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Gaia is now a reality

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Abstract

Gaia, ESA's astrometric mission designed to perform a 3D map of one billion stars in our Galaxy, was successfully launched in December 2013. The nominal operations are ongoing since end of July, after an extended commissioning phase. The expected operations of alignment and focusing of both telescopes, the software onboard testing and many other checks and tuning were executed nominally. The health of the payload and scientific instrumentation was evaluated and end-of-mission performances were assessed for astrometry, spectrophotometry and spectroscopy. Gaia will deliver the promised revolution in the many fields of astrophysics during the next decades. This paper reviews all these findings and provides the scenario for the future data releases.

1 Introduction

The Gaia mission is the cornerstone astrometric mission of ESA's in operations since its launch in December 19$^{\rm th}$, 2013. Gaia continuously scans the whole sky during $5-6$ years yielding positional and velocity measurements to build the first 3-D map of the Galaxy from one billion stars and at the level of μas precision. Gaia's main scientific goal is to quantify the early formation, and subsequent dynamical, chemical and star formation evolution of the Milky Way although the science case is much wider covering from Solar System objects to extragalactic sources and addresses key topics of fundamental physics (see [5, 3, 7]).

Gaia is continuously observing the sky at an average of 50 million transits per day, each transit consisting of images at the sky mapper, nine measurements in the astrometric field, two low-resolution spectra for all sources until magnitude 20, and three high-resolution spectra until magnitude 16.5. This data is routinely received at three ESOC ground stations (Cebreros, Malargüe and New Norcia) and passed on to the European Space Astronomy Center (ESAC) for the full processing. This processing is responsibility of the Data Processing

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and Analysis Consortium (DPAC) structured in several Coordination Units (CUs) and Data Processing Centers (DPCs) spread all around European institutes. After Gaia's launch and insertion into its Lissajous orbit around L2 point of the Sun-Earth system in early January 2014, an extensive commissioning phase took place until mid July 2014. Since then, science operations are progressing nominally. The commissioning activities revealed some undesired features, but also confirmed the huge potential of the mission.

This paper reviews the Gaia progress after launch and its current status. The paper is organized as follows: Sec. 2 describes the liftoff preparation activities, the launch and the trip to L2; Sec. 3 evaluates the commissioning phase with the list of positive and not so positive findings about the satellite and payload; Sec. 4 explains the science operations in process, and Sec. 5 assesses the end-of-mission performances. Finally, Sec. 6 provides the conclusions and the prospects for the early data releases.

