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Testing Gravity with Gaia

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Abstract

On April 25th (2018) the second release of the Gaia catalogue (DR2) became available to the scientific community worldwide. It contains the five-parameter astrometric solution (positions on the sky, parallaxes, and annual proper motions) for more than 1.3 billion sources, within the Gaia magnitude range $3 < G < 20.7$, and median radial velocities for more than 7.2 million stars. Uncertainties of the DR2 astrometry are still too high to detect clearly the varying relativistic effects associated with the received null geodesic from within the multi-gravitational fields of the Solar System. However, a method of differential astrometry applied to the individual observations appears capable of spotting the complex light deflection by Jupiter; and this technique could be extended to consider passing gravitational waves that affect photon propagation.

Moreover, the independent astrometric solution underway at the Italian data processing center in Turin (DPCT), for verification purposes, is based on a high-accuracy general relativistic treatment of the data that implements, in

a sophisticated high-performance computing infrastructure, theoretical models for the observables and the observer.

This implies that the five-parameter global astrometric solution, made available with each release of the Gaia catalog, must be understood as providing relativistic kinematics demanding in turn, at least for consistency, a relativistic representation of the Galaxy's dynamics.

1 Introduction

The extraordinary advancement in astronomical observations and instrumentation brought about by Gaia requires coding light propagation, i.e. null geodesic, at an unprecedented level of precision. Gaia-like measurements, in fact, need to take into account the ever present and ever changing overlapping local gravitational fields in which the observer is embedded to the accuracy level required by the measurements, i.e., whenever these are comparable to the local curvature (even if weak) due to the gravity source or background geometry. Once the observer is properly defined, null geodesics represent the real physical link through space-time up to the star. As far as Gaia is concerned, this has been renamed as "Relativistic Astrometry" providing, already at the micro-arcsecond level (μas), a fully general-relativistic analysis of the inverse ray-tracing problem, from the observational data (e.g., stellar images on a digital detector) back to the position of the light-emitting star [1] (Crosta et al. and references therein).

Gaia is already delivering [2, 3] a huge amount of spectroscopic, photometric and, most importantly, astrometric data of unprecedented quality (to 100 μ as for brighter stars), and much more is to come till the final release (to 25 μas for brigther stars).

In summary DR2 contains: median radial velocities (i.e. the median value over the observation epochs) for more than 7.2 million stars with a mean G magnitude between 4 and 13; G magnitudes for more than 1.69 billion sources, with precisions varying from around 1 milli-mag at the bright (G<13) end to around 20 milli-mag at G=20; GBP (blu) and GRP (red) magnitudes for more than 1.38 billion sources, with precisions varying from a few milli-mag to around 200 milli-mag at G=20; epoch astrometry for 14,099 known solar system objects based on more than 1.5 million CCD observations; about 87 million sources with line-of-sight extinction AG and reddening E(BP-RP); for a part of this last subset (around 76 million sources) luminosity and radius as well; finally, classifications for more than 550,000 variable sources consisting of Cepheids, RR Lyrae, Mira. Details can be read on the ESA web portal dedicated to the mission [4].

Nonetheless, all the goals of Gaia will not be achieved without the correct characterization and exploitation of the relativistic astrometric data.

Nowadays, our modeling of the Universe depends critically on our understanding of gravity; despite the fact General Relativity (GR) is the standard theory of gravity, deviations from GR could profoundly impact our conclusions on the best theory suitable to explain the "dark" ingredients that make up the Universe. On the other hand, experimental verifications of the GR weak effects are difficult, but could be as fundamental and complementary as any other observations that test manifestly the validity of Einstein's field equations, which underpin strong gravity. The recent LIGO observations of a merging binary black hole (Abott et al. 2016 [5]) further strengthen the confidence in GR in the strong-field regime; however, tests of GR in the weak-field regime remain very difficult on astronomical scales.

Gaia-like missions are offering the unique possibility of being a multi laboratory for extensively testing weak gravitational fields at local (Solar System) and more distant (MIlky Way) scales. In particular, the potential of Gaia is to probe the validity of GR by testing: i) PPN parameters and possibly new tiny relativistic effects on the light deflection due to the Solar System bodies; ii) the structure of our Galaxy as a product of the cosmological evolution shaped by gravity (Local Cosmology), namely the relations among baryonic structures (and their evolution) and the dark components of the Universe.

2 Solar System tests

While GR is currently the preferred theory of gravity, indeed any subtle deviations from GR should be predicted in experiments and the solar system represents the most natural arena to carry out such tests. For any alternative theory of gravity should present at least the same predictions of GR in the Solar System.

The first independent verification of GR in the solar system was made by Dyson, Eddington, and Davidson during the solar eclipse of 1919 to verify Einstein's General Relativity prediction of a 1.75" astrometric deflection of light by the Sun. However, Eddington-like measurements of light deflection by the Sun during eclipses remain with large uncertainty; the best constraint to date is about 20%. Nearly a century later, astrometry remains one of the most fundamental and sensitive methods to test the validity of GR in the weak-field regime. The Gaia global astrometry will provide a massive repetition of the Eddington astrometric test of GR with 21st century technology, and this thanks to a combination of analytical and numerical relativistic methods [1]. As the systematic errors in DR2 [3] are still relatively large, the expectation is to estimate a deviation, from the GR predicted value of 1, for the PPN γ at the level of 10^{-6} when final calibrations after DR3: at the end of the mission astrometric accuracies are expected to be better than 5-10as for the brighter stars and 130-600μas for fainter targets.

