Detection of Extra-Solar Planets by GAIA Photometry

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Abstract. The transit of exoplanets across a stellar disk will often occur in GAIA observations. A safe detection of the slight dimming of the star can be made many hundred times, i.e. in cases where the star is sufficiently constant in intensity, and the photