) is an increasingly active area of research in Galactic stellar astrophysics. Put simply, there exists a minimum absolute luminosity for the WD remnants of a given stellar population of finite age. A plot of the number of WDs per unit volume per absolute magnitude interval (the WD luminosity function) will show, in principle, a sharp cut–off at the faint end below which WDs are no longer observed (Liebert, Dahn & Monet, 1988).

It is only comparatively recently that digitised sky surveys have reached the depth and time coverage required to extract large samples of cool WDs via the technique of reduced proper motion (e.g. Harris et al., 2006). Recently, Rowell & Hambly (2011) – hereafter RH11 – report the largest sample achieved to date based on the legacy Schmidt all–sky photographic surveys. Despite the limited passband coverage (photographic $B_JR_FI_N$) and image quality (seeing typically $> 2$ arcsec), a sample of $\sim 10,000$ WDs was assembled covering $3\pi$ str of sky with accurately characterised completeness and reliability.

Despite recent advances, however, there remain several important but unresolved issues regarding the Galactic WDLFs and associated age determinations. Firstly, the ages are only poorly constrained because the volume sampled for the faintest and coolest (and therefore oldest) WDs is small due to magnitude limited surveys ($R_F=19–20$). Secondly, limited passband coverage allows photometric distance determinations accurate only to $\sim 50\%$. This smears out features in the LFs, and forces us to assume atmospheric compositions for the candidate WDs, preventing accurate accounting of the effects of H or He–dominated atmospheres; coupled with the previous problem, these result in uncertainties in the interpretation of the limited observational data at the faint end of the WDLF (e.g. Bedin et al., 2008).

The combination of Gaia trigonometric parallaxes with next–generation ground–based surveys
will make a huge impact on studies of the faint end of the WDLF. While the sample size of cool WDs will not increase dramatically from Gaia data alone (because current surveys are magnitude–limited at $m \sim 20$ as opposed to proper motion limited), new trigonometric parallax relationships for WDs will be produced from large samples of all atmosphere types, and those relations can be applied to much larger samples from deeper ground–based surveys.

RH11 present a new technique that enables a decomposition of the major kinematic population WDLFs (thin disk, thick disk and spheroid). This not only enables considerably more reliable disk age estimates by removal of contaminating WDs from older populations (a problem pointed out by several researchers, e.g. Reid 2005, but which remained unaddressed until this study), but of course also enables age determinations for those older populations for the first time. For example, a WDLF study using data from Pan-STARRS (e.g. Beaumont & Magnier, 2010) and Gaia (e.g. Jordan, 2007) will advance WDLF cosmochronometry to ‘precision’ levels for all three major kinematic components of the Galaxy. Using simple scaling arguments, we can calculate by what factor we can increase WDLF samples over those in RH11. Volume sampled for a uniformly distributed population (e.g. the local spheroid population) will go as $d^3$ for distance $d$ limited by magnitude ($d_{PS}/d_{RH11} = 10^{(r_{PS} - r_{RH11})/5}$) and proper motion ($d_{PS}/d_{RH11} = \mu_{RH11}/\mu_{PS}$) where $r$ is the magnitude limit for the PanSTARRS (PS) and RH11 surveys, and $\mu$ is similarly the limiting proper motion. Current measurements from survey data indicate $r_{PS} = r_{RH11} + 1.5$, while a conservative estimate for the proper motion limit of the 12 epoch, 3.5yr PS $3\pi$ survey is $\mu_{PS} \sim 10$ mas yr$^{-1}$ as against $\mu_{RH11} = 40$ mas yr$^{-1}$. Hence the number of PS spheroid WDs will be $\sim 2^3 \times 4^2 = 512$ times higher than in RH11. For the thin disk component, scale height effects reduce the distance exponent to 2, so the factor increase is $2^2 \times 4^2 = 64$; the thick disk increase will be somewhere between the two. Assuming the analysis of Wood & Oswalt (1998), the ages of all three components will be determined to well below 1% in terms of the statistical uncertainty. Contrast this with the present situation, where the thin disk is known to $\sim 10\%$ at best (Kilic et al., 2010) but with a larger systematic uncertainty due to contaminating WDs from the older populations, while the thick disk and spheroid ages are as yet undetermined.

Such a study will do much more than measuring the ages of the three kinematic components.
The availability of grizy photometry from PS, in conjunction with Gaia trigonometric parallaxes and UKIDSS/VISTA infrared data for large subsamples, will enable a finer analysis of atmospheric compositional effects leading to better photometric distance estimates for the full magnitude limited sample. Hence, starburst features in all WDLFs, if present, will be more pronounced leading to a better understanding of the star formation histories of the progenitor populations. The elusive, but fascinating ‘ultra cool’ WDs exhibiting unusual SEDs (Rowell et al., 2008 and references therein) will be prevalent in the new sample, leading to a much better understanding of their nature and effect on the faint end of the WDLF via follow–up studies. Finally, it will be possible to make an observational census (as opposed to a theoretical model extrapolation) of the total number of cool, very low luminosity stellar remnants in the disks and spheroid and a measurement of their contribution to the total baryonic mass of the Galaxy, with implications for interpretation of microlensing experimental results that invoke $\sim 0.5M_\odot$ stellar remnants as the lensing candidate (Calchi Novati, 2005).

Age of the Galactic disk

A recent assessment of the total number counts of disk white dwarfs using Monte Carlo techniques was done by Torres et al. (2005). Using their data we pay attention to some specific matters regarding the disk white dwarf luminosity function. In particular we ask to what precision the age of the Galactic disk can be estimated. They found that the sample of disk white dwarfs that Gaia will eventually detect is almost complete in magnitude up to $G \simeq 20$, and all white dwarfs within this sample will have measurable proper motions. Using the $1/V_{\text{max}}$ method (Schmidt, 1968), taking into account that the proper motion cut does not play any role at all, and binning the luminosity function in smaller luminosity bins (five bins per decade) they showed that the expected statistical errors will be really small, see Table 2.1.

These errors can be considered as upper bounds, as they depend somewhat on the binning, and more precisely, on the number of white dwarfs in the last bin. As can be seen the errors will be small. The typical error estimate obtained using the actually observed white dwarf luminosity function is 1.5 Gyr, 5 times larger. Hence, Gaia will allow a precise determination of the age
Table 2.1: Expected statistical errors in the determination of the age of the disk, as obtained from fitting the cut-off in the disk white dwarf luminosity function, in terms of the age of the disk. See text for details.

<table>
<thead>
<tr>
<th>$T_{\text{disk}}$ (Gyr)</th>
<th>$\Delta T_{\text{disk}}$ (Gyr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>0.15</td>
</tr>
<tr>
<td>9</td>
<td>0.30</td>
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<tr>
<td>10</td>
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<tr>
<td>11</td>
<td>0.30</td>
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<tr>
<td>12</td>
<td>0.15</td>
</tr>
<tr>
<td>13</td>
<td>1.13</td>
</tr>
</tbody>
</table>

of the Galactic disk which may be compared with that obtained using other methods, like turn-off stars and isochrone fitting. In this case, moreover, it should be taken as well into account that Gaia will allow very rigorous tests of the main sequence and red giant stellar evolutionary models, so additional information will be available to constrain the (pre-white dwarf) stellar models.

Neutrinos

Neutrinos are the dominant form of energy loss in white dwarf stars down to $\log(L/L_\odot) \simeq -2.0$, depending on the stellar mass. As a consequence, the evolutionary timescales of white dwarfs at these luminosities sensitively depend on the ratio of the neutrino energy loss to the photon energy loss, and, hence, the slope of the white dwarf luminosity function directly reflects the importance of neutrino emission. Although the unified electroweak theory of lepton interactions has been well tested in the high-energy regime the white dwarf luminosity function would be helpful in producing an interesting low-energy test of the theory. Torres et al. (2005) showed that the drop-off in the white dwarf luminosity function is not affected by neutrinos. However, the slope of the disk white luminosity function, which reflects the cooling rate, is sensitive to the treatment of neutrinos. More interestingly, Gaia will be able to measure
the cooling rate and, thus, to probe the electroweak theory at low energies.

**Discriminating among different cooling models**

After examining the physical mechanisms that operate at moderately high luminosities, say \( \log(L/L_\odot) \geq -2.0 \), we focus now on one of the crucial issues in the theory of white dwarf cooling, namely on crystallization and phase separation (García-Berro et al., 1988) at low core temperatures \( T_c \sim 10^6 \text{ K} \). As discussed in Isern et al. (1997) and demonstrated recently in García-Berro et al. (2010) the inclusion of phase separation upon crystallisation adds an extra delay to the cooling (and, thus, considerably modifies the characteristic cooling times at low luminosities), which depends on the initial chemical profile (the ratio of carbon to oxygen), on the adopted phase diagram and on the transparency of the insulating envelope. All this modifies the position of the cut-off of the white dwarf luminosity function. Consequently, if a direct measure of the disk age with reasonable precision is obtained by an independent method, say via turn-off stars, Gaia will directly probe the physics of crystallisation. It is worth noting as well that not only the exact location of the drop-off of the disk white dwarf luminosity function is affected by the details of the cooling sequences but also, the position and the shape of the maximum of the white dwarf luminosity function, thus allowing additional tests.

**2.3.2 Star formation rate**

The white dwarf luminosity is sensitive to the star formation history. However, recovering the exact dependence of the star formation history is difficult since an inverse problem must be solved. In fact, the origin of the problem is the long lifetimes of low mass main sequence stars. This implies that the past star formation activity is still influencing the present white dwarf birthrate. To overcome this problem there exist two alternatives. The first and most straightforward method requires an “a priori” knowledge of the shape of the star formation history and consists of adopting a trial function, depending on several parameters, and searching for the values of these parameters that best fit the observed luminosity function by minimising
the differences between the observational and the computed luminosity function. The second possibility consists of computing the luminosity function of massive white dwarfs (Diaz-Pinto et al., 1994), which have negligible main sequence lifetimes, thus making the solution of the inverse problem much easier.

The simulations of Torres et al. (2005) indicate that a sizeable fraction of massive white dwarfs ($M > 0.8 M_\odot$) will be observed by Gaia. This fraction varies from 7% for a constant star formation history, to 4% for a exponential one and to 3% for a episodic star formation history — see Torres et al. (2005) for details. These fractions are large enough to obtain the history of the star formation activity in the solar neighborhood using the method explained in Diaz-Pinto et al. (1994). Although these fractions may seem small when taken at face value, the absolute numbers of massive white dwarfs are impressive, since for the case of a constant star formation rate, 700 massive white are expected to be found, whereas for the other two star formation histories 500 and 300 massive white dwarfs will be found respectively, thus allowing a determination of the luminosity function of massive white dwarfs.

### 2.3.3 Solar neighbourhood

White dwarfs are relatively numerous in the Solar neighbourhood, however, because of their intrinsic faintness, a significant fraction that reside within even a fairly small volume near the Sun have escaped detection to date. In fact, Holberg et al. (2008) show that we are $\sim$20% incomplete within 20 pc and Subasavage et al. (2009) show that we are $\sim$60% incomplete within 25 pc. While the compilation methodologies differ slightly between the two works, the results are consistent with one another as the volume is nearly doubled when one extends from 20 pc to 25 pc. In general, the missing members comprise the coolest and least luminous white dwarfs. As the brightest representatives of this class of stars, it is imperative that we have a complete local sample that we can then use to compile robust statistics (e.g., multiplicity, luminosity function, mass function, fraction with metal pollution). Also, the coolest members of this sample will provide empirical constraints for theory as current atmospheric models do not provide an accurate characterisation in this regime.
Significant efforts exist that attempt to close this incompleteness gap. The favored method of identifying white dwarfs is that of reduced proper motion (RPM; e.g., Jones, 1972). Indeed, dozens of nearby white dwarfs have been discovered with this method (e.g., Subasavage et al., 2007, 2008; Sayres et al., 2010). The inherent bias with this method, and a significant one at that, is that it requires the candidates to have significant proper motions in order to be identified as potential nearby stars. With the addition of synoptic photometric surveys such as the Sloan Digital Sky Survey (SDSS), accurately calibrated photometric magnitudes permit reliable white dwarf candidate discrimination solely based on colour-colour selections. However, the colours of cooler white dwarfs ($T_{\text{eff}} \leq 7,000$ K) overlap with the more numerous F, G, and K main-sequence stars and are thus photometrically indistinguishable (Harris et al., 2006). It is precisely within this temperature regime that the white dwarf luminosity function peaks (see elsewhere in this Section) giving rise to the possibility of significant incompleteness in a volume–limited sample in the solar neighbourhood. In the case of the SDSS, both astrometric and photometric data have been combined to successfully identify white dwarfs candidates with cooler temperatures (Kilic et al., 2006; Sayres et al., 2010). In fact, Sayres et al. (2010) identified two white dwarf candidates that were spectroscopically confirmed and likely reside within 15 pc of the Sun (a volume known to contain only $\sim$50 white dwarfs with accurate trigonometric parallaxes). The SDSS covers only a fraction of the entire sky and other synoptic surveys (e.g., Pan-STARRS, LSST) will produce data products that permit identical analyses over larger regions of the sky. Yet, the intrinsic bias toward large proper motions remains.

To remove the proper motion bias, an all-sky survey that provides accurate astrometry (in particular, trigonometric parallaxes) of all stars down to a limiting magnitude is required. Gaia will provide exactly that and thus permit the compilation of the most complete volume-limited white dwarf sample. As can be seen in Figure 2.4, Gaia will complete the 25 pc sample with better than 1% astrometric accuracies, including even the coolest white dwarfs. We can expect Gaia to uncover at least 150 new white dwarfs in this volume alone. Should Gaia uncover new white dwarfs closer than 10 pc, our currently accepted value for the local density changes thus increasing the number expected farther out. While not wholly complete, Gaia
Figure 2.4: Plot of the volume limits that Gaia can expect to be complete as a function of white dwarf $T_{\text{eff}}$ and expected astrometric accuracy. End-of-mission trigonometric parallax accuracies are labeled. Expected astrometric accuracies for Gaia were adopted from Lindegren et al. (2008).

will significantly impact more distant samples by identifying rare and exotic white dwarfs too few to be found in smaller volume samples (e.g., Gänsicke, 2011).

One crucial element that Gaia will not provide is spectroscopy. With astrometry from Gaia, white dwarf stellar types will be without question based on their location in the H-R Diagram. However, accurate spectral classification (e.g., DA, DB, DC) for all white dwarfs and accurate characterisation for exceptional white dwarfs will require follow-up spectroscopy. With these additional data, the scientific return of Gaia astrometry is greatly enhanced. For example, metal-polluted white dwarfs are thought to have been enriched by planetary debris disks in the very recent past or perhaps during the current epoch (Farihi et al., 2010). The implications for planetary system remnants and possible scenarios for their evolution as the host star evolves...
are great. Yet, without the follow-up spectroscopy, these systems appear astrometrically indistinguishable. Additional follow-up data products include high-resolution spectroscopy for radial velocity determinations as well as high-resolution imaging. Both of these data products will probe into the question of white dwarf multiplicity that will not be available from Gaia data alone, in most cases.

In summary, the “Age of Astrometry” that we are currently experiencing is quite exciting. Gaia will be the next profound milestone in this regard, the full implications of which can only be imagined. With respect to the local sample of white dwarfs, the quality of the Gaia data will undoubtedly illustrate limitations in our understanding of white dwarf theory. These empirical constraints will, in turn, feed back into revised theories thus perpetuating a progression of our understanding of the universe.

2.3.4 Testing physical theories and new physics

Several non-standard theories predict the existence of exotic particles. Since very often there are not laboratory experiments in the relevant energy range able to obtain empirical evidences of their existence or properties, it is necessary to use stars to obtain information about them (Raffelt, 1996). The general procedure adopted in this case consists in comparing the observed properties of selected stars, or of a family of stars, with well-measured properties with the predictions of the theoretical stellar models obtained under different assumptions about the underlying microphysics. In particular, the hot and dense interior of stars is a powerful source of low-mass weakly interacting particles that freely escape to space. Thus, these hypothetical particles constitute a sink of energy that modifies the lifetimes of stars at the different evolutionary stages, thus allowing a comparison with the observed lifetimes. This technique has been applied to many of the frontier problems in Physics but the poor quality of the observational data sets, among other limitations — mainly due to our poor knowledge of the Galactic populations, see below — have only allowed us to obtain upper bounds to the characteristics of these particles, or to obtain loose constraints to other hypothetical physical processes of interest. Typical examples are the bounds to the mass of the axions (Raffelt,
White dwarfs (and the white dwarf populations) can be excellent laboratories for testing new physics since: i) Their evolution is just a simple cooling process, ii) The basic physical ingredients necessary to predict their evolution are well identified, and iii) There is an impressively solid observational database to which the predictions of the different theories can be compared, that Gaia will undoubtely enlarge. In essence, the important fact to be used for such purpose is simple. Since the core of white dwarfs is completely degenerate, these stars cannot obtain energy from nuclear reactions, and their evolution is just a gravothermal process of contraction and cooling that can be roughly described as:

\[ L_{\text{ph}} + L_{\nu} = - \frac{d(E + \Omega)}{dt} \quad (2.4) \]

where \( E \) is the total internal energy, \( \Omega \) is the total gravitational energy, and \( L_{\text{ph}}, L_{\nu} \) and \( L_{\text{es}} \) are the photon, neutrino and additional sink luminosities, respectively. Therefore, the inclusion of an additional sink or source of energy would modify the characteristic cooling time and, consequently, the individual (for instance, the secular rate of change of the period of pulsation of variable white dwarfs) or the collective (namely, the white dwarf luminosity function) properties of white dwarfs, which are sensitive to this time scale, would be modified.

The white dwarf luminosity function is defined as the number of white dwarfs of a given luminosity per unit of magnitude interval, and from a theoretical point of view can be easily computed using the expression:

\[ n(l) \propto \int_{M_1}^{M_e} \Phi(M) \Psi(t) \tau_{\text{cool}}(l, M) \, dM \quad (2.5) \]

where \( t = T - t_{\text{cool}}(l, M) - t_{\text{PS}}(M) \) is the time at which the progenitor star was born, \( l \) is the
logarithm of the luminosity in solar units, \( M \) is the mass of the parent star (for convenience all white dwarfs are labeled with the mass of the main sequence progenitor), \( t_{\text{cool}} \) is the cooling age for the corresponding luminosity, \( \tau_{\text{cool}} = dt/dM_{\text{bol}} \) is the characteristic cooling time at his luminosity, \( M_s \) and \( M_i \) are the maximum and the minimum masses of the main sequence stars able to produce a white dwarf of luminosity \( l \), \( t_{PS} \) is the lifetime of the progenitor of the white dwarf, and \( T \) is the age of the population under study. The remaining quantities, the initial mass function, \( \Phi(M) \), and the star formation rate, \( \Psi(t) \), are not known a priori and depend on the astronomical properties of the stellar population under study. Since the total density of white dwarfs is not yet well known, the computed luminosity function is customarily normalised to the bin with the smallest error bars in order to compare theory with observations. Equation (2.5) clearly shows that in order to use the luminosity function as a physical laboratory it is necessary not only to have good enough observational data but also to know the properties of the population under study. In particular, for the case of the luminosity function of disk white dwarfs the Galactic star formation rate, the initial mass function, and the age of the Galactic disk must be provided. Actually, the white dwarf luminosity function can be used to obtain, or at least to constrain, them. This represents a fundamental limitation of the method, since any anomalous behavior of the white dwarf luminosity function can be attributed to a peculiar Galactic property, and not to a new physical phenomenon.

