The Gaia mission: the dawn of Astrometric Cosmology? Status and prospects after 14 months of science operations

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The Gaia mission: the dawn of Astrometric Cosmology? Status and prospects after 14 months of science operations

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Abstract. The concept of precisely gauging a gravity-dominated Universe like ours through the individual observations of its fundamental constituents, the stars, immediately calls astrometry, the oldest quantitative specialty of astronomy, into play. Today, thanks to the launch of the Gaia satellite, astrometry has reached such levels to become a key player in the field of local cosmology and experimental gravitation. Updates on the status of the mission, orbiting in L2 since January 2014 and in nominal observation mode since July 2014, are presented. We also discuss how the astrometric observations from within the gravitational fields of the Solar System can uniquely probe possible deviations from General Relativity and how accurate absolute kinematics at the scale of the Milky Way can, for the first time *in situ*, account for the predictions of the CDM model for the formation of the Galactic halo.

1. Introduction

Gaia is a cornerstone ESA mission that is producing the fullest 3D Galactic census to date. Its outcome will be a detailed astrometric catalogue with positions, distances (parallaxes), and proper motions for more than one billion stars, down to $G \simeq 20$ mag, throughout most of the Milky Way. In addition, the Gaia catalog will contain the astrophysical parameters estimated using low-resolution spectra providing information on effective temperature, line-of-sight extinction, surface gravity, and chemical composition. Furthermore, the on-board radial velocity spectrometer will provide radial velocities for stars down to $G_{\rm RVS} = 17$ mag.

2. Gaia operations: an update after 14 months

Gaia is now in its second year of science operations at L2 of the Earth-Sun System, after accomplishing the following main steps:

- Launch on December 19, 2013 from ESA/CNES Launch base in Kourou (French Guiana)
- Extended commissioning phase formally ended on July 18, 2014
- July-August 2014: about 1-month of science calibrations
- August 21, 2014: beginning of the routine science operations
- March 2015: decision to extend the Gaia survey to G =20.7 ($V \sim 21$)

The first release of the Gaia data to the worldwide community is confirmed for the Summer of 2016.

Table 1. Expected end of mission Gaia performances.

	Hipparcos	**Gaia**
Magnitude limit	12 mag	21 mag
Completeness	7.3 – 9.0 mag	20 mag
Bright limit	0 mag	3 mag (assessment for brighter stars ongoing)
Number of objects	120 000	47 million to $G = 15$ mag
		360 million to $G = 18$ mag
		1192 million to $G = 20$ mag
Effective distance limit	1 kpc	50 kpc
Quasars	1 (3C 273)	500 000
Galaxies	None	1 000 000
Accuracy	1 milliarcsec	7 μarcsec at $G = 10$ mag
		26 μarcsec at $G = 15$ mag
		600 μarcsec at $G = 20$ mag
Photometry	2-colour (B and V)	Low-res. spectra to $G = 20$ mag
Radial velocity	None	15 km s^{-1} to $G_{\rm RVS} = 16$ mag
Observing	Pre-selected	Complete and unbiased

During the long commissioning phase, the Gaia Data Analysis Consortium (DPAC) had to tackle various issues that posed a challenge to the data reduction pipelines. First, significant stray light levels were identified. Second, the transmission of the optics resulted degradated due the contamination by water ice. Finally, the intrinsic instability of the basic angle which separates the lines of sight of the two telescopes appeared significantly larger than expected. While a number of additional calibration procedures were put in place in order to mitigate, and possibly correct these undesired effects, the impact on the astrometric, photometric, and spectroscopic performance of Gaia is still under evaluation. A non negligible degradation is expected at the faint end, but the hope is that for bright and intermediate magnitudes ($G < 18$) such complications will still fit within the 20% margin included in pre-launch calculations.

The currently expected Gaia performances with respect to the previous mission Hipparcos are summarized in Table 1. Further details can be found in the recent review by de Bruijne et al. [6].

3. The Gaia science cases: an overview

Gaia represents a huge advance on its predecessor, Hipparcos, both in terms of the numbers of objects observed and in terms of astrometric accuracy (see Table 1).

Thanks to accurate individual observations and trigonometric parallaxes of large numbers of stars of all kinds, including rare objects, Gaia is expected to have a strong impact on luminosity calibration and improvement of the distance scale. Although the main target is Galactic dynamics and evolution, the Gaia catalogue will have a significant advancement across many fields, including stellar astrophysics, variable stars, open clusters, globular clusters, binary stars, exoplanets, solar system objects, fundamental physics, and cosmology.

