The European Space Agency Gaia mission: exploring the Galaxy

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Abstract.

The Gaia astrometric mission was approved by the European Space Agency in 2000 and the construction of the spacecraft and payload is on-going for a launch in late 2012. Gaia will continuously scan the entire sky for 5 years, yielding positional and velocity measurements with the accuracies needed to produce a stereoscopic and kinematic census of about one billion stars throughout our Galaxy and beyond. The main scientific goal is to quantify early formation and the subsequent dynamic and chemical evolution of the Milky way. The stellar survey will have a completeness to \( V = 20 \) mag, with a precision of about 25 \( \mu \)as at 15 mag. The astrometric information will be combined with astrophysical data acquired through on-board spectrophotometry and spectroscopy, allowing the chemical composition and age of the stars to be derived. Data acquired and processed as a result of the Gaia mission are estimated to amount to about 1 petabyte. One of the challenging problems is the close relationship between astrometric and astrophysical data, which involves a global iterative solution that updates instruments parameters, the attitude of the satellite, and the properties of the observed objects. The European community is organized to deal with Gaia products: (a) the Data Processing and Analysis Consortium is a joint European effort in charge of preparation and execution of data processing, (b) the GREAT network is a platform for collaboration on the preparation of scientific exploitation.

1. Introduction

The Gaia mission aims to study the origin, formation, and evolution of the Milky Way and its components. Our Galaxy mainly contains stars of several types and ages, interstellar gas and dust in a disk, a spheroidal halo with old stars, a bar and a bulge in the center, and the ubiquitous dark matter. The disk shows a spiral structure, with the arms being the preferred location of the star-forming regions. Although these general features are rather well known, much remains to be elucidated, including the number and detailed structure of the spiral arms, the disk warp, the shape and rotation of the bulge and halo, the global dynamics and the kinematics, and the distribution of dark matter. Also, the process in which the Galaxy was assembled, presumably from small building blocks, and the history of star formation are not well understood.

To address these, one needs a deep full-sky survey covering a significant volume of the Galaxy. This is what Gaia will do (ESA 2000, Perryman et al 2001) by creating the largest and most precise three-dimensional survey of our Galaxy and beyond with unprecedented positional, proper motion, radial velocity, and spectroscopic data for about one billion stars in our Galaxy and throughout the Local Group. The Gaia launch is scheduled for late 2012 and the mission ends 5 years later. The detailed design and construction phase started in February 2006, with the development and construction are progressing as planned.

The operating principle is that of its successful predecessor, the Hipparcos satellite of the European Space Agency (ESA) (ESA 1997, Lindegren et al 2008). Gaia performs wide-angle astrometry by means of two telescopes and two associated viewing directions, allowing the determination of absolute trigonometric parallaxes. The size of the primary mirrors and of the field of views and the use of CCD detectors in the focal plane mean an enormous step further than achieved with the Hipparcos mission. While Hipparcos yielded precisions of 1 mas at 9 mag and measured about 120,000 stars, Gaia will yield 25 \( \mu \)as at 15 mag and will survey a billion objects. Although Hipparcos seems, in retrospect, like a modest project, it was the first space astrometric mission and it revolutionized our view of the Galaxy, despite the reduced number of observed stars. Gaia builds on the experience acquired with Hipparcos; it is an entirely European mission supported by a wide and motivated scientific and technological community, which holds the leadership in the space astrometry domain.

This review discusses the scientific goals of the mission and the mission itself, with a description of its operating principle and instruments, and the status of development as well as the organizational scheme with respect to its bodies and responsibilities. A detailed presentation of the scientific case and mission design at the 2000 stage can be found in ESA (2000) and a review of the mission at the 2004 stage in Turon & Perryman (2005).
2. The scientific case

The scientific goals of Gaia have been extensively discussed (ESA 2000, Perryman et al 2001), the main one being the production of a homogeneous and accurate catalogue to carry out the deepest and most well grounded study thus far of the structure, origin, formation, and evolution of the Milky Way. Since Gaia is a survey mission, the observations are not limited to the stars in the Galaxy, since any object in the fields of view will be recorded. Thus, Gaia will impact on all fields of astronomy and astrophysics as well as on fundamental physics. In the following, we outline some of science goals.

