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GAIA: the mission and (some of) its scientific applications

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Abstract. A general outline of the GAIA mission is presented, along with some of its numerous scientific applications.

Key words. Space vehicles: instruments – Stars: fundamental parameters – Galaxy: fundamental parameters – Galaxies: stellar content – Cosmology: observations

1. Introduction

GAIA is a cornerstone mission of the ESA Space Program, that will perform an all-sky survey and produce accurate astrometry, photometry and spectroscopy for a very large number of stars in the Galaxy. GAIA will produce a stereoscopic and kinematic view of about 10^9 objects down to a limiting magnitude of 20 mag, and the complementary use of multicolour photometry and low resolution spectroscopy will allow to address key questions of modern astrophysics regarding the formation and evolution of the Milky Way. Such an observational effort has been compared to the mapping of the human genome for the impact that it will have in Galactic astrophysics.

In addition, GAIA will provide a fundamental contribution in a much broader range of scientific areas [1] (see Sect. 3).

GAIA represents a hugely improved follow up of the Hipparcos mission in terms of i) measurement accuracy, ii) limiting magnitude and hence number of observed objects, and iii) the combination of nearly simultaneous astrometric, photometric and spectroscopic observations.

2. Overview of the GAIA mission

GAIA will be launched at the end of 2011 from Kourou by a Soyuz-Fregat launcher, that will put it in a Lissajous-type eclipse-free orbit around L2 point of the Sun-Earth system. The design lifetime is 5 years, with a possible extension to 6 or 7 years. The satellite will perform a continuous scanning of the sky at a rate of 60 arcsec s^{-1}, with a precession period of the spin axis of 70 days. As a result of this scanning law, at the end of the mission the whole sky will have been observed several

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[1] More detailed information on the GAIA mission and its science can be found in the *Concept and Technology Study Report* (2000), the Proceedings of the Symposium *The 3-Dimensional Universe with Gaia* (2005), and at the ESA website http://www.rssd.esa.int/Gaia.

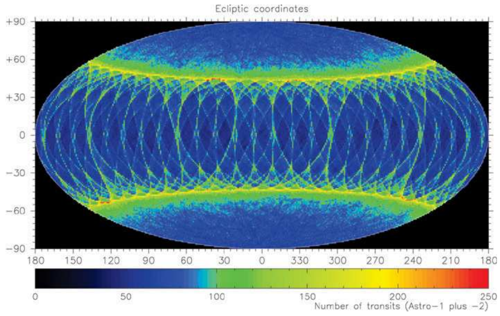

Fig. 1. Dependence of the total end-of-mission number of focal plane transits on position on the sky. Shown is an all-sky equal-area Hammer projection in ecliptic coordinates.

times, from a few tens to more than 200 depending on the position (see Fig. 1), the average value being around 80.

2.1. Measurement principle

The main goal of the mission is to perform global (wide field) astrometry as opposed to local (narrow field) astrometry. In local astrometry, the star position can only be measured with respect to a neighbouring star in the same field. Even with an accurate instrument, the propagation of errors is prohibitive when making a sky survey. The principle of global astrometry is to link stars with large angular distances in a network where each star is connected to a large number of other stars in every direction.

Global astrometry requires the simultaneous observation of two fields of view in which the star positions are measured and compared. Therefore, the payload will provide two lines of sight, obtained with two separate telescopes, but, like Hipparcos, the two images will be focalised, slightly spaced, on a unique focal plane assembly. Objects are matched in successive scans, attitude and calibrations are updated, and object positions are solved and fed back into the system. The procedure is iterated as more scans are added (Global Iterative Solution), and in this way the system is self-calibrating by the use of isolated non variable point sources that will form a sufficiently large body of reference objects for most calibration purposes, including the definition of the celestial frame. Extragalactic objects (e.g. QSOs) will then be used to attach this to the International Celestial Reference Frame.

2.2. Instruments and performances

The payload consists of a toroidal structure (optical bench) holding two primary mirrors whose viewing directions are separated by 106.5 deg (the Basic Angle). These two fields of view get superposed and combined on the same focal plane, that contains i) the Sky Mapper (an array of 2x7 CCDs for on-board star detection and selection), ii) the Astrometric Field (an array of 9x7 CCDs for astrometric measurements and integrated white-light photometry), iii) the Blue and Red Photometers (two columns of 7 CCDs each for low resolution spectrophotometry in the 330-680 nm and 640-1050 nm wavelength ranges, respectively), and iv) the Radial Velocity Spectrometer (an array of 3x4 CCDs for spectroscopy at 847-874 nm with resolution R ~ 10,000).

