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GAIA I: THE MISSION - THE ADVENTURE BEGINS

M. Altmann[1,2]

RESUMEN

La misión satelital Gaia de la ESA, lanzada el 19 de diciembre del 2013, dejará, sin lugar a dudas, una profunda huella en los estudios de dinámica Galáctica, revolucionando muchos aspectos de esta área. Nueve meses después del lanzamiento, terminada la fase de comisionamiento, y habiendo Gaia comenzado la fase de cinco años de mediciones, es un momento adecuado para ofrecer un vistazo de la misión y lo que se puede esperar luego de que se haya evaluado in situ el potencial real del satélite. Este artículo provee de una breve descripción de la misión como un todo, al que le sigue la contribución de Figueras en este volumen, que se focaliza en la ciencia que realizara Gaia.

ABSTRACT

The ESA Gaia satellite mission, launched on Dec. 19, 2013, will undoubtedly leave a profound impact on Galactic dynamics, revolutionising many aspects of the trade. Nine months later, with the commissioning phase over and the regular five year measuring phase of Gaia starting, it is time to give an overview of the mission, what to expect after the potential of the spacecraft has been fully assessed in situ. Moreover this paper will give a brief description of the mission as a whole, to be followed by a second contribution by Figueras (2015) focussing on Gaia science.

Key Words: astrometry — Galaxy: structure

1. GAIA - THE PROMISE

ESA's cornerstone space mission Gaia was started in the 1990's as a successor of the then ongoing mission Hipparcos (Perryman et al. 1997; van Leeuwen 2007), to take a further giant leap in the exploration of our Galaxy and it's denizens, the stars. Gaia built up on Hipparcos and moved space astrometry into the age of CCDs and ever more powerful micro electronics. While the former mission already was a novel approach to astrometry, removing the atmosphere, and all of its detrimental influences, from the measuring process, it was clear that a more powerful approach was needed to address many of the urging questions in Galactic astronomy. These include the fixation of the Cosmic distance ladder, especially calibrating the Cepheid period-luminosity relationship. Also, a significant fainter magnitude limit allows to study the kinematics and structure of the Milky Way beyond the immediate solar neighbourhood (Hipparcos astrometry was essentially restricted to distances of about 1 kpc or less) even up to the Milky Way's satellite galaxies, such as the Magellanic clouds and the dwarf spheroidals. Moreover, for magnitudes fainter than about 7, Hipparcos relied on a proposal driven input list, the Hipparcos Input Catalogue (Turon et al. 1993). give access to new areas of dynamic astronomy such as the 3D internal kinematics of star clusters, and questions of fundamental physics. Additionally Gaia, being a drift scan mission, will detect a large number of small solar system bodies, such as Near Earth Objects and also other transients, from certain species of variable stars (Novae, R CRB, flare stars) over extragalactic supernovae, to AGN.

Gaia will observe every object in the sky[3] to a magnitude of 20, leading to an inventory of about 1% of the entire Milky Way stellar population. As an example for Sun-like stars, i.e. those with an absolute magnitude of +5 mag, Gaia will cover a sphere with a radius of 10,000 pc, granting access all the way from the Galactic centre[4] to the outer disk. For the famous old population tracer stars, such as HB stars and luminosity class III giants, Gaia reaches out far into the halo even covering the Magellanic clouds. Altogether Gaia will observe about 1 billion stars astrometrically and photometrically, as well as a brighter subset of 100 million objects with high resolution spectroscopy, deriving radial velocities, phys-

[1]Zentrum für Astronomie, Universität Heidelberg, Mönchhofstr. 12-14, D-69120 Heidelberg, Germany (maltmann@ari.uni-heidelberg.de).

[2]SYRTE, Observatoire de Paris, Av. Denfert Rochereau 77, F-75014 Paris, France.

[3]except the major solar system objects, and possibly the brightest stars - although the latter is being assessed

[4]parts of this will be hampered by the extreme interstellar extinction in this direction

ical atmospheric parameters such as $\log g$ and $T_{\rm eff}$ as well as abundances[5].

