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The promises of Gaia

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Gaia is an ESA mission performing astrometry, photometry and spectroscopy of about one billion objects in our Milky Way galaxy and beyond. The extent and content of the Gaia Catalogues will enable major progress to be made in many fields of galactic and stellar astronomy. The prime industrial contractor, EADS Astrium, Toulouse, is manufacturing the spacecraft and its payload for launch in 2013. Parallel to the space segment development the ground segment is getting ready as well. The Mission Operations Centre in Darmstadt, the Science Operations Centre in Madrid and the Gaia Data Processing and Analysis Consortium having members in many institutes across Europe are all tackling the challenges imposed by the high scientific requirements of the mission. The Gaia observing principles, overall status and scientific performances will be outlined.

1 Introduction

Gaia is an ESA corner stone mission due to launch in 2013. Gaia will perform astrometry, photometry and spectroscopy of more than 1 billion objects. The unique capability to measure positions extremely precisely allows Gaia to provide parallaxes at the level of accuracy unobtainable from the ground. In addition, photometry will be provided for all astrometrically detected sources. In spectroscopy Gaia will run out of photons yet the catalogue of radial velocities will contain some 150 million objects.

2 Scientific topics

The scientific requirements of Gaia are set to address the large number of open questions related to our own Milky Way Galaxy. The combination of astrometry, photometry and spectroscopy provide in addition to positional and kinematic information also characterization of stellar properties. This allows to address the issues of the structure and dynamics of the Galaxy as well as the star formation history. To meet the scientific goals of the Milky Way studies, Gaia is going to scan the full sky in an unbiased manner to very high precision. This observing strategy enables many more science areas beyond the Milky Way studies to be explored.

For various problems in stellar astrophysics the observational test has the biggest uncertainty due to the inaccuracy in distances. The improvement of parallaxes due to Gaia will allow more rigorous observational constraints to various models of stars at different stages of evolution. The high spatial resolution will benefit studies of binaries and multiple stellar systems by providing orders of magnitude bigger samples and much higher precision in orbital parameters. Furthermore, from Gaia perspective exoplanets are simply a low mass extension to multiple stars and several thousand systems are expected to be found. For faint rarer objects such as brown or white dwarfs Gaia will provide a valuable census in the solar neighbourhood. The strength of observing an unbiased sample of 1 billion sources is that also short living phases of stellar evolution can be explored with a sample provided by Gaia.

Gaia is optimized to detect fixed celestial point sources i.e. stars. However, the on-board detection algorithm recovers any source close enough being point like. This will include solar system objects, but also galaxies and quasars. In solar system topics Gaia is anticipated to provide a massive improvement of asteroid ephemeridies. In some cases where two bodies have a close enough encounter to cause the orbits to change, it is possible to deduce the masses of the objects based on the changes Gaia measures in their ephemeridies. Also a large sample of asteroids done in a homogeneous photometric system allows taxonomic classification work to be done. The same is valid also for the few million galaxies Gaia is expected to detect. When moving on to quasars, we shift toward issues related to reference systems and fundamental physics. Gaia accuracy is sufficient to perform some general relativity tests. General relativity is not only applied to find true positions of stars after the photons have been influenced by the gravitational field of our solar system, but it is also possible to constrain fundamental physics parameters at higher accuracy levels than by any other means.

When Hipparcos, the predecessor of Gaia, released its catalogue of some 118 000 stars, the astronomy changed. Gaia will give 1 billion objects, move from milliarcsec astrometry to microarcsec astrometry, and provide as part of the mission the radial velocities, which Hipparcos could not.

