Astrometry and Exoplanet Characterization: Gaia and Its Pandora's Box

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Introduction

In its all-sky survey, Gaia will monitor astrometrically hundreds of thousands of main-sequence stars within ≈ 200 pc, looking for the presence of giant planetary companions within a few AUs from their host stars. Indeed, Gaia observations will have great impact in the astrophysics of planetary systems (e.g., [1]), in particular when seen as a complement to other techniques for planet detection and characterization (e.g., [2]). In this paper, I briefly address some of the relevant technical issues associated with the precise and accurate determination of astrometric orbits of planetary systems using Gaia data. I then highlight some of the important synergies between Gaia high-precision astrometry and other ongoing and planned, indirect and direct planet-finding and characterization programs, both from the ground and in space, and over a broad range of wavelengths, providing preliminary results related to one specific example of such synergies.

1. Exoplanet Orbits with Gaia Astrometry: The Challenge

We are about to enter the age of micro-arcsecond (μas) astrometry with Gaia. In the matter of astrometric detection of planetary-mass companions around nearby stars, the improvement of over two orders of magnitude in single-measurement precision with respect to present-day Hipparcos astrometry is absolutely mandatory to finally put an end to the long list of 'blunders' that this technique has delivered (for a review, see [3]). However, the improved accuracy of the Gaia measurements will not resolve by itself the technical problems associated with the modeling of the astrometric signatures of planetary systems, which will have to be carefully dealt with.

1.1 *Orbital Fits of Planetary Systems*

The problem of the correct determination of the astrometric orbits of planetary systems using Gaia data (highly non-linear orbital fitting procedures, with a large number of model parameters) will present many difficulties. For example, it will be necessary to assess the relative robustness and reliability of different procedures for orbital fits. Consistency checks between different solution algorithms will be mandatory as a way of learning the lessons of radial-velocity surveys, that are showing us, particularly in the case of multiple-planet systems, how disagreement on orbital solution details, and sometime number of planets!, based on the same datasets is not that uncommon (e.g., [4] [5]). A detailed understanding of the statistical properties of the uncertainties associated with the model parameters will have to be developed, based on the relative merit of different metrics tailored to this task, such as covariance matrices, χ^2 surface mapping, and bootstrapping procedures. For multiple systems, a trade-off will have to be found between accuracy in the determination of the mutual inclination angles between pairs of planetary orbits, single-measurement precision and redundancy in the number of observations with respect to the number of estimated model parameters. It will constitute a challenge to correctly identify signals (and the associatederrors on model parameters) with amplitude close to the measurement uncertainties, particularly in the presence of larger signals induced by other companions and/or sources of astrophysical noise of comparable magnitude. Finally, in cases of multiple-component systems where dynamical interactions

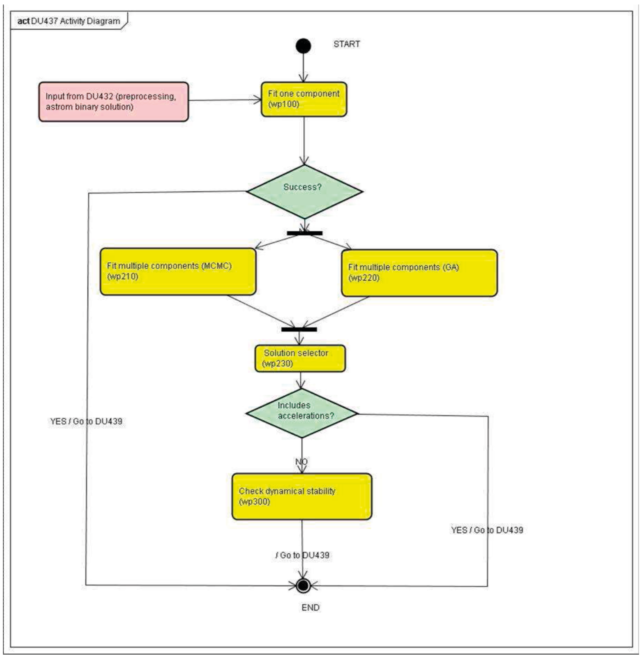

Figure 1: DU 437 Activity Diagram.

are important (a situation experienced already by radial-velocity surveys), fully dynamical (Newtonian) fits involving an N-body code might have to be used to properly model the Gaia astrometric data and to ensure the short- and long-term stability of the solution [6].