2. OUTLINE OF THE PRINCIPLES OF THE GAIA MISSION

In many respects Gaia is rather similar to the preceding Hipparcos mission. Both share the two aperture approach aiming at optimizing the full sky astrometry, and a whole sky scan law. However Gaia incorporates far more advanced technology, reflecting the progress between the 1980's and the 2000's. While Hipparcos had to cope with photoelectric detectors, Gaia features a 2 dimensional 106 CCD chip array for the measurements, see Fig. 1. The much larger bandwidth in today's communication and telemetry stations allow the transfer of far larger data quantities making the use of such devices feasible. Likewise, this also allowed the number of observations to surge dramatically, with Gaia observing 1 billion stars instead of Hipparcos' 120,000. This also has consequences for science of object samples. While the former mission utilized an input list for stars fainter than a threshold of $H = 7.3$ mag, Gaia will record every objects brighter than $G = 20$ mag leading to survey unbiased by a priori scientific interest. But not only technological progress has contributed to the definition of Gaia, past experience from Hipparcos itself also has. As an example, for this reason, Gaia also has a spectrograph to measure radial velocities (and other quantities, such as abundances, stellar parameters, etc.) - since this was a drawback for the Hipparcos data, since many stars did not have measured radial velocities, i.e. the full 6 dimensional position velocity space was not complete for those objects. Therefore this instrument was added - since a spectrometer requires much more light than imaging, it is obvious that the limiting magnitude is higher than that of the astrometry, it is foreseen to cover about 100 million stars to the magnitude of 17 mag, depending on spectral type.

While Hipparcos/Tycho offered two passband photometry[6], namely $V_{\rm T}$ and $B_{\rm T}$, Gaia has two spectrophotometers, which in reality are two very low resolution spectrographs, one for the red part (RP) and the other for the blue part (BP) of the spectrum. This allows the composition of different passbands as required, and also a narrow band photometric classification for each object.

While the available bandwidth for downloading data has vastly improved since the days of Hipparcos, it is still not possible to download all recorded data back to earth. Therefore objects are registered and cut out with brightness depending sets of apertures, and only these "stamps" are sent to earth, the rest of the frames are discarded. For the BP/RP something similar applies. Only this way the number of measurements and objects can be maintained.

Since Gaia is a global absolute astrometry project, not only the angles between nearby stars, i.e. those projected onto the focal plane at any given time are of importance, as it is in the case of small field astrometry, but also large angles between distant objects. In the small field case, the procedure is to project the x, y-coordinates derived from the image of the target field into an astrometric coordinate system using an appropriate function (which compensates for optical distortions and other effects and conducts a gnomonic projection of the plane onto the celestial sphere). The coordinate system is represented by a reference catalogue giving the positions of a number of objects in the target field. Global astrometry is a bit more complicated - here the full sky catalogue itself is being constructed and then hinged into a standard reference system using the positions of the sources defining this reference system. Such an undertaking requires a rigid internal structure; this means that angles of both close by objects and objects far away from each other need to be known, essentially to the same degrees of precision and accuracy. This is not easy to achieve, especially in the case of a moving spacecraft. A viable method is to project two fields of view into the same focal plane at any given time under the condition that the angle between them is extremely stable and well known. This is the way Gaia (and previously Hipparcos) measures the large angles needed to form the framework of the global astrometry. In the case of Gaia, the two apertures are pointing at regions 106.5°apart (see Fig. 2). The reason for this rather odd number is to prevent antialiasing effects from happening, i.e. to prevent the same two fields being observed too often, which would happen if the angle between both FOV's were close to a small common fraction of the full circle, such as 90°, 60°, 120°, etc. This rigid framework of the full celestial sphere allows absolute astrometry, since all shifts in positions, be it the annual parallax circle or the proper motion are being seen in respect to the whole reference frame, defined by the rigid angles and hinged to the coordinate system defining sources. As mentioned, the downside of this approach is that the angle between the two

[5]the straylight problem (see Sect. 3 will likely reduce the yield of this part. Please also note that not all of the above quantities can be obtained for all of the subset, some, relying on higher S/N spectra, will accordingly have a brighter cutoff magnitude.