- Galactic structure, kinematics and dynamics and star-formation history
  The huge number of stars to be observed by Gaia, the impressive astrometric accuracy, and the faint limiting magnitude will allow us to quantify the structure and motions of stars within the bulge, the spiral arms, the disk, and the outer halo. The positions and velocities are linked through gravitational forces, and through the star-formation rate as a function of position and time. The initial distributions are modified, perhaps substantially, by small- and large-scale dynamic processes, including instabilities that convey angular momentum and mergers with other galaxies. The star-formation history defines the luminosity evolution of the Galaxy directly. In combination with the relevant chemical abundance distributions, the accretion history of gas may be derived, while together with kinematics, the merger history of smaller stellar systems can be defined. The sum of these three processes comprises what is loosely known as galaxy formation, and the Gaia mission will provide the first quantitative determination of the formation history of our Galaxy.

- Stellar structure and evolution
  The study of stellar structure and evolution provides fundamental information on the properties of matter under extreme physical conditions. Gaia will return information about luminosities, surface temperatures, abundances, masses for all types of stars, including rare objects. This will allow us to study the sizes of the convective cores of massive stars, the internal diffusion of the chemical elements, and the outer convective zones and to solve the current discrepancies among observations and theory. In addition, Gaia will provide multi-epoch, multi-color photometry. These data will permit detection of diverse variable phenomena, allowing a global description of stellar stability and variability across the Hertzsprung-Russell diagram.

- Stellar ages and age of the universe
  The primary age-determination method relies on comparisons of stellar models or isochrones with the best available data for individual stars or stellar groups. Determination of the age of the oldest stars provides a lower limit to the age of the universe, which in turn constrains cosmological models. Gaia will improve the age estimate of the oldest stars by improving their distance–luminosity determination. The number of subdwarfs with accurate distances will considerably increase in each metallicity interval, allowing us to derive the distance of a greater number of globular clusters of various chemical compositions.

- Distance scale
  Measures of trigonometric parallaxes will be unique. Gaia will have a major impact upon our knowledge of the distance scale in the universe by providing accurate distances and physical parameters for all types of observable primary distance indicators in the Milky Way and in the closest galaxies of the Local Group. It will generate a complete sampling of these indicators, allowing the corrections necessitated by metal, oxygen, or helium contents, color, population, age, etc. In particular, Gaia will observe countless Cepheids and RR Lyrae, thus providing solid calibrations for cluster-sequence fitting and period-luminosity relations.

- Binaries, multiple systems and planetary systems
  One of Gaia’s unique features is the unbiased survey over the entire sky. In looking at a nearby sample, many resolved binaries have periods short enough for orbit determination by Gaia. The study of binaries will facilitate the discovery of thousands of low-mass low-luminosity companions of stellar nature, brown dwarfs, or planets through the motion inferred to their parent stars. The detection of 10,000–20,000 exoplanets and the determination of orbits for some 5000 of them is expected, with estimates of the actual planet masses.

- Solar system
  It is estimated that some 10^5 – 10^6 asteroids will be discovered (compared with the 65,000 known), plus some hundreds of Kuiper’s belt objects. Orbits of Near-Earth objects will be known with a precision 30 times higher than what is possible today. Positional and photometric observations spanning the 5-year mission will provide masses, sizes, and composition, as a function of the distance to the Sun, thus improving our understanding of the history of the solar system’s formation.

- Gravitational light deflection
  The detected photons are bent during the last hours of their long journey, under the influence of the gravitational fields of the Sun, planets, moons, asteroids, etc. The amount of this light deflection depends on the mass of the perturbing object, its distance to the observer, and the angular separation at which the photon passes the object. The actual measurements of the blending of the light will constrain the various parameters of post-Newtonian theory.

