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Gaia: the challenge begins

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Abstract

By the end of 2013 Gaia will be in its path to L2. After four months of commissioning a waterfall of scientific data, flowing during five years, will start feeding a complex data processing system aimed to deliver the impressive amount of unprecedented high quality data expected from the mission. We summarize the key aspects of the mission and review its present status and plans until the start of operations. We will describe the data reduction system as well as the present plans and schedule for releasing scientific data. The multidimensional view of the Galaxy provided by Gaia will open a new era for the understanding of its history, the main goal of the mission, but Gaia data will have an important impact in a large number of topics from stellar physics to Solar System studies and cosmology. The use of available simulated data and the expected science performances allow the potential users to evaluate Gaia capabilities in a particular field. National and international plans to fully exploit the vast amount of Gaia data that are going on, as well as observational campaigns to complement the satellite data are relevant aspects that will be briefly considered in this paper.

1 Introduction

Gaia is the next launch of the ESA's Scientific Programme, forecast for the last quarter of 2013 from Kourou. Based on the same fundamental principles that built the success of the Hipparcos mission in the 90's, Gaia is expected to set the observational foundations of the astrophysics of the coming decades, by providing large sets of unprecedented quality data impacting in almost all the astrophysic's fields. Gaia will provide positions, proper motions, parallaxes and spectrophotometry for more than one billion stars. Additionally the mission will provide radial velocities and detailed atmospheric parameters for impressive numbers of objects. The main objective of the mission is to dissentangle the history of formation and evolution of our galaxy, but in top of that Gaia will provide a flood of data that will allow a new view on stellar astrophysics, binary systems, brown dwarfs, extrasolar planets, etc. As Gaia scans the sky continously it will provide tens of thousands of observations of minor bodies of the Solar Sytem, but at the same time it can detect supernovae and other transitory events. The impressive Gaia capabilities allow the observation of stars in nearby galaxies.

Figure 1: The Gaia satellite after a sunshield deployement test (image courtesy EADS-Astrium).

Aproved in 2001 Gaia posed two main challenges: building the satellite itself, by its mechanical and thermal requirements, and including the construction of the largest focal plane ever built for space, and, on the other hand the management of enormous amounts of data, and the extraction from them of the scientific data with the required precision. Gaia was conceived as a fully integrated unique instrument performing the astrometric, spectrophotometric and spectroscopic measurements.

To cope with the data, the "Gaia Data Analysis and Processing Consortium (DPAC)" was created, joining the efforts of more than four hundred people and six computing centers around Europe.

The exploitation of the Gaia data will be demanding. The amount and quality expected for the data requires appropriate tools, more sophisticated models and additional complementary data. As the launch date approached, the scientific community started to organize in order to be ready for a third challenge.

We review in this paper the main elements of the mission, from the satellite, how it operates and what is its current status, to the data management systems structure and plans. We will describe the plans for data releases as well as the important networking activities around the scientific exploitation of Gaia data.

2 The Gaia mission

The main science goal of the Gaia mission is to unravel the dynamical and chemical evolution of the Galaxy- back in time to its formation-, and to study its kinematics, dynamics and structure. To do that Gaia will perform a multidimensional survey of about the 1% of the stellar content of our galaxy, that is, more than a billion of stars will be observed by Gaia.

Although Gaia is based in the fundamental principles of the succesful Hipparcos mission, the first astrometric space mission, the precision of the astrometric data will be two orders of magnitude better. The number of objects being 10^5 times larger, we can think in something like a 10^7 factor of improvement, but the comparison has no sense, because Gaia by providing spectrophotometry, and spectroscopy, and hence, radial velocities for large number of stars will provide a database which supersedes all the existing (and planned) surveys. The Gaia products can be summarized as:

- Positions, proper motions and parallaxes for one billion stars ($G < 20$)
- Low resolution spectrophotometry for one billion stars, allowing estimations of $T_{\rm eff}$, log$g$, A_v and [Fe/H]
- Radial velocities for 150 million of stars ($G < 16$)
- Atmospheric parameters and rotational velocities for 5 million stars ($G < 12$)
- Detailed chemical abundances for 2 million stars ($G < 11$)

Details on the expected precision for each variable can be found in the mission web page `http://www.rssd.esa.int/index.php?project=GAIA&page=Science_Performance#PerformanceModel`. In Table 1 the expected end-of-mission errors are given for the parallax for three types of (unreddened) stars.