1.2 *Exoplanets Treatment in the Gaia Data Processing Pipeline*

All the above issues could have a significant impact on Gaia's capability to detect and characterize planetary systems. For these reasons, within the pipeline of Coordination Unit 4 (object processing) of the Gaia Data Processing and Analysis Consortium (DPAC), in charge of the scientific processing of the Gaia data and production of the final Gaia catalogue to be released sometime in 2021, a Development Unit (DU437) has been specifically devoted to the modelling of the astrometric signals produced by planetary systems. The DU is composed of several tasks, which implement multiple robust procedures for (single and multiple) astrometric orbit fitting (such as Markov Chain Monte Carlo and genetic algorithms) and the determination of the degree of dynamical stability of multiple-component systems. I provide here a quick-look view of the software and its status.

1.3 *Fitting Algorithms: Highlights*

Figure 1 shows the activity diagram of DU437. The main feature of this software module consists of the use of two different solution algorithms for fitting astrometric orbits of planetary systems to Gaia data.
The first algorithm is based on a hybrid Markov Chain Monte Carlo (MCMC) approach. The global non-linear least-square problem is partially linearized in the parameters a_j, ω_j, Ω_j, and i_j (for $j = 1, \ldots, n$, where n is the number of planets) using the Thiele-Innes elements representation [7]. An iterative period search provides seeds for initializing the MCMC procedure (a parallel-tempering algorithm upgrade is in the works). An MCMC chain is then run on the non linear parameters (e_j, P_j, τ_j), drawing from Gaussian independent distributions. Each step of the chain drives a linear LSQ solver (SVD). Multiple MCMC chains are run (one is used for inference), and convergence is checked via the Gelman-Rubin test. Finally, the set of parameters with the highest likelihood is the seed for a local non-linear minimization in the least-squares sense using the Levenberg-Marquardt algorithm.

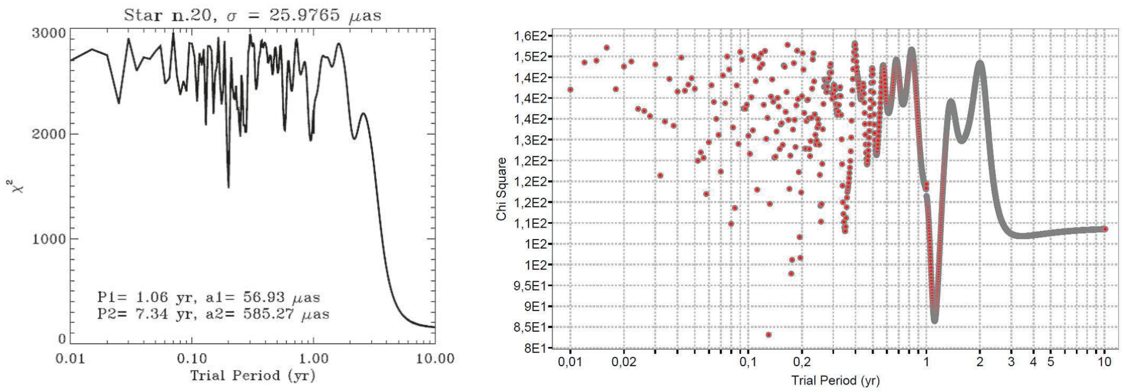

Figure 2: Left: First-pass periodogram for a star with a long-period planet. Right: The periodogram after the removal of the signature of the outer planet.

The second orbital solution module implements an approach based on a genetic algorithm (GA). The first step consists of the generation of a population of $7*n$ chromosomes. The fitness of each chromosome in the population is evaluated, and the selection of ‘parent’ chromosome pairs is made from the population according to their fitness. The next step includes the iterative modeling using a set of operators such as mutation, cross-over, Levemberg-Marquardt, and period scan. Finally, acceptance of new offsprings in the population is realized, and further iterations of the algorithm using the new population are carried out.

The last important element of the DU437 software module is constituted by its orbital stability analysis component. At present, a simple Hill stability criterion is applied [8]. For a two-planet configuration, the system will be considered Hill-stable if the following inequality is satisfied:

$$-\frac{2M}{G^2M_\star^3}L^2h > 1 + 3^{4/3}\frac{m_1m_2}{m_3^{2/3}(m_1+m_2)^{4/3})}, \tag{1}$$

where M is the total mass of the system, m_1 and m_2 are the planet masses (the subscript 1 refers to the inner planet), m_3 is the mass of the star, G is the gravitational constant, $M_\star = (m_1m_2 + m_1m_3 + m_2m_3)$, L is the total angular momentum of the system, and h is the energy. This is sufficient to double-check dynamically pathologic (while potentially correct in a χ^2 sense!) solution sets (e.g., orbit-crossing due to $e \sim 1.0$) obtained by the MCMC and GA algorithms. Limited use of an N-body integrator (e.g., Bulirsch-Stoer) is being tested at the time of writing.