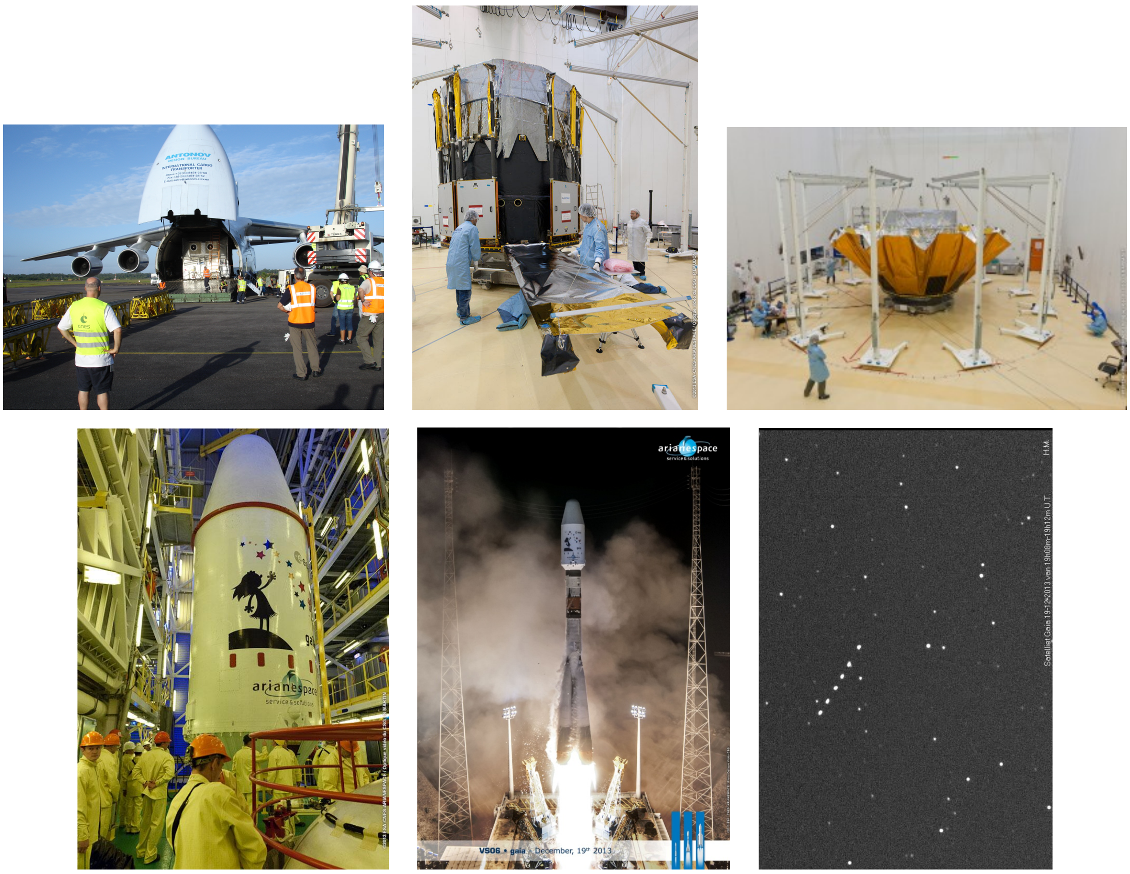


Figure 1: Top left: The spacecraft arriving at Europe's Space Center at Kourou on Aug 23th, 2013 onboard an Antonov airplane. Top middle: The assembly of the sunshield to the spacecraft. Top right: Testing the deployment of the sunshield. Bottom left: Gaia was already placed into the upper phase for launch. Bottom middle: The launch at 9:12:19 UT Dec 19$^{\text{th}}$, 2013. Bottom right: Gaia in its way to L2 as seen from Earth (by H. Musterman, Meppel, Netherlands).

2 Liftoff preparations, launch and trip to L2

The Gaia spacecraft was shipped to Europe Spaceport at Kourou, French Guiana in August 2013 in two deliveries: the spacecraft itself on the 23^{th} and the deployable sunshield on the 28^{th}. The twelve carbon fibre folding frames of the sunshield were assembled to the spacecraft in Kourou's facilities and the deployment was extensively tested in the cleanroom. The sunshield is a key element of the Gaia spacecraft because it prevents the direct illumination of the Sun onto the telescopes and allows to keep the service module and payload at low and stable temperature. Also the sunshield carries some of the solar arrays providing power to the satellite. Therefore the deployment was a key step in the mission operations.

The launch happened at 9:12:19 UT on December 19^{th}, 2013, from the Europe Spaceport at Kourou, French Guiana by a Soyouz-Fregat launcher. The several Soyuz and Fregat propulsion phases and separation were run as nominal, as well as the sunshield deployment, which happened from 10:27 to 10:38 UT. After launch, activities for testing several subsystems onboard the satellite and the payload decontamination started. Soon after, the focal plane (its 106 CCDs and the related payload proximity electronics) were switched on. Meanwhile the Gaia spacecraft was observed from Earth as a tiny moving object on the sky on its way to the L2 Lagrangian point of Sun-Earth system, at 1.5 million kilometers from Earth opposite the Sun. On the evening of January 7^{th} 2014, 19 days after launch, five of Gaia's eight thrusters were commanded to fire an automated burn lasting almost two hours. It was a critical manoeuvre meant to bring Gaia onto its planned operational orbit about L2 (a second, smaller, burn 7 days later completed the process). The final routine Lissajous orbit is inside a box of 263 000 km$\times$707 000 km$\times$370 000 km to avoid Earth's shadow. After all these preparatory actions, Gaia was ready to start the full commissioning activities. Figure 1 shows several of the events during the launch preparation and post-launch period.