Table 1: Predicted end-of-mission parallax standard errors, averaged over the sky for a uniform distribution for unreddened B1V, G2V and M6V stars

	B1V	G2V	M6V
V - I	- 0.22	-0.75	3.85
Bright stars	5 - 14 μas ($6 < V < 12$)	5 - 14 μas ($6 < V < 12$)	5 - 14 μas ($8 < V < 14$)
V = 15 mag	26 μas	24 μas	9 μas
V = 20 mag	330 μas	290 μas	100 μas

The precision at $V = 15$ mag of 20 μas means a 1% error in distance at 0.5 kpc, or a 10% error at 5 kpc, that is, Gaia will allow detailed studies of close regions like Orion, with a 2 pc resolution, and will provide high precision distances for almost all types and groups of stars, i.e. most of the known galactic Cepheids will have Gaia parallaxes better than 3%. Gaia will observe some thousands of Cepheids even in LMC and SMC.

For sky-averaged positions and proper-motion errors, (in μas and μas yr^{-1}), the following relations can be used, derived from scanning-law simulations:

- $\sigma_\alpha = 0.787\ \sigma_\pi$
- $\sigma_\delta = 0.699\ \sigma_\pi$
- $\sigma_{\mu\alpha} = 0.556\ \sigma_\pi$

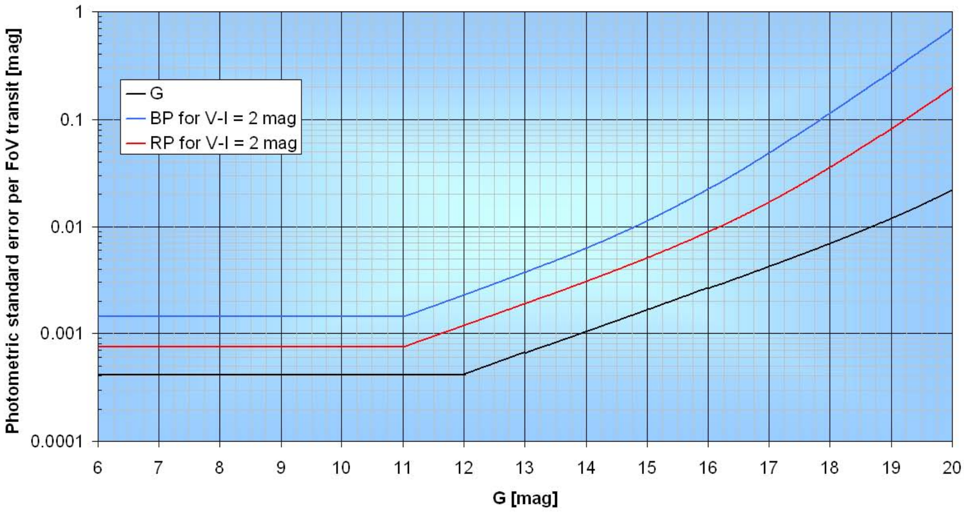

Figure 2: G, BP and RP band photometry standard error per observed transit

- $\sigma_{\mu\delta} = 0.496\ \sigma_\pi$

being σ_π the expected error in parallax.

From these figures we can see that Gaia can detect extrasolar planets around 0.5 million stars (20 μas yr^{-1} is equivalent to 10 m s^{-1} at 100 pc), measure the slower stars's motions up to 10 kpc, and measure at 5 km s^{-1} the internal LMC kinematics for AGBs.

Gaia observations are performed with no filter, then a wide band G magnitude is obtained for all the stars. The spectrophotometric observations in the blue (BP) and red band (RP) are almost simultaneously obtained. In Fig. 2 the standard errors for a single observation in the G, BP and RP bands are given.

The predicted end-of-mission radial-velocity formal errors averaged over the sky for a uniform distribution, for unreddened B1V, G2V, and K1III-metal-poor stars shown in Table 2.

The values quoted in the previous tables give clues to what the Gaia mission will provide. Details on how these values translate into astrophysical parameters can be found in [6, 4].

