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Detection of transits of extrasolar planets with GAIA

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Abstract

Extensive simulations of planetary transits in the epoch photometry of the future space astrometry mission has been performed. Thousands to tens of thousands of transiting planets should be detected with GAIA.

1 INTRODUCTION

At present, about 60 extrasolar planetary systems have been detected (see [1] for an updated list). Basing on the size of the star sample surveyed for searching extrasolar planets, Marcy et al. [2, 3] estimate that about 4% of solar type stars have a planetary system. With GAIA, this proportion represents millions of stars. The question is then: will GAIA be able to detect them? The present paper studies the capability of GAIA to detect those who will transit their parent stars.

The depth of transits made by a planet passing in front of its star is given by the square of the ratio of the planet diameter by the star diameter. For a solar diameter, it is 10^{-4} for an Earth-like planet, 0.01 for a Jupiter-like planet. The individual accuracy of a GAIA epoch photometry observation as a function of apparent magnitude is given in figure 1. It has been computed by Carme Jordi (private communication) on the basis of the last satellite and CCD configuration. To be conservative, 1 millimagnitude has quadratically been added to this accuracy to take account of any eventual systematic errors. The adopted individual epoch accuracy per field is about 1 millimagnitude for the brightest stars and increases to a few hundredths for the faintest stars. Planets much smaller than Jupiter will then be out of reach of GAIA (at least as far as transit detection is concerned).

If R_*, π, M_* and P are respectively the radius, the parallax, the mass of a star and the period of the planet orbiting this star, the duration of the transits is given by:

$$\frac{R_* P^{1/3}}{\pi M_*^{1/3}} \qquad (1.1)$$

for a circular orbit and neglecting the radius of the planet over the radius of the star. It is 0.15% of the period for the Earth, 0.013% for Jupiter and 3.2% for the planet orbiting around HD 209458 which has a period of about 3.5 days.

The number of GAIA individual epoch photometry observations will be between 100 and 300 for most of the stars. This means that planets with periods shorter than a few days only will have a chance to exhibit several transits in the GAIA epoch photometry.

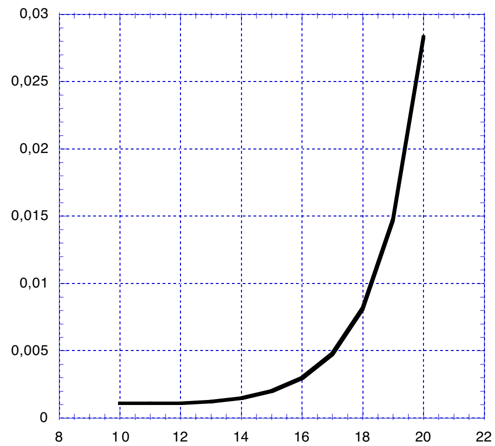

Fig. 1. Epoch photometric accuracy of the GAIA G band as a function of the apparent G magnitude.

Among the 60 known stars with a planetary system, a quarter are orbited by "hot Jupiters" having a period shorter than 15 days. For these stars, the probability that the inclination of the planet orbit makes it transiting is of few percents while it is only 0.5% for the Earth around the Sun and less than 0.05% for Jupiter. On the other hand, the minimum observed period known for extrasolar systems is around 3 days which probably corresponds to a real limit under which the planet just cannot exist for stability or temperature reasons.

2 SIMULATION

In order to have a quantitative idea of the number of stars with transiting planets, an extensive Monte-Carlo simulation has been done. This simulation uses the Galaxy model of Haywood (private communication) which is derived from the Besançon model of population synthesis (see for example [4]): in a given field, this model can simulates star counts with observable properties such as magnitudes in any band, proper motions, radial velocities... following any observational constraints (censorships in magnitude...). Star counts in the model have been normalized such as they reproduce quite well several star catalogues such as Hipparcos, Tycho, 2MASS...

Interpolating counts in several fields of one square degree all over the sky, the model gives the density $d(\beta, G, M_V)$ of stars in slides of the galactic latitudes β, apparent GAIA magnitudes G and absolute magnitudes M_V. Unfortunately, only stars fainter than $M_G = 3.5$ have been considered in the Galaxy model simulations in order to be able to limit the distance and to make simulations faster on computers. With the accuracy of GAIA, planets should be detected around stars at least 3 or 4 magnitudes brighter (up to 2 or 3 solar radius). New simulations need then to be done which will increase the number of detected planets.