Nevertheless, this situation has recently changed. Firstly, it has been recently realised (Isern & García-Berro, 2008) that, since for large enough luminosities the characteristic cooling time is not strongly dependent on the mass of the white dwarf, it is possible to cast Equation (2.5) in the form:

\[
n(l) \propto \langle \tau_{\text{cool}} \rangle \int \Phi(M)\Psi(t)dM
\]  

(2.6)

Hence, if only bright white dwarfs are considered — namely, those with \( t_{\text{cool}} \ll T \) — the boundary condition of Equation (2.5) can be satisfied for a wide range of masses of the progenitor stars. That is, by stars of different masses born at very different times. Because of the strong dependence of the age of the progenitor on the mass, the lower limit of the integral
in Equation (2.5) is almost independent of the luminosity and the different values that takes the integral for different values of $\Psi$ can be incorporated into the normalization constant, in such a way that the shape of the bright part of the luminosity function only depends on the characteristic cooling time.

Secondly, the quality of the observational data necessary to arrive to a definite conclusion has also been substantially improved, owing to the enhanced rate of discovery of new white dwarfs of the extant large surveys, like the SDSS. This can be theoretically assessed in the following way. Since the number density of white dwarfs at each magnitude bin depends on the time that each star takes to cross it, when a non-standard source of energy is included this number changes as:

$$N = N_0 \frac{L_0}{L_0 + L_1}$$

where $L_0$ is the luminosity of the star obtained with standard physics and $L_1$ is the contribution of the non-standard terms. Consequently, the allowed values of $L_1$ are essentially constrained by the observational uncertainties (Isern & Garcίa-Berro, 2008; Isern et al., 2008). The left panel of Figure 2.5 displays the situation just before the beginning of the large surveys. The error bars were large and the dispersion of the different measurements was large as well. The right panel of this figure shows the dramatic change introduced by the wealth of observational data from the SDSS catalogues. The accuracy and precision of this data has been recently proved by Rowell & Hambly (2011) using the data obtained from the SuperCOSMOS Sky Survey.

Gaia will not only improve by two orders of magnitude the size of the current samples, but it will also allow to determine the position of the age cutoff, which is basic for some applications, like constraining the secular variation of the gravitation constant $G$. Additionally, it will also allow to disentangle in an absolute way the influence of the star formation rate by obtaining the luminosity function of massive white dwarfs (Diaz-Pinto et al., 1994; Torres et al., 2005).
The case of axions

One solution to the strong CP problem of quantum chromodynamics is the Peccei-Quinn symmetry (Peccei & Quinn, 1977b,a). This symmetry is spontaneously broken at an energy scale that gives rise to the formation of a light pseudo-scalar particle named axion (Weinberg, 1978; Wilczek, 1978). This scale of energies is not defined by the theory but it has to be well above the electroweak scale to ensure that the coupling between axions and matter is weak enough to account for the lack of positive detection up to now. The mass of axions and the energy scale are related by: $m_a = 0.6(10^7 \text{ GeV/}f_a) \text{ eV}$. Astrophysical and cosmological arguments have been used to constrain this mass to the range $10^{-4}\text{ eV} \leq m_a \leq 10^{-4}\text{ eV}$. For this mass
range, axions can escape from stars and act as a sink of energy. Therefore, if they exist, they can noticeably modify the cooling of white dwarf stars.

Axions can couple to photons, electrons and nucleons with a strength that depends on the specific implementation of the Peccei-Quinn mechanism. The two most common implementations are the KSVZ (Kim, 1979) and the DFSZ models (Dine, Fischler & Srednicki, 1981). In the first case, axions couple to hadrons and photons, while in the second they also couple to charged leptons. For the temperatures and densities of the white dwarf interiors under consideration, only DFSZ axions are relevant, and in this case they can be emitted by Compton, pair annihilation and bremsstrahlung processes, but only the last mechanism turns out to be important.

Figure 2.6 displays the luminosity function for different axion masses, a constant star forma-
tion rate and an age of the Galactic disk of 11 Gyr. All the luminosity functions have been normalized to the luminosity bin at $\log(L/L_\odot) \simeq -3$ or, equivalently, $M_{\text{bol}} \simeq 12.2$. The best fit model – namely that which minimises the $\chi^2$ test in the region $-1 > \log(L/L_\odot) > -3$ (that is, $7.2 < M_{\text{bol}} < 12.2$), which is the region where both the observational data and the theoretical models are reliable – is obtained for $m_a \cos^2 \beta \simeq 5.5$ meV and solutions with $m_a \cos^2 \beta > 10$ meV are clearly excluded (Isern et al., 2008, 2009). Taken at face value, these results not only provide a strong constraint on the allowed mass of axions, but also a first evidence of their existence and a rough estimation of their mass. This is of course a strong statement but it is also a typical example of the problems to be solved or posed with the future white dwarf luminosity functions that Gaia will provide.

### 2.3.5 IMF

The initial mass function (IMF) is the distribution of stellar masses at birth. It is a fundamental property that quantifies the efficiency of the conversion of gas into stars in galaxies and thus, it is needed to understand many fundamental astrophysical problems: star formation in galaxies, chemical evolution and nucleosynthesis, supernova rates in galaxies, models of galaxy formation and evolution...

The initial mass function is usually expressed as $\frac{dN}{d(M)} \propto M^{-\alpha}$, or in its logarithmic form, $\frac{dN}{d(\log(M))} \propto M^{-\Gamma}$, where $M$ is the stellar mass. Up to now, most authors have been using what is called the standard initial mass function, which was determined by Salpeter more than 50 years ago (Salpeter, 1955), where $\Gamma = -1.35$. However, Scalo (1986) noticed that a single power law cannot reproduce the shape of the IMF over the full stellar mass range, since there was a strong rollover at low masses and a steepening of the function relative to Salpeters at masses higher than $1M_\odot$. Subsequent studies have confirmed the decrease in slope at low masses obtaining a multisegment power law which is often used in the literature (Kroupa et al., 1993).

There are several fields within Astronomy and Astrophysics that have the aim of understanding
the formation of the Universe and our Galaxy. One way is to observe galaxies similar to ours but located at large distances, although the stellar populations are not fully resolved and to measure star formation rates requires the adoption of an initial mass function, with some authors favouring top-heavy prescriptions (e.g. Baugh et al., 2005). A direct test is possible locally in our Milky Way by studying stars of the halo and thick disk populations, which were formed at the same age of the Universe as the starbursts observed in the distant galaxies. The evolution of white dwarfs is driven by a simple cooling process, which has a duration of the order of the age of the Galaxy (Salaris et al., 2000). Thus, they have imprinted a memory of the various episodes that the Galaxy has been subject to over its history, constituting useful objects to probe its structure and evolution (Isern et al. 2001; Liebert, Bergeron & Holberg 2005).

Although all population II stars more massive than the Sun evolved away from the main sequence long ago, the early IMF can be reconstructed from the luminosity function of the relic white dwarf population. The thin disc luminosity function is a complicated convolution of the star formation history of the Galaxy, the IMF, the initial-final-mass relationship, secular evolution of the thin disk scale height and other effects. A deconvolution is thus extremely difficult. However, the interpretation of the thick disc/halo luminosity function is much more straightforward. The formation history of the halo and thick disc was probably complex, but observations of field stars and globular clusters indicate that most stars are very old. So we can assume that both halo and thick disc were formed over a short period of time with no further star formation afterwards. Higher mass stars evolved to the white dwarf stage after only a short amount of time and can now be found piled up at the cool end of the white dwarf luminosity functions. Thus, it is essential to detect and study cool white dwarfs in order to be able to study the oldest population of white dwarfs, and in this way obtain information about the initial start formation bursts.

Oppenheimer et al. (2001) reported a very large population of white dwarfs belonging to the galactic halo – in line with a top heavy IMF. This result was disputed by Reid, Sahu & Hawley (2001) and Pauli et al. (2006), but all these investigations are based on very local samples and large uncertainties remain, because of small number statistics. A particular problem is the lack
of confirmed very cool population II white dwarfs, which are most interesting, because they evolved from the most massive progenitor stars. Even the population I white dwarf luminosity function constructed by Harris et al. (2006), comprising of 6,000 WDs selected from the SDSS contains only 35 cool WDs with absolute magnitudes $>15$ mag. In a recent work, Kilic et al. (2010) identified few cool white dwarfs using SDSS data, although only a couple have proper motions compatible with the halo population.

Napiwotzki (2009) constructed a model of the Galactic WD population, based on the model of Galactic structure by Robin et al. (2003). These simulations consider the WD cooling sequences from Bloecker (1995), the stellar tracks of Girardi et al. (2000) and the initial-final mass relationship of Weidemann (2001). The Salpeter IMF is assumed, although the simulations can be run with other IMFs (Baugh et al., 2005; Kennicutt, 1983). The population identification is then based on the results of the kinematic study of Pauli et al. (2006), calibrated with the local sample (Holberg et al., 2008) and checked against the proper motion selected sample of cool WDs by Oppenheimer et al. (2001). According to these simulations 2552, 1655 and 444 white dwarfs with $T_{\text{eff}}<4000$K belonging to the thin-disc, thick disc and halo, respectively, will be detected by Gaia. Gaia will also provide accurate trigonometric parallaxes and proper motions that will guarantee a correct population identification and will allow a considerable increase of the census of the halo white dwarf population.

