Gaia — A White Dwarf Discovery Machine

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Abstract. Gaia is a satellite mission of the ESA, aiming at absolute astrometric measurements of about one billion stars ($V < 20$) with unprecedented accuracy. Additionally, magnitudes and colors will be obtained for all these stars, while radial-velocities will be determined only for bright objects ($V < 17.5$). However, the wavelength range for the radial-velocity instrument is rather unsuitable for most white dwarfs. Gaia will probably discover about 400,000 white dwarfs; up to 100 pc the detection probability for white dwarfs is almost 100%. This survey of white dwarfs will have very clear, easy to understand selection criteria, and will therefore be very suitable for statistical investigations. The Gaia data will help to improve the construction of a luminosity function for the disk and the halo and will provide a more accurate determination of the age of our solar neighborhood. Moreover, reliable stellar dynamical investigations of the disk and halo components will be possible. For the first time it will be possible to test the mass-radius relation of white dwarfs in great detail. Moreover, more accurate masses of magnetic and cool white dwarfs can be expected. Gaia is also expected to discover many new pulsating white dwarfs. The Gaia measurements can also complement the measurements of gravitational waves from close white dwarf binaries with Lisa.

1. The Gaia mission

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 (see Fig.1): 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 $45^\circ$ 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 (see Fig. 2). 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: $R = \lambda/\Delta\lambda = 11\,500$. 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, and finally, deviations from general relativity are accounted for by solving for the post-Newtonian parameter $\gamma$.

The number of observations for the $10^8$ primary stars is about $6 \cdot 10^{10}$. The condition equations connecting the unknowns to the observed data are non-linear but linearize well at the sub-arcsec level. Direct solution of the corresponding least-squares problem is infeasible, because the large number of unknowns and their strong inter-connectivity, prevents any useful decomposition of the problem into manageable parts. The proposed method is a block-iterative scheme called the Global Iterative Solution. Intensive tests are currently under way and have already demonstrated its feasibility with $10^6$ stars assuming realistic random and systematic errors in the initial conditions.

Later, with a good solution for the attitude and the geometric parameters based on the measurements of the $10^8$ primary stars, the remaining $9 \cdot 10^8$ stars can be linked into the system.

The precision of the astrometric parameters of individual stars depends on their magnitude and color, and to a lesser extent on their location in the sky. Sky-averaged values for the expected parallax precision are displayed in Table 1. The corresponding figures for the coordinates and for the annual proper motions are similar but slightly smaller (by about 15 and 25%). Note, that a parallax accuracy of 25 microarcseconds (the thickness of a human hair seen from a distance of 200 km) means an accuracy of the distance determination of 0.1% for 40 pc, and 1% for 400 pc.
Figure 1. Gaia’s two fields of view, separated by a basic angle of 106.5° scan the sky according to a nominal scanning law: Rotation period: 6 hours, solar aspect angle: 45°, precession period: 63 days.

Additionally to the astrometric measurements the entire sky will be observed with the same spectro-photometric system and with unprecedented homogeneity. Moreover, radial velocities are measured with a precision between 1 km/sec (V=11.5) and 30 km/sec (V=17.5). Photometric measurements are not only nice to have but will allow the correction of relative displacement between an early-type and very red stars (chromaticity) which may be as large as 1 milliarcsecond. The measurements of radial velocities are important to correct for perspective acceleration which is induced by the motion along the line of sight.

Gaia is currently scheduled to be launched from Kourou, French Guiana, in December 2011 with a Soyuz-ST rocket (which includes a restartable Fregat upper stage). Initially the Fregat-Gaia composite is placed into a parking orbit, after which a single Fregat boost injects Gaia on its transfer trajectory towards the L2 Lagrange point. In order to keep Gaia in an orbit around L2, the spacecraft must perform small maneuvers every month. After a commissioning phase Gaia will measure the sky for five years with a possible extension for another year. Subsequently, the final catalog, which includes astrometric and photometric information, radial-velocity determinations, and a classification of the objects, will be produced. The completion of the Gaia mission is intended to be around 2020 (at the time of the 22nd European Workshop on White Dwarfs?). However, it is not implausible that preliminary products will be delivered earlier, since even the results from only one year of measurements would considerably surpass the precision of all existing star catalogs.
2. Gaia’s performance for white dwarfs

The number of currently known white dwarfs amounts to almost 10,000, 5500 in the online version of the Villanova White Dwarf Catalog \(^1\), 9316 confirmed white dwarfs in the SDSS according to Kleinman et al. (these proceedings). Torres et al. (1999) have performed intensive Monte-Carlo simulations and arrived at about 400,000 white dwarfs down to \(V = 20\) 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.

The question, whether Gaia can distinguish between disk and halo stars was also investigated by Torres et al. (1999). Since the wavelength range of the Gaia radial-velocity spectrograph \((8470 – 8740\ \text{Å})\) does not allow the measurement of radial velocities for almost all white dwarfs, they used only a reduced-proper motion criterion which additionally throws away the direction of the proper motion. From this they concluded that the distinction between both populations is extremely difficult. However, if one uses the direction information, halo white dwarf can be detected more easily, as was e.g. demonstrated by Carollo et al. (these proceedings). With the Gaia sample, a detailed investigation of different disk components (“thin disk”, “thick disk”) and their scale heights will also

1\.[http://www.astronomy.villanova.edu/WDCatalog/index.html](http://www.astronomy.villanova.edu/WDCatalog/index.html)
Table 1. End-of-mission parallax precision in microarcseconds. Representative values are shown for unreddened stars of the indicated spectral types and V magnitudes. The values are computed using the actual Gaia design as input. The performance calculation used does not include the effects of radiation damage to the CCDs.

| Star type | V magnitude | 2006 nominal performance |
|-----------|-------------|--------------------------|
|           | < 10        | 5.2                      |
| B1V       | 15          | 20.6                     |
|           | 20          | 262.9                    |
| G2V       | < 10        | 5.1                      |
|           | 15          | 19.4                     |
|           | 20          | 243.4                    |
| M6V       | < 10        | 5.2                      |
|           | 15          | 8.1                      |
|           | 20          | 83.9                     |

be possible. Moreover, distinctive luminosity functions can be constructed for all disk and halo components, considerably improving our understanding of our Galaxy’s formation.

Due to the very large errors in the distance determination even one of the fundamentals of the theory of white dwarfs is not yet tested with sufficient accuracy: the mass-radius relation. Vauclair et al. (1997) used 22 state-of-the-art ground-based or Hipparcos parallaxes (with 13% error on average) and were unable to account for the theoretical mass-radius relation. Provencal et al. (2002) used only the best three white dwarf parallaxes measured by Hipparcos (3% error on average) and came somewhat closer to the goal of verifying the theory. The number of white dwarfs with high-precision distance determinations is simply too small for a detailed analysis of this question. With the typical 0.1%-1% accuracy of the Gaia parallaxes, it will be possible to study the dependence of the mass-radius relation on \( T_{\text{eff}} \) and the chemistry in great detail, with the further ability to discriminate between different hydrogen envelope masses.

Moreover, by such an investigation Gaia will certainly find out whether strange things like strange matter (Fontaine et al. these proceedings) or strange interiors like iron cores (Shipman & Provencal 1999) exist!

Gaia will also detect a large number of spectroscopic white dwarf binaries by finding strong disagreement between spectroscopic and astrometric parallaxes. The discovery of close spectroscopic binaries is very important for the identification of sources for gravitational waves measured by the Lisa mission. Independent measurements of masses and separations from the Lisa data are only possible with accurate distances (Stroer et al. 2005).

In the case of strongly magnetic white dwarf, the simultaneous presence of the Zeeman and Stark effect does not allow a reliable estimation of \( \log g \). Therefore, masses can only be quantified by combining photometry, spectroscopic determinations of effective temperatures, and parallaxes. Therefore, this field will also considerably benefit from the Gaia measurements, and the question whether
magnetic white dwarfs are more massive \cite{Liebert1988} for all field strengths can be scrutinized together with its consequence for the identification of the main-sequence progenitors.

However, the inability to determine reliable masses is not only limited to magnetic white dwarfs. As was discussed in detail \cite{Bergeronetal2013} and \cite{Kepleretal2013}, the masses of cool white dwarfs ($T_{\text{eff}} < 10000\,\text{K}$), as inferred from spectroscopy, strongly deviate from those at higher temperatures. With the addition of reliable distance determinations this mystery can certainly be solved. The question, whether DAs and non-DAs have the same mass distribution can also be answered with a higher precision.

Not only the astrometric measurements will be important for white dwarf research: Many new non-radial pulsators will be found by analyses of the high-precision photometry. The nominal scanning law will lead to a very non-uniform sequence of detections in time: one FoV transit corresponds to 1.5 minutes, the time separation between the two FoVs is 1.8 or 4.2 hours, and up to 14 transits within about 40 hours are possible; smaller groups of observations are more frequent, but most groups contain at least two transits. The question, which periods and amplitudes are detectable has to be studied in more detail, but it is certain that the number of confirmed pulsating white dwarfs will increase significantly.

Additionally to all these details, 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 \cite{Kleinmanetal2013}.

One can clearly conclude that white dwarf research will tremendously benefit from the Gaia data. This is not surprising, because there is hardly any topic in astrophysics that will not be affected (at least indirectly) by the measurements of this satellite mission!

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