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THE RELATIVISTIC ALL-SKY ANALYSIS WITH GAIA

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Abstract

By providing an homogenous all-sky survey of high precision parallaxes, space motion (proper motions and radial velocities) and astrophysical characterization for more than one billion stars throughout the Galaxy and thanks to the depth of the volume achievable, Gaia will deliver a huge amount of astrometric, spectroscopic, and photometric data. Gaia will contribute also to the determination of an optical reference frame by observing many thousands of quasars. In doing so Gaia will have a huge impact across many fields, including many branches of stellar astrophysics (details of the structure and stellar evolutionary phases), exoplanets, solar system objects, the cosmic distance ladder (through a model independent of the primary calibrators) and fundamental physics. New "accurate" distances and motions of the stars within our Galaxy will provide access to the cosmological signatures left in the disk and halo offering independent, direct and detailed comparisons the predictions of the most advanced cosmological simulations. But all the above goals will not be achieved without the correct characterization and exploitation of the "relativistic", i.e. very high

accuracy, astrometric data. Since a Gaia-like observer is positioned inside the Solar System, the measurements are performed in a weak gravitational regime which can be regarded as "strong" when one has to compare these slow varying fields with the accuracy achievable by Gaia.

1 Gaia Mission

Gaia (European Space Agency, ESA) is the first astrometric mission of the twenty-first century dedicated to the study of the Milky Way and was successfully launched on 19th December 2013 from the European base of Kourou in French Guyana.

At L2 Sun-Earth system Gaia is performing absolute parallaxes, combining at the same time two different stellar directions in one focal plane, observing all objects that pass away in its two fields of view, and scanning repeatedly the sky for at least 5 years. Precession at fixed angle to the Sun (45 degrees) ensures sky coverage. Nearly one-two billion astronomical objects will be observed on about 80 times, leading to around 630 CCD transits, so a total of more than 150 billion measurements at the end of the mission. Routine science operations started end-of-August 2014, after an extended commissioning phase which formally ended on July 18, 2014, followed by approximately 1-month of science calibrations with Gaia in EPSL (spin axis not precessing at 45 deg on ecliptic) using Ecliptic Pole special catalog.

Gaia's survey provides the detailed 3D distributions and space motion of some 1 billion individual stars in our Galaxy and beyond, extended to G=20.7 (i.e., V=21), but not complete at this magnitude limit.

The schedule for the first general all-Gaia data delivery (DR1) has been confirmed on 14th September 2016 (corresponding to 1000 days into science operations in Nominal Scanning Law). DR1 contains the five-parameter astrometric solution - positions, parallaxes, and proper motions - for stars in common between the Tycho-2 Catalogue and Gaia (TGAS), namely for 2 million stars complete to V=11.5 (solar neighborhood, open clusters and associations, moving groups, ..) with sub-milliarcsec accuracy (10 % at 300 pc), while at the end-of-mission the astrometric accuracies are expected better than 5-10μas (microarcsecond) for the brighter stars and 130-600μas for faint targets.

The location of an object in astrometry is considered reliable if the relative error in parallax is less then 10 %. This implies that with the microarcsecond level of accuracy we get the galactic scale. Such a depth allows Gaia to contribute to our knowledge of Galaxy origin and formation, Galactic structure and dynamics; it will provide detailed information to better understand the physics of stars and their evolution; tens of thousands of brown dwarfs and white dwarfs will be identified; ten million binaries within 250 pc will be resolved; many thousands extra-solar planets and thousands of extragalactic supernovae will be discovered; 500 000 quasars will be pinpointed for celestial reference frames; the solar-system observations will include hundreds of thousands of minor planets, near-Earth objects, inner Trojans and new trans-Neptunian objects; finally, even fundamental physics will be tested (section 3). For details, refer to http://www.cosmos.esa.int/web/gaia.

2 Relativistic astrometric sky modeling

Having a control on the error budget at the level of μas for Gaia is even more critical if one considers that the solar system generates perturbations of the order of accuracy of the measurements. This turns out to trace back the direction of light to the position of the star from within the ever-present and ever-changing gravitational fields of our solar system. Consequently, also the retarded time terms due to the varying gravitational fields of the bodies need to be taken into account, namely the time when the gravitational field of the source actually began to propagate along the light cone. The major effects are the deflections of light due to the planets: already at the first post newtonian approximation they produce overlapping contributions up to the order of several μas; the contribution amounts just 1 μas, for example, at 180 deg from the limb of the Sun and at 90 deg from that one of Jupiter.

Therefore, achieving high astrometric accuracy translates into a fully self consistent relativistic model suitable to describe correctly the observables.

Thanks to the need of using General Relativity (GR) for Gaia, nowadays there exist different ways to model an astrometric observable. Their availability is required in order to consolidate the results. From the experimental point of view, in fact, relativistic astrometry opens a largely uncharted territory and it is of capital importance to allow the existences of different and cross-checked models which exploit different solutions to interpret the same experimental data. In this regard, inside the *Data and Processing Analysis Consortium* (DPAC) constituted for the Gaia data reduction, two models are considered: i) GREM (Gaia RElativistic Model, baselined for the Astrometric Global Iterative Solution for Gaia (AGIS), and ii) RAMOD (Relativistic Astrometric MODels) implemented in the Global Sphere Reconstruction (GSR) of the Astrometric Verification Unit (AVU) at the Italian data center (DPCT), the only center, together with the DPC of Madrid, able to perform the calibration of positions, parallaxes and proper motions of the Gaia data.