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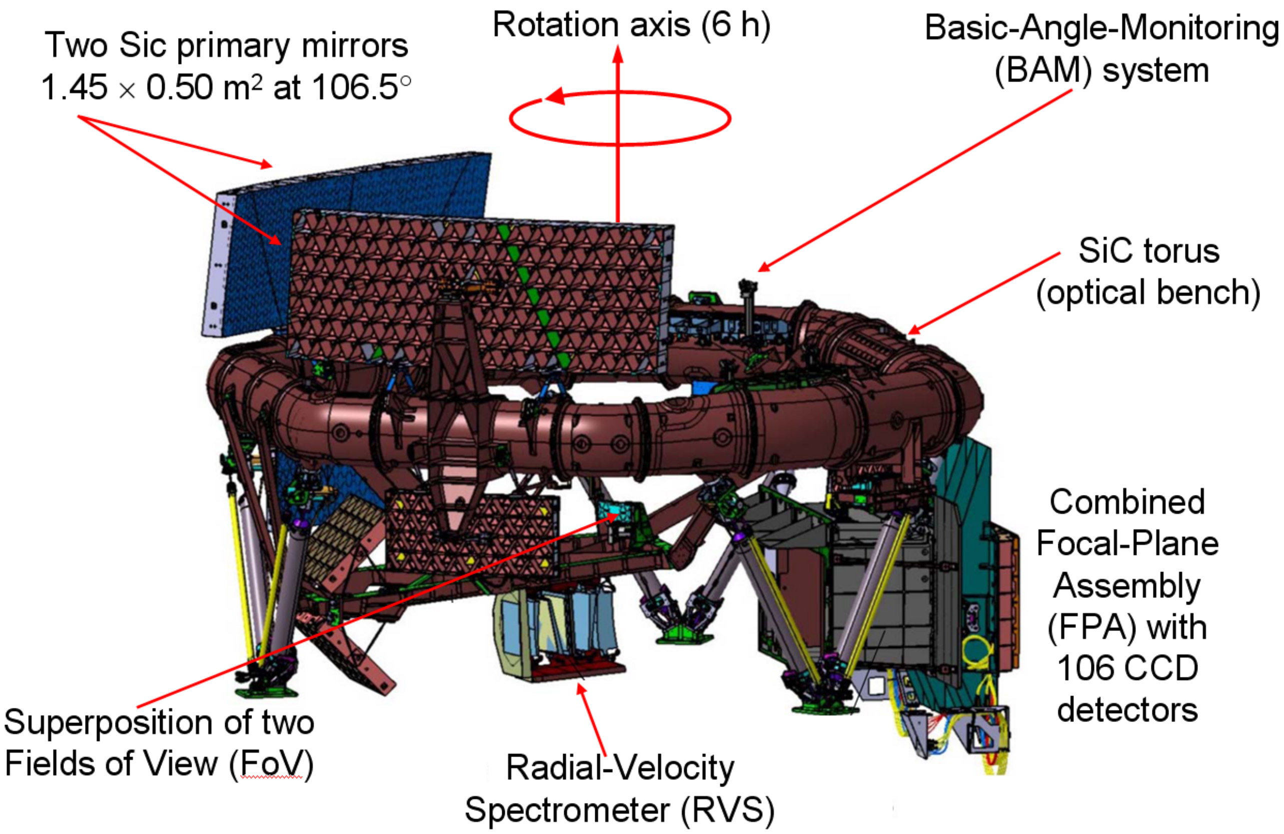

Fig. 1 (online colour at: www.an-journal.org) The Gaia payload module (copyright EADS Astrium).

It is easy to anticipate major steps being made in the topics outlined above. However, maybe the most exciting science will be the one we have not anticipated and not described here.

3 Payload and telescope

The Gaia satellite is built by European industry with EADS Astrium as the prime contractor. Unlike many science missions, in Gaia also the payload is procured by the industry. This approach was chosen due to the very strong overall system aspect imposed by the payload to the other facilities in the spacecraft.

The core of the Payload Module (PLM) is the optical bench which is also called the Torus due to its shape (see Fig. 1). The Torus supports the two telescopes with lines of sight separated by 106.5° required for the wide field astrometry of Gaia. Both telescopes are also used for the photometric and spectroscopic measurements. All measurements are done in the common focal plane where 106 CCDs are located for the combined two fields of view. In addition to all mirrors, the instruments too are all attached to the Torus.

The astrometric measurements are performed in a wide photometric band, called the G-band, with the intention simply to collect as many photons as possible. The photometric measurements are done using prisms in the Focal Plane Assembly (FPA) just in front of the CCDs. Given the method of photometry in the Gaia context we are actually speaking of spectrophotometry. The spectroscopy is done with the Radial Velocity Spectrometer (RVS).