Given the absolute character of such releases of the Gaia catalogs, the Consortium constituted by ESA for the Gaia data reduction (DPAC) agreed to set up two independent astrometric sphere solutions: AGIS and GSR. Beside the determination of the most fundamental PPN parameter, which enters as unknown the global reduction process, the Gaia observable relies on completely different relativistic observation equations and least-squares solution methods, namely AGIS, adopted as the baseline, that uses the GREM relativistic model, and GSR that is based on the RAMOD modeling of GR. This in itself represents a powerful test of General Relativity thanks to the billions of observation equations delivered by Gaia. 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, therefore validating GR - or provide a new stringent limit on GR validity.

Focusing on RAMOD, the fundamental step toward the realization of the Gaia catalogue is the global astrometric sphere reconstruction (GSR), which determines the celestial reference frame using the observations of a selected subset of up to 100 million stars (primary sources), among those observed by Gaia, in order to validate the baseline method adopted for Gaia. Recent blind simulations show that GSR works as expected in the range of accuracy required for Gaia [6]. In order to make the comparison useful, the largest degree of independence between the two solutions had to be guaranteed. Basically AGIS and GSR present: independent relativistic astrometric model; independent relativistic attitude model; independent (iterative) least-squares solution method (all-unknowns solved).

Observations from global astrometry can be used also to create small stellar reference frames against which tiny relativistic light deflection effects due to a single source can be tested.

Thanks to the multiple observations over a few consecutive scans and the appropriate statistical analysis of the local coordinates on the two Gaia fields of view (FOVs), differential astrometry is used to adjust all the frames to a common frame by means of translations, rotations and possible distortion terms if necessary [7]. The first application has been the detection of the apparent shift in the position of bright stars during their near-occultation by Jupiter to test light deflection due to both the monopole and the quadrupole (never measured before, i.e. the oblateness of the planet). Jupiter offers an optimal target for second order light deflection experiments, thanks to its precisely known mass, relatively large deflection, and the ability to observe a target very close to the limb without the difficulties posed by the Sun. For Jupiter the magnitude of the monopole deflection for a grazing ray is $\sim$16 milli-arcsecond (mas), to which a component from the quadrupole moment is superimposed with an amplitude of $\sim 240\mu$as (Crosta and Mignard, 2006).

On the same subject we have a multi-epoch, multi-orbit HST proposal (PI S. Casertano, STScI). Therefore, this study is accomplished by comparing the performances expected, respectively, with Gaia and WFC3 on the Hubble Space Telescope, in spatial scan mode. The actual GAREQ (for GAia Relativistic Experiment on Quadrupole) experiment was carried out by the satellite on February 22th, 2017 and by HST on April, 6, 2017.

Gaia's spin axis orientation was optimized to catch a star close to the limb of Jupiter in 2017. Actually, the initial spin phase axis orientation was decided in 2014 to maximize the measurement success and on 8 Feb 2017. At the beginning of 2017, and towards the end of February 2017, Gaia provided measurements for 31 bright reference stars (G <13 mag) all lying within a field of 0.8×1.3 degree surrounding the target star (G= 12.68 mag). The target star was seen a total of 26 times over a 2-month period out of which we use 15 transits over a time interval of a couple of days surrounding the observation at closest approach.

Both observation epochs were executed successfully and are under reduction (Abbas et al. 2017 [9]). Results are still embargoed and will be published as soon as possible.

Moreover, the GAREQ experiment provides an important science case and a conspicuous potential for assessing the health of the main astrometric payload during the mission. The operational importance resides in the fact that, thanks to the precise predictions of GR, we can compare the reconstructions of the relativistic deflections done with the Gaia observations to absolute numbers providing the means for accurate external tests on the satellite actual astrometric performances.

The differential astrometry technique can be utilized also to detect astrometric shifts on the light-of-sight over small stellar fields due to passing gravitational waves. The critical aspect in this case is the implementation of an appropriate retrieval and calibration procedure at DPCT, which is on-going.

3 Milky Way tests

The Milky Way (MW) is the product of the cosmological evolution at z=0. In the field of Local Cosmology, Gaia can provide tests on galactic models for their comparison with ΛCDM predictions.

The purpose is to check if it is worth pursuing a GR coherent phase-space picture of the MW against which theories, simulations, predicting dark matter components or possible deviations from GR (and not only from Newtonian or Keplerian mechanics) can be tested. Given the relativistic reduction process for the Gaia data, for the sake of consistency, a weakly relativistic scenario should be considered while dealing with the application of Gaia's data to test GR.