- Extragalactic astrophysics
  Astrometric and photometric observations for about 500,000 active galactic nuclei and quasars will be derived over the whole sky, allowing us to establish the inertial reference frame to an accuracy of ∼0.4 µas yr^-1. Galactocentric acceleration of the Sun will be derived at a precision of 0.2 nm s^{-2}. It is expected that ∼100,000 supernovae will be discovered, and ∼40 · 10^6 galaxies will be surveyed.
3. Gaia operations, instruments and status of development

Operating from a Lissajous orbit around the second Lagrange point of the Sun-Earth/Moon system, the satellite will continuously scan the sky. During its 5 years of life, *Gaia* will rotate, at a fixed speed of 60 arcsec s$^{-1}$, around a slowly precessing spin axis at 45 deg of the Sun (Fig. 1). As a result, objects continuously traverse the focal planes. *Gaia* has two telescopes (focal length is 35 m) with two associated viewing directions. The primary mirrors are $1.45 \times 0.5$ m$^2$ in size each. The two viewing angles are separated by a highly stable basic angle of 106.5 deg.

The telescope assemblies consist of four mirrors for each line of sight and two common additional mirrors (Fig. 2). The two fields of view are combined into a single focal plane of $104 \times 42$ cm$^2$ (along scan \times across scan) covered with 106 CCD detectors. All the parts are mounted on a torus and all of them are made of SiC, offering thermal and mechanical stability. The mirrors are silver coated.

*Gaia* observations will be made using high-quality, large-format CCDs in the common focal plane (Fig. 3). The CCDs are operated in time delay and integration mode. Charge images will be transported in synchrony with images moving across the field due to the rotation of the satellite. The focal plane has four main sections:

a. Stars entering the focal plane first pass across dedicated CCDs that act as a sky mapper (SM). Here, the objects are detected and the strategy of observations in the rest of the focal plane is established case by case (only pixels around the objects are read and sent to the ground).

b. The astrometric field (AF) is sampled by an array of 62 CCDs. Astrometric observations are made with unfiltered light in order to minimize photon noise. The mirror coatings and the CCD QE effectively define a broad (white-light) passband covering the wavelength range of about 350–1000 nm, with a mean wavelength of 673 nm and a full width at half-maximum of 440 nm.

c. The spectrophotometric CCDs record low-resolution spectra produced by two slitless spectrographs, BP (blue photometer) and RP (red photometer), covering the wavelength intervals 330–680 nm and 650–1050 nm, respectively. The goal is to provide astrophysical classification and parameterization of observed objects.

d. The radial velocity spectrometer (RVS) CCDs, combined with high-resolution integral field spectrograph ($R = 11500$) in the range 847–874 nm on the IR Calcium triplet, allows derivation of the radial velocities and chemical composition of the brightest stars.

By measuring the instantaneous image centroids from the data sent to ground, *Gaia* measures the relative separations of the thousands of stars simultaneously present in the combined fields. Scans in different directions during the 5-year mission allow the measurement of a given star in relation to many others in differently oriented great circles. At the end of the mission, this translates into a precision in angle measurements of about 25 μas at $V = 15$, that is, 25% precision in distance at 10 kpc, and equivalent to measuring a Euro coin at the Moon distance. This kind of measurement also allows the separation of parallax-induced motion in the sky from the star’s own motion, thus yielding the distance and the proper motion of the star with respect to the observer. In summary, the targeted numbers at the end of the mission are:
– One billion objects (0.34 \cdot 10^6 to V = 10 mag; 26 \cdot 10^6 to V = 15 mag; 250 \cdot 10^6 to V = 18 mag)
– Positions and proper motions with precisions better than 25 \mu as and 25 \mu as yr^{-1} at V = 15
– Parallax data with 25 \mu as at V = 15
– Stellar atmospheric parameters (temperature, gravity, chemical composition) for all stars up to V = 18
– Radial velocities of \sim 15 km s^{-1} precision at V = 17

The total mass of the satellite including payload, service module, etc., amounts to 2100 kg, requiring a power of 1630 W that is to be provided by an assembly of solar panels. The spacecraft will be launched by a Soyuz-Fregat launcher from Kourou facilities. The ground-segment is provided by the 35-m antenna of ESA's Cebreros station, with a rate of 30 GB per day downlink. When Gaia is scanning the galactic plane, a second antenna, at the New Norcia station, will provide the necessary additional telemetry time.