The Gaia catalogue will be also complemented by on-going or proposed large-scale photometric and spectroscopic surveys, both in the visible and in the infrared (e.g. APOGEE,

LAMOST, VPHAS, UKIDSS, VVV VISTA, RAVE, Gaia-ESO Survey, etc.). Thus, for the first time, radial velocities, proper motions, distances, and metallicity will be homogeneously derived for a huge number of stars of all the galactic populations (i.e. disk, bulge, and halo) and used to unravel the formation history, evolution, structure, and dynamics of our Galaxy, the Milky Way [13].

Nevertheless, these goals will not be achieved without the correct characterization and exploitation of the "relativistic", i.e. very high accuracy, astrometric data. Gaia, in fact, brings to the fore the relativistic nature of astrometry and, for the first time, it will be able to redraw celestial cartography, shifting the perspective from which we observe the universe from a Euclidean geometry to a purely relativistic one.

In the following sections we focus on the impact of the General Relativity applied to Gaia and on the local cosmology studies related to the Milky Way formation scenarios. A comprehensive review on the prospects of "astrometric cosmology" is presented by Lattanzi [12].

4. The dawn of Relativistic Astrometry

In order to compile stellar maps with the exquisite positional precision of Gaia (micro-arcsecond), the proper treatment of satellite data demands the most accurate treatment of gravity. For this, it is necessary to take into account our local *unavoidable* Solar System dynamical gravitational fields and, therefore, to use General Relativity (GR) for proper data processing. In this regard, a Relativistic Astrometric MODel (RAMOD) was conceived and developed (see Crosta et al. [5] and references therein) providing a fully general-relativistic analysis of the inverse ray-tracing problem, from observational data back to the coordinate position of the light-emitting star. RAMOD is, actually, a family of models of increasing intrinsic accuracy all based on the geometry of curved manifolds where light propagation is expressed in a general relativistic context, suitable for other applications besides astrometry.

As far as RAMOD for Gaia is concerned, the rigorous relativistic modeling of the Gaia observables consistently with the precepts of GR and the theory of measurements [7] is being throughly assessed, as relativistic consistency of the whole data processing chain is the indispensable prerequisite for having the physical correct determination of distances, parallaxes and proper motions. Once a relativistic model for the data reduction has been implemented, any subsequent scientific exploitations should be consistent with the precepts of the theory underlying such a model.

Moreover, the realization of the celestial sphere with RAMOD is not only a scientific validation of the absolute parallaxes and proper motions in Gaia, it is also is the largest experiment in GR ever made with astrometric methods since 1919, by the number of celestial objects (up to 100 million "reference stars") and directions involved (the whole celestial sphere, a relativistic all-sky including QSOs at different redshifts).

This astrometric experiment might attain the sensitivity for testing the dilaton-runaway scenario [17]. Gravity theories alternative to GR require the existence of this scalar field and predict it fades with time, so that today's residue, if real, would manifest itself through very small deviations from Einstein's GR in the weak field regime. Very accurate global astrometry is a very powerful and independent tool to unveil the presence of the scalar field. This outcome can be regarded as an independent verification of other proposed experiments and also for testing gravity theories inside the Solar System providing available scenarios *without* dark components.

While the global tests will be done toward mission's end, when most of the observations will be collected, differential experiments, exploiting the precision of the elementary measurements, can be implemented also in the form of repeated Eddington-like experiments by comparing the evolution of angular distances in bright stellar asterisms consecutively observed by the satellite within a few planet's radii from the limb of a giant planet like Jupiter. Results based on simulated observations of actual star fields near Jupiter's orbit prove Gaia's ability to detect the light deflection due to Jupiter's quadrupole [4], predicted by GR and yet to be detected, with opportunities quite early into the mission in 2017. Any further tests on GR, even if performed in the well tested weak field regime, will constitute new independent constraints for theories alternative to GR.

Thank to Gaia, Astrometry is becoming part of fundamental physics and the physics of gravitation in particular [1].

5. Local cosmology

The old stellar populations in the solar neighborhood can serve as a probe of the formation history of the Galaxy. By comparing the kinematics, and chemical abundances of thick disk and inner halo, it is possible to identify the processes playing a dominant role in the formation of these Galactic components.

The stellar halo offers the best opportunity for probing details of the merging history of the Milky Way. Cold Dark Matter (CDM) models predict that structures grow by hierarchical merging, i.e. by the progressive assembly of sub-units into larger units, mainly driven by dynamical friction and tidal disruption [18], leaving streams and substructures as relicts of this process.