The scanning law of the satellite is very similar to the Hipparcos one. In the present configuration of the mission with a 4 full years of observation, the number of observations roughly varies from 100 to 300 as a function of ecliptic latitude β with a maximum around $35°$ and a mean of 130. According to equation 1.1 the proportion of time spent in transits depends mainly on the period of the planet (and secondly on the size of the star...). The combination of the scanning law of GAIA with the light curve of a planet gives the probability distribution of the number of points observed during transits for any given star at a latitude β orbited by a planet of period P. Figure 2 left shows the folded light curve of HD 209458 as it would be observed by GAIA for two different values of the origin of GAIA observations. One can see that the number of points during transits can be zero in a (very) unfavourable case. Two examples of the distribution of the number of points observed during transits are plotted in figure 2 right: in a favourable configuration such as a 3 day period planet orbiting around a star at $\beta = 35°$, the probability of having more than 10 observed points during transits is larger than 15 % while the probability of having more than 7 observations during transits is only 3 % for a 10 day planet around a star at $\beta = 5°$.

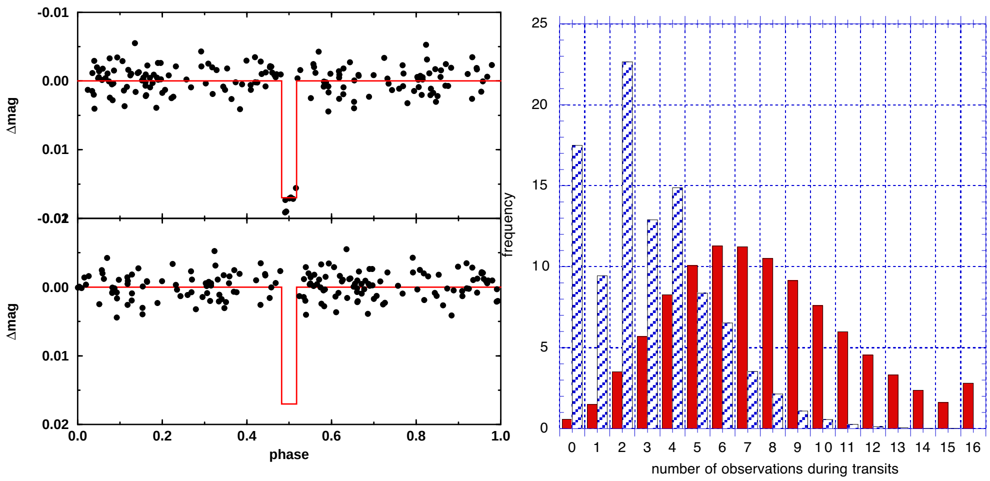

Fig. 2. Left: GAIA simulation of the folded light curve of HD 209458 for two different values of the time origin of GAIA. Top: 6 observations occur during transits. Bottom, no points are observed. Right: probability distribution of the number of observations during transits for a planet with a 3 day period orbiting a star at $\beta = 35°$ (filled histogram) and a planet with a 10 day period around a star at $\beta = 5°$ (hatched histogram).

The probability of observing a transited star with a planet of period P and radius R_P is the product of the geometric probability of observing it by the probability of having a planet of period P. As shown in figure 3, the probability distribution of known extrasolar planets is compatible with a law proportional to $1/P$ (for $P > 3$ days) and about a quarter of them have periods smaller than 20 days. The probability density of solar type stars with hot Jupiters has then been chosen to be proportional to $1/P$ and normalized to represent 1% of all stars (a quarter of 4%).

The probability of a given number of false detections follows a binomial law and depends on the number of observations and on the ratio of the depth of the transits by the photometric accuracy of a single observation. Therefore, it depends on the radii of the star and the planet and on the apparent magnitude of the star (which drives the photometric accuracy). For example, the probability of having randomly 5 observations out of 200 deviating by more than 3 sigmas is smaller than 5.10^{-7} but is about 0.002 for 2.5 sigmas.