[6]Hipparcos also has unfiltered H magnitudes, analog to Gaia's G magnitudes

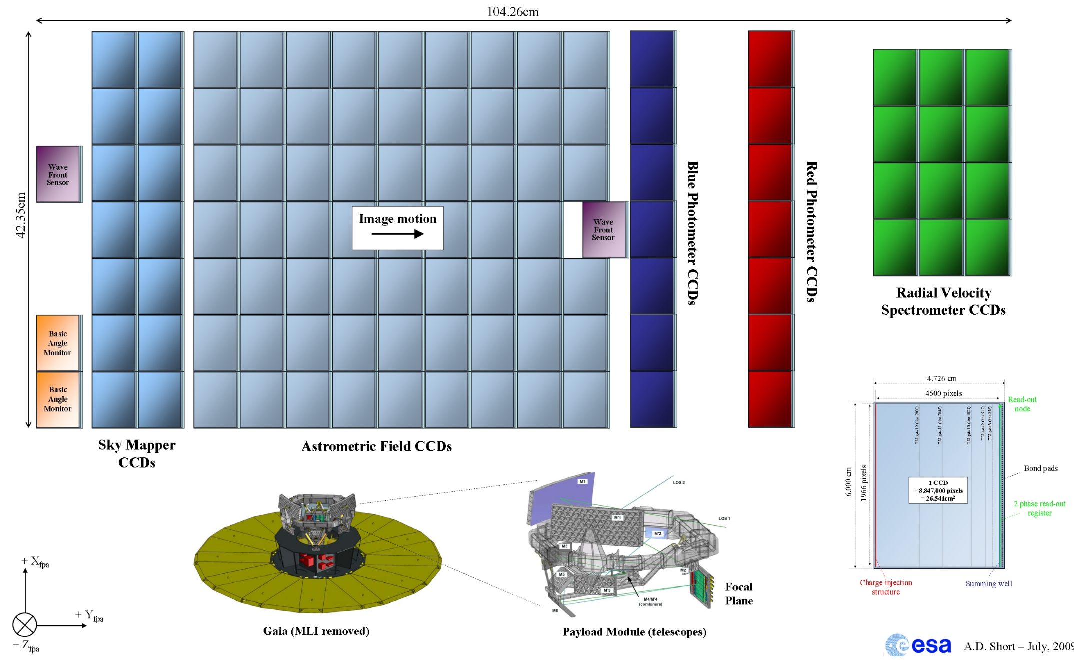

Fig. 1. A schematic representation of Gaia's focal plane. The main components are from left to right: The two star mapper columns for identification of the stars from each FOV, the 9 astrometric columns (with some redundancy), the RP/BP spectrophotometric arrays, and the shorter RVS detector arrays. The chips to the left of the main assembly and in the middle of the 9th astrometric column are diagnostic/calibrational devices serving for the Basic Angle Monitor (BAM, see text) and the wavefront sensor.At the bottom of this figure the position of the focal plane assembly within the optical payload module, and of the module inside the satellite are shown, as well as the layout of an individual CCD chip. Courtesy, ESA, Alexander Short.

apertures must be extremely stable and well known. For Gaia's ambitious aims this means that this angle, called the Basic Angle, must be constrained to 4 μas in accuracy, and 7 μas in precision. Considering the size of Gaia's focal assembly of about 3 m, the stability of the system must be in the order of 50 ppm, the typical size of an atom (e.g., Carbon = 77 ppm) being in the same order. This means that the material out of which Gaia's optical assembly is built, had to be extremely stable and have a negligible thermal expansion coefficient. The material chosen for this is Silicon Carbide, a very hard and stable material related to diamond.

Apart from the layout of the optical instrument an important part of the Gaia mission is the scan law. Gaia uses two different scan laws, one the Ecliptic Scan Law (EPSL) which covers the Ecliptic poles in each rotation, and which is mainly used for the early commissioning phase and possibly later for diagnostic purposes, and the Nominal Scan Law (NSL, see Fig. 2), used for the scientific measurements. The reason for the EPSL is to get regular access to two fields in which the stellar inventory and its photometric properties are well known. For this the fields around the poles of the Ecliptic have been chosen, allowing for a rather simple scan law.

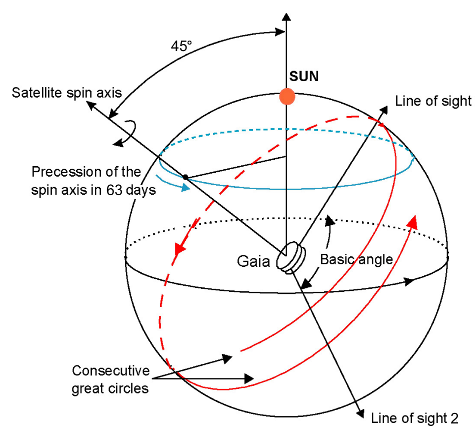

Fig. 2. Geometry of the Nominal scan law utilized by Gaia. Courtesy: ESA.

The NSL is optimized for equal sky coverage and thruster energy consumption. The spacecraft rotates with a period of 6 hours, i.e. the 2nd FOV follows the first one by about 1 hr 46 minutes. It keeps an aspect angle in respect to the Sun of 45°at all times, preceding once around the Sun every 63 days.

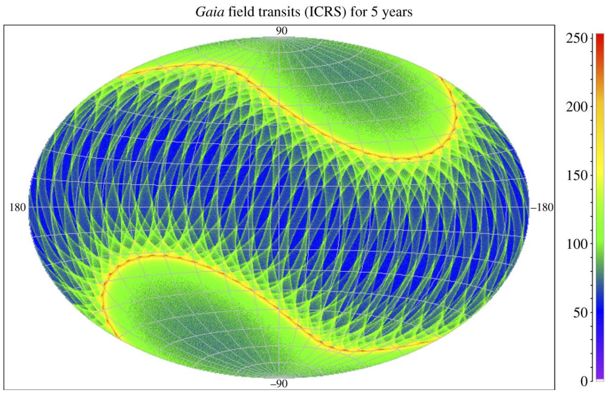

Fig. 3. Sky coverage after 5 years at the end of the nominal mission. The dark areas (blue in the online version) have the fewest transits, and the light parts (yellow and red in the online version) have the highest number. Most parts of the sky have at least 70 transits - Courtesy: ESA, Berry Holl.

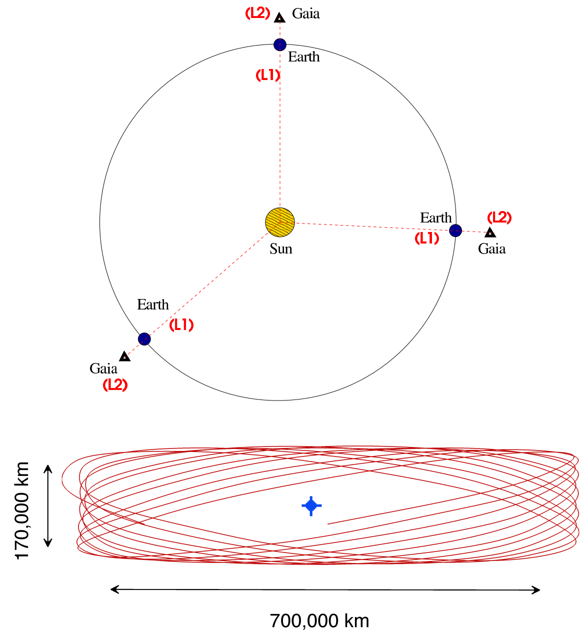

Fig. 4. Gaia's orbit: the top panel shows the location of Gaia or (strictly speaking) the L2 in respect to the Sun-Earth system for 3 occasions during one year. The lower panel shows the Lissajous orbit of Gaia around the L2 point (marked by a target symbol in the middle of the plot) during the 5 year nominal mission. Note that during this time Gaia does not come too close to the actual immediate L2 vicinity where a permanent solar eclipse persists - lower panel: courtesy ESA (adapted by the author).

This way each part of the sky is covered $\simeq 70\times$ on average during the mission time of 5 years as shown in Fig. 3. Since the Lagrange 2 point is unstable and since there is a permanent Solar Eclipse by the Earth at the L2 which would lead to a cutoff of Gaia's solar panel based power supply, Gaia oscillates on a Lissajous type orbit around this point, which ensures that it does not get occulted by the Earth's shadow during the 5 years of the mission, see Fig. 4.

Finally since Gaia is a drift scan the continuous readout speed of the CCD's of the focal plane array need to be synchronized with the rotational velocity so that the PSF of the stars are not smeared out as they wander across the focal plane.