3 Commissioning phase

Meanwhile the long payload cool down was taking place (during about 50 days since December 26^{th}), the commissioning phase started. This phase aimed to test and tune every subsystem on the service module (thrusters, fuel consumption, temperature detectors, electronics, antenna, etc), on the payload (optics, wave front sensors, basic angle monitoring device, full focal plane, etc) and onground interfaces (telemetry downlink, transfer of data among data centers, decompression, ingestion, initial treatment, etc). The in-orbit commissioning phase ended on mid-July, and since July 25^{th} 2014, the planned science operations are taking place. Critical items during commissioning were the alignment and co-focusing of both telescopes. This was done by commanding small movements to the secondary mirrors (at the level of micrometers) until reaching the optimal image quality that Gaia can deliver, well balanced across the large focal plane and the three instruments (astrometric, spectrophotometric and spectroscopic). This is no small achievement considering the complexity of the optics. Another key item was the synchronization of the spin rate with the TDI functioning of the CCDs. This way the electrons on the CCDs move along the columns at the same rate the sources are transiting along those columns yielding sharp images of the sources.

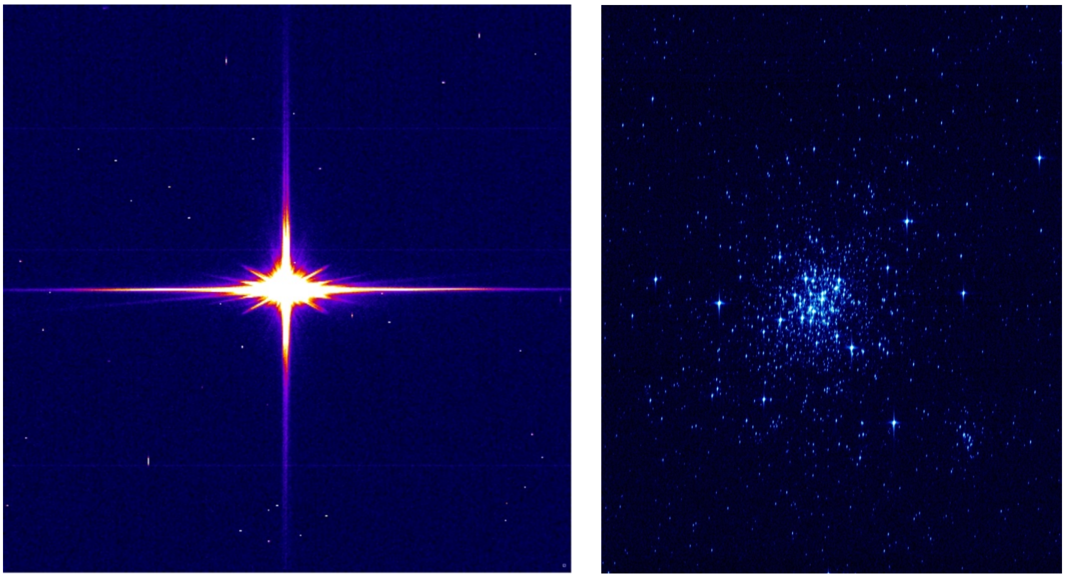


Figure 2: Left: Saldalmelik (α Aqr) a star of magnitude 2.94 as seen by Gaia. Right: NGC1818 a young star cluster in the Large Magellanic Cloud. The image corresponds to an integration of 2.85 seconds and 212×212 arcsec^2 as performed in the sky mapper. Each Gaia telescope has a FoV more than a hundred times this image. Both images were taken when the telescopes were not yet aligned nor focused. Other first Gaia images can be found in `http://www.cosmos.esa.int/web/gaia/media-gallery/images/ig_commissioning`.

The first testing and calibration images from Gaia already confirmed the good health of the optics (see Fig. 2). Figure 3 shows the efficiency of the onboard source detection and confirmation chain running on the sky mapper and the first astrometric-field images. Figures 4 and 5 show examples of the low-resolution blue and red spectra for the classification and parameterization of the observed sources and the high-resolution spectra for the measurement of radial velocities and chemical abundances. All these images and spectra demonstrated that Gaia was working as expected. The several measurements along the 5 years mission will allow to investigate the motion and parallaxes of the sources, their flux variability and the possible multiplicity.