Gaia performs low-resolution spectroscopy in four different bands, which can be rebinned into photometric bands. Comparing SDSS magnitudes in the Gaia filter set ($G_{BP}$ and $G_{RP}$) to these synthetic Gaia magnitudes, a rough estimate of $T_{\text{eff}}$ can be obtained for white dwarfs. The photometric spectral energy distribution from Gaia also is sensitive to different compositions at low temperatures, meaning it is possible to discern between H or He-rich atmospheres. However, IR photometry is also required for a complete characterisation (accurate $T_{\text{eff}}$ and $\log g$) of the white dwarfs detected.

Even though Gaia is not very deep, $G=20$, it will cover the whole sky which guarantees the detection of cool, nearby white dwarfs. For instance a 3,000K white dwarf will be detected by Gaia only if its closer than 44 or 31 pc, for $\log g=8.0$ or 8.5, respectively. Once we have a
large sample of cool white dwarfs a more comprehensive halo white dwarf luminosity function will be obtained. This will also enable us to infer which of the initial mass functions in the literature is the most realistic one.

2.3.6 Galactic populations of white dwarfs
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2.4 Magnetic fields (origin and evolution)

Magnetic fields have been measured in approximately 200 white dwarfs with field strengths of $10 \text{kG} < B < 1000 \text{MG}$. The Sloan Digital Sky Survey (SDSS) has been important in discovering new magnetic white dwarfs: where the spectroscopic data has been particularly important for identification and determination of magnetic field strengths through spectral fitting along with other useful parameters, such as the temperature.

There are multiple hypothesis for the origin of these objects (see e.g. Külebi, 2010): One of them, the “fossil field” hypothesis suggests that magnetic fields are products of an earlier stage of stellar evolution. In this picture, the field strengths are amplified due to the contraction of the core, during which the magnetic flux is conserved to a major extent. From the perspective of this hypothesis, chemically peculiar Ap and Bp stars were proposed to be the progenitors of MWDs (Angel et al., 1981).

The “fossil field” hypothesis has certain problems, the most important one being the incommensurable incidence of the magnetism in different stages of the stellar evolution. Namely, the inferred incidence of MWDs with respect to the total white dwarf population outnumbers the incidence of Ap/Bp stars within the A/B population (Kawka et al., 2007). One other problem of the fossil field hypothesis is the relatively massive nature of the MWDs (Liebert, 1988; Vennes & Kawka, 2008). While the mean value of the masses of the MWDs is $\approx 0.93M_\odot$, the mean mass of the non-magnetic white sample is $\approx 0.56M_\odot$ (Liebert, 1988). It has been suggested that this could be a result of the influence of magnetism on the mass loss. This possibility was tested by Wickramasinghe & Ferrario (2005) via population synthesis. Their conclusion was that current number distribution and masses of high-field magnetic white dwarfs (HFMWDs, $B \leq 106 \text{G}$) are not mainly due to an inclusion of a modified IFMR but rather by assuming that $\approx 10\%$ of A/B stars have unobservable small scale magnetic fields.

Magnetism is thought to be present in more than $10\%$ of white dwarfs in the local population (Liebert et al. 2003), with Kawka et al. (2007) finding the incidence of magnetism as $21 \pm 8\%$.
Accurate parallax and distance measurements for targets will mean estimates for the radius of objects can be obtained – a parameter which is difficult to determine accurately. The proper motion information from Gaia could help to reveal the origins of magnetic fields in white dwarfs. In a study by Anselowitz et al. (1999), the statistical properties, cooling ages and vector components of the three-dimensional space motions U, V, W were examined for a sample of 53 magnetic white dwarfs in the fourth edition of the Catalog of Spectroscopically Identified White Dwarfs (McCook & Sion 1999). They concluded that the sample of magnetic white dwarfs appeared to descend from young disk stars, due to their small motions relative to the sun. This supports the hypothesis that magnetic fields in white dwarfs could be remnants from magnetic fields in main-sequence stars, such as Ap/Bp stars. However, they also suggested that the magnetic white dwarf population could have a mixture of progenitors, as no difference in velocity dispersion was detected between the hotter (with shorter cooling ages) and cooler magnetic white dwarfs (with longer cooling times), which would be expected if the magnetic white dwarf population descended solely from young disk stars. The information acquired from the Gaia mission will provide unprecedented parallax, distance and proper motion accuracy facilitating similar studies to be carried out with much larger sample sizes to allow thorough statistical analysis.

The accurate luminosities obtained from the photometry will yield some information regarding the variability of the magnetic white dwarf population. Periods of photometric variability may not be determined from the Gaia observations alone, however it will indicate those showing signs of modulations to be followed-up later from ground-based facilities. It is currently thought that ~40% of magnetic white dwarfs show signs of photometric variability (Brinkworth et al. 2007), revealing information regarding the rotation properties of the object. Recently, a unique variable magnetic DA white dwarf was discovered in the Kepler field by Holberg & Howell (2011, in prep.). The object was found through its non-sinusoidal modulations of 4.92% peak-to-peak with a period of 0.2557 days (6.138 hrs). With the absence of evidence to suggest that there may be a companion or pulsations, it illustrates that the photometric variability exhibited by some magnetic white dwarfs can be used as a method for
identifying the objects.

Ground-based follow-up spectroscopy of these objects will be crucial to getting the most out of the Gaia observations. In combination with spectral fitting and evolutionary models, information regarding the object’s temperature, magnetic field strength, composition and cooling age can be determined. Estimates will also be possible for the mass and radius of the object, although these parameters will depend on the evolutionary models.

Sophisticated models for the analyses of such follow-up observations could be used to determine magnetic field strengths and estimation for the magnetic field geometry as was demonstrated e.g. by Külebi et al. (2009) for the SDSS data.

One of the obstacles in analysing magnetic white dwarfs is that surface gravities cannot reliably be determined from the spectral lines. This is due to the lack of atomic data in the presence of both a magnetic and an electric field for arbitrary strength and arbitrary angles between two fields. Therefore, only a crude approximation (??) is used in our model and systematic uncertainties are unavoidable, particularly in the low-field regime (≤ 5 MG) where the Stark effect dominates. Therefore, mass can only be estimated if the determination of the effective temperature (which is more reliably possible) is supplemented by parallax determinations.

Work conducted by Külebi et al. (2010) demonstrates what can be achieved with accurate parallax measurements, follow-up spectroscopy and theoretical modelling. They observed the highly magnetic, hot and ultra massive white dwarf REJ0317-853 with HST to determine the parallax of the object and its DA white dwarf companion. The mass, radius and cooling ages were then calculated for a range of temperatures and surface gravities using carbon-oxygen core white dwarf cooling models with thick hydrogen layers (Wood 1995; Holberg & Bergeron 2006)\(^1\) and oxygen-neon white dwarf cooling models with thin hydrogen layers (Althaus et al. 2005, 2007)\(^2\). In the case of REJ0317-853 this information together with an analysis of its companion LB 9802 allowed to explore different evolutionary scenarios for REJ0317-853.

\(^1\)http://www.astro.umontreal.ca/bergeron/CoolingModels
\(^2\)http://www.fcaglp.unlp.edu.ar/evolgroup/tracks.html
Since Gaia is expected to find \( \approx 400,000 \) white dwarfs (Torres et al., 2005; ?) that a few percent will be identified as being magnetic by follow-up observations. By analysing this sample with model spectra we can obtain a much clearer picture of this population. We can test whether the masses of magnetic white dwarfs are indeed larger than for non-magnetic white dwarfs (Liebert, 1988), whether there is a dependence of the magnetic field strength with age (using the effective temperature and mass). With the help of population synthesis models we will be able to further constrain the question of the origin of magnetic white dwarfs.

Of particular importance is the studies of magnetic whites in wide binaries (Külebi et al., 2010), common-proper-motion systems (Girven et al., 2010), and open clusters because these systems provide additional age constraints and allow the study of the evolution of these objects in great detail.

**Bibliography**

2.5 Pulsating white dwarfs

White dwarf (WD) asteroseismology is a powerful tool to study WD interiors. It allows the measurements of various stellar parameters, such as stellar mass, the mass of the H/He external layers and the stellar rotation rate. It can also provide precious information on the core chemical composition, neutrino (and axion) cooling, and even crystallization for massive white dwarfs. Wide review papers on WD asteroseismology are from ), ), and ). Along their cooling sequence, there are four instability strips at various effective temperatures. Thus asteroseismic studies allow detailed study of white dwarfs at different effective temperatures and different evolutionary phases. The ZZ Ceti (or DAV) instability strip is by far the most populated one, with about 150 DAV stars known (?).
2.5.1 Photometric finding of ZZ candidates

ZZ Ceti stars are pulsating white dwarfs with effective temperatures close to the maximum of the strengths of the Balmer lines. For this reason even at about the Gaia magnitude \( G \approx 19 \) Balmer lines can be identified if all BP low-resolution spectra are added up. These objects can be regarded as ZZ Ceti candidates and checked for photometric variability. Moreover, they can be tested for periodicity as described in Sect. 2.5.2.

2.5.2 Direct Period detection with Gaia

Varadi et al. (2009) and Varadi et al. (2011) have performed studies to determine whether Gaia can directly measure the periods of ZZ Ceti stars. The Gaia time sampling and the CCD data acquisition scheme allow, in principle, the probing of stellar variability on time scales even as short as several tens of seconds, thereby giving potential access to the study of variable stars in a large and homogenous sample of stars. In order to test this, continuous ZZ Ceti light-curves were simulated with a nonlinear ZZ Ceti (DAV) light-curve simulator based on a model by Schlund (2006). The model takes periods, amplitudes and phases as input to define a pulsation pattern at the base of the convective zone and solves the problem of flux propagation through the convective zone to derive the relative flux variations at the photosphere.

In order to simulate photometric Gaia time series of ZZ Ceti stars, the continuously simulated ZZ Ceti light-curves were sampled according to the nominal scanning law of Gaia assuming different positions of the objects on the sky. Subsequently Gaussian noise was added with a level consistent with the precision of the Gaia satellite.

It turned out that at the Gaia magnitude \( G = 15 \), periods could be partially recovered with a probability of 72% if the power spectrum does not change during the mission. If the pulsation modes change once during the mission the recovery probability drops to about 50%. Even at \( G = 18 \) a substantial percentage of periods is recovered.
Bibliography


2.6 Binaries

2.6.1 Finding new binaries

2.6.2 Common proper motion binaries

2.6.3 Interesting companions

2.6.4 Evolution

2.6.5 Type 1a Supernovae

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2.7 Planetary systems

Current exoplanet research is strongly oriented towards main sequence (MS) stars, with the main goal of finding rocky analogues of our Earth, and towards planetary system formation, while the late-stage evolution after the MS remains poorly understood. Indeed, the large majority of the almost \( \approx 550 \) extrasolar planets detected so far orbit MS stars, and these planets were detected mostly using radial velocities (RVs) or transits. Both methods present strong limitations for compact stars with high gravities and small radii, such as the white dwarfs and their progenitors, including the extreme horizontal branch (EHB) stars. This is why most of the ongoing RV or transit searches, including CoRoT and Kepler, will not add much to this topic. For compact stars more efficient techniques are given by timing and astrometry. Both methods, unlike RVs and transits, are sensitive to planets with orbital distances of the order of 1 AU or more. This, in some sense, corresponds to the general expectation that very close
planets can barely “survive” the most critical phases of stellar evolution like the red giant branch (RGB) expansion, the asymptotic giant branch (AGB) expansion, and the planetary nebula (PN) ejection. To model these phenomena is difficult: the first attempts are very recent (Villaver & Livio, 2007, 2009; Nordhaus et al., 2010) and lack observational constraints. For these reasons increasing the poor statistics of these rare systems is important.

Presently, only few post-RGB planetary systems are known (see Silvotti et al. 2011 for an updated list): apart from the pulsar planets, they were all discovered in the last 3 years and were almost all detected using the timing method. Their host stars are EHB stars or cataclysmic variables. For single white dwarfs, we know of only two planet candidates: orbiting GD66 (Mullally et al., 2008, 2009) and GD356 (Wickramasinghe et al., 2010), both of which are not yet confirmed. At the same time we know that at least 21 white dwarfs show dusty/gaseous circumstellar disks, likely due to tidal disruption of asteroids (see e.g. Farihi, 2011; Gänsicke, 2011).

In other terms, we do not know yet whether white dwarfs have planets or not and at which orbital distances, but we see debris disks which are likely the remnants of old planetary systems. Moreover, potentially, white dwarfs could host not only 1st generation planets formed from the original protoplanetary disk, but also 2nd or even 3rd generation planets formed more recently from the stellar material ejected during the RGB, AGB or PN phase (see e.g. Perets, 2011).

In this context it is evident that Gaia can play an important role.

**2.7.1 Detection by astrometry**

The astrometric accuracy of Gaia is enough to detect giant planets around nearby white dwarfs. Preliminary calculations have shown that Gaia should be able to detect WD planets around \(10^3\) white dwarfs within \(\sim100\) pc from the Sun, with low mass limits of a few Jupiters (Silvotti, Sozzetti & Lattanzi, 2011). The exoplanet discovery space of the Gaia mission is
represented in Fig. 2.7. More detailed simulations will be done in the next months in order to evaluate the Gaia sensitivity with a real sample of white dwarfs.

Figure 2.7: Exoplanet discovery space for the Gaia mission based on double-blind tests (Carestiano et al., 2008). Detectability curves are defined on the basis of a 3σ criterion for signal detection. The upper and lower curves are for Gaia astrometry with $\sigma_A = 15$ μas (where $\sigma_A$ is the single-measurement astrometric precision), assuming a 0.59-M$_\odot$ WD primary at 100 pc ($V<15$) and 50 pc ($V<13$), respectively. Survey duration is set to 5 yr. Pink dots indicate the inventory of Doppler-detected exoplanets as of May 2010. Transiting systems are shown as light-blue filled diamonds, while the red hexagons and the dark-green squares are planets detected by microlensing or timing respectively. When the inclination of the system is not known, in particular for the pink dots and the dark-green squares, we used the minimum mass. Solar System planets are shown as light-green pentagons. The small yellow dots represent a theoretical distribution of masses and final orbital semi-major axes from Ida & Lin (2008).
2.7.2 Detection by transits

Bibliography

2.8 Gaia and other late stages of stellar evolution

Gaia’s (Lindegren & Perryman, 1996) role in exploring the end states of stellar evolution is not limited to the study of white dwarfs, but extends to many stellar types which are their immediate progenitors or (sometimes) progeny. Many of these are rare and distant; Gaia will provide the first opportunity to measure proper motions, and distances for many, as well as radial velocities and photometry of unprecedented precision (Cacciari, 2009). These data will help to complete a picture of stellar evolution which is severely complicated by the diverse consequences of interaction between two stars in a binary system.

Although all stars commence evolution burning hydrogen in their cores, with lifetimes ranging from \(< 10^6\) to \(> 10^{10}\) years, their subsequent fate is strongly correlated with their mass. Excepting the comparatively rare massive stars, most stars develop a degenerate helium core as they become red giants. In some circumstances, such a star can lose almost its entire hydrogen envelope while its helium core is still small; then helium cannot ignite and a helium-core WD results. If mass-loss from the red giant is gradual, the helium core will grow until conditions for helium ignition are achieved, some \(10^9\) years after leaving the Main Sequence (for a \(1.0\)M\(_\odot\) star). A helium flash occurs, the degeneracy of the core is lifted, core helium-burning is established, the core expands, the hydrogen-burning shell is cooled, the total radius drops, and a horizontal branch star results, with a typical lifetime of \(10^8\) years (for a \(0.5\)M\(_\odot\) helium core).

The radius and future evolution of a horizontal branch star turns out to depend on how much hydrogen remains around the helium core. In extreme cases and usually in a binary system, a red giant may lose nearly all of its hydrogen envelope at or just before the helium flash. The resulting horizontal-branch star is virtually a helium main-sequence star, lying well to the blue of the hydrogen main sequence. Such stars are identified with subdwarf B stars. For these and other blue horizontal-branch stars, the absence of a hydrogen envelope means that, as core-helium burning is followed by shell-helium burning, possibly as a subdwarf O star, the available fuel store is exhausted and the star will evolve directly to become a hybrid white
dwarf having a carbon-oxygen core with a helium cocoon.

Providing the hydrogen envelope is sufficiently massive, core contraction after helium exhaustion causes the hydrogen shell to heat and returns the star to the Asymptotic Giant Branch (AGB), where it develops a degenerate carbon-oxygen core. Thermal pulses are associated with unstable burning in the helium shell, whilst the star’s great luminosity comes from the hydrogen shell. Convective dredge-up, strong stellar winds and interaction with potential binary companions produce a variety of stellar types associated with the AGB. Further details are given by Herwig (2005).

Ultimately, the hydrogen layers of an AGB star are blown away, and hydrogen-burning ceases. With no nuclear support, the star contracts rapidly, first at constant luminosity, initially as an embedded IR source, then as a post-AGB F or A star, then as a subdwarf O star. The remnant of the hydrogen envelope may still be close enough to be ionised by the hot central star of a planetary nebula (CSPN).

At this point the star is almost a carbon/oxygen WD, with a thin helium shell and an even thinner hydrogen envelope. The mass of the helium shell is dictated by the point of the AGB thermal-pulse at which hydrogen-burning switched off. With the right conditions, the unstable helium shell may make one final shell flash whilst the stars is contracting, or even after it has reached the white dwarf cooling track. This final flash forces the star to expand in just a few years, mixing the outer layers with massive amounts of helium, carbon and oxygen. After expansion, the star again contracts, possibly as a hydrogen-deficient CSPN, and later a PG1159 star or DO white dwarf.

If the expansion of a normal giant or AGB star brings it into contact with a less massive companion, a sudden transfer of mass can produce a common-envelope surrounding both stars. Friction makes the stars lose orbital energy and spiral towards one another, whilst the heat generated expands and expels the common envelope. The stripped giant may now be, for example, a white dwarf in a close binary system. When the secondary itself becomes a giant, the process can be repeated, yielding a hot subdwarf or another white dwarf. By this and other
means, binary systems can evolve to the point where both components are WDs.

Theory suggests that all binaries will emit gravitational radiation (GR) at a rate proportional to $P^{-2/3}$. Whilst GR removes orbital energy, it is only significant for very short-period binary white dwarfs. When the orbit has shrunk so that the less massive component fills its Roche lobe (and the period has been reduced to 3 minutes or so), mass transfer will commence. Loss of mass causes the WD donor to expand. Transfer of mass causes the orbit to expand. Several outcomes are conjectured. If the mass ratio (donor/receiver) is small, the donor expansion will be slower than the orbit expansion, so mass transfer is stable, and possibly intermittent. Likely candidates are **AM Canem Venaticorum (AM CVn) variables**, short-period hydrogen-deficient white dwarf binaries with an accretion disk. If the mass ratio is closer to unity, the expansion of the donor exceeds the orbital expansion, so a runaway process occurs, the donor is destroyed on the timescale of an orbital period and the debris accretes on to the receiver. What happens next depends on the WD masses. The merger of two helium WDs is thought to lead to helium ignition and the creation of a hot subdwarf, possibly a **helium-rich sdB or sdO star**. This may explain the fraction of sdB stars believed to be single. A CO+He WD merger will lead to helium-shell ignition, and has been argued to produce **R Coronae Borealis (RCB) variables** and **extreme helium (EHE) stars**. If the final combined mass approaches the Chandrasekhar limit, a type Ia supernova may ensue.