1.4 *A Readiness Test*

I show in Fig. 2 and Fig. 3 some results from the application of the MCMC algorithm on a simulated Gaia data for a stellar sample of 100 nearby ($d < 100$ pc) solar-mass stars with Gaia magnitude $G < 10$ mag and orbited by two planets with periods up to twice the nominal 5-yr mission duration. Given the present-day Gaia astrometric error model, inclusive of the effects of a gate scheme to avoid saturation at the bright end ($G < 13$ mag), in this sample $\approx 1/3$ of the systems were not detectable in Gaia astrometry, $\approx 1/3$ had one detectable planet, and $\approx 1/3$ had two detectable companions. For example, in a two-planet system with a long-period planet identified in the initial periodogram (Fig. 2, left panel), the correct removal of the outer planet’s orbit unveils in the periodogram the clear signal of the second, inner planet (Fig. 2, right panel). Similarly, in the case of a system with two planets inducing low-S/N signatures of comparable magnitude, the periodicity analysis correctly identifies the periods of both components already in the first pass (Fig. 3, left panel). The resulting quality of the fitted periods (shown in Fig. 3, right panel) in detectable two-planet systems is in good agreement with earlier results [1].

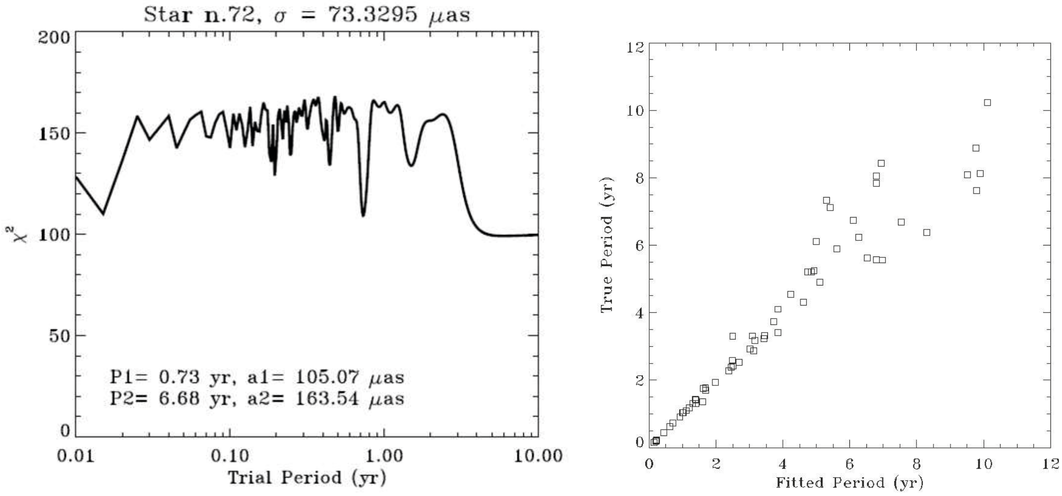

Figure 3: Left: First-pass periodogram for a star with two low-S/N planets. Right: Fitted vs. true values of the orbital period for detectable two-planet systems.

2. The Gaia - Exoplanets Synergy Potential

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 ($G < 13$) stars across all spectral types, screened with constant astrometric sensitivity. As a result, the actual impact of Gaia measurements in exoplanets science is broad, and rather structured. The Gaia data have the potential to: a) significantly refine our understanding of the statistical properties of extrasolar planets; b) help crucially test theoretical models of gas giant planet formation and migration; c) achieve key improvements in our comprehension of important aspects of the formation and dynamical evolution of multiple-planet systems; d) aid in the understanding of direct detections of giant extrasolar planets; 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 a review, see [3].

The broad range of applications to exoplanets science is such that Gaia data can be seen as an ideal complement to (and in synergy with) many ongoing and future observing programs devoted to the indirect and direct detection and characterization of planetary systems, both from the ground and in space, and across a broad range of wavelengths. Gaia will contribute critically, for example, to the definition of input catalogues for proposed quasi-all-sky photometric transit surveys (PLATO, TESS); it will inform ground-based direct imaging programs (e.g., SPHERE/VLT, EPICS/E-ELT) and spectroscopic characterization projects (e.g., EChO, FINESSE) about the epoch and location of maximum brightness of (primarily non transiting) exoplanets, in order to estimate their optimal visibility, and will help in the modeling and interpretation of giant planets' phase functions and light curves. Another critical aspect will concern the large effort in terms of ground-based follow-up activities to improve the characterization of astrometrically detected systems (and possibly those found transiting by Gaia photometry). For example, high-precision radial-velocity campaigns (both at visible and infrared wavelengths) will be a necessary complement, with the three-folded aim of improving the phase sampling of the astrometric orbits found by Gaia, extending the time baseline of the observations (to put stringent constraints on, or actually characterize, long-period companions), and search for additional, low-mass and/or short-period components which might have been missed by Gaia due to lack of sensitivity.

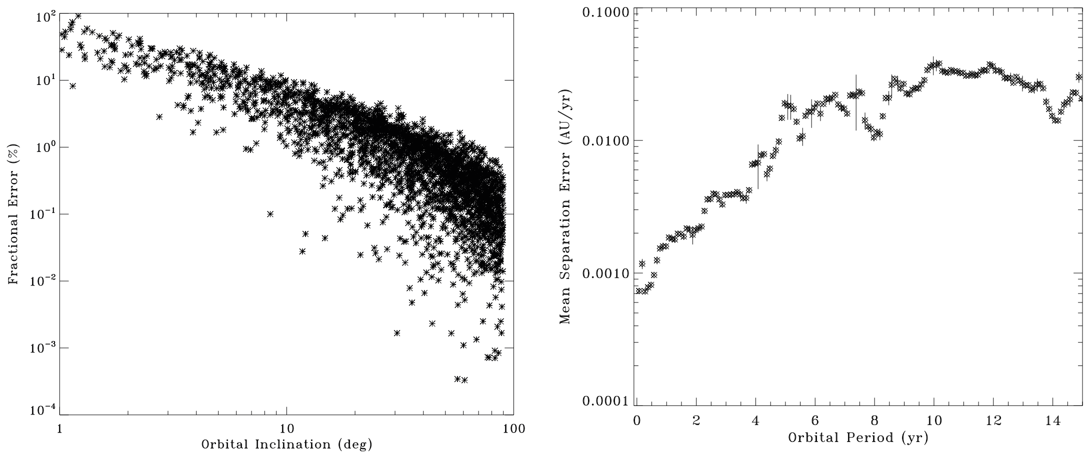

Figure 4: Left: Fractional error on the inclination angle i as a function of i itself. Right: Degradation rate in the prediction for the value of orbital separation of the planet as a function of its orbital period.

2.1 *A Synergetic Example: The Gaia survey of Nearby M Dwarfs*

Cool, nearby M dwarfs within a few tens of parsecs from the Sun are becoming the focus of dedicated experiments in the realm of exoplanets astrophysics. This is due to the shift in theoretical paradigms in light of new observations, and to the improved understanding of the observational opportunities for planet detection and characterization provided by this sample. Gaia, in its all-sky survey, will deliver precision astrometry for a magnitude-limited ($G = 20$) sample of M dwarfs, providing an inventory of cool nearby stars with a much higher degree of completeness (particularly for late sub-types) with respect to currently available catalogs.
I present here preliminary findings of a simulation experiment aimed at gauging the Gaia potential for precision astrometry of exoplanets orbiting a sample of known, nearby dM stars [9]. Gaia sensitivity thresholds are expressed as a function of system parameters and in view of the latest mission profile, including the most up-to-date astrometric error model. The simulations also provide insight on the capability of high-precision astrometry to reconstruct the underlying orbital elements and mass distributions of the generated companions. These results will help in evaluating the complete expected Gaia planet population around late-type stars.
The synergy between the Gaia data on nearby M dwarfs and other ground-based and space-borne programs for planet detection and characterization is also investigated, with a particular focus on: a) the potential for Gaia to precisely determine the orbital inclination, which might indicate the existence of transiting long-period planets; b) the ability of Gaia to carefully predict the ephemerides of (transiting and non-transiting) planets around M stars; and c) its potential to help in the precise determination of the emergent flux, for systematic spectroscopic characterization of their atmospheres with dedicated observatories in space, such as EChO.

Simulation Scheme The basis is constituted by the Casertano et al. [1] simulation setup. This has been updated by including the last Gaia scanning law, for a nominal $T = 5$ yr mission duration. The most up-to-date error model as a function of Gaia G-band mag has been utilized, with the exclusion of the presently envisioned gate scheme (affecting only some 20% of bright ($G < 12$) M dwarfs). Single-measurement errors are typically $\sigma_m \sim 100$ μas. The actual list of targets encompasses 3150 M dwarfs ($0.09 - 0.6\ M_{\odot}$) within 33 pc from the Sun from the LSPM-North Catalog [9], with average $G \sim 14.0$ mag. One planet was generated around each star, with mass $M_p = 1M_J$, orbital period $P < 3T$, and moderate eccentricities ($e < 0.6$). All other orbital elements were uniformly distributed within their respective ranges.

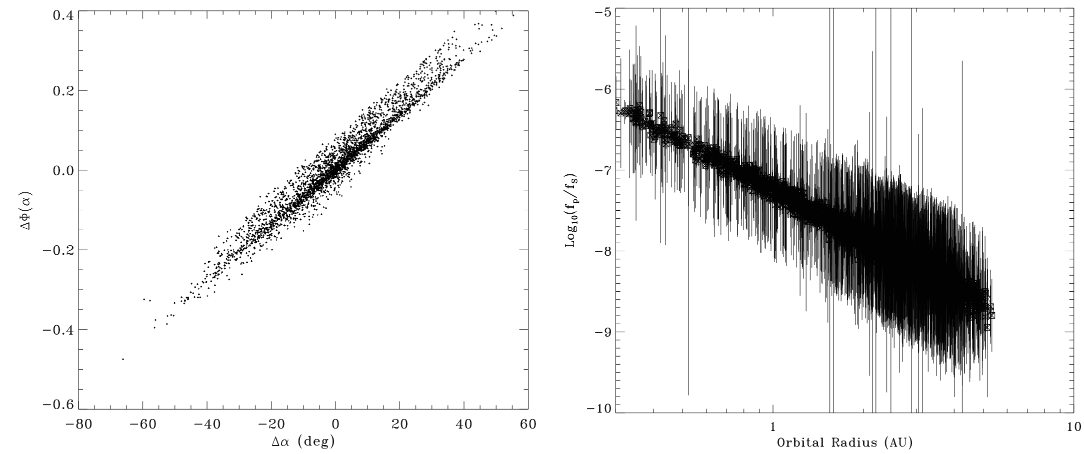

Figure 5: Left: Error on the planetary phase function (assuming a Lambert sphere) as a function of uncertainty on the reconstructed planetary phase. Right: Predicted planetary emergent flux (and uncertainty) as a function of orbital separation from the M dwarf primary.

Preliminary Results The main findings in this experiment can be summarized as follows:
1) For detected giant planets with periods in the range $0.2-5$ yr (i.e., with accurately determined masses and orbits), inclination angles will be determined with enough precision (<1%, see Fig. 4, left panel) so that it will be possible to identify long-period planets which are likely to transit;
2) for well-sampled orbits ($P < T$), the uncertainties on planetary ephemerides, separation ρ and position angle ϑ, will degrade at typical rates of $\Delta\rho < 0.01$ AU/yr (see Fig. 4, right panel) and $\Delta\vartheta < 1$ deg/yr, respectively. These are over an order of magnitude smaller than the degradation levels attained by present-day ephemerides predictions based on milli-arcsec precision HST/FGS astrometry [10];
3) Planetary phases will be measured with typical uncertainties $\Delta\alpha$ of a few degrees, resulting (assuming a simple purely scattering atmosphere) in average errors on the phase function $\Delta\Phi(\alpha) \approx 0.1$ (Fig. 5, left panel), and expected uncertainties in the determination of the emergent flux of wide-separation ($a > 0.3$ AU) giant planets of $\sim 15\%$ (Fig. 5, right panel).
All the above conclusions help to quantify the actual relevance of the Gaia observations of the large sample of nearby M dwarfs for in a synergetic effort to optimize the planning and interpretation of follow-up/characterization measurements of the discovered systems by means of transit survey programs, and upcoming and planned ground-based as well as space-borne observatories for direct imaging (e.g., SPHERE, EPICS) and simultaneous multi-wavelength spectroscopy (e.g., EChO).

Conclusion

The largest compilation of high-accuracy astrometric orbits of giant planets, unbiased across all spectral types up to $d < 200$ 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.
In this paper, I have first discussed some of the relevant issue related to the robust assessment of astrometric orbits of planetary systems detected by Gaia, with a focus on readiness tests of the DU437 software module in charge of providing (single and multiple) orbital solutions for exoplanets within the context of the Gaia data processing pipeline. Then, I have presented preliminary results on an investigation of the synergy between Gaia astrometry on nearby M dwarfs and other ground-based and space-borne programs for exoplanet characterization, focusing on: a) the potential for Gaia to precisely determine the orbital inclination, which might indicate the existence of transiting long-period planets; b) the ability of Gaia to carefully predict the ephemerides of (transiting and non-transiting) planets around M stars; and

c) its potential to help in the precise determination of the emergent flux, for systematic spectroscopic characterization of their atmospheres with dedicated observatories in space.

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