The following is a summary of the commissioning phase findings:

- Gaia experienced a very good launch and orbit insertion performance, which left plenty of propellant available for the mission operations,
- the service module commissioning went very smoothly,
- the chemical and micro propulsion systems function well, with the latter providing tiny (micro-Newton) thrusts to maintain Gaias spin rate, compensating for torques due to solar radiation pressure and micrometeoroid hits,
- the phased array antenna is operating very well, better than expected, ensuring that

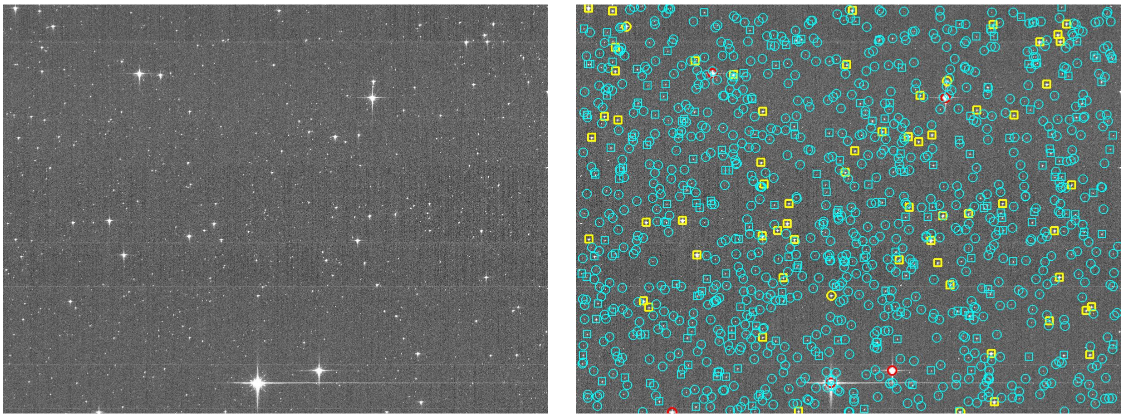


Figure 3: Left: An image of the sky as recorded by one of the sky mapper CCDs. Right: the assignment of windows to all point-like sources detected and confirmed above a given threshold flux. The limiting magnitude of Gaia for this image is $G = 20$. Several symbols and colours encircling the sources are used for different ranges of magnitudes.

we can maintain the high data rates that are needed to downlink all the science data,

- the rubidium atomic clock works to required accuracy. The clock is indispensable for the μas precision measurements,
- the telescopes alignment and co-focusing operations were performed satisfactorily for the three instruments (astrometric, spectrophotometric and spectroscopic),
- the focal plane with the 106 CCD detectors and the associated electronics units, as well as the seven onboard computers that manage the CCDs work fine since the switch-on in January $3^{\rm rd}$ 2014,
- the configurable parameters onboard have been tuned for the maximum scientific return, specially for coping with observations of the very bright stars (as bright as 2 magnitude) and tests have been performed to reach 21st magnitude,
- the Attitude Orbit Control System performs as expected, detecting accelerations suddenly induced by micrometeoroid hits and acting to return the spin rate to the nominal value, and
- the data flow chain from the satellite to ESOC, DPAC/SOC works smoothly
  - Excellent flight control team at ESOC,
  - DPAC operations teams calm and competent,
  - About 40 DPAC Payload Experts analysed the commissioning data,
  - Many software patches and fixes were needed to cope with real data but all in controlled manner.