4 Focal plane

The CCDs in the focal plane within the FPA are shown in Fig. 2. In the figure one can see from left to right in the first row the two CCDs dedicated to monitor the (small) relative changes in the 106.5° angle between the two lines of sight with the help of the Basic Angle Monitor (BAM). In that row there is also one CCD equipped with the Wave Front Sensor (the other one is visible in the astrometric field). The next two rows are the Sky Mapper CCDs. One row for each of the telescopes. Their task is to image the whole sky for point source detection and for bookkeeping of the objects as the rest of the focal plane is common to both telescopes. The following 9 rows are dedicated to astrometry. After the astrometric CCDs there is one row for the blue part of the spectrophotometry and another row for the red part. The last 12 CCDs are for the RVS.

The CCDs are operated in time delayed mode which means that they are constantly read at the same speed as Gaia is scanning the sky. This means that the observing efficiency is maximized with Gaia always collecting photons from the sky. The pixels have size of 59 by 177 milliarcsec. This pixel size limits the instantaneous resolution of Gaia.

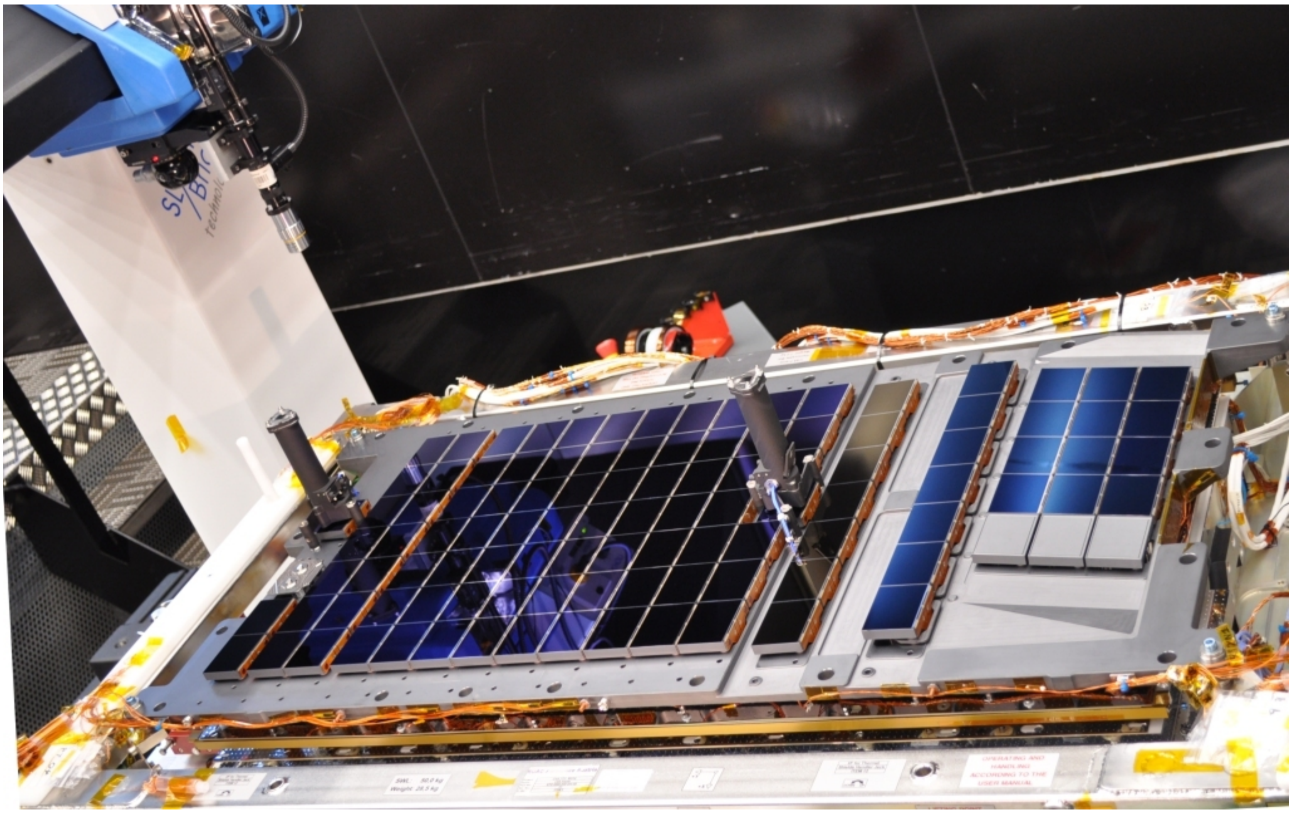

Fig. 2 (online colour at: www.an-journal.org) The Gaia focal plane with 106 CCDs and two Wave Front Sensors (copyright EADS Astrium).

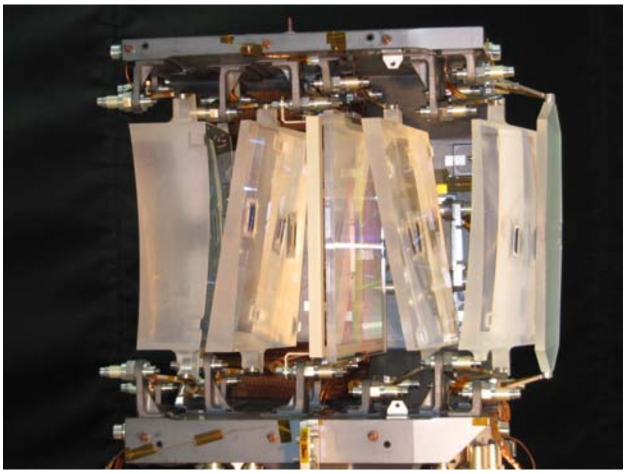

Fig. 3 (online colour at: www.an-journal.org) The Radial Velocity Spectrometer of Gaia (copyright EADS Astrium).