RAMOD stands originally for Relativistic Astrometric MODel, conceived to solve the inverse ray-tracing problem in a general relativistic framework not constrained by a priori approximation 1, 2). RAMOD is, actually, a family of models of increasing intrinsic accuracy all based on the measurement protocol in GR 3), where light propagation is expressed in a general relativistic context, not necessarily applied only to astrometry. RAMOD can be adapted to many different observers settings. The solutions interface numerical 4) and analytical relativity 5).

Since both models are used for the Gaia data reduction, any inconsistency in the relativistic model(s) would invalidate the quality and reliability of the scientific outputs. Indeed, the main Solar System curvature perturbation amounts approximately to 100 microarsecond, which will cause the individual parallaxes to fast degrade beyond 1 kpc, while completely invalidating the most accurate calibration of, e.g., the primary distance calibrators. This alone is sufficient reason for allowing the existence and making a theoretical comparison of different approaches a necessity.

3 All-sky GR testing with Gaia

The relativistic observable takes into account the measured abscissa along the scanning direction. In principle, once determined the local-line-of sight according to the RAMOD solutions and defined an appropriate relativistic attitude, each observation is a function of the Astrometric, Attitude, Instrument, and Global parameters which are accumulated in a large system of linearized observation equations in the case of GSR. Direct solution, no block-adjustment, of such a system via an iterative method provides estimates of variances. The dependence on the PPN parameter γ - which measures the amount of curvature produced by unit rest mass, equal to one in GR - gives the estimation of such a parameter as a by-product of the sphere reconstruction. Then, given the suitable relativistic models for analyzing the data, a mission like Gaia, repeatedly observing over 5 years millions of bright and stable stars uniformly scattered across the sky to a precision of 10-20 micro-arcsecond, will constitute by far the largest and most thorough astronomical experiment in testing GR ever attempted since its formulation (one century ago), possibly with the sensitivity for testing the dilaton-runaway scenario 6). Gravity theories alternative to GR require the existence of this scalar field and predict it fades with time, so that this residue would manifest itself through very small deviations from Einsteins GR in the weak field regime. Very accurate global astrometry is a very powerful and independent tool to unveil the presence of this scalar field, providing even available scenarios without dark components. Current simulations with the present configuration of Gaia suggest a final estimate of $|\gamma - 1|$ at the 10^{-6} level of accuracy, mainly due to a trade-off in the measurement performances between the faint and the bright end of the stellar sample.

While global tests will be done toward the 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 compound observed fields near Jupiter's orbit - against a selected reference frame of fiducial stars for different scanning directions - prove Gaia's ability to test the light deflection due to Jupiter's quadrupole, predicted by GR and yet to be detected, with opportunities quite early (february 2017).

Gaia accurate space-phase structure can fully probe the Milky Way outer halo (*i.e.* mass content and distribution) and compare the prediction of ΛCDM models *in situ*. The aim is to search for new kinematic streams in the local halo and redefine membership of known streams. Cold Dark Matter (CDM) models predict that structures grow by hierarchical merging, mainly driven by dynamical friction and tidal disruption, leaving streams and substructures as relicts of this process considered as tracers of the distribution of dark matter. Simulations predict the presence of hundreds of streams in the solar vicinity. However, although several groups of halo stars originating from common progenitor satellites have already been identified within a few kpc of the Sun, their small velocity dispersion inside the streams requires a very high precision on 3D-velocity (about 5 km/s) to unambiguously separate them from the field. Recent simulations taking into account dynamical friction with the addition of the Gaia errors, show the possibility to detail the localization of the different streams in the halo structure 7).

Finally, the proper motions measured by Gaia have the potential to further confirm the Galactic warp 8).

4 Conclusion

All the goals of Gaia will not be achieved without a correct implementation of General Relativity in the data processing and analysis.

Gaia will not only greatly enhance our knowledge of the Galactic structure, but it will also provide precise information allowing astronomers to frame a much more detailed kinematical picture of our Galaxy than what presently available. A 6 - dimensional accurate reconstruction of the individual stars across a large portion of the Milky Way necessarily needs extremely accurate astrometric observations modeled within a fully, comparably accurate, relativistic framework. Once a relativistic model for the data reduction has been implemented, any subsequent scientific exploitation should be consistent with the precepts of the theory underlying such a model. Any discrepancy between the relativistic models, if it can not be attributed to errors of different nature, will mean either a limit in the modeling/interpretation - that a correct application of GR should fix - and therefore a validation of GR, or, maybe, a clue that we need to refine our approach to GR. Moreover, given the number of celestial objects (a real Galilean method applied on the sky!) and directions involved (the whole celestial sphere!), the realization of the relativistic celestial sphere is not only a scientific validation of the absolute parallax and proper motions obtained with Gaia. Reaching 10-20 μas accuracy on individual parallax and annual proper motions for bright stars (V $<$ 16) is also the key possibly to perform the largest GR experiment ever attempted from space with astrometric methods (since 1919).

And beyond the micro-arcsecond? Gaia represents only a ground step, increasing the level of accuracy requires to refine consistently the metric of the solar system, the solutions for the null geodesic, the observables, the attitude, and so on..

Therefore, the astronomers need to be ready to exploit all of the scientific potential of the local measurements entangled to the varying gravitational fields from within the Solar System and to maximize its impact. After Gaia, Astrometry becomes part of fundamental physics and, in particular, in that of gravitation.

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