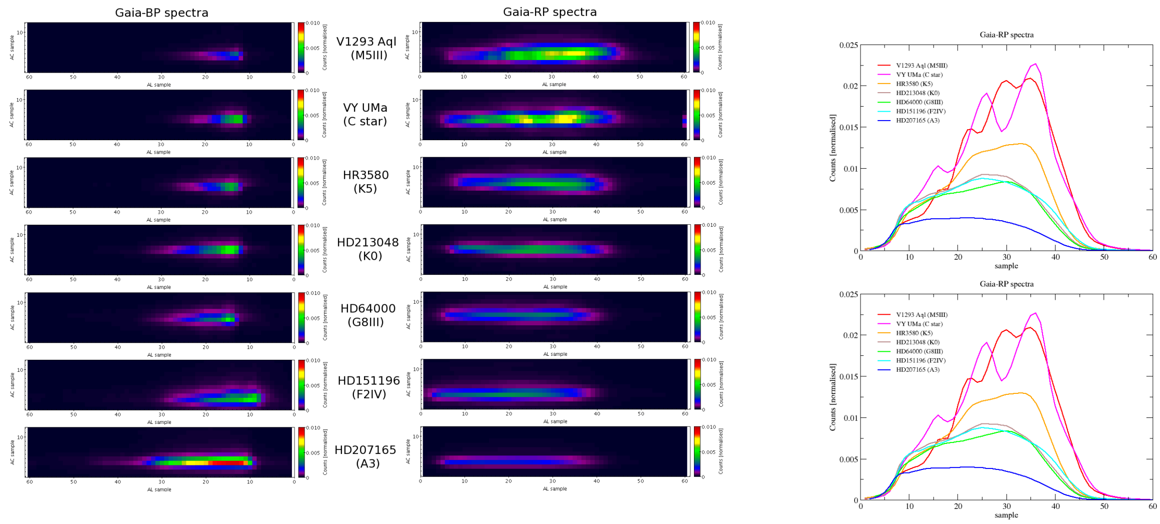


Figure 4: Left: Examples of 2D spectra as observed with the blue (BP) and red (RP) low-resolution spectrographs onboard Gaia for several stars of different spectral types. Right: The same spectra collapsed into 1D. This spectral energy distribution the classification and parameterization of the observed sources. The spectra were taken when the centering of the extraction windows was not yet optimized. Gaia will take 2D spectra for bright sources and 1D spectra for the faint ones.

Besides all the positive aspects, some unexpected features were also found:

- Gaia looks about 3 magnitudes fainter than expected as seen from Earth, at magnitude 21 rather than 18. This has been solved by shifting the Gaia's Ground-Based Observation Tracking from the planned 1-m telescope class to the 2.0-m Liverpool Telescope on La Palma and ESOs 2.6-m VST on Paranal. This ensures the needed precision with a suitable exposure time in the measurements for Gaia's tracking,

- some micro and chemical propulsion system anomalies were detected at the very beginning. Software alternatives have been designed for the dead thruster and the one malfunctioning,

- the stability of the basic angle between the two telescopes is monitored by the basic angle monitoring device, which revealed larger variations than expected. At the end of the commissioning phase, the one-day-astrometric solution indicated that measured variations (of the order of picometers in the payload structure) were real. The posterior investigations have confirmed this and provided more insights into the real causes of the variations, correlations with the stellar density, solar aspect and so on. The current understanding is that the Astrometric Global Iterative Solution will cope with these variations,

- there is undesired stray light from the Sun (scattered and diffracted on sunshield edges) and night sky sources reaching the focal plane along unforeseen paths. The impact of