The on-board point source detection algorithm sets the upper limit of 0.7 arcsec to sources which will be observed by Gaia as targets. Although the whole sky is imaged, the reading of the CCDs is optimized to the detected point sources only. Thus most of the pixels are flushed at the read out node and only the pixels where the Sky Mapper has detected a point source will be included in the telemetry transmitted to the ground.

5 Photometry

The spectrophotometry on Gaia is performed in two separate wavelength bands. The Blue Photometer (BP) covers the range from 330 to 680 nm and the Red Photometer (RP) from 640 to 1000 nm. The resolution is typically about 10 allowing extraction of astrophysical parameters from the data. In addition to the spectrophotometry, the astrometric measurements can be calibrated photometrically. Although the broad band does not offer any color information, the high sensitivity gives possibilities to variability studies also for objects with a very low amplitude variability.

6 Spectroscopy

The RVS instrument provides spectroscopy between 847 and 874 nm at the resolution of 11 500. The instrument is a very compact assembly of prisms, wedge lenses and a grating (Fig. 3). The RVS CCDs will be operated in two modes where the full resolution is obtained to objects brighter than 10 mag. For fainter stars binning of data is done on the CCD to reduce the effect of the readout noise. Extraction of astrophysical parameters is possible for the full resolution objects and also for the brightest stars which have been binned. The faintest end of the stars observed with the RVS have low signal to noise ratios even after combining all data of the mission, that only radial velocities can be deduced.

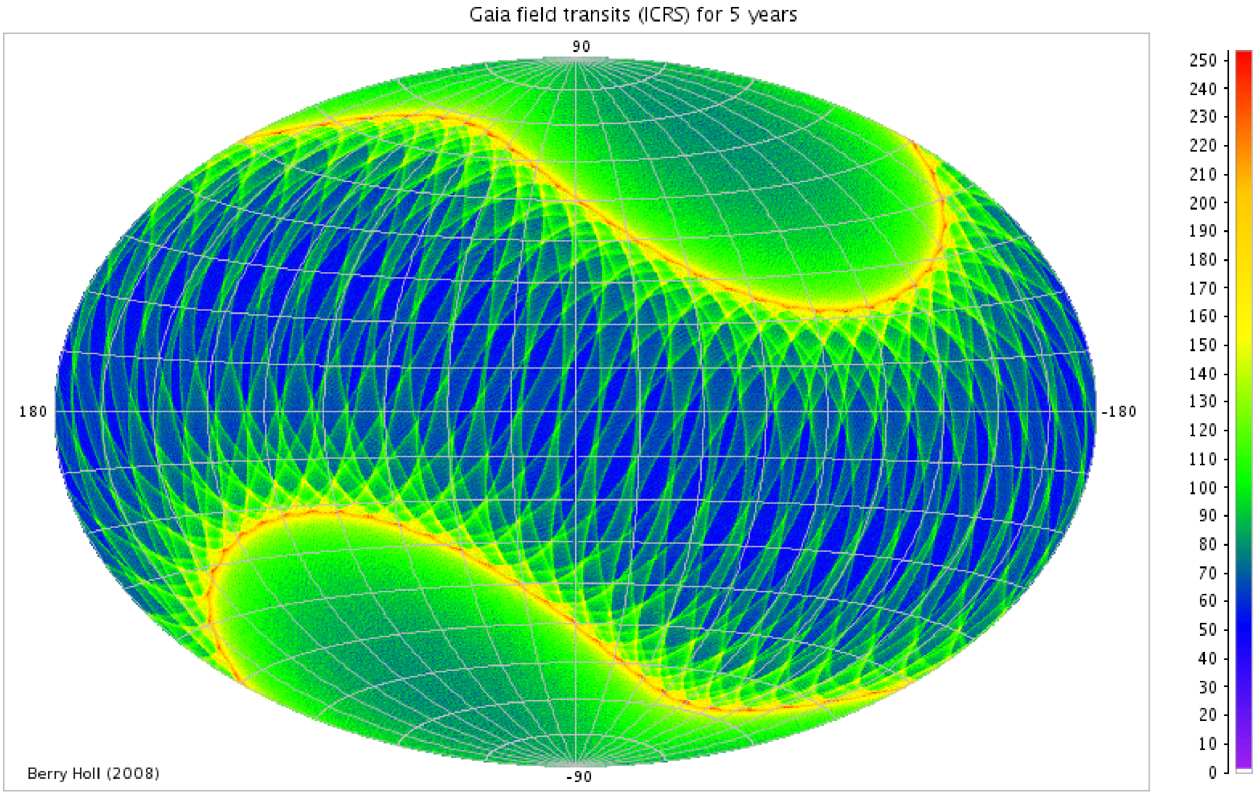

Fig. 4 The sky coverage of Gaia after 5 years of operations (copyright Berry Holl).

7 Operations

The operational life time needed to fulfill the scientific requirements is 5 years. The spacecraft and its consumables are designed for 6.5 years to cover 6 months for commissioning and 1 year operational extension. The operational concept of Gaia is very simple. The preference is to initiate the planned scanning law at the beginning and continue observing exactly the same way for the whole 5 year period. In practice there will be moments of dead time and maneuvers to keep the orbit of the satellite or to avoid eclipses, but the principle is to stick with the routine scanning.

The scanning pattern of Gaia is designed to fulfill two scientific requirements. Firstly, the sky coverage should be as homogeneous as possible. Secondly, all positions on the sky should be scanned from different angles to benefit homogeneously of the astrometric accuracy which is primarily based on the high accuracy in the scanning direction. These two scientific requirements must be merged with the engineering constraints such as very constant solar aspect angle of 45° to maintain the thermal balance. An estimate of the end sky coverage can be found in Fig. 4.

For Gaia a standard ground segment concept for operations is followed. The Mission Operations Centre (MOC) in Darmstadt, Germany is responsible of the spacecraft communications and the safety of the satellite. The scientific operations are executed through the Science Operations Centre (SOC) in Madrid, Spain. The scientific operations of SOC are always channelled to Gaia through MOC. The scientific community involved in data processing is interacting with satellite information and data through SOC.

The Gaia launch is currently scheduled to August 2013. With 4 month commissioning period the estimated start of routine operations will be early 2014.

