SOLAR SYSTEM DYNAMICS WITH THE GAIA MISSION

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ABSTRACT. The Gaia mission is to be launched on December 19th, 2013 by the European Space Agency (ESA). Solar System science is well covered by the mission and has been included since the early stages of its concept and development. We present here some aspects on the astrometry and dynamics of Solar System Objects (SSO) – in particular asteroids, comets and satellites – as well as ground-based support. We also touch upon the future of SSO astrometry that will be achieved indirectly, after mission completion, from the Gaia astrometric catalogue.

1. INTRODUCTION

Gaia – “the billion star surveyor” – is the next cornerstone mission to be launched by ESA. At the time of writing this proceeding, Gaia launch is scheduled on December 19, 2013. Following on the success of Hipparcos, Gaia is an extremely high-accuracy astrometric European space mission. Gaia is much more than a second Hipparcos though, its main scientific objective being to obtain a new global picture of the Galaxy (Perryman et al., 2001). With a focal plane containing more than hundred CCD detectors, Gaia will map the whole sky down to 20th magnitude, providing unprecedented astrometric accuracy and multi-wavelength data. Where Hipparcos catalogued a little less than 120 000 stars with parallaxes at a precision of 1 mas (milli-arcsecond), Gaia promises to observe 1 billion of stars and celestial objects with parallaxes at better than 10 μas (micro-arcsecond), in several colours at visible wavelength, including radial velocity measurements. Thus Gaia by probing about 1% of the stars of the Milky Way will yield a 3-D – or even 6-D – picture of a good fraction of our Galaxy, and hence a big leap in our understanding of its origin, structure and evolution. Besides, the Gaia mission will cover several scientific objectives, stellar physics, quasar and galaxies, exoplanets, reference frames, fundamental physics, Solar System...

2. THE MISSION

Performing astrometry from space has many advantages as has already been proved by the Hipparcos/Tycho missions. For Gaia in particular, the thermo-mechanical stability of the spacecraft, combined with the selection of a station at L2 Sun-Earth Lagrangian point for operations, makes it a very stable environment for operations; the drawback being that the data downlink is less favorable. Gaia’s instrumentation provides absolute astrometry, broad-band photometry, spectro-photometry from low resolution spectra, and modest imaging capabilities. Additionally, spectroscopic data with higher resolution $R = 11\,500$ will be obtained for the sources down to 17th magnitude, yielding measure of radial velocity at a 10 km/s level. The final catalogue will be published in 2022 soon after the mission completion, with nominal duration of five years and a possible one year extension. With the amount of data collected and later processed on ground, Gaia is a petabyte (10^{15}) mission.

Since Gaia is regularly scanning the whole sky – acquiring observations with no input catalogue – a very large number of Solar System Objects (SSO) will be observed by the telescope(s), with roughly 60 transits per source on average, at solar elongation in the range 45–135° (see Table 1). Given the present catalogued population in the Solar System, one can expect to observe about 300 000 SSO, mainly main-belt asteroids, and mostly known. Nevertheless Gaia will observe some dwarf planets, Jupiter Trojans, Centaurs and trans-Neptunian objects (TNO) orbiting beyond Neptune (including Pluto), and closer to the Earth some near-Earth objects (NEO, including potentially hazardous asteroids, PHA). Additionally Gaia will observe about 200 Jupiter family comets (JFC) and a few long period comets, and about 20 planetary satellites, on either regular or irregular orbits, around Mars, Jupiter, Saturn, Uranus and Neptune. Besides, Gaia will indirectly detect the reflex motion due to exoplanets orbiting around their host star. Worth to notice, the detection algorithm implemented on board of the spacecraft yields additional limitation: Objects larger in size than an apparent diameter $\rho \gtrsim 0.7 - 0.9$ arcsecond will not be observed; thus no data is expected neither for planets, nor the Galilean satellites, and in some occasions no data for the dwarf planet Ceres. While performing well for SSOs, the satellite and mission has been optimally designed for its primary purpose: observations of stars. There are hence a few particular aspects, and numbers reported in Table 1, for SSOs observation by Gaia. The average number of observations (transits of one of the field-of-view) for bodies in the ecliptic is somewhat lower than for a typical star. The astrometric precision of use for SSO is the one of a transit, which is lower than the precision of stellar positions and parallaxes at the μarcsec level given in the literature, since the latter is derived at the end of the mission from the collection of all the transits for a given star.

Table 1: Gaia mission - general fact sheets for SSOs.

Launch	Dec. 19, 2013
Duration	5years +1year extension
Observing mode	CCD, TDI scanning
Solar elongation	45–135°
# of observations	60 obs./target
Limiting magnitude/size	20 (possibly 21)
Limiting upper size	$0''.7$–$0''.9$
Astrometric precision /CCD	0.2 – 3 mas
Photometric precision	0.001 mag
Catalogue release	$\approx$ 2022

Gaia will provide big advances in the science of Solar system objects (Mignard et al. 2007, Hestroffer et al. 2010). The broad-band photometry and snapshot spectro-photometry enables the reconstruction of rotation properties (rotation period, spin direction, ellipsoidal shape). The CCD signal shall also provide size determination for approximately 1000 objects, and detection of binaries at separation larger than $\approx$100 mas. Last, the astrometry will provide some advances as described in the following.

3. SCIENCE IN THE SOLAR SYSTEM

There are two different pipelines for data reduction and analysis. The short-term pipeline of data reduction – performed on a daily basis – is processing the SSO identification, astrometric reduction, observations threading and initial orbit computation for unidentified objects, and science alert. The long-term pipeline – performed on a semester basis – treats all data for all objects together, and for SSOs it will derive the shape and spin of the asteroids, orbit adjustments, and analysis of global effects on the dynamics.