As it was clearly stated at the study phase that concluded with the formal presentation to ESA in 2001, [2], Gaia will, in addition to its main science goal, impact in a large number of areas, among which:

- Stellar Astrophysics (i.e. luminosity calibration of the complete HR diagram)
- Multiple stellar systems (i.e providing masses at 1% accuracy level for more than 10000

Table 2: Predicted end-of-mission formal errors, averaged over the sky for a uniform distribution for unreddened B1V, G2V and K1III metal poor stars

Spectral type	V (mag)	radial-velocity error
B1V	7	1
B1V	12	9
G2V	13	1
G2V	16.5	13
K1III	13.5	1
K1III	17	13

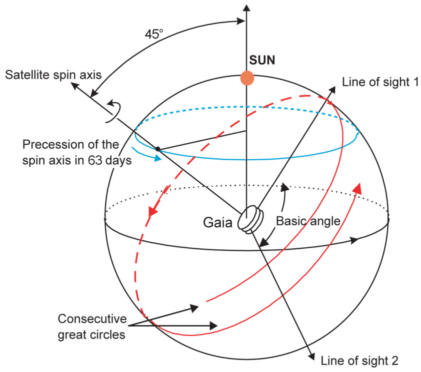

Figure 3: Gaia scanning motions

objects)

- Solar System (i.e. discovering $10^5 - 10^6$ new asteroids)
- Exoplanets (i.e. discovering some tens of thousands of new ones)
- Galaxies and QSOs (i.e. half a million QSOs and 10^4 supernovae will be detected)
- General relativity (i.e. measuring the light deflection by the Sun and Jupiter)
- ... and others

See [1] and references therein for miscellaneous science cases.

Gaia's launch is forecast for the fourth quarter of 2013, for a five year operations period. The data reduction is expected to end around 2021. As we will discuss later, intermediate results will be published enabling a prompt start of the scientific exploitation.

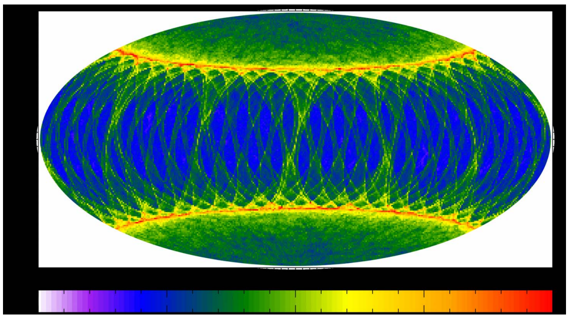

Figure 4: Average number of observations as a function of ecliptic coordinates. Scale from 0 (white) to 200 (red). The average number of transits per stars is 70 (taken from [1]).

3 The spacecraft

The Gaia spacecraft will operate in a Lissajous-type orbit around L2, where it will arrive one month after launch from Kourou by a Soyuz-Fregat rocket. L2 gives a quiet environment to Gaia. A large sunshield, more than 10 m diameter, to protect the payload from the sunlight is a distinctive element of the spacecraft (Fig. 1).

Gaia has to be compliant with the main principles of space global astrometry, that is, it has to be capable of simultaneously observe two fields of view (FOV) separated by a large angle, while scanning continously the sky. The spacecraft rotates (at a rate of one degree per minute) around an axis perpendicular to the plane containig the two viewing directions separated by an angle of 106 degrees. The axis of rotation makes an angle of 45 degrees with the Sun direction and precesses around it with a 63 days period (see Fig. 3).

The Gaia payload is conceived as a unique integrated instrument performing the three types of observations: astrometric, spectrophotometric and spectroscopic. A large toroidal structure gives support to the two identical telescopes of focal length 35m. The main mirrors have an aperture of 1.45 m x 0.50 m. After two additional reflexions, both images are combined in a unique beam to the common focal plane. The ultraestable torus also supports the prisms for low resolution spectroscopy and the radial-velocity spectrometer.