A massive star will not develop a degenerate core and helium burning begins without the Helium Flash. Eventually a supernova explosion is expected to occur and if in a binary, and the binary remains bound, a **low-mass X-ray binary (LMXB)** could result where one component is a neutron star (or black hole) and the other an unevolved object often referred to as the donor star. Modelling and understanding the survival of a binary during a supernova explosion presents a challenge, as does the subsequent transfer of mass from the donor star to a neutron star or black hole.

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3The GR timescale for a CO+CO WD binary with a period of 2 hr is approximately $10^{10}$ yr.
2.8.1 Gaia and fundamental parameters

While the formation and evolution of a few of the objects representative of the late stages of stellar evolution appear to be understood in principle, there is an uncomfortable dependency on luminosities inferred from companions in binary systems where it is supposed that the companion has evolved as though it were a single star. None of the types of object briefly discussed above is close enough to the Sun to have allowed an accurate parallax measurement from the ground or by the Hipparcos satellite. Gaia can be expected to provide accurate distance determinations for most of the various types of object discussed above.

Accurate luminosities follow from precise distances, and from these, stellar energy distributions at the tops of the photospheres may be directly inferred from their observed counterparts at the top of the Earth’s atmosphere; this provides an exacting test of model stellar atmosphere calculations, which is particularly important for hot stars where Local Thermodynamic Equilibrium (LTE) cannot be assumed and line-blanketting is necessarily more approximate. The likely need for improved non-LTE model stellar atmospheres would stimulate new atomic physics calculations of radiative and collisional data. Any improvement to model stellar atmospheres should give better determinations of effective temperature, surface gravity and abundances. Comparisons of improved abundances are needed for studying the consequences of mass transfer in binary systems. Better stellar radii follow from accurate luminosities and improved effective temperatures.

With a better knowledge of luminosities and radii, stellar evolution models are more constrained. In the context of hot stars in a poorly understood late stage of stellar evolution and known to be a component of a binary system, a knowledge of the luminosity in particular will facilitate an understanding of differences between binary and single star evolution. The evolution of some objects, which are apparently single stars, can only be understood if they formed from the merger of two white dwarfs; precision measurements of parallax, proper motion and radial velocity by Gaia will help confirm these as single objects and so probably a consequence of a merger between two WDs. In the case of sdB stars, for example, it would
then be possible to make a detailed comparison between those formed by a WD merger and those formed as a consequence of binary interactions affecting RGB evolution.

The adequacy of stellar evolution calculations for interpreting colour-magnitude diagrams of resolved stellar populations is reviewed by Gallart et al. (2005); they emphasise the need for a better knowledge of conductive opacities, neutrino energy losses and the correct nuclear cross-section for the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction. The calculated size of the helium core at the top of the Red Giant Branch, which determines the luminosity at this point, the subsequent luminosity on the Horizontal Branch, core helium burning lifetime and understanding the subsequent stages of stellar evolution directly depend on our knowledge of conductive opacities, neutrino energy losses and the correct nuclear cross-section for the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction. At the moment stellar evolution models fit observed colour-magnitude diagrams of resolved stellar populations reasonably well but Gaia can be expected to provide observations as outlined above which place much tighter constraints on the models.

Accurate parallaxes, proper motions and radial velocities measured by Gaia would give reliable space motions relative to the Local Standard of Rest of all stars observed and for those representing the poorly understood late stages of stellar evolution in particular. A knowledge of space motions then enables the stellar evolution of the objects concerned to be studied in the wider context of the dynamical evolution of the Galaxy. It would for example be possible to establish whether helium-rich subdwarf-O stars have a different galactic distribution from their helium-poor counterparts.

Although much can be anticipated using Gaia photometry, spectrophotometry from the far ultraviolet to far infrared would also be needed for an exacting test of model stellar atmospheres. Much useful spectrophotometry, or measurements of flux density as a function of wavelength already exists in archives from previous space missions and ground-based observations; prospects for obtaining more such data already exist and could be proposed for future space missions and ground-based observatories. For binary stars, the prospect of time-dependent observations of flux density is eagerly anticipated through multi-wavelength stellar astrometry, to be obtained by the proposed Sim Lite mission (Coughlin et al., 2010).
2.8.2 Gaia and hot subdwarfs

Hot subluminous stars (Heber, 2009) are an important population of faint blue stars at high Galactic latitudes and are immediate progenitors to white dwarfs. They have recently been studied extensively because they are common enough to account for the UV excess observed in early-type galaxies. Several thousands have been identified in the Galaxy and outnumber the white dwarfs among the faint blue stars ($U - B < -0.4$) to 18 mag. Pulsating sdB stars became an important tool for asteroseismology, and sdB stars in close binaries may qualify as Supernova Ia progenitors.

Subluminous B stars (sdB) have been identified as extreme horizontal branch (EHB) stars, i.e. they are core helium-burning stars with hydrogen envelopes that are too thin to sustain hydrogen burning. Therefore they evolve directly to the white-dwarf cooling sequence by avoiding the AGB. The fraction of sdB stars in short period binaries is very high, about half of the sdBs are found in binaries with periods of ten days or less. Obviously, binary evolution plays an important role in the formation of sdB stars, in particular when merging of close binary white dwarfs system are also considered to explain the formation of single stars.

However key issues in the field remain to be resolved:

1) The most fundamental property of a stars is its mass. Because no direct measurement is available for a hot subdwarf star, it is often assumed that an sdB star has half a solar mass, which is the canonical mass for the core helium flash. Binary population synthesis predicts mass distributions from 0.3 to 0.8 M$_\odot$. The details depend on several poorly constrained parameters. Asteroseismology has successfully probed the interior of sdB stars and determined masses and envelope masses, but the results are model dependent.

2) Most of the companions to binary sdB stars are very faint and are therefore outshone by the primary. From indirect mass estimates a large variety of companions have been identified, ranging from substellar objects (brown dwarfs) and low-mass main sequence stars to white dwarfs and even more massive compact objects (possibly neutron stars).
Usually, only the mass ratio of the system can be determined and, therefore, the interpretation is hampered by the unknown mass of the sdB star.

3) The stellar population of the Galactic bulge is similar to that of early-type galaxies and, therefore, provides a laboratory to study the UV-excess phenomenon. Hot subluminous B have been discovered in the Galactic bulge but no quantitative results are available yet.

4) Space densities, scale heights and birthrates of the disk sdB stars are poorly constrained. Subluminous B stars have an absolute visual brightness similar to the Sun with little scatter: $M_V = 4.2 \pm 0.5$ mag. Hence they sample both the thin and thick disk. An accurate knowledge of the scale heights are required to derive the birthrates, which is a key to understanding the various evolutionary channels that lead to the formation of a white dwarf.

5) Hot subluminous stars can be traced out into the halo. Indeed, halo sdBs have been identified in galactic globular clusters as well as in the field. Comparing the different population of sdB stars (thin disk, thick disk and halo) will allow the time and metallicity dependence of sdB evolution to be studied.

6) The fastest moving stars allow the dark matter mass of the galactic halo to be probed. Radial velocity surveys revealed the existence of hyper-velocity stars (HVS) travelling so fast that they may be unbound to the Galaxy. Amongst the first three stars discovered serendipitously in 2005, the hot subdwarf US 708 stands out as the only low mass, highly-evolved HVS known. The place of origin of HVS is supposed to be the Galactic centre, because it hosts a supermassive black hole (SMBH) and tidal disruption of a binary by a SMBH is believed to be the only mechanism capable of achieving the required acceleration.

7) Subluminous B stars in close binaries are very frequent. However, surveys have been restricted to periods of ten days or less. The frequency of longer period systems is poorly constrained.
Gaia will resolve these issues. Items 1 and 2 will be resolved through accurate parallaxes. Items 3 to 6 will require the accurate proper motions in addition to parallaxes. At \( V = 20 \) mag, Gaia will measure and discover lots of hot subdwarfs in Baade’s window, in the galactic bulge and in the halo (to 20 kpc), and also in the Galactic Plane, which is still largely \textit{terra incognita} as UV excess surveys have had to avoid the Galactic Plane. The RVS is an ideal instrument to tackle item 7. Although the spectral window around the CaT lines is not well suited for early type stars, sdB stars do show a couple of lines suitable for radial velocity measurement. The five years of operation will allow a search for long-period radial velocity variations. A sufficiently large sample of sufficiently bright sdB stars (<17 mag) is available to derive statistically significant results.

### 2.8.3 Gaia, planetary nebulae and their central stars

### 2.8.4 Gaia and cataclysmic variables

Cataclysmic variables (CVs) are close interacting binaries in which a white dwarf accretes from a low-mass companion star, and represent an important benchmark population for the study of a wide range of astrophysical questions.

These include, on the one hand, the evolution of binary stars. CVs descend from main sequence binaries with unequal mass ratios. As the more massive star evolves off the main sequence, it eventually fills its Roche volume, initiating mass transfer onto its lower-mass companion. This mass transfer is unstable in most cases, and leads to a common envelope phase. Following the common envelope, the evolution of CVs is driven by orbital angular momentum loss via stellar magnetic wind braking and/or gravitational wave radiation. Common envelope evolution and angular momentum loss are critical ingredients in the formation of a vast range of exotic objects, such as stellar black hole binaries, milli-second pulsars, or double-degenerate white dwarf pairs and neutron star pairs, which are potential progenitors of SN Ia and short GRBs, respectively. Despite the overarching importance, our understand-
Figure 2.8: The population of the CVs (purple stars) discovered by SDSS in a \((u - g, g - r)\) colour-colour diagram (left) and \((g, g - r)\) colour-magnitude diagram (right). Within SDSS, CVs overlap very strongly with the parameter space spanned by quasars (shown with increasing redshift as blue, cyan, green, yellow, orange and red dots). Main-sequence stars and white dwarfs are shown in gray. Gaia will provide comparable all-sky colour information, as well as distances, proper motions, and variability, unambiguously identifying all CVs to its magnitude limit.

