Gaia and the Astrometry of Giant Planets

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Abstract. Scope of this contribution is twofold. First, it describes the potential of the global astrometry mission Gaia for detecting and measuring planetary systems based on detailed double-blind mode simulations and on the most recent predictions of the satellite's astrometric payload performances (launch is foreseen for late Summer 2012). Then, the identified capabilities are put in context by highlighting the contribution that the Gaia exoplanet discoveries will be able to bring to the science of extrasolar planets of the next decade.

1. Gaia in a nutshell

The Gaia mission is the new global, all-sky, astrometric initiative of the European Space Agency with a launch possibility occurring in late Summer 2012. A Soyuz-Fregat launcher will take the Gaia module to a transfer orbit, which in one month will allow the satellite to reach its operational environment on a Lissajous orbit at Sun-Earth L2, 1.5 million kilometers away from Earth. During its 5 years of operational lifetime (with the possible extension of an extra year) Gaia will monitor all point sources in the visual magnitude range 6 – 20 mag, a huge database of some \( \sim 10^9 \) stars, a few million galaxies, half a million quasars, and a few hundred thousand asteroids.

As for the observing strategy, Gaia’s mode of operation has adopted the principles successfully experimented with the Hipparcos mission (ESA 1997). In particular, it will continuously scan the sky implying that all detected objects, irrespective of their magnitudes, are observed for the same amount of time during each field-of-view crossing, with mission-end observing time mainly depending on ecliptic latitude (Lindegren 2010).

In this way, it is anticipated that Gaia will determine the five basic astrometric parameters (two positional coordinates, two proper motion components, and the parallax) for all objects, with end-of-mission (sky-averaged) precision between 7-25 \( \mu \)as (microarcsec) down to the Gaia magnitude \( G^p = 15 \) mag and a few hundred \( \mu \)as at \( G = 20 \) mag, depending on color. Objects redder than \( V - I = 0.75 \) are expected to have better astrometry, while that of extreme blue targets is estimated to degrade by a factor of two.

A combination of an ambitious science case, wishing to address breakthrough problems in Milky Way astronomy, and lessons learned from the Hipparcos experience brought European astronomers to realize that modern astrometry
cannot do without spectrophotometry. That is why Gaia’s astrometry is complemented by on-board spectrophotometry and (only for objects brighter than $G = 17$) radial velocity information. These data have the precision necessary to quantify the early formation, and subsequent dynamical, chemical and star formation evolution of our Galaxy. The broad range of crucial issues in astrophysics that will be addressed by the wealth of the Gaia data is summarized by e.g., Perryman et al. (2001). One of the relevant areas on which the Gaia observations will have great impact is the astrophysics of planetary systems (e.g., Casertano et al. 2008), in particular when seen as a complement to other techniques for planet detection and characterization (e.g., Sozzetti 2009).

2. Project organization

The main partners behind the Gaia project are: i) the European Space Agency (ESA), which has the overall project responsibility for funding and procurement of the satellite, launch, and operations. Of interest is the fact that in this case satellite procurement includes the payload and its scientific instruments, unlike ESA’s other science missions for which scientific instruments are usually PI-lead and funded (or, at least, co-funded) by participating national space agencies; ii)EADS Astrium, who was selected in 2006 as the prime industrial contractor for designing and building the satellite according to the scientific and technical requirements formulated to fulfill the mission science case as approved at time of selection (ESA 2000); the Gaia Data Processing and Analysis Consortium (DPAC), charged with designing, implementing and running a complete software system for the scientific processing of the satellite data, resulting in the Gaia Catalogue a few years after the end of the operational (observation) phase.

DPAC was formed in 2006 in response to an Announcement of Opportunity issued by ESA. The Consortium currently lists nearly 400 individual members in more than 20 countries, including a team at the European Space Astronomy Center near Madrid (Spain). Six data processing centers participate in the activities of the consortium, which is organized in eight coordination units each responsible for the development of one part of the software like, e.g., simulations, core processing (global astrometry), photometry, and non-single stars, the unit devoted to the processing of astrometrically ”noisy” stars, which will include potential planetary systems. Most of the financial support is provided by ESA (for the team at ESAC) and by the various national space agencies through a legally binding long–term funding agreement, a real first for ESA run missions.