8 Data processing

While the spacecraft and its payload are constructed by the industry, the data processing is done by the European scientific community. The community efforts have been gathered around the Gaia Data Processing and Analysis consortium (DPAC) which has been formally approved by ESA to perform the tasks required to produce the scientific catalogues from the mission. Naturally the DPAC tasks include production of the fundamental astronomical catalogues containing data of position, parallax and proper motion as well as photometry and spectra. In addition it was early on taken into the data processing concept that more advanced data products will also be produced by DPAC due to the huge processing effort needed to handle the full Gaia data volume.

9 Scientific performance

The scientific performance estimates are calculated with the best knowledge of the actual hardware and taking into account all noise contributions from known calibration issues. In the first step the performance estimates are made with the

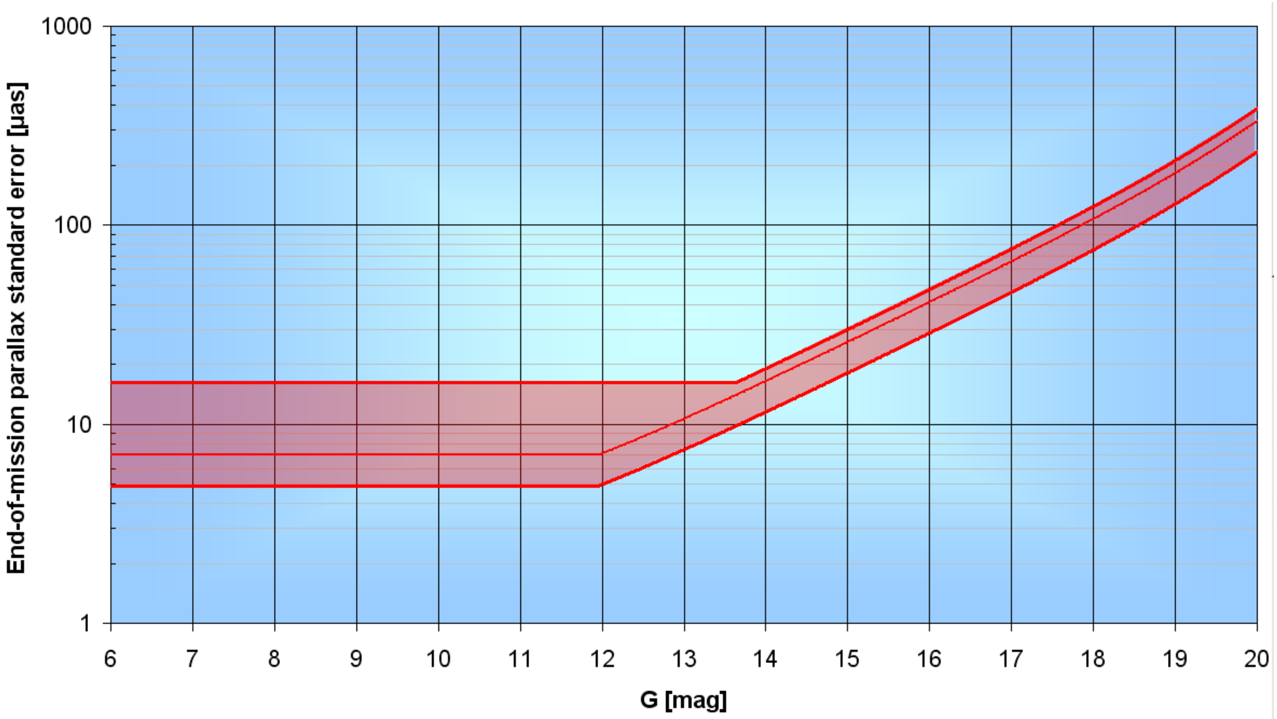

Fig. 5 The astrometric parallax accuracy of Gaia (copyright ESA).