Therefore the data produced by GAIA will be of three types:

- Astrometry (parallaxes, proper motions);
- Photometry, both integrated (such as the G-band from the Astrometric Field and the G_{BP} and G_{RP} from the blue and red photometers) and low-dispersion (R ~ 20-100) spectrophotometry (BP/RP spectra);
- Spectroscopy (radial velocities).

The predicted performance as a function of V of the various instruments are summarised in Table 1.

However, the CCDs will be affected to some degree by radiation damage, which produces a trap of the charge in the leading samples and a subsequent release of this charge some time later. This Charge Transfer Inefficiency (CTI) is going to have a negative effect on the predicted performance, which is presently being evaluated. This effect, as well as other features presently being tested, is not included in the estimates of Table 1. The quoted uncertainties of the integrated G and $G_{BP/RP}$ magnitudes refer to the internally calibrated photometry (Jordi et al. 2007).

Table 1. End of mission sky average performance predictions as a function of V magnitude, from various contributions in *The 3-Dimensional Universe with Gaia* (2005).

V	$\sigma(\pi)$ μas	$\sigma(G)$ mmag	$\sigma(G_{BP/RP})$ mmag	$\sigma(RV)$ km s^{-1}
10	4	1	1	< 1
12	5	2	2	1
15	11	5	7	5
17	27	12	25	10
20	160	70	350	−−

The accuracy of the absolute photometric calibrated data will depend on some additional factors, e.g. on the accuracy of the Spectro Photometric Standard Stars (SPSS) spectral energy distributions that will be used to derive the instrument response of the GAIA photometric system. This will typically be of a few to several percent depending on the magnitude and on specific spectral ranges for the BP/RP spectra.

Around 2019-2020 a final Catalogue will be produced, containing the end-of-mission measurements for the complete sample of objects ($\sim 10^9$) down to V=20 mag (about 3.5 10^5 sources to V=10, 2.6 10^7 to V=15, and 2.5 10^8 to V=18). Intermediate catalogues might be released before the end of the mission, as appropriate. No proprietary data rights are implemented.

2.3. Science data processing: the DPAC

All aspects of the GAIA mission are charge and responsibility of ESA, except the processing and analysis of the science data that are assigned to the European astronomical community. To this purpose the community has formed the Data Processing and Analysis Consortium (DPAC), that collects the contribution of ∼ 380 scientists from 24 Institutes, and is structured in 8 Coordination Units (CUs) dealing with all aspects of the data processing.

In addition, a number of Data Processing Centres are dedicated to the data handling and processing of specific parts of the pipeline, namely: ESAC (Spain), CNES (France) and the DPCs in Barcelona, Torino, Toulouse, Cambridge and Geneva.

Several boards and committees assist in all aspects of this enormous and complex effort, we only mention the GAIA Science Team (GST), whose 8 members are proposed by the scientific community, that advises in all science related matters.

The Italian response to GAIA, coordinated by the P.I. M. Lattanzi (OA Torino), includes the contribution of about 70 scientists from 12 Institutes in Bologna, Catania, Padova, Napoli, Roma, Teramo, Torino and Trieste. The main activities where the Italian community is involved and responsible cover a broad range of topics, including i) astrometric verification, monitoring of the Basic Angle, various simulations, general relativity models (Torino); ii) astrophysical parameters - stellar libraries, special objects - (Padova, Napoli); iii) flux extraction in crowded conditions (Roma, Teramo); iv) absolute flux calibration - modelling & SPSS observing campaign (Bologna); v) variability analysis (Bologna, Catania, Napoli, Roma, Teramo).

3. Science with GAIA

GAIA represents a huge leap from Hipparcos: the astrometric accuracy will improve by > 2 orders of magnitude (1 mas to 5 μas at V=12), the limiting sensitivity by > 3 orders of magnitude (12 to 20 mag) and the number of objects by 4 orders of magnitude (10^5 to 10^9).

One billion stars in 3-D will provide (just a few examples):

In the Galaxy ...

- distance and velocity distributions of all stellar populations (spatial and dynamical structure, formation and chemical history - evidence of accretion/interaction events);
- rigorous framework for stellar structure and evolution theories;
- clean HR diagrams throughout the Galaxy;
- detection and dating of all spectral types and Galactic populations;

• rare stellar types and rapid evolutionary phases in large numbers;
• detection and characterisation of variability for all spectral types;
• large-scale survey of extra-solar planets (up to ~ 20,000);
• Solar System science (taxonomy, masses, orbits, $\sim 5 \times 10^5$ bodies);
• solar physics (solar J2 accuracy $\sim 5 \times 10^{-7}$);
• support to developments such as JWST.