This way a self contained highly stable measuring pattern is ensured, there are no moving parts on Gaia, the presence of which would disturb the stability of the setup.

The underlying astrometric principles are described in more detail in Lindegren et al. (2012) and Jordan (2008).

3. THE FIRST MONTHS AFTER LAUNCH

Gaia was finally launched from ESA's space port near Kourou, French Guyana on December 19, 2013, at 9:12 UT sitting on a Soyuz rocket with a Fregat booster, used for the transfer to the L2 region. The launch went extremely smooth, and the precision of the procedure reduced the amount of maneuvering necessary so much, that the fuel supply would allow for an extra year of operations[7]. Since January 2014 Gaia is on site on its Lissajous orbit around the Earth Sun L2 point.

The commissioning phase in essence started immediately after launch and the first maneuvers which included the slew to a Solar Aspect Angle of 45°, heating of the optical assembly to get rid of residual volatile substances, switching on and testing the CCD's and many more. It was soon found that all components were operating well and had obviously survived the launch phase. The microthrust boosters responsible for keeping up the rotation of the satellite were operating even more smoothly than specified. So while the satellite was operational there were a number of annoying or even harmful issues soon discovered and identified - as is the case in most if not all satellite missions, which are extremely complex and sensitive by nature and thus prone to mistakes and malfunctions. The most important of these are:

- The Basic Angle, which is supposed to be very stable, see Sect. 2, shows a large periodic vari-

[7] Which does not mean that there will be an extra year of measurements which depends on more than just the fuel supply - other critical aspects are the state of the CCD detectors (which are expected to deteriorate over time in the harsh radiative environment in the L2 region), and funding.

ation (2 mas peak to valley), about 400× the specified tolerance. This was problematic, since as described in Sect. 2 this would add a significant amount of error to the astrometry, and would hamper the ability to measure self contained absolute parallaxes[8]. The nature of this oscillations is not yet understood, its period is compliant with the rotational period of the satellite. Fortunately long term measurements have since shown that this pattern is highly stable over time which allows to correct for this effect in the global solution. However as with any additional signal imposed on a measured quantity, also more noise is added, so some degradation is expected, however this seems to be small. This means that the adverse effect of this problem will most likely be minor.

- A bit more serious is the occurrence of stray light on the optical assembly, which also underlies a period of 6 hours. The cause of this was determined to be apart from residual Sun light, the diffuse light from the Milky Way which was not considered in the pre launch simulations, so that ironically the very subject of Gaia's measurements, our Galaxy itself, negatively interferes with the observations. Recently it was discovered that some of the residual Sun light, which was supposed to be completely shielded by the two layer main shield was diffracted by loose fibres of the shield fabric which were not properly treated during the spacecraft's assembly. The impact of the stray light issue is less a concern for the astrometry, but a severe limitation for the high resolution spectroscopy were it can be expected that 1 magnitude of depth will be lost. For the photometry and astrometry the precision for the faint objects ($G > 18$ mag) will go up somewhat, but not significantly, there will still be a significant improvement over Hipparcos at the faint end[9].

- A third problem, which first became obvious a few weeks after launch is the accumulation of some contaminant on the optical surfaces, at first causing more than a magnitude throughput loss in the light path of FOV2, somewhat less in that of FOV1. If this would have continued this way, it could have threatened the outcome of the mission. Fortunately after a series of rigorous heating sessions, during each of which the contamination was completely gone, the recurrence of the buildup of the contaminant, which was quickly identified as being water vapour, became slower and slower (and hopefully will vanish altogether some day), so that at its current state it will be able to conduct months of uninterrupted measurements without the need to redo the decontamination heating - the problem with the heating cycles, it that while the heating phase itself is short (a couple of hours) the cooling down to thermal equilibrium takes weeks, during which no nominal observations can be done. Given the fact that the return of the contamination is decreasing each time one can assume that the impact on the measurements is minor, but there will be gaps in the time available for measurements caused by the heating cycles, so that coverage per object may be slightly lower than expected. One must note that while the overall trend is favourable, the development in the future is totally unpredictable.