...ing of the physical processes that are at work in the evolution of compact binaries are still in its infancy, and the observational constraints are poor. Because they are common, easily accessible to ground and space based studies, and structurally simple in terms of their stellar components, CVs are the natural choice for observational population studies that can test and guide the further development of the theories of compact binary evolution.

Beyond these bulk properties, CVs are excellent laboratories for accretion physics. Most CVs contain a non-magnetic white dwarf, and the mass flow occurs via an accretion disc. The discs in CVs share many physical properties with the discs in X-ray binaries, proto-stellar systems, and AGN, but offer the advantage that their structure can be directly probed by orbital phase-resolved observations, either via Doppler tomography (Marsh & Horne, 1988) or eclipse mapping (Horne, 1985). The small physical size of CV discs also implies that their dynamical behaviour can be studied in exquisite detail on time scales of weeks to months (Lasota, 2001; Cannizzo et al., 2010).

*The impact of Gaia*
In the past, observational population studies of CVs were haunted by selection effects, leading to severely skewed and incomplete CV samples (e.g. Kolb & Baraffe, 1999). Over the past few years, this situation has changed markedly as SDSS has identified a large and homogenous sample of CVs that led to new constraints on the theory of CV evolution (Gänsicke et al., 2009; Knigge et al., 2011). SDSS efficiency in finding CVs was a by-product of their non-stellar colours, which mixes them into the parameter space spanned by quasars (Fig.2.8). Gaia will take observational CV population studies to an unprecedented level of detail, as the combination of colour, distance, proper motion, and variability is bound to identify every single CV down to the Gaia’s magnitude limit.

CVs are intrinsically faint, and, compared to single white dwarfs, relatively rare. Hence, Hipparcos observed only a tiny handful of CVs, and despite additional intensive (and expensive!) ground and space-based parallax programs, the number of CVs with accurate distances remains very small (Thorstensen, 2003; Thorstensen et al., 2008; Harrison et al., 2000; Beuermann et al., 2003). Gaia will measure high-quality parallaxes of pretty much all known (and new) CVs. The knowledge of the distances to many hundreds of CVs will truly revolutionise the field, as it will lead to accurate determinations of the mass transfer rates, a key parameter both for the evolution of the systems, as well as for the structure and dynamics of their accretion discs. In addition, it will be possible to measure the white dwarf masses of a large number of CVs (based on the Gaia distances, spectrophotometric radii, and mass-radius relations), which will settle the important question whether the accreting white dwarfs grow in mass in CVs grow, or not.

Data needs beyond Gaia.

A detailed classification of the CVs discovered by Gaia will require spectroscopic follow-up at higher spectral resolution ($R \sim 5000$) covering the entire optical range ($3800$ – $9200$ Å).

The Gaia scanning law is too coarse to provide accurate long-term light curves of CVs, denser ground-based monitoring, such as currently carried out by e.g. the Catalina Real Time Transient Survey (Drake et al., 2009) would be highly desirable.
Gaia will discover a large number of eclipsing CVs, which are key targets for detailed physical parameter studies. This will require access to 2–4 m telescopes in both hemispheres, equipped with high-speed CCD cameras such as ULTRACAM (Dhillon et al., 2007).

### 2.8.5 Gaia and AM CVn variables

AM CVn stars are interacting binary stars of extremely short period (5 to 65 minutes) in which white dwarfs accrete from hydrogen-deficient, degenerate companions which may themselves once have been white dwarfs. They, and the related but much more numerous detached double white dwarfs, are of interest as gravitational wave sources and possible Type Ia supernova progenitors. The properties of AM CVn stars depend strongly on their orbital period. At short periods ($P < 20$ mins) they have bright accretion discs which outshine the underlying white dwarf. The systems are in a permanent high state; examples are AM CVn itself and the recent discovery from Kepler, SDSS J1908+3940 (Fontaine et al., 2011) At intermediate periods, $20 < P < 40$ mins, AM CVn stars show outbursts of a few magnitudes, while for $P > 40$ mins they seem to exist in a stable low state, although they can exhibit considerable short-timescale flickering activity.

AM CVn stars are hard to find, and we know of only ~ 30 systems, and have measured periods of only 18 of these. The best current estimate of their space density is from 1 to $3 \times 10^{-6}$ pc$^{-3}$ (Roelofs et al., 2007). If all had absolute magnitudes similar to the faintest so far observed, $M_V = 12$, we could expect from 200 to 600 AM CVn stars to be surveyed by Gaia down to $V = 20$. AM CVn stars can however be considerably brighter than $M_V = 12$, (several are known with $M_V = 5$ to 7, Roelofs et al.) so several thousand may be within reach.

Gaia can help in the discovery of AM CVn stars in the following ways: (i) location in the HR diagram as a population of blue, faint objects, (ii) variability, (iii) colours and (iv) RVS spectra. The first two of these will end with AM CVn stars being grouped with other faint blue variables, with pulsating sDBs and DB white dwarfs overlapping at the bright and faint ends.
of their distribution, but with hydrogen-rich cataclysmic variable stars (CVs) likely to be the major source of confusion since they have very similar variability characteristics, colours and magnitudes. The chief means to select between AM CVn stars and CVs from Gaia data alone will be methods (iii) and (iv). Colours will differ in detail because of the strong He I lines of long period AM CVn stars (the majority) compared to the strong Balmer lines of CVs. The RVS spectra may also provide some discrimination from the presence of Ca II and Paschen lines in CVs versus N I lines in AM CVns in the range the RVS samples. The separation is unlikely to be perfect, and ground-based follow-up will be essential to confirm AM CVn stars from Gaia, as it will for determination of their orbital periods. Nevertheless, there are excellent prospects for a significant addition to the current small sample, and of course Gaia will provide us with secure distances for these poorly understood systems.

2.8.6 Gaia and low-mass X-ray binaries

Black holes and neutron stars provide the best laboratories in the Universe for studying general relativity. Stellar mass black holes represent an ideal class of system for understanding accretion onto black holes – the vast majority of accretion physics is ”scale-free”, meaning that it should function in the same manner for stellar mass black holes in X-ray binaries as it does for the supermassive black holes in active galactic nuclei – and without the solid surface that provides complications in the cases systems with neutron star and white dwarf accretors. On the other hand, the viscous timescale from the inner edge of the accretion disk in most active galactic nuclei will be longer than the lifetime of the typical astronomer – AGN variability is fundamentally ”weather”, while in X-ray binaries one can understand how systems respond to changes in mass transfer rate.

Accreting neutron stars present their own opportunities to understand fundamental physics. The equation of state of neutron stars determines their mass-radius relation, and is determined by interactions between particles at nuclear density. Accurate measurements of the masses and radii of neutron stars thus give the opportunity to study particle interactions in a regime which cannot be probed in a laboratory or an accelerator. It has also been suggested that neutron
stars’ spin evolutions may be controlled, in part, by gravitational radiation.

Finally, black holes and neutron stars are the remnants of the most massive stars – the stars which provide most of the metal enrichment in the Universe. Understanding their key system parameters – their masses, distances, space velocities, and orbital inclination angles – is fundamentally important for understanding how these objects form, and for taking full advantage of their capability of probing relativity and accretion physics.

Gaia will revolutionise a few key aspects of studies of neutron stars and black holes. Both distances and proper motions of X-ray binaries are necessary for extracting some of the most important fundamental physics that can, in principle, be obtained from these systems. Additionally, searches for astrometric wobble associated with black holes in wide binaries would be fundamentally important for understanding the black hole mass function.

**Distances**

Accurate distance measurements to X-ray binaries are notoriously difficult. At the present time, two geometric parallax measurements have been reported, both based on radio data (Sco X-1 – Bradshaw, Fomalont & Geldzahler 1999; and V404 Cyg – ?). About 10% of X-ray binaries are located in globular clusters, so their distances are known to about 10% accuracy as well.

The bulk of X-ray binaries have had their distances estimated by far more indirect techniques – for typically from using the flux and temperature of the donor star, plus an estimate of the radius of the donor star based on the requirement that it fills its Roche lobe at the measured orbital period. Unfortunately, in most X-ray binaries, even in quiescence, the accretion light contributes significantly in the optical and infrared, leading to difficulties in measuring the actual flux of the donor star properly. This leads to systematic uncertainties in the distances to the systems.

It also leads to incorrect interpretations of the size of the ellipsoidal modulations of the donor
stars, which are used to estimate the inclination angles, since the donor stars’ ellipsoidal mod-
ulations are being diluted by the accretion light. Direct distance measurements from parallax
thus can also be used to decompose the light into donor star and accretion light components.
This in turn will give better mass estimates for the accretors, and allow spectral fitting of the
remaining accretion light in quiescence allowing for better modeling of accreting black holes
and neutron stars at the lowest luminosities.

For the neutron star systems in particular, getting accurate distances is of great importance.
The radii of neutron stars can be estimated by fitting models to their X-ray spectra in the two
cases where they are dominated by thermal emission from the surface of the neutron star –
in quiescence, or during the Type I X-ray bursts – the runaway nuclear burning episodes that
take place on the neutron star surface. However, the radius measurements are only as good as
the distance estimates to the neutron star. While this has been done in some cases in globular
clusters, it is of great value to have as large a range of neutron stars as possible to test, since
a single combination of mass and radius for a single neutron star can, in principle, rule out a
wide array of equations of state for supranuclear density matter.