These substructures not only trace the Galaxy's past, but have enormous potential as probes of its gravitational field and hence as tracers of the, yet very uncertain, distribution of dark matter. These cosmological models are now sufficiently well advanced theoretically [2] that the Milky Way provides a means of directly testing and constraining these theories by observing the profiles of density, age, and metallicity of the structures and substructures identified in the local Universe. This will help to understand the relation between the two competing theories of halo formation, accretion of disrupted satellites vs. *in situ* formation [3].

Simulations predict that hundreds of streams could be present in the solar vicinity [8] and several groups of halo stars originating from common progenitor satellites have already been identified within a few kpc of the Sun ([9], [10], [11]). However, the small velocity dispersion of the stars inside the streams requires a very high precision on 3D-velocity (about 5 km/s) to unambiguously separate them from the field.

As an example, Figure 1 shows the kinematic distribution in angular momentum space of the debris resulting from different progenitors [15]. These streams correspond to the accreted stellar particles within 5 kpc of the Sun from the simulations of Sanderson et al. [16] with the addition of Gaia errors expected for FGK dwarfs as estimated by Re Fiorentin et al. [14].

The resulting L_{xy} vs. L_z distribution of the "expected" local streams using the "true" values is shown in the bottom panel, while the sensitivity of the current ground based surveys is represented in the top panel. Here, the black stellar symbols represent the halo stars belonging to the kinematics groups detected by Re Fiorentin et al. [14]. The polygon defined by the dashed line includes the new group(s) discussed by these authors, while the three boxes defined by a solid line represent the *locus* of the streams discovered by Helmi et al. [9] (right), Kepley et al. [10] (left), and the region corresponding to the debris of the Ω Centaury progenitor (middle).

As shown in the middle panel, the improved precision of the Gaia catalogue will provide a much clearer view of the phase space structure in the solar neighborhood. This will help to understand the halo formation processes and to constrain the hierarchical ΛCMD models.

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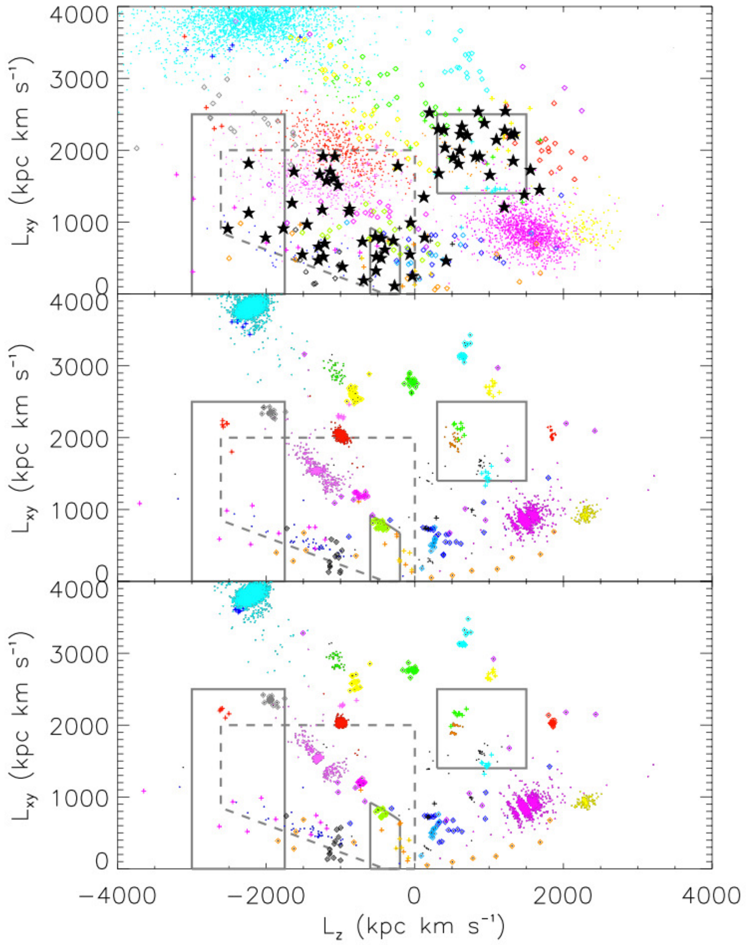

Figure 1. L_{xy} vs. L_z distribution of simulated halo streams in the solar neighbourhood ($d < 5$ kpc). The debris from different satellites are evidenced with different colours. See text.

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