... and beyond
• definitive and robust definition of the cosmic distance scale with direct parallax calibration of all primary distance indicators, e.g. Cepheids and RR Lyrae, to LMC/SMC (age of the Universe);
• rapid reaction alerts for supernovae and burst sources (~ 20,000);
• QSO detection and reference frame (~ 500,000 in 20,000 deg^2 of the sky);
• redshifts;
• gravitational lensing events: ~ 1000 photometric, ~ 100 astrometric;
• microlensing structure;
• dark matter (potential tracers);
• fundamental quantities to unprecedented accuracy (e.g. $\gamma \sim 5 \times 10^{-7}, \beta \sim 5 \times 10^{-4}$).

A more general and comprehensive description of GAIA science case is given in *The 3-Dimensional Universe with Gaia* 2005 and in the *Concept and Technology Study* (2000) compiled by the GAIA Science Advisory Group. Here only a few cases are presented to illustrate briefly the impact that GAIA will have on our understanding of the Galaxy and its stellar populations.

3.1. The Pleiades

The Pleiades have been the subject of several distance determinations in recent years, with some discrepancy in the results. The values of the parallax that have been obtained are π=7.59±0.14 *mas* (Pinsonneault et al. 1998, main-sequence fitting), 7.69 *mas* (Kharchenko et al. 2005, average of various methods), 7.49±0.07 *mas* (Soderblom et al. 2005, average of 3 HST parallaxes), and 8.18±0.13 *mas* (van Leeuwen 2007, new reduction of Hipparcos data). The two supposedly most accurate estimates, from HST and Hipparcos, are the most discrepant ones, by more than 3-σ.

The distance to the Pleiades is less than 150 pc, and since all the stars down to M_V=14 within 150 pc will be measured by GAIA to better than 1%, then the Pleiades distance and internal stellar distribution will be defined with extremely high precision.

In Fig. 2 we show the comparison of the ground-based, Hipparcos and simulated GAIA data for the Pleiades individual members.

3.2. The distance scale: local calibrators

• RR LYRAES

RR Lyrae variable stars are the most traditional standard candles, as their absolute magnitude can be expressed to a first approximation as $M_V = \alpha + \beta[Fe/H]$, with β ~0.2. However, the zero-point α of this relation is determined to much lower accuracy than the slope β.

Hipparcos measured parallaxes for 126 RR Lyrae stars with <V> = 10 to 12.5 *mag* (750-2500 pc Fernley et al. 1998), but only one star, RR Lyr itself, had a parallax measured to better than 20%, π=3.46±0.64 *mas* (van Leeuwen 2007). However, the parallax measured by Benedict et al. (2002) using HST data π=3.82±0.20 *mas*, which is nominally much more accurate, leads to a shorter distance modulus by 0.21 mag. This discrepancy is far too large and definitely not acceptable for what is supposed to be the basic luminosity/distance calibrator and the first step in the cosmic distance scale.

GAIA will obtain the trigonometric distances for *all* the field RR Lyraes within 3 kpc with *individual* accuracy $\sigma(\pi)/\pi$ <1% (better than 10% for most galactic RR Lyraes), and the mean distances to all globular clusters up to 30 kpc, and hence their RR Lyraes', to better than 1% (by averaging the individual parallaxes of thousands of cluster members). This will allow to calibrate the $M_V - [Fe/H]$ relation with extremely high accuracy (< 1%), for application to all stellar systems where a good estimate of

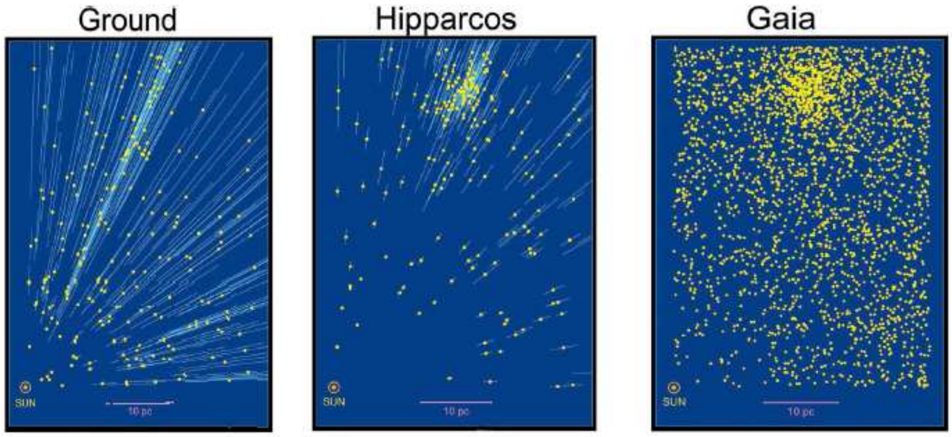

Fig. 2. Comparison of the projected distances to the Pleiades as derived from ground-based observations or indirect methods, from the Hipparcos data (new reduction by van Leeuwen 2007) and as expected from GAIA.

the RR Lyrae metallicity and mean V magnitude is possible.

• **CEPHEIDS**

Cepheids, along with RR Lyrae stars, form the cornerstone of the extragalactic distance scale. Classical (Pop I) Cepheids are several magnitudes brighter than RR Lyraes, and with the use of the HST and other large ground-based telescopes can be observed in many nearby galaxies as far as 25 Mpc (thus reaching the Fornax and Virgo clusters).

The Hipparcos data provided the first opportunity to calibrate independently the critical parameters in the Period-Luminosity-Colour (PLC) relation for classical Cepheids in the Galaxy. Hipparcos measured parallaxes for about 250 Cepheids, ∼ 100 of which with parallax accuracies of 1 *mas* or less. With the use of these data and additional HST parallax measures for 9 stars, van Leeuwen et al. (2007) derived a new calibration of the PLC relation leading to a distance modulus for the LMC of 18.48±0.03 mag (no metallicity correction). This is certainly an excellent result, but is still affected by significant uncertainties due to the various parameters involved in the definition of the calibration itself.

GAIA is expected to measure distances to <4% for all galactic Cepheids (<1% up to 3 kpc), therefore will provide a definitive resolution of the controversy about the zero-point of the PLC relation, as well as about the dependence on period, colour and metallicity.

Cepheid parallaxes can also be measured in extragalactic systems such as the Sagittarius dwarf galaxy (with $\sigma(\pi)/(\pi) < 10\%$) and the Magellanic Clouds (with $\sigma(\pi)/(\pi)$ between 20-30%). This will allow to reach a few fundamental goals: i) define a very accurate PLC relation, including the possible dependence on metallicity; ii) establish its universality, namely the applicability to all galaxies and hence the possibility to derive H_0; iii) establish the distance to the LMC on a completely trigonometric basis, with no need of any intermediate step based on a calibration relation.

3.3. The age of globular clusters: M3

The best clock that stellar evolution theory can provide for dating Population II stars is the luminosity of turn-off stars M_V(TO). This has been parameterised by Renzini (1993) as:
$Logt_9 \propto 0.37M_V(TO) - 0.43Y - 0.13[Fe/H]$

M_V(TO) is sensitive to input physics and assumptions that affect the size and energy production of the radiative core. Comparison of

the various most recent M_V(TO) vs. age relations shows that an intrinsic - hence systematic - theoretical error of ∼5% in the age determination may be present. In addition to this, random errors on the observable parameters entering the M_V(TO)-age relation must be considered. This error budget can be summarised as:
• $0.85\sigma(V_{TO})$: error associated to the photometric determination of the TO. Extremely accurate and well defined main sequences can presently be obtained with instruments such as the HST and other large ground-based facilities, however the isochrones are nearly vertical at the TO, and V_{TO} is rather difficult to define. We assume $\sigma(V_{TO})$ ∼0.05 mag;
• 0.85σ(mod): error associated to the distance determination, which is presently known to ≥0.10 mag;
• $2.64\sigma(A_V)$: error associated to the extinction determination, presently known to ∼0.03 mag;
• $0.99\sigma(Y)$: error associated to the Helium abundance, presently known to ≥0.03 dex;
• 0.30σ[M/H]: error associated to the chemical abundance, presently known to ≥0.10 dex.

The final accuracy with these values is of ∼13% namely ≥1.5 Gyr.

GAIA will provide substantial improvement in two of the above items, the reddening determination and the distance. The reddening will be monitored for each object as part of the astrophysical parameter determination and may not be very accurate individually, but the statistical use of all cluster stars could lead to a rather accurate mean estimate. To be conservative, we assume only a factor 2 improvement in the accuracy of the reddening values.

On the distance determination, however, the improvement will be by more than a factor 10. M3 is located at about 10 kpc ($\pi \sim 0.10$ *mas*) and its red giant and horizontal branch stars (V=12.5 to 15) will have individual parallaxes determined to ∼0.01 *mas*. The average of about 1000 such stars will yield an accuracy on the mean distance determination of ∼0.007 mag.

As a result of the *GAIA data alone*, the error on the *absolute* age determination will be nearly halved, down to ∼7% (errors on theoretical models not included). This will provide a very important contribution to cosmological issues such as the determination of H_0 and the age of the Universe.

4. Conclusions

A very short overview of the GAIA project, its technical aspects and science case have been presented, as well as a few examples of scientific applications where the GAIA contribution will provide a substantial and fundamental improvement to our knowledge.

Acknowledgements. This overview of the GAIA project borrows freely from previous scientific and technical publications, and from the information available on the GAIA website. The effort of the many people involved in the GAIA project is implicit in this synthesis.

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