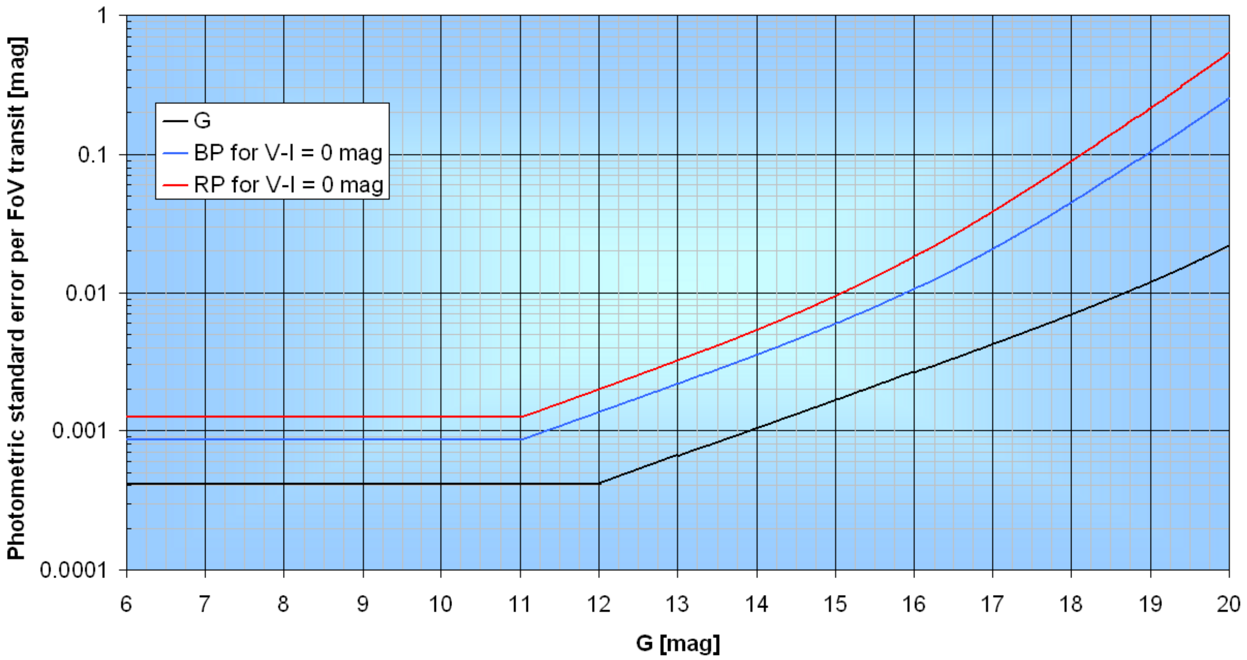

Fig. 6 The photometric accuracy of Gaia (copyright ESA).