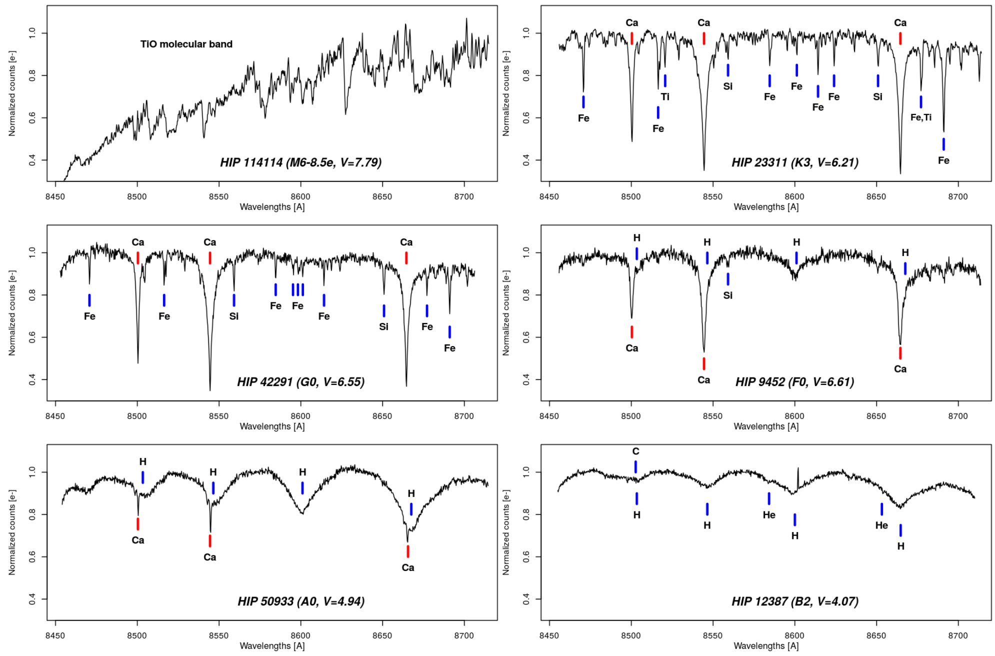


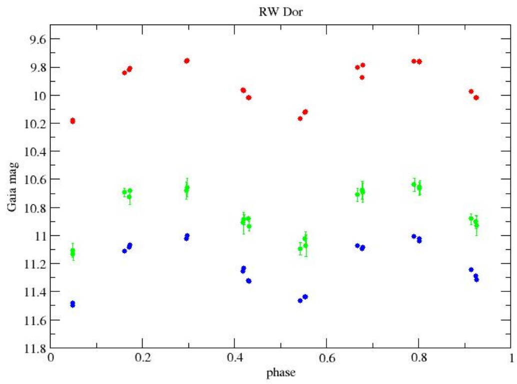
Figure 5: Examples of spectra of six stars observed by the Radial Velocity Spectrometer (RVS) onboard Gaia, ordered from left to right and from top to bottom by spectral type or increasing temperatures (roughly: 3000, 4700, 6000, 7300, 10000 and 21000 K). The spectra are used to derive radial velocities and chemical composition.

the stray light is a loss of performances at the faint end, with the largest impact on the limiting magnitude of the Radial Velocity Spectrograph (RVS). The operations onboard have been redesigned to minimize this impact, and RVS will be working at high resolution by default, with a limiting magnitude of $V \sim 16.5$ mag, and

- there is water trapped on the spacecraft that was not completely removed in the decontamination after launch (by heating the full satellite). This translates into a throughput loss with time by deposited ice on the optics. Three additional decontamination campaigns have been performed (two during the commissioning phase and one during nominal operations) and a strategy for future decontamination events is being worked out.

4 Science operations

The commissioning phase was followed by an undisturbed (no modification in operations or configurations on the payload were performed) period of 28-days of observations with a scanning law covering the ecliptic poles, from Jul 25$^{\mathrm{th}}$ to Aug 21$^{\mathrm{st}}$. This aimed to initialize the photometric calibrations. The data is being processed by the several units within DPAC, firstly by astrometry (CU3, see [6, 2]), photometry (CU5, see [1]) and spectroscopy (CU6), and their products are later treated by non-well behaved objects (CU4, binaries, solar system, extended, etc), variability (CU7), and classification and parameterization (CU8) units.



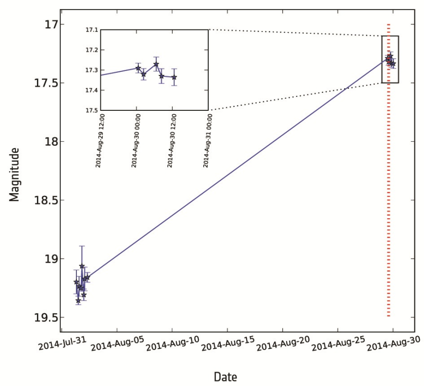


Figure 6: Left: Light curve of RW Dor, an eclipsing binary of $V = 11.2$ and a period of about 0.285 days that was observed repeatedly in a short interval of time during the commissioning phase. The blue and red dots correspond to the integrated flux in the BP and RP spectra, respectively. The green dots correspond to the mean of the 9 white light measurements in the astrometric field of view in each individual transit. The error bars are the standard deviation of the 9 measurements. All measurements shown here are uncalibrated. Right: Light curve of galaxy SDSS J132102.26+453223.8 showing the brightening up between two consecutive Gaia observations performed with an interval of about one month. The Gaia low-resolution spectra and the follow-up observations with the Liverpool telescope has confirmed that Gaia14aaa is a Type Ia supernova.