Knowing the probability distributions described above, the number of detected planets has been simulated in bins of ecliptic latitude (10° bins), apparent and absolute magnitudes (1 mag bins) and period (0.5 day bins). In each bin, the number of false detections has also been

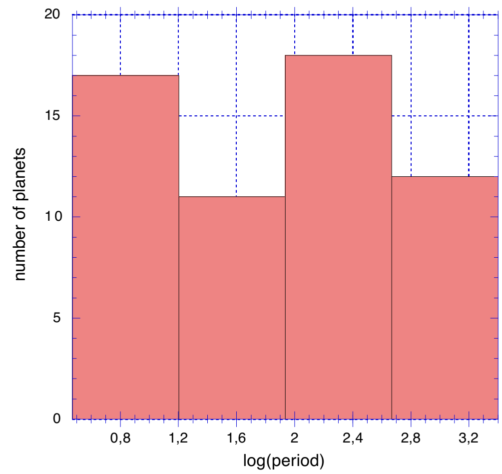

Fig. 3. Distribution of the periods of the 60 known extrasolar planets

computed and the detected planets have been counted only when the ratio of false detections over detected planets is smaller than 10%.

3 RESULTS

Simulations have been performed under several hypotheses concerning the mission duration, the size of the planet and the number of observations during transits needed to recover the period.

The mission, as it is defined now, includes 4 full years of observation. An increase of 1 year is not unrealistic at this stage of the mission definition if strong arguments can be exhibited in favour of it. Anyway, if the satellite is still alive after 4 years of observation, an extension would seem reasonable.

Two different planet radii have been used: 1.0 and 1.3 Jupiter radius (the radius of the planet orbiting HD 209458). This range of radii should cover most of "hot Jupiter" [5, 6].

Recovering the value of the planet period from GAIA photometric observations would deserve a separate study. Obviously, at least three different transits must be observed which correspond to at least 5 GAIA observations during transits since, most of the time, GAIA observations are coupled: the preceding and following fields are separated by less than an hour. In the following, a planet is considered as detected if it is observed more than 5 times during transits. To be conservative, a more stringent limit of 7 observations during transits has also been considered. In fact, observing only one transit of a planet is theoretically enough to detect it and this would dramatically increase the number of detections. But no information would be available on the period and the photometric following of the stars would be much too time consuming since stars should be observed continuously to detect new transits. On the contrary, observing 3 or 4 different transits would reduce considerably the possible numbers of the period values and would then allow to predict the times for reobserving transits with a pointing instrument (on ground or in space). In this context, a detected planet is defined as a planet for which the period can be known to some extent.

The following table gives the predicted number of extrasolar planets detected by transits under these different hypotheses. This number varies from 4000 to 40000 planets, with less than 10 % of false detections.

duration of the mission	4 years	5 years	5/4
$R_P = 1.0 R_{\rm Jup}$ Npts/transit > 5	9400	13700	+46%
$R_P = 1.3 R_{\rm Jup}$ Npts/transit > 5	25500	36300	+42%
$R_P = 1.0 R_{\rm Jup}$ Npts/transit > 7	3700	6900	+85%
$R_P = 1.3 R_{\rm Jup}$ Npts/transit > 7	10100	17800	+76%

Table 1. Predicted number of detected planets under several hypotheses on the planet radius, the required number of observations during transits and on the mission duration.

Extending the planet radius from 1 to 1.3 Jupiter radius triples the number of detections. Most of "hot Jupiters" probably having a radius in this range [5,6], the real number of detections should be in between the numbers obtained using 1 and 1.3 Jupiter radius.

Choosing 7 observations during transits (equivalent to observing at least 4 different transits) instead of only 5 (3 different transits observed) reduces the number of detections by a factor of 3. This question of the detection algorithm needs then to be studied further.

Extending the mission by one year would increase the number of detection by 40 to 85%.

Figure 4 shows the detailed numbers of detected planets as a function of its period and of the absolute magnitude of its parent star.