The focal-plane assembly serves five main functions (see Fig. 6):

- (i) the wave-front sensor (WFS) and basic-angle monitor (BAM);
- (ii) the Sky Mapper (SM), autonomously detecting objects entering the fields of view and communicating details of the star transits to the subsequent CCDs;
- (iii) the main Astrometric Field (AF), devoted to astrometric measurements;
- (iv) the Blue and Red Photometers (BP and RP), providing low resolution spectrophotometric measurements for each object over the wavelength ranges 330–680 and 640–1000 nm, respectively;

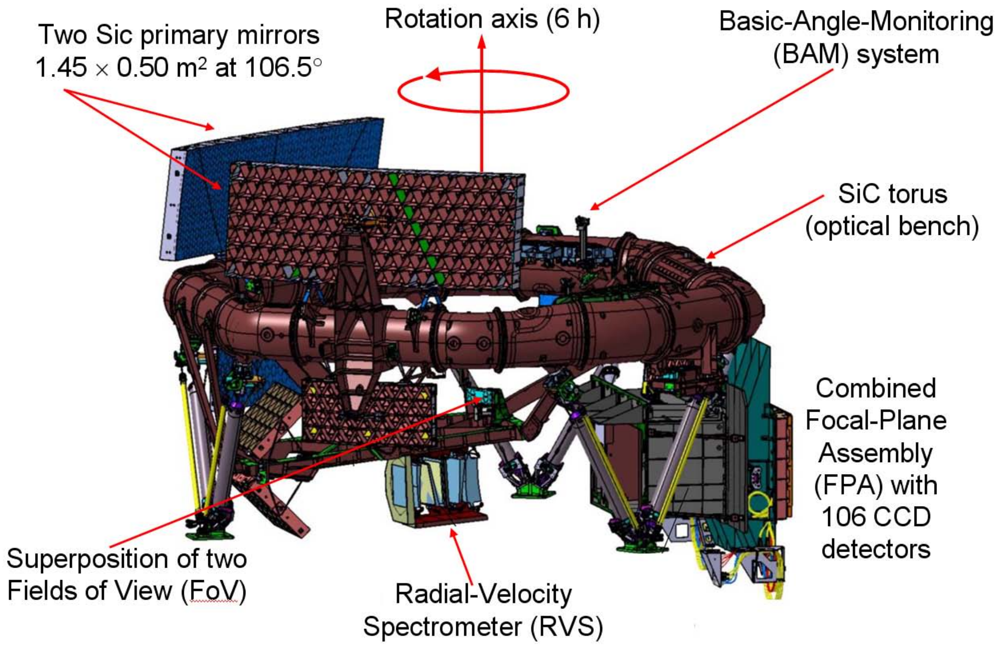

Figure 5: The payload core is a SiC torus supporting all the optical elements and the focal plane assembly

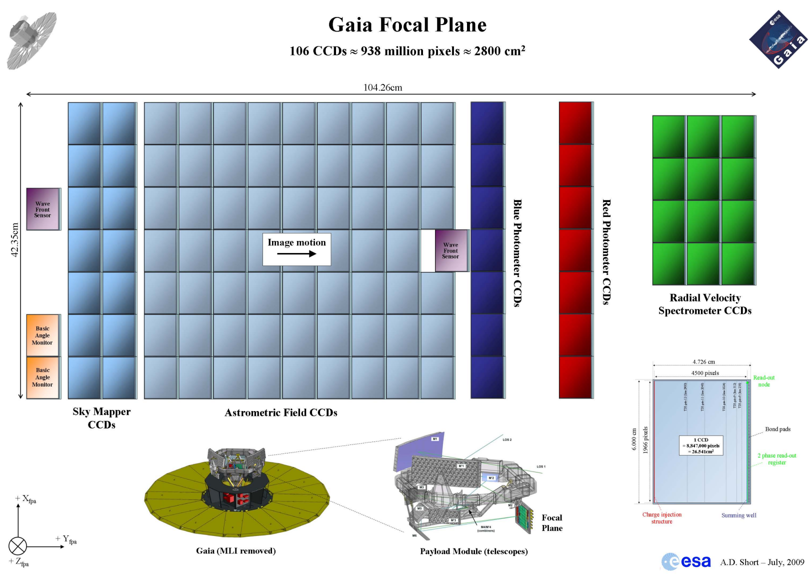

Figure 6: The Gaia focal plane. The images of the two viewing directions are superimpossed on it.