On 22$^{\text{nd}}$ Aug the nominal scanning started, which will continue until the end of the mission. The data is routinely transmitted to ground, ingested into the DPAC system (see [6]) and processed nominally. The several issues discovered during the commissioning phase imply a redesign of several subsystems in the whole pipeline. This has been done already in some cases, but in other cases the right approach is still being studied.

The completed commissioning phase and the science operational period already passed have confirmed the huge capabilities of Gaia. Some examples:

- Figure 6 (left) shows the example of RW Dor an eclipsing binary observed several times in a short interval of time during the commissioning phase,
- Figure 6 (right) shows the example of one photometric alert triggered by the brightened up of the SDSS J132102.26+453223.8 galaxy in two consecutive observations by Gaia at the end of July and August. The BP and RP low-resolution spectra showed the possible nature of a supernova Type Ia explosion, which was confirmed with onground observations with the Liverpool telescope at La Palma. This was

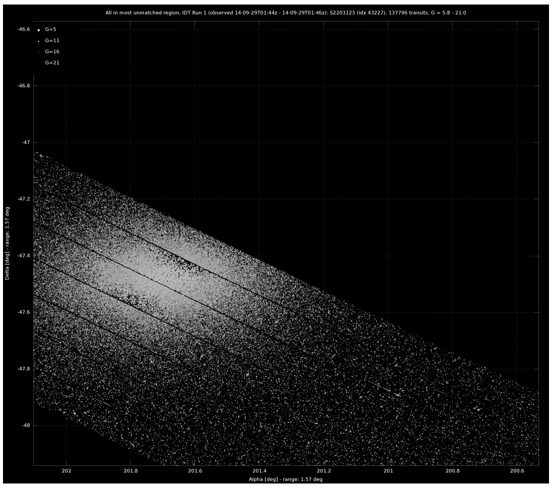


Figure 7: Artificial representation of the "sky" seen by Gaia when passing through the Omega Centauri globular cluster. The traces of the seven Video Processing Units (with small gaps in between) scanning the cluster are clearly seen. The dots represent the positions where a source was detected, confirmed and actually measured. The number of windows to assign is limited and so there are some "missing" stars in the dense nucleus of the cluster.

the first supernova discovered by Gaia, and at the moment of writing these proceedings, seven more were confirmed. Other issued photometric alerts can be found at `http://gaia.ac.uk/selected-gaia-science-alerts`,

- the performance of Gaia in extremely high stellar density areas can be seen in Fig. 7. Each dot indicates an observed star by Gaia when scanning over the globular cluster ω Cen. In about a minute Gaia was able to detect and measure over 137 thousand stars, sending all their information to the ground segment where DPAC systems were eager to process all these precious data. The "missing" stars in the cluster nucleus are due to the limited number of windows to assign to all detected stars. In the following scans of the same area, the windows will be assigned to different stars and hence all stars will have been observed at the end of the mission,

- during the 28-days of ecliptic poles scanning law the cadence of the observations on a given source has been much larger than in nominal operations. The Large Magellanic Cloud (LMC) located close to the South ecliptic pole has been observed rather frequently. This has lead to the detection of events like the microlensing shown in Fig. 8 (left). Microlensing events towards the LMC are very rare and it is extremely lucky that one has been spotted (The MACHO and OGLE projects only spotted 1.75 and 0.33 events per year, respectively). From the shape of the light curve, the lensing object has a small mass and/or a large velocity. The $BP - RP$ colour of the star was also checked and is constant, as expected for a microlensing event, and

- the Cat's Eye Nebula is closely located to the North ecliptic pole and has also been