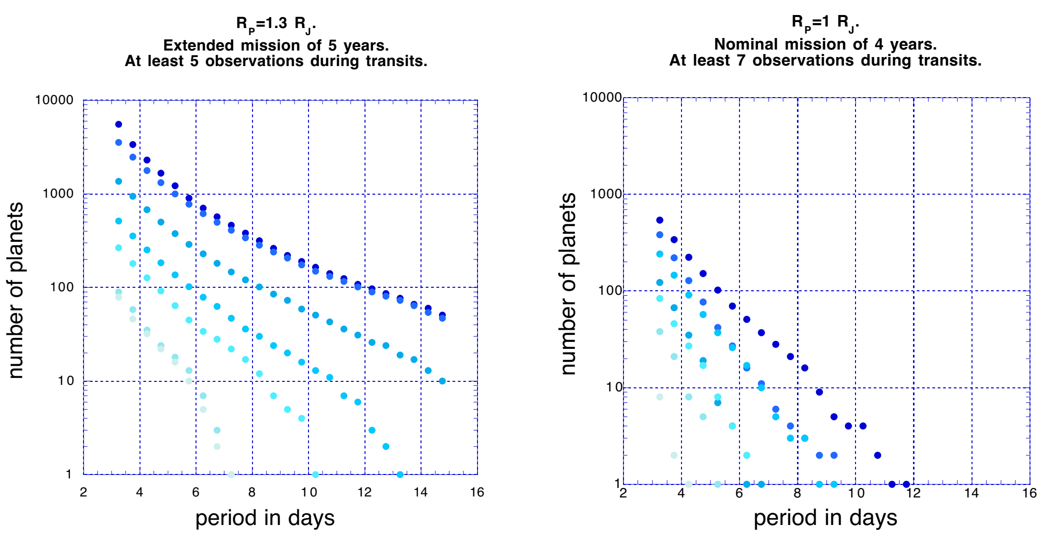

Fig. 4. Number of detected planets in period bins of 0.5 day and for different values of the absolute magnitude of the parent star: from top to bottom $M_G = 4$ to $M_G >= 11$.

The vast majority of the detected planet will have a very short period of 3 to 5 days. This is the combination of the chosen period distribution with the geometric probability of having a transit and with the proportion of time spent during transits which all decrease when the period increases. Nevertheless, tens to hundreds of planets will be detected with periods larger than 10 days.

Most of the detected planets orbit quite bright dwarfs although the proportion of "hot Jupiters" has been taken to 1% whatever the mass of its star is and although the distribution number of dwarfs in GAIA increases with the absolute magnitude. This is just due to the fact that intrinsically bright stars are also statistically apparently bright and then have a better photometric accuracy. Most of the planets will then be detected around solar type stars. This reinforces the validity of the numbers given in this study since it is around this type of stars that the planet number statistics are presently known. On the other hand, tens to hundreds of planets will be detected around K or M dwarfs if these stars hold planetary systems.

4 CONCLUSIONS

Realistic simulations of extrasolar planet transits observed by GAIA show that 4000 to 40000 Jupiter-like planets with known periods will be detected. The majority of these planets have a period of 3 to 5 days and orbit Sun-like stars. It is also shown that a 1 year extension of the mission would increase the number of planet detected by 40 to 85%.

These simulations have to be refined in several ways:
- The Galaxy model used here has to be checked.
- The simulations must be extended to intrinsically brighter stars.
- The detection algorithm i.e. the number of observed transits needed to recover the periods has to be improved.

But these refinements shouldn't change the predicted numbers by orders of magnitude.

Few statistics are available concerning extrasolar planet properties needed in such simulations. Proportion of stars with planetary systems as a function of spectral type or mass, radius distribution and minimum period of planets are not presently known. These statistics will be available in the next years and the models will be improved consequently.

No study has been done here to estimate the importance of other physical effects which can mimic planetary transits. Star spots in cool dwarfs should produce periodic decreases of star flux and a way has still to be found to differentiate them from real transits. Grazing eclipsing binaries produce light curves very similar to those of planetary transits. Fortunately, they also produce a signature in radial velocity which should be detectable with the spectroscopic instrument of GAIA for most of them.

Finally, an unbiased way of recovering the real distribution of planets as a function of period, planet mass, parent star mass... from the future distribution which will be observed by GAIA is still to be done.

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