There will be no proprietary periods for the scientific exploitation of the data. The final Gaia catalogue will be produced and immediately delivered to the astronomical community worldwide as soon as ESA and DPAC will agree on the processed data having reached the targeted (science) quality. This catalogue is expected to be ready three years after the end of operations. Finally, intermediate releases, of some provisional results, are planned after a few years of observations.

More information can be found in Lindegren (2010), while other organizational details and the latest news on payload and satellite developments are available on the Gaia web pages at [http://www.rssd.esa.int/gaia/](http://www.rssd.esa.int/gaia/).
3. Gaia and extrasolar planets

3.1. What will Gaia see?

As explained above, Gaia’s mode of operation is such that there cannot be any optimization to the case of extrasolar planets. The fundamental requirement, i.e. to have sufficient astrometric accuracy at magnitudes brighter than $V = 13$, was established at time of the science case definition. Since little can be done with the photometric and spectroscopic capabilities aboard the satellite, which cannot compete with present and planned ground-based facilities for very high precision radial-velocity measurements (Pepe & Lovis 2008) and space-borne observatories devoted to ultra-high precision transit photometry (e.g., Sozzetti et al. 2010), the potential contribution of Gaia to exoplanets science must be purely gauged in terms of its astrometric capabilities.

3.2. The Gaia Double-Blind Tests Campaign

A number of authors have tackled the problem of evaluating the sensitivity of the astrometric technique required to detect extrasolar planets and reliably measure their orbital elements and masses (Sozzetti 2005, and references therein). Those works mostly relied on simplifying assumptions with regard to a the error models to be applied to the data (e.g., simple Gaussian distributions, perfect knowledge of the instruments) and b the analysis procedures to be adopted for orbit reconstruction (mostly ignoring the problem of identifying adequate configurations of starting values from scratch). The two most recent exercises on this subject (Casertano et al. 2008; Traub et al. 2009) have revisited earlier findings using a more realistic double-blind protocol. In this particular case, several teams of “solvers” handled simulated datasets of stars with and without planets and independently defined detection tests, with levels of statistical significance of their choice, and orbital fitting algorithms, using any local, global, or hybrid solution method that they judged was best. The solvers were provided no information on the actual presence of planets around a given target.

In the large-scale, double-blind test (DBT) campaign carried out to estimate the potential of Gaia for detecting and measuring planetary systems, Casertano et al. (2008) showed that a planets with $\alpha \approx 6\sigma$ (where $\sigma$ is the single-measurement error) and orbital periods shorter than the nominal 5 yr mission lifetime could be accurately modeled, and b for favorable configurations of two-planet systems with well-separated periods (both planets with $P \leq 4$ yr and $\alpha/\sigma \geq 10$, redundancy over a factor of 2 in the number of observations) it would be possible to carry out meaningful coplanarity tests, with typical uncertainties on the mutual inclination angle of $\leq 10$ deg. Both subtle differences as well as significant discrepancies were found in the orbital solutions carried out by different solvers. This constitutes further evidence that the convergence of non-linear fitting procedures and the quality of orbital solutions (particularly for multiple systems and for systems with small astrometric signals) can be significantly affected by the choice of the starting guesses for the parameters in the

\footnote{A magnitude–limited, or better, $S/N$ threshold-limited survey, uneven coverage, including time sampling and scanning geometry, depending on ecliptic latitude.}
Figure 1. Gaia discovery space for planets of given mass and orbital radius compared to the present-day sensitivity of other indirect detection methods, namely Doppler spectroscopy and transit photometry. Red curves of different styles (for completeness in planet detection and orbit measurement to given accuracy) assume a 1-$M_\odot$ G dwarf primary at 200 pc, while the blue curves are for a 0.5-$M_\odot$ M dwarf at 25 pc. The radial velocity curve (pink line) is for detection at the 3 $\times$ $\sigma_{RV}$ level, assuming $\sigma_{RV} = 3$ m s$^{-1}$, $M_\star = 1M_\odot$, and 10-yr survey duration. For transit photometry (green curve), $\sigma_V = 5$ milli-mag, $S/N = 9$, $M_\star = 1 M_\odot$, $R_\star = 1 R_\odot$, uniform and dense (> 1000 datapoints) sampling. Black dots indicate the inventory of exoplanets as of October 2007. Transiting systems are shown as light-blue filled pentagons. Jupiter and Saturn are also shown as red pentagons. Credits: Casertano et al. 2008
orbital fits, by the adoption of different statistical indicators of the quality of a solution, and by varied levels of significance of the latter.