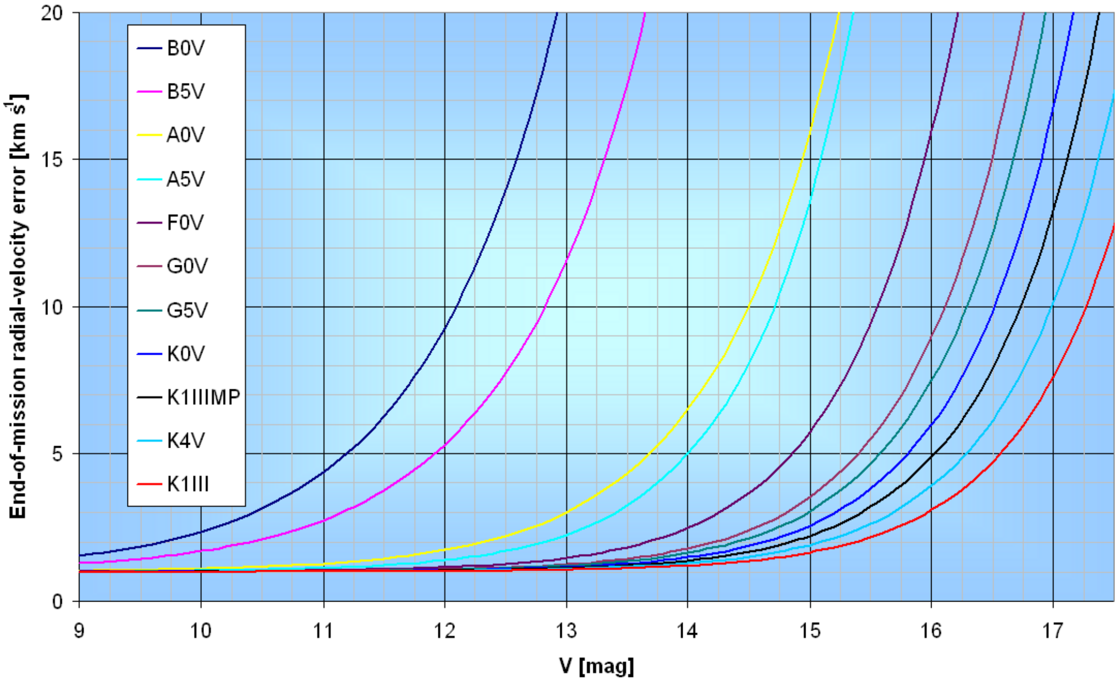

Fig. 7 The radial velocity accuracy of Gaia (copyright ESA).

assumption that the sky is perfect with clean point sources only. Due to the fact that the real sky is more complex there is a 20 % science margin included in all the presented estimates. This makes the given performances more realistic. Below representative values of scientific performances are given. A more complete and more detailed presentation of the accuracies can be found from the Gaia science webpages (www.rssd.esa.int/Gaia) which will also be updated in case some later test results indicate different behavior than currently anticipated. The estimates can be found in the pages under the item "Science Performances".

For the astrometric performance parallax accuracies are given (Fig. 5). The position and proper motion accuracies can be found from the above mentioned webpages with essentially similar kind of flat behavior for bright stars and photon noise limited behavior for the stars between 12 and 20 magnitudes.. The bright star parallax performance is expected to be below 10 μarcsec. Between 6 and about 12 magnitudes the operation are done with CCDs close to the saturation limit. In order not to saturate the detector, the CCDs are exposed only partially for the very brightest stars. This is achieved by introducing electronic gates in the CCDs to control the amount of integration time per star. The absolute brightness limit is determined by the Sky Mapper CCDs which are not able to record a point source detection of the extremely saturated objects brighter than about 5.7 magnitudes.

For photometric precision an estimate is given for a $V - I = 0$ colour star in G and integrated BP and RP bands at single epoch (Fig. 6). The science performance webpages provide more information of precision as a function of colour or as the end of mission accuracy estimates for constant targets. The performance is excellent as long as precision is concerned and the crucial aspect is the calibration accuracy achievable for the systematics of the bright stars as far as variability studies are concerned. The webpages contain also compilations of estimated accuracies of astrophysical parameters from spectrophotometry as analyzed by the members of the DPAC consortium.

The radial velocity accuracies are presented as the function of magnitude in the red RVS band ($\mathrm{G_{RVS}}$) and spectral type (Fig. 7). Given the selection of the RVS wavelength range in the red, the performances are better for red than for blue stars. The bright end of the performances is limited to 1 km/s and is fully dominated by the expected systematic calibration accuracy level. For red stars the "bright star domain" extends to 13 to 14 magnitudes before the photon noise takes over leading to the very rapid increase of error for the very faintest objects. The performance webpages contain information of the other astrophysical parameters DPAC intends to deduce from the RVS spectra.

10 Data releases

The parallax measurements are probably the most waited results from the mission. The guiding principle of data processing is that results are made public as soon as possible after reduction and verification by DPAC. Nevertheless, it is necessary to remember the intrinsic issue of separating parallax from proper motion requiring at least one year of measurements. Furthermore, Gaia is not observing all objects constantly, but rather 70 times (on the average) over the 5 year operational period. This means that Gaia has to observe the sky well over one year before an astrometric solution can be obtained. With verification activities included, the first 5 parameter astrometric solution from Gaia is currently expected not earlier than 28 months after the launch (assuming 4 months for the commissioning period which cannot be used for the astrometric solution). A more detailed data release scenario is being worked out and will be published in the Gaia science webpages.

11 Conclusions

There are many promises of Gaia. The launch approaching clearly raises the expectations. At the moment industry, ESA and DPAC are all working in high gear toward the launch with an expectation that everything will go well. If we get that, there is one promise Gaia can make: astronomy will change.