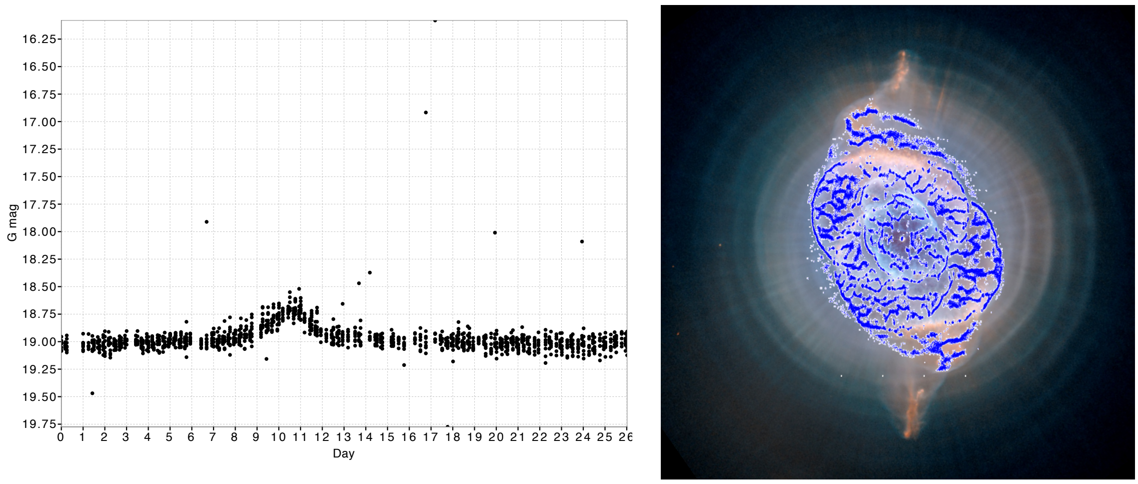


Figure 8: Left: A microlensing event towards the Large Magellanic Cloud detected during the 28-days of ecliptic pole scanning law. The colour of the star is constant during this period, as expected for such an event. Right: The several point-like sources detected and observed on the Cat's Eye Nebula (NGC 6543) are represented by blue dots overplotted on an HST image of the nebula.

observed frequently. The detection and confirmation onboard has lead to a set of point-like sources that draw very well the several spots in the nebula (see Fig. 8 right). Perhaps the proper motion of the several shells will be determined at the end of the mission.

5 Scientific performances

The reassessment of the scientific performances after the commissioning phase findings has been performed. The major impact is due to the undesired stray light that increases the background intensity. Obviously, this impacts the observations of faint sources. These observations have lower signal-to-noise ratio and some performance is lost. Table 1 shows the summary of the end-of-mission precision for a solar type star. More cases can be found at `http://www.cosmos.esa.int/web/gaia/science-performance`. The listed performances confirm that such degradation does not prevent the science goals of the mission. However, the performances at the faint end pushes the RVS limiting magnitude about 1 mag brighter (at about $V \sim 16.5$ mag) while it is kept at 20 mag for astrometry and spectrophotometry. In terms of the bright limit, the early Gaia data confirm that such limit can be pushed from the expected 6 mag to as bright as 2 mag.

Table 1: Summary of the reassessed scientific performances after the commissioning phase for a G2 V type star.

V magnitude	Astrometry (parallax)	Photometry (BP/RP integrated flux)	Spectroscopy (radial velocity)
3–12	5–14 μas	4 mmag	
3–12.3			1 km s^{-1}
15	24 μas	4 mmag	
15.2			15 km s^{-1}
20	540 μas	60(RP)–80(BP) mmag	

6 Conclusions

After about 15 years of Gaia mission preparations, the spacecraft was successfully launched in Dec 19$^{\text{th}}$ 2013. The commissioning phase took longer than expected because of some undesired findings (stray light, ice contamination and large basic angle variations) and was completed by mid July 2014. Since then, the observations are performed as planned, first with a 28-days period of a scanning law on the ecliptic poles, and since end of August 2014 with the nominal scanning law. The data is being collected by the satellite and processed by the several units of the Data Processing and Analysis Consortium (DPAC) without major issues. The treatment of some of the issues found is being accommodated into the designed pipelines of the several DPAC units.

The inspection of some raw astrometric, spectrophotometric and spectroscopic data confirm the great expectations in terms of scientific outputs for the next decades. The validation processing efforts have started to ensure early data releases as soon as possible. The first release (positions and G magnitude) for single-like stars and the Hundred Thousand Proper Motions catalogue based on the Hipparcos stars [4] are expected for summer 2016. The first catalogue with proper motions, parallaxes, colours and mean radial velocities are expected 6 months later.

Acknowledgments

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