- Another problem became obvious 2 nights after the launch, after the slew to a Solar Aspect Angle[10] of 45°. It was discovered that Gaia was approximately 3 mag fainter than expected, being at R=21 mag instead of 18 mag. While this is not a problem at all for the operation of the satellite itself, it does negatively affect the Ground Based Optical Tracking (GBOT) of the Gaia spacecraft campaign (Altmann et al. 2014), which relies on a network of 1-2 m telescopes distributed around the globe. This effort is required to ensure the full accuracy for even those objects which have the most precise measurements by Gaia (mainly to completely eliminate the effect of aberration) and also solar system objects, for which precise knowledge of the baseline between a pair of measurements is crucial. Previously relying on a small network of 1-2 m class telescopes, the GBOT group subsequently reassessed its methods and found that with some trade offs and relying on 2m+ class telescopes only the required precision can still be reached[11]. Please note that GBOT in-

[8] It would still be possible to calibrate the parallaxes using background extra galactic sources, so most of the science could be rescued, but the effort increases significantly

[9] which is several magnitudes fainter than the 12 mag faint limit for Hipparcos

[10] the angle between the Sun-Earth line and Gaia's rotational axis

[11] Whether the overall quality, i.e. including effects on accuracy, can be reached remains to be seen, this is only possible when the collected data are reduced again using Gaia astrometry as the underlying reference catalogue material - this will be done sometime during 2016. This open question is an issue

put only affects the quality of the best measured stars and not the bulk of the objects Gaia measures, for the fainter part, the declining precision dominates any accuracy effect.

These issues have surely had their impact on the commissioning phase and lead to this phase being longer than planned. Fortunately they can all be compensated or corrected, so that the toll on the outcome of the mission is limited, at current time the most severe being the stray light issue. It remains to be seen[12] whether Gaia can fully achieve its promises in full extent and what potential trade offs will be - even if it doesn't completely achieve its goals, it will still obtain an astrometric dataset of unprecedented quality which will without doubt revolutionize Galactic science. On the positive side Gaia's astrometric precision is significantly higher than nominal, and even in this very early stage with all kinds of calibration not yet in place or only poorly constrained the single measurement noise for Gaia is better than Hipparcos' end of mission results and that for stars which are more than 1000× fainter and 10,000× more numerous than what Hipparcos measured. Therefore one can still expect, despite the problems, that Gaia will produce astrometry of unprecedented quality and quantity. The commissioning phase ended on July 25 when Gaia entered the nominal part of the mission, first staying on the EPSL for some weeks when it was switched to NSL on August 22. After another heating cycle the normal measurements started in September. Since Gaia's performance is a topic with a possibly changing outcome, please refer to `http://www.cosmos.esa.int/web/gaia/science-performance` for the most current information.

4. DATA RELEASES

Unlike many other astronomical missions, Gaia needs to accumulate data over some time in order to deliver meaningful data products and results. There needs to be sufficient sky coverage to attempt a global astrometric solution, and time coverage to distinguish motion due to parallaxes from proper motion. Gaia's results will not be published in one release at the end of the mission, it is rather foreseen to issue data releases whenever a global solution is computed. Several releases are planned, each encompassing more data types of more objects of higher quality. The current release scenario is described in detail in Prusti (2012). Here we only mention the highlights of the scheduled releases (each incremental release of course also containing the data products of the previous issue):

1. Launch+22 months release (currently foreseen, mid-2016): Very limited release with positions and G-magnitudes only and full astrometry for the Hipparcos stars,
2. Launch+28 months release (early 2017): Full astrometry for "well behaved objects", colour photometry, possibly radial velocities,
3. Launch+40 months release (2017/8): binary stars astrometry for binaries with orbital periods between 2 months and 75% of the mission operation time, astrophysical parameters of "well behaved objects",
4. Launch+65 months release (2018/9): variable star data, solar system objects, etc.,
5. Final release (2022).

The prolonged commissioning phase and the added complications caused by some of the operational problems, described in the previous section will take their toll on the release schedule. Clearly the more into the future a release is the less certain are time of publication and scope. The dates given in this paper are those as stated in early 2015, for more current information, please consult `http://www.cosmos.esa.int/web/gaia/release`.

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from the beginning of the GBOT program, and has nothing to do with the problem described here.

[12]in any case, regardless of these adverse issues

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