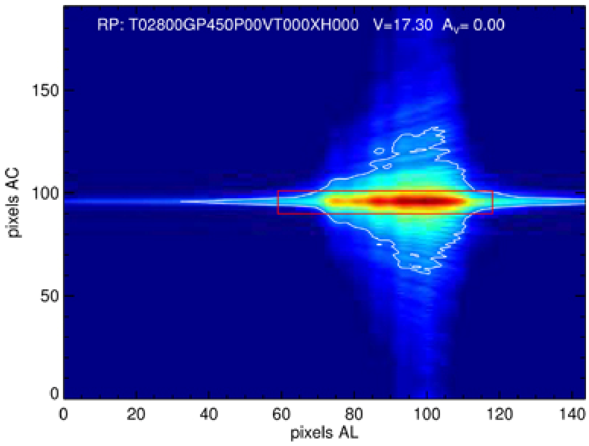

Figure 7: Simulation of the RP spectrum of a unreddened M6V of V= 17.3 star. Only the red window is downloaded

- and (v) the Radial-Velocity Spectrograph (RVS), registering spectra of all objects brighter than about 17-th magnitude.

The focal plane of Gaia is the largest one ever built for space. In its 106 cm x 42 cm surface we can found 106 CCDs organized to perform the five functions listed above. Each CCD contains 4500 x 1966 pixels, 10 x 30 μm each. As the satellite scans the sky the image of an object will cross the entire focal plane, in a short time interval of some 4 seconds per CCD. To have signal enough all the CCDs are operated in Time Delayed Integration (TDI) mode sincronized with the satellite's rotation, that is as the image move from one pixel to the next one, the charge created is also moved, thus integrating the signal for the full 4 seconds. Note that the number of CCD rows dedicated to spectroscopy is smaller, thus, the number of observations per object at the end of the mission is correspondingly smaller. The two vertical structures are WaveFont sensors. The two additional CCD at the left hand down corner are used to monitor the Basic Angle (BAM).

Gaia (as Hipparcos also did) has to accurately determine the time when the center of a star image has a well defined position in a CCD. This time is an along-scan measurement of the stellar position relative to the instrument axes which is the important one to perfom astrometry. The position across-scan is much less accurate (see [5]).

According to scan parameters and average stellar density Gaia will make some 45 millions observations per day. The objects are detected by the SM, and once confirmed in the first AF row a small window is dessigned to follow the star. The across information is in general binned and the resulting histogram downloaded. For some cases 2D windows are downloaded. The time at which the centroid (calculated in the on-ground process) of this histogram crosses a fiducial line in a given CCD is the "elementary data" to perform the astrometric measurements. As there are 9 astrometric CCDs in a row and an average of 70 transits per object (Fig. 4), we will have more than 600 elementary astrometric observations per object.

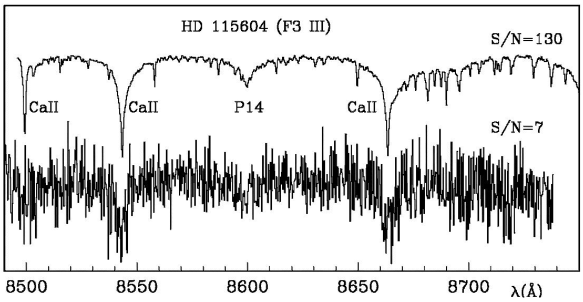

Figure 8: Simulated spectra of one transit and end-of-mission of a giant F3 star observed with RVS.

After the crossing of the AF the stellar image will enter the Blue (330–680 nm) and Red (640–1000 nm) spectrophotometers were appropiate windows and binning are defined. The spectral dispersion of BP/RP depends on the wavelength from 3 to 27 nm pix^{-1} in BP, and from 7–15 nm pix^{-1}in RP. Figure 7 shows a simulated RP spectrum.

The process of observation ends with the star crossing the Radial Velocity Spectrometer. The RVS is an integral field spectrograph giving a resolution of 11500 in the wavelength range 847 - 874 nm. Its limiting magnitude is around 17 mag. As the rest of the instrument, it is also operated in TDI mode. Figure 8 shows a simulated spectra of a F3 III from one, and from 40 RVS observations. The estimated S/N = 7 for one transit, for the end of mission (40 transits) increases up to 130.

4 The data reduction

The data reduction of Gaia is a very demanding task. It includes, only for the astrometric data, some 10^{12} individual measurements to determine 5 billion unknows, the astrometric parameters for one billion stars, plus 150 millions data describing the attitude of the satellite, some tens of millions of calibration data and some tens of global parameters. In addition, all the data gathered by Gaia are related, i.e. photometry is needed to determine the LSF to be used for centroiding determination of the elementary data, good astrometry is needed to determine the attitude and instrumental calibrations, and so on. Several effects, like the Charge Transfer Inefficiency, induced by the radiation [8], or its correction via Charge Injections, followed by a Charge release profile, will be also solved in the data processing chain. It is important to realize that at the level of precision of Gaia observations each time a star is observed its position will be slightly (not so slightly for fast moving objects like Solar System bodies or high proper motion stars) different.