The industrial consortium, selected in February 2006, for the Gaia spacecraft is spread over Europe, with EADS-Astrium at Toulouse acting as prime contractor. The design, building, and test phase is currently ongoing, with expected finalization in mid 2012. The payload has passed the critical design review and the spacecraft critical design review is foreseen during summer 2010. The sixteen segments composing the torus structure were built and the torus has been successfully brazed (Fig. 4), one of the main achievements of the building phase. The SiC substrate structure of the mirrors has been manufactured and polished. Testing and coating are ongoing for some of them, and some have already been coated, finalized, and delivered (Fig. 5). The delivery of all mirrors shall be completed by summer 2010. CCD production is also in progress, with 85% of the devices already finalized and tested. Other elements of the scientific instruments and spacecraft are either finalized or under planned development.

4. Organizational structure and responsibilities
The Gaia satellite and mission operation is fully funded by ESA. The management structure includes a project manager and a project scientist. The project manager is in charge of supervising industrial development and ground segment management. The project scientist supervises the
accomplishment of the scientific goals in the design phase and is assisted by a group of scientists external to ESA and representing the scientific community.

Processing of the acquired data is the responsibility of the Data Processing and Analysis Consortium (DPAC, Mignard et al. 2008), comprising more than 430 members in 11 countries who are joining their efforts to overcome the challenging problem of managing the 1 petabyte of Gaia data. DPAC activities are supported by governments that have signed a multilateral agreement with ESA to ensure the stability of the scientific teams for the necessary interval of time. The work inside DPAC is presently organized in eight coordination units, with fields of competence and leaders. Processing will be done on the premises of six Data Processing Centers also made up of scientists and engineers from the countries who have signed the multilateral agreement.

Linked to DPAC, the Marie Curie Research Training Network "European Leadership on Space Astrometry (ELSA)" was created. Its aim is the development and training of the next generation of experts in the field of astrometry.

Neither ESA nor DPAC has direct responsibility for Gaia data exploitation, which, instead, is to be conducted by the scientific community at large. It is up to this community to organize the best use of Gaia’s products. Since the DPAC community has deep knowledge of the Gaia mission and extensive expertise in astrometry, synergy with the community at large is obvious and necessary for making use of the enormous legacy that Gaia will provide. To that end, several networks are currently in place, such as GREAT (Gaia Research for European Astronomy Training), founded by the European Science Foundation and others at national level. These networks aim to strengthen the cooperation between teams, thereby joining expertise in observations, Gaia knowledge, theoretical analysis, model development and interpretation, and statistical treatment. Complementary observations on-ground covering the areas of science alerts, IR photometry, and high resolution spectroscopic surveys are being studied.

5. Summary

The Gaia mission is one of the cornerstone missions within the cosmic vision of ESA’s program.

The development and manufacturing phase is well on track towards a scheduled launch in August 2012. Transfer to orbit around the second Lagrange point and commissioning will take up to 3 months, to be followed by the routine science operations phase. The science operations will last 5 years, with a possible extension of one year. Data processing will start as soon as data are received by the on-ground segment and will continue some 2–3 years after the mission’s end. The final catalogue is expected around 2021, but with intermediate data releases produced during the operational phase.

A scientific and technical community of more than 400 members is currently involved in this project, which maintains European leadership in the space astrometry field. The scientific community is excited by Gaia’s goals and products and by the legacy that it will represent for future generations of astronomers. Doubtless, Gaia will revolutionize the concept of our Galaxy and beyond and the view of our solar system.

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