Observable systems

X-ray binaries are among the rarest binary stars in the Galaxy. Still, approximately 25 X-ray
binaries are brighter than 20th magnitude in $V$, including several black hole systems (GRO
J1655-40, V404 Cyg, GX 339-4, Cygnus X-1, XTE J1118+480) – see Liu et al. for a com-
pilation of X-ray binaries with properties including their donor star fluxes. It is additionally
likely that some quiescent X-ray transients will be discovered through Gaia observations. The
orbital period distribution of X-ray binaries is extremely difficult to estimate either from the-
torical concerns (because of the large number of poorly constrained parameters that go into
binary evolution calculations) or from observations (because to date, nearly all known X-ray
binaries were first discovered in outburst, leading to potentially strong selection effects, since
the probability that a source will have undergone an outburst over the 50 year history of X-ray
astronomy is likely to be strongly correlated with its orbital period). Nearly any X-ray binary
will have a radial velocity amplitude larger than 10 km/sec, and so it seems likely that Gaia
will detect nearly all X-ray binaries brighter than $V = 17$. 

**Inclination angles** Getting good inclination angle estimates is important for a few other reasons. Several systems seem to show evidence of relativistic jets which are not perpendicular to their binary orbital planes, which could be interpreted as evidence that the black hole spins in these binaries are misaligned (Maccarone, 2002). Better distance estimates will allow for the relativistic motions of the jets to be converted into inclination angles and jet speeds more accurately, while better estimates of the inclination angles of the binary planes will allow firmer conclusions about the misalignment of jets, perhaps leading to strong evidence for rapidly rotating black holes, derived in a manner completely independent from the normal X-ray spectral fitting methods. Additionally, the GEMS mission, soon to be launched by NASA, will attempt to find evidence for rotating black holes from the X-ray polarisation properties of thin accretion disks around black holes – but the interpretation of these measurements, too, will be inclination angle dependent.

**Proper motions**

Isolated radio pulsars show a space velocity distribution far larger than that of their parent population or massive stars, indicating that they are often, or perhaps always, formed with strong natal kicks. The evidence for such kicks at kick for neutron stars in X-ray binaries, and especially for black holes, is less secure. About a decade ago, it was generally believed that neutron stars would all form with kicks, while black holes would not. The spin period-eccentricity relation in double neutron stars (?) and the high space velocity of the black hole X-ray binary GRO J1655-40 have cast doubt on this sharp distinction. Theoretical work done in recent years has also suggested that electron capture supernovae might be responsible for the formation of a low velocity kick mode of neutron star formation, while some black holes might form through a process in which a supernovae takes place forming a neutron star which lives only a short time before a fall-back disk accretes onto it, producing a black hole. It is thus of great interest to measure the proper motions of X-ray binaries, in conjunction with their distances, to determine whether they have locations and velocities consistent with having
been formed with velocity kicks.

**Direct inclination angle measurements**

For a few systems, Gaia may be able to map out the orbit of the donor star, leading to a direct measurement of the system inclination angle (under the well-justified assumption of a circular orbit). Such measurements will provide an extra degree of redundancy which will allow testing of the ellipsoidal modulation method of inclination angle estimation. They will additionally give the position angles of the orbits, which will allow for additional checks on whether jets are perpendicular to the binary orbital planes.

**Non-accreting binaries with black holes and neutron stars**

At the present time, with the exception of a few microlensing black hole candidates, the black holes known in the Milky Way are all in accreting binary systems. The masses of the black holes in these binaries are almost certainly affected by binary evolutionary processes. On the other hand, most massive stars are not in such wide binaries. The mass function of black holes measured to date is thus severely biased in ways which are not well understood.

Gaia holds the potential to help solve this problem, by indentifying very wide binaries containing compact objects through either astrometric wobble, or radial velocity wobble. About $10^8 - 10^9$ black holes should have formed over the lifetime of the Galaxy (van den Heuvel, 1992). Assuming that the space density of black holes traces the space density of stars in general, there should then be approximately $10^3 - 10^4$ black holes within 100 pc. Within that distance range, even M dwarf counterparts should be detectable by Gaia, although relatively few white dwarfs will be detectable.

The optically emitting star in a wide binary containing a black hole will be a small fraction of the total mass of the binary system (except in the cases of very bright, massive stars). As a result the motion of the optical star will account for nearly the full orbital motion of the
binary, so 1 milliarcsecond wobble will result for orbital periods as short as about 2 weeks, even at a 100 pc distance. Systems with orbital periods shorter than 2 weeks will have radial velocity amplitudes of order 100 km/sec or faster, so all binary systems containing black holes will be detected by Gaia as either spectroscopic or astrometric binaries unless they are almost perfectly face-on short period binaries, or have orbital periods sufficiently long that the astrometric orbital motion shows no curvature on the 5 year mission it. The orbital period distribution of binaries containing black holes is almost completely unknown, but if one assumes that it follows the distributions followed by G dwarfs (Duquennoy & Mayor, 1991), that of a log normal distribution peaking at 180 years, with a dispersion of 2.3 dex, we find that about 1/3 of the binaries should have periods shorter than about 20 years. It thus seems reasonable to expect that at least 100 or so wide binaries with black hole primaries will be discovered by Gaia, with around 1/3 of them having orbital periods shorter than 2 years, thus allowing for Gaia to have sampled the orbit directly, thus giving the opportunity to measure precise black hole masses – this sample would be similar in size to the sample of stellar mass black holes in X-ray binaries whose masses have been estimated, allowing for a direct probe of whether binary evolutionary strongly affects the black hole mass function.

2.8.7 Gaia and White Dwarf Mergers

The dynamical mergers of two white dwarfs are believed to give rise to progeny of several types depending on initial masses and composition. The most populous are likely to be low-mass helium main-sequence stars, most likely manifest as helium-rich sdB or sdO stars, or possibly as single subdwarf B stars. The next most populous are the R CrB variables and extreme helium stars. More massive mergers are conjectured to result in an explosion of one type or another, either Type Ia SNe or short-duration $\gamma$-ray burts. A number of critical questions will be answered directly using Gaia 6-space measurements:

*What is the galactic distribution of double-white dwarf binaries (DWD’s)?* Binary-star population-synthesis studies provide quite specific predictions regarding the space density and distribution of DWD’s as a function of type and history. In particular, these
predictions are sensitive to the star formation history of the Galaxy (including rate, and initial mass and period distribution), and to assumptions about the physics of common-envelope ejection in close binaries. Contemporary surveys are discovering increasing numbers of short-period DWDs. Complete six-space positions for all observable DWDs will verify these assumptions.

Is there a demonstrable connection between the galactic distribution of double white dwarfs and their supposed progeny? For example, from their distribution on the sky, R CrB and EHe stars appear to belong to a galactic bulge population. However population synthesis studies suggest that their binary progenitors must come from a much younger galactic disc population. With accurate distances and proper motions for RCBs and EHEs (for example), this question will be resolved immediately.

What are the masses and luminosities of supposed merger products? Binary-star population-synthesis models predict the mass-distribution of DWD mergers. Models for post-merger evolution predict evolution tracks as functions of merged mass. At present, luminosities and masses can only be inferred. Direct distance measurements will give both and will verify conclusively the post-merger evolution calculations. They will also test whether DWD mergers are likely to be conservative (in mass), and hence the physics of the merger process.

Do DWD mergers produce explosions? Some models predict that Type Ia supernovae and possibly some short-duration $\gamma$-ray bursts arise from super-Chandrasekhar and some He+He mergers respectively. Comparing space densities of DWDs with observed Ia and GRB rates will address this question.

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2.9 Synergy with future projects

2.9.1 Provide candidates for Plato

In the framework of the PLATO project, the 1st option to build the PLATO Input Catalogue (PIC), from which to select the PLATO targets, is to use a preliminary Gaia catalogue. Specific informations about this issue can be found in several PSPM (PLATO Science Preparation Management) documents, e.g. from http://www.oact.inaf.it/plato/PPLC/PSPM/PSPM.html. This general choice has important implications also for the white dwarfs: the large sample of white dwarfs that will be observed by Gaia (≈400,000 objects, Jordan 2007) will contain a ~3-4% subsample of DAV pulsators (plus a much smaller fraction of DBVs and PG 1159 pulsators). For some of them, pulsations will be directly detected by Gaia photometry (see Sect. 2.5.2 for more details). For the others, Gaia will at least tell us precise distances and luminosities, from which it will be possible to isolate those close to the DAV instability strip. The possibility to observe some of these pulsators with PLATO is an interesting development considering that it is unlikely that these objects will be observed by CoRoT or Kepler. The probability to find a sufficiently bright WD pulsator in its field of view is virtually zero for CoRoT and very small for Kepler. Moreover, as the Kepler “survey phase” (in which the best asteroseismic targets have been selected) is already finished, it is quite unlikely that a new WD pulsator in the Kepler FOV can be identified and observed by Kepler in the next months/years of the mission.

On the other hand, the number of DAV pulsators in the much larger PLATO FOV will be large enough to be able to observe some of them. Considering a limiting magnitude $V \leq 16.0$ and a local space density of DAVs of $1.9 \times 10^{-4} \text{ pc}^{-3}$ (obtained from the number of DAVs in the local WD sample of Holberg et al. 2008, see also Sion et al. 2009), the number of DAVs in a single PLATO FOV of ~2,200 sq. degr. should be about 10. Considering that PLATO will observe different fields (2 long-term fields of 2-3 yrs each plus another 5-6 step & stare fields of 2-5 months each), the total number of DAVs observable with PLATO is about 70. These numbers increase by a factor of 2 when going deeper by half magnitude.
In conclusion, a timely identification of white dwarfs in the Gaia catalogue, possibly followed
by ground-based spectroscopy/photometry in order to select the best DAVs or DAV candidates, is an important issue in order to be able to observe some of them with PLATO. Thanks to the outstanding quality of PLATO data in terms of duty cycle, photometric accuracy and homogeneity, these observations would be a major step towards detailed WD asteroseismology, allowing to study in much greater detail the internal structure of these degenerate stars.

Bibliography

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Chapter 5

Conclusions