Gaia directly measures the kinematics of the stellar component of the MW. Provided that the Galaxy is not a point source but an extended source, the first attempt is to apply the relativistic kinematics delivered by Gaia to trace the MW rotation curves without any a priori assumption on the origin of its observed flatness at large radii from the galactic center, which is actually explained as a deviation from the Newtonian velocity profile possibly because of the presence of dark matter or of a modified gravity law (see MOND for example).

The Ansatz to be tested assumes an axially symmetric, stationary and asymptotically flat Galaxy-scale metric and, in parallel, the mass inside a large portion of the Galaxy, far away from the central bulk, can be simplified as a pressure-less perfect fluid (i.e. "dust" for GR) avoiding the bulge where resides the axis of symmetry. Although a pressureless fluid is not a pure vacuum, however it may be considered an approximation very close to a low energy density regime. A co-rotating dust is defined to be a continuous distribution of matter with stress-energy tensor $T_{\alpha\beta}$ in the form of (in geometrizied units): $T_{\alpha\beta} = \rho u^\alpha u^\beta$, where the time-like vector field u^α represents the 4-velocity of the co-rotating fluid proportional to the killing vector k^α (namely a static observer), which in virtue of the definition of $T_{\alpha\beta}$, and in the limit of small density (ρ) results geodetic. The considerations above constitute the basis of the metric solution found by Balasin and Grumiller (BG) [10] in order to trace the velocity profiles for galactic curves in a weakly relativistic scenario. As argued by these authors, those assumptions simplify the dynamics to be solved as compared to the vacuum case.

Solving the nonlinear partial differential equations from Einstein's field equation, and by removing all the unphysical values which could violate the weak energy condition, the singularity along the axis at the center of the Galaxy, and the assumption of vanishing pressure, the functional expression for the BG velocity profile results (with z=0, on the galactic plane)

$$V_\phi^{BG}(R) = \frac{V_0}{r}\Big(R_{out} - r_{in} + \sqrt{r_{in}^2 + R^2} - \sqrt{R_{out}^2 + R^2}\Big) \tag{1}$$

where the three parameters V_0, R_{out}, r_{in} have been chosen respectively as the flat regime velocity, the maximum extension of the Galaxy, and to the bulge size, i.e the parameters that define the upper and lower radial validity limits of the model.

The study of the rotation curve profile of our Galaxy requires the selection of the most suitable stellar tracers of the bulk circular velocity around the galactic center, i.e., of early type stars like, e.g. OB stars. To this end, we selected DR2 sources according to the requirements for a proper 6-dimensional reconstruction of the phase-space location occupied by each individual star as derived by the same observer, namely: (i) availability of the complete astrometric set, and of its corresponding error (covariance) matrix; (ii) availability of the Gaia-measured velocity along the line of sight, RV, and its error; (iii) parallaxes good to 20%, i.e., $p/\sigma_p \geq 5$; (iv) avalaibility of a cross-matched entry in the 2MASS catalog for the materialization of the sample [11].

The BG fit to the MW rotational data has been compared with wellstudied classical models for the MW (MWC), which is comprised of a bulge, a stellar disk and a Navarro-Frenk-White (NFW) dark matter (DM) halo.

To quantitatively asses this, a Monte Carlo Markov Chain (MCMC) analysis was done and compared the results for the two models. For the likelihood analysis the BG and MWC models appear almost identically consistent with the data (see [11]). For the MWC model, the estimated parameters are, within the errors, compatible with the very latest literature values. This is important in itself, proving that the 11 kpc range in (galactocentric) cylindrical radius covered by our DR2 sample of disk stars is sufficiently large already for the task.

As for the BG model, we obtain the important result on the lower limit parameter r_{in}, which is estimated below 1 kpc confirming *a posteriori*, the hypothesis of validity the BG model. In fact, inward of $R \sim 1$ kpc it would not be possible to neglect the z-dependence of velocity due to the presence of the MW bulge.

As for the local baryonic matter density, estimated via the 00-term of then Einstein field equation, we obtain $\rho_\odot(R = R_\odot, z = 0) = 0.088 \pm 0.005 M_\odot pc^{-3}$ that is perfectly in line with current estimates. Then, it appears that no extra-mass is required for the GR rotational curve!

Details on this study are under publication. References and full text are available in Crosta et al. [11].

4 Conclusion

Gaia-like missions are offering the unique possibility of being a multi laboratory for extensively testing weak gravitational fields both at the Solar System and Milky Way scales. Much more will be expected after DR3.

While after the first detections of GWs many efforts are concentrated on the strong field sources, the large amount of highly precise data from Gaia offers also the unique opportunity to test "complementary" weak gravitational regime and the subtle nonlinear effects as provided by the Einstein equation itself.

To trace light trajectories back to the emitting stars requires an appropriate treatment of local gravity and a relativistic definition of the observable, according to the measurement protocol of GR. Individual distances, phase-space stellar distributions can be achieved only from *in situ* investigations, i.e.

from within the local universe: the μas accuracy is not enough to probe directly Mpc scale, the nanoarcsecond regime will be needed, which comprises also the detection of GWs due to binary sources.

After Gaia, null geodesics should be as fundamental in astrophysics as the equations of stellar evolution.

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