Overall, the authors concluded that Gaia could discover and measure massive giant planets ($M_p \geq 2–3 M_J$) with $1 < a < 4$ AU orbiting solar-type stars as far as the nearest star-forming regions, as well as explore the domain of Saturn-mass planets with similar orbital semi-major axes around late-type stars within 30–40 pc (see Figure 1). These results can be used to infer the number of planets of given mass and orbital separation that can be detected and measured by Gaia, using Galaxy models and the current knowledge of exoplanet frequencies. By inspection of the tables in Figure 2, one then finds that Gaia’s main strength will be its ability to accurately measure orbits and masses for thousands of giant planets, and to perform coplanarity measurements for a few hundred multiple systems with favorable configurations.

4. The Gaia Legacy

Gaia’s main contribution to exoplanet science will be its unbiased census of planetary systems orbiting hundreds of thousands nearby ($d < 200$ pc), relatively bright ($V \leq 13$) stars across all spectral types, screened with constant astrometric sensitivity. The Gaia data have the potential to:

a) significantly refine our understanding of the statistical properties of extrasolar planets: the predicted database of several thousand extrasolar planets with well-measured properties will allow for example to test the fine structure of giant planet parameters distributions and frequencies, and to investigate their possible changes as a function of stellar mass, metallicity, and age with unprecedented resolution;

b) help crucially test theoretical models of gas giant planet formation and migration: for example, specific predictions on formation time-scales and the role of varying metal content in the protoplanetary disk will be probed.
with unprecedented statistics thanks to the thousands of metal-poor stars and hundreds of young stars screened for giant planets out to a few AUs; c) achieve key improvements in our comprehension of important aspects of the formation and dynamical evolution of multiple-planet systems: for example, the measurement of orbital parameters for hundreds of multiple-planet systems, including meaningful coplanarity tests will allow to discriminate between various proposed mechanisms for dynamical interaction; d) aid in the understanding of direct detections of giant extrasolar planets: for example, actual mass estimates and full orbital geometry determination for suitable systems will inform direct imaging surveys about the epoch and location of maximum brightness, in order to estimate optimal visibility, and will help in the modeling and interpretation of giant planets’ phase functions and light curves; e) provide important supplementary data for the optimization of the target selection for future observatories aiming at the direct detection and spectral characterization of habitable terrestrial planets: for example, all F-G-K-M stars within the useful volume (\(\sim 25\) pc) will be screened for Jupiter- and Saturn-sized planets out to several AUs, and these data will help probing the long-term dynamical stability of their Habitable Zones, where terrestrial planets may have formed, and maybe found.

5. Conclusions

The largest compilation of astrometric orbits of giant planets (in many cases signposts of more interesting systems!), unbiased across all spectral types up to \(d \simeq 200\) pc, will allow Gaia to crucially contribute to several aspects of planetary systems astrophysics (formation theories, dynamical evolution), in combination with present-day and future extrasolar planet search programs.

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References
Bienaymé, O., Robin, A. C., & Crézé, M. 1987, A&A, 180, 94
Lindgren, L. 2010, Proc. IAU Symp. 261, 296
Casertano, S., Lattanzi, M. G., Sozzetti, A., et al. 2008, A&A, 482, 699
ESA 1997, \textit{The Hypparcos and Tycho Catalogues}, ESA SP-1200
ESA 2000, \textit{Gaia: Composition, Formation, and Evolution of the Galaxy}, ESA-SCI(2000)4
Pepe, F., & Lovis, C. 2008, Physica Scripta, 130, 014007
Perryman, M. A. C., et al. 2001, A&A, 369, 339
Sozzetti, A. 2005, PASP, 117, 1021
Sozzetti, A. 2009, EAS Publication Series, in press \cite{arXiv:0902.2063}
Sozzetti, A., et al. 2010, to appear in ASP Conf. Ser. \cite{arXiv:0912.0887}
Tabachnik, S., & Tremaine, S. 2002, MNRAS, 335, 151
Traub, W. A., et al. 2009, EAS Publication Series, in press \cite{arXiv:0904.0822}