The basic idea of the astrometric data reduction is the comparison between the observed and predicted CCD data of the stars, provided that we have a model of the object, instrument calibrations, satellite orbital data, attitude data and so on (see Fig. 9). The observation equation depends on the astrometric parameters of the star, the attitude parameters for the relevant observations, the calibration parameters for each particular CCD, and some global

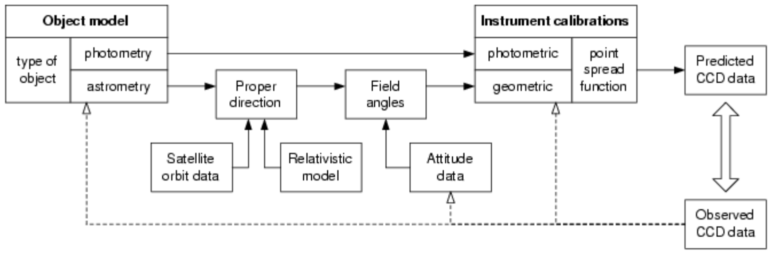

Figure 9: Elements entering the astrometric data reduction

data (i.e. parameters for relativistic light deflection). The resulting huge system of equations describing this approach can be solved by internal iterations in each one of its elements (attitude, scientific data, calibration, global parameters) followed by external iterations of the four tasks for a set of 100 million "well behaved stars". This process is named AGIS (Astrometric Global Iterative Solution). The system has been proved to be convergent (see [7]). As the mission progresses new elementary data are available, and AGIS is producing better calibrations, attitude and source data, and, consequently, all the elementary data from the very beginning of the mission can be recalculated, in a very huge task, the Intermediate Data Updating. The full chain can be iterated until no relevant improvement is obtained. In parallel with this huge "global astrometric" tasks, two similar procedures are ran: the Photometric Global Iterative Solution and the GRVS data produced. Other processes take care of specific objects like binaries or Solar System objects, while others analyze variabilty, classification of objects and determination of astrophysical parameters.

To take care of all these tasks (not all well defined at the epoch) and Announcement of Opportunities was issued by ESA in 2005. To answer it [3] a large european consortium (Data Processing and Analysis Consortium, DPAC) was built gathering at present more than 400 scientists and engineers and six data centers. DPAC is structured, as can be seen in Figure 10, in several Coordination Units, taking each one a well defined part of the task.

Let us remark that the Spanish contribution to DPAC is very relevant. We are leading CU2, producing simulations that have feeded the full DPAC system, as well as simulations of the Gaia results and of the Gaia observable universe. In CU3 we contribute with two main systems: (a)the Initial Data Treatment which takes care of the daily telemetry and produces the first elementary data from the observations, and (b) the IDU process described above. For CU5 we take care of the calibration models, the selection of internal reference stars and contribute to the on-ground observations of standard stars. The outlier analysis in the CU8 unit (Univ. de la Corua) and the global variability studies in CU7 (UNED) are also under Spanish responsibility. We also contribute with large infrastructures like the Mare Nostrum supercomputer at the Barcelona Supercomputing Center where the simulator and IDU run and the CESCA computers where IDT is developped, deployed and tested.

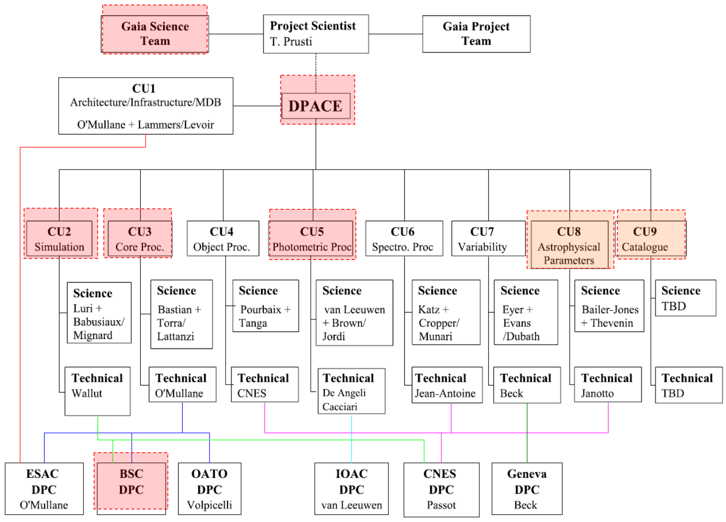

Figure 10: Structure and main tasks of the DPAC Consortium. DPC: Data Processing Centers. Red boxes indicates Spanish contribution.

5 The scientific exploitation

There are no guaranteed data rights in Gaia. All the data available will be published by a new Coordination Unit, which is now being created. At the end of 2012 a Call will be issued by ESA to build this CU. In the meanwhile a Gaia Archive Preparation Group has started to work on the technical aspects of the final data archive. About the availability of Gaia data, it has been agreed that several intermediate releases, see Figs. 11 and 12, will be published, the first one around September 2015.

On the other hand as the launch begun to be close several European and national groups took inititives to organize large teams of experts gathering the capabilities needed to extract the full scientific content of the Gaia data. It was soon realized that to do that, new techniques and tools, new models and a new approach in most cases will be necessary. These networks are becoming very active organizing seminars, meeting and courses (see Figueras, this volume).

GREAT-ESF (2010-2015) is a network financed by the European Science Foundation, joining now 90 groups of 17 countries and offering possibilities for meetings and visits abroad. GREAT-FP7 (2011-2015) is an ITN joining 32 Institutes, three of them in Spain, financing predoctoral studies. REG is the Spanish Gaia Network, joining more than 120 people at 20 institutions. The network's web pages offer detailed information of activities, meetings and so on. For the people interested in the use of simulated data, the Gaia Universe Model Snapshot [9], offers what can be at the best knowledge today, an idea of the contents of the Gaia catalogue.

First release: launch + 22 Months Nov-2013 →Sep-2015	• Positions (α,δ) and G-mag for single-like stars (90% of the sky) • the Hundred Thousand Proper Motions (HTPM) catalogue based on the Hipparcos stars
Second release: launch + 28 Months Mar-2016	• Updates of above + • **Mean radial velocities for stars** with non-variable radial velocity (90% of the sky)
Third release: launch + 40 Months Mar-2017	• **Positions (α,δ), proper motions, and parallaxes** and G-mag for single stars (90% of the sky) • Orbital solution for period between 2 months and 75% of the observation duration • Integrated photometry RP/BP • Spectrophotometry from RP/BP for sources for which astrophysical parameters are simultaneously released • **Source classification based on BP/RP and astrometry** for stars with sufficiently high quality data • Mean RVS spectra for sources where single epoch spectra are usable and APs are simultaneously released

Figure 11: Details of the releases

Fourth release: launch + 65 Months Apr-2019	Updates of all above + • Source classification plus **multiple stellar astrophysical parameters** derived from BP/RP, RVS and astrometry for the majority of stars • **Variable star classifications and parameters** as available, and the epoch photometry • **Solar system results** with preliminary orbital solutions and individual epoch observations • Non-single star catalogue
Final release: End Mission + 3 years (36 months) **Nov-2021/2022**	Full astrometric, photometric, radial velocity catalogue • All available variables and non-single stars solutions • Source classifications (probabilities) plus multiple astrophysical parameters derived from BP/RP, RVS and astrometry for stars, unresolved binaries, galaxies and quasars. Precision improved with respect to 4th release. Some parameters may not be available for fainter stars. • Non Single Stars solutions and exo-planet list • All epoch and transit data for all sources • All Ground Based Observations made for data processing purposes (or links to it)

Figure 12: Details of the releases (cont.)

6 Present status of the mission

Since the X SEA meeting took place, the activities of test and integration of Gaia have been given very positive results. Very recently Gaia launch date has been foreseen to October 2013. The Flight Acceptance Review will take place in March 2013. It seems to be no show stoppers for the completion of the remaining test being the most crucial the thermal test starting now. For the point of view of data processing the Operations Rehearsal 2 will start soon integrating all the critical items.

Delicate moments are coming: launch, injection, commissioning, first scientific data arrival, let's cross fingers for a succesfull mission!

Acknowledgments

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