The identification. Source that has not been matched to stars from stellar catalogues at first look, will be cross-matched with a specific planetary ephemerides computation. A routine has been implemented in the data reduction pipeline to identify theses objects; it is based on the `SkyBot` engine of precomputed ephemerides (Berthier et al. 2006), regularly updated from the IAU Minor Planet Center (MPC) collection and the `astorb` database of orbital elements. Then, given the expected position and magnitude of all planetary bodies at the given date and in the direction of observations, one can identify known SSOs. Observations of moving objects that would not be identified by this way will next be thread together and an initial orbit is computed for newly discovered objects.

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Gaia-FUN-SSO. Given the advance in present ground-based surveys (LINEAR, Catalina, Pan-Starrs, etc.), and the limiting magnitude of Gaia, most of the SSOs that Gaia will observe are already catalogued. Nevertheless, Gaia has the potential to discover new objects because it scans the whole sky in very good observing conditions, and goes down to low solar elongations (45°). Hence Gaia can be efficient at discovering quasi satellites of the Earth or Atiras (on inner Earth orbits). A support programme of ground-based observations has been set-up – Gaia-FUN-SSO – for science alerts; this network will perform follow-up observations in order not to loose a newly detected NEO. Several observatories worldwide, yet mostly in the Northern hemisphere, with telescopes in the range 0.4 – 2 m, including some Schmidt telescopes, participate to the network. The central node will validate and trigger the alerts, request ground-based observations providing dedicated ephemerides, and collect the final astrometry. Besides the Gaia astrometry as well as the ground-based one are systematically sent to the MPC, since – following the ESA and DPAC policy – all such science alert data has to be made public with no proprietary period.

Global effects on dynamic. On the long term, when astrometric data has been acquired over more that one year one can adjust the orbits of asteroids and comets. By using the Gaia data alone over 5 years, a general improvement of a factor of 30 is expected on the orbit determination (depending on the actual number of observations per target). Given the high astrometric accuracy, established in a high quality reference frame, one will be able to detect small effects and estimate both physical and dynamical parameters. Asteroid mass determination is expected from close encounter of several thousands targets asteroids with more massive one (Mouret et al. 2007), and from resolved binary asteroids. This will provide a revolution in the field that still suffers from low-number statistics (Carry et al. 2012). Detection of NEOs and orbit refinement for PHAs will provide better impact probability estimates. Astrometry of comets and small objects orbiting close enough to the Sun will provide detection and modelling of non gravitational effects, in particular the Yarkovsky effect. Long term astrometry of asteroids (essentially NEOs) will enable to derive simultaneously and directly the Solar quadrupole J_2 and the parameterised-post-Newtonian PPN parameter β, in addition to a measure of $d(G\,M_\odot)/dt$, providing hence an independent local test of General Relativity.

Several satellites will be observed by Gaia (excluding the large Galilean one as mentioned in Sect. 1), yielding again high accuracy astrometry. All these topics will benefit from a combination of Gaia data with high precision ground-based data. This is the case for the dynamics of planetary satellites that depends on long-period effects, larger than just the 5 to 6 years mission duration. When combined to all astrometric data available (including classical telescopic ones, radio science, mutual phenomenon, old photographic plates, etc.) dynamical models can be improved and subsequently models for the outer major planets, through derivation from their centre-of-mass pseudo-positions as given by their satellites (Morisson et al. 1997). Combination of high accuracy space+ground-based data, as provided by current radar observations programs (Margot & Giorgini 2010) is also advantageous for deriving secular drifts on NEOs or other SSOs orbit from relativistic acceleration. Similarly, a treatment for exoplanets is performed, combining all astrometric data together, and with a dedicated orbit computation. This will enable to confirm the presence of a planetary companion and if so the derive fundamental parameters of the system. In some cases complementary ground-based radial-velocity observations and data will advantageously improve the knowledge of the exoplanetary system.

Finally Gaia will valuably contribute to the Space Situational Awareness program of ESA through the detection capabilities of PHAs and high astrometry of near-Earth objects, since such observations dramatically reduce the uncertainty and error propagation of the ephemerides and yield better impact probabilities estimates (Bancelin et al. 2013). In contrast to the science alert data for critical SSO – such as newly discovered NEO, variable star, etc., any other data is not distributed automatically on the short-term reduction pipeline, but at final Gaia catalogue publication and also at intermediate releases. There will be several such intermediate releases starting twenty-two months after launch for the basic positions and magnitude.

4. PROSPECTIVE

In addition to the scientific results the mission will harvest by observing directly thousands of SSOs with high accuracy, Gaia – through the use of its stellar catalogue – will moreover have a big impact

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on future (and past) astrometry of SSOs, changing considerably the science of the Solar System. Indeed current astrometry of asteroids is mainly limited by systematic effects. The Tycho catalogue has shown to be more advantageous in this respect than the Hipparcos catalogue, the latter having only 3 stars/deg^2, far from being enough for doing astrometric measurements. Nevertheless, even the Tycho catalogue is not dense enough in a typical field-of-view of 15'×15', and the USNO or UCAC catalogues – sometimes combined with 2MASS data – are mostly used in the community. USNO and UCAC catalogues however suffer from strong zonal errors, introducing bias in any analysis and orbit improvement. As shown by Chesley et al. 2010, these errors can be corrected to a certain amount; yet the Gaia catalogue of stars – being by essence an astrometric catalogue – will make that future astrometry precision will essentially reach the stochastic precision due to photon noise and centroiding (Desmars et al. 2013). Not only can this be applied to future CCD observations, but to past observations too – including old photographic plates – that can be re-reduced once the Gaia catalogue is available (e.g. NARRO, Arlot et al. 2013).

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