SF2A 2009
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DETERMINATION OF PLANETARY SYSTEMS WITH GAIA

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Abstract. The astrometric performance of Gaia will allow to discover thousands of extrasolar planets. This work especially focuses on the detection of multiple-planet systems subject to strong gravitational interactions, for which the assumption of independent Keplerian orbits breaks down. We present the first results obtained by using a Bayesian approach to fit the numerous parameters of the systems.

1 Introduction

The astrometric performance of Gaia (few μas) will allow to discover thousands of extrasolar planets (Sozzetti et al. 2007; Casertano etal 2008). Therefore, in these papers it is shown that Gaia might detect massive planets (Mp 2-3 MJupiter) at an orbital distance from 1 to 4 AU.

In this large sampling of extrasolar planets, Gaia will detect systems with multiple companions and some of them will present complex dynamics through strong gravitational interactions and/or resonant orbits. For these systems independent Keplerian orbits break down. This work focuses on the detection of multiple-planet systems subject to strong gravitational interactions. We present the first results obtained by using a Bayesian approach in order to fit the numerous parameters of the planetary systems.

2 Model and Bayesian approach

We study perturbations induced by planetary companions on the barycentric motion of the star in the astrometric data. Therefore the astrometric signature for one planet is

$$\alpha = \frac{a_p}{d}\frac{M_{pl}}{M_\star} \tag{2.1}$$

where, M_p, $M_\star$ are masses of the planet and star, a_p semi-major axis of the orbit and d distance Earth-Extrasolar system.

The number of parameters to fit in this problem is 7 times the number of planets, where the 7 variables are the semi-major axis (or log(Period)), eccentricity, inclination, ascending node, argument of periastron, mean anomaly, and planetary mass.

Ford (2005), Ford etal (2005), and Gregory (2007) applied successfully the Bayesian approach to radial velocity measurements. Following these works we develop a Bayesian model to fit multi-planetary systems to Gaia astrometic data. Indeed, the Bayesian method is well designed to explore efficiently the parameter space and to avoid local minima inherent to Levenberg-Marquardt method or high number of iteration as in Genetic Algorithms (see discussion in Ford 2005). We use a Markov Chain Monte Carlo (MCMC) technique in order to compute the probability functions that is well suited for high-dimensional parameter spaces. The orbital problem is solved by numerical integration of the N-body problem in order to take into account the mutual interactions. Figure 1(a) is a simulation that illustrates the behavior of one (very short) Markov Chain and Figure 1(b) shows the corresponding probability distribution for the eccentricity. In this optimistic case the MCMC method converges towards the expected orbital values.

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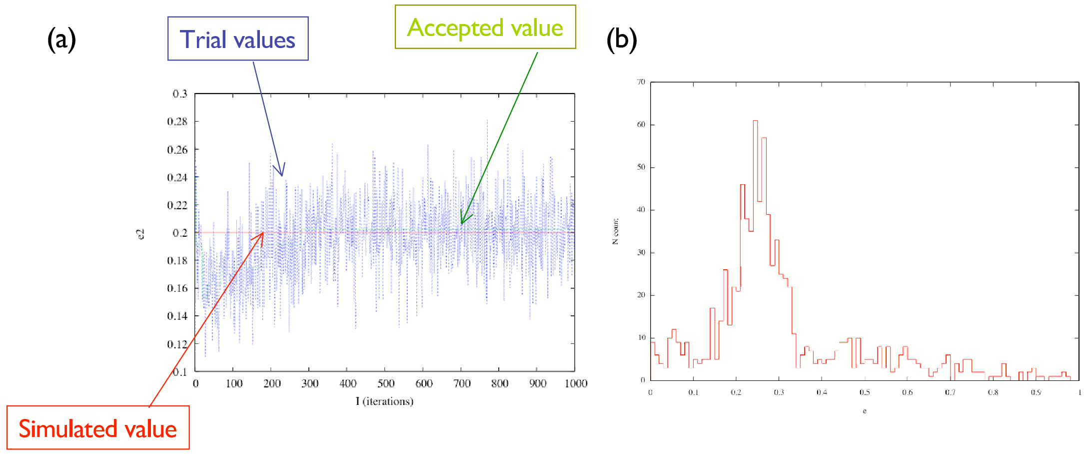

Fig. 1. (a) Example of Markov Chain (in practice the chain is around 10^5 iterations). (b) Probability distribution for the eccentricity.

We carry on to improve the model and to test the convergence process for various scenarios of orbital configuration. The first main difficulty in the Gaia framework is to develop an automatic scheme. Indeed, the efficiency of the Markov Chain depends on the correct ratio of rejected/accepted trial in order to sample well the parameter space (and to find the global minimum) in a relatively short computer-time. The second point is to introduce the Gelman-Rubin criteria in order to decide the convergence of the chain. The main challenge for the Gaia module is to obtain an automatic and efficient algorithm for measurements and at the same time an algorithm robust enough to avoid false detections.

3 Stability Criteria

In order to obtain realistic orbital parameters, we check the fit with stability criteria. One possibility is to use analytical (i.e. fast) stability criteria such as the Hill criterion (Marchall and Bozis 1982; Barnes and Greenberg 2007):

$$-\frac{2M}{G^2 M_*^3} c^2 h > 1 + 3^{4/3} \frac{m_1 m_2}{m_3^{2/3}(m_1+m_2)^{4/3}} - \frac{m_1 m_2 (11 m_1 + 7 m_2)}{3 m_3 (m_1+m_2)^2} \tag{3.1}$$

where M is the total mass of the system, m_1 is the mass of the more massive planet, m_2 is the mass of the less massive planet, m_3 is the mass of the star, G is the gravitational constant, $M_* = m_1 m_2 + m_1 m_3 + m_1 m_2$, c is the total angular momentum of the system, and h is the energy.

Nevertheless, this criteria is not efficient for resonant orbits or more than 3-body problem. Other criteria are studied as for example the chaotic diffusion of orbits.

This work inscribes in the module CU4-DU437 of Gaia. Its objective is dedicated to the search of the stability of the extrasolar planets and to characterize the existence of planetary companions (N2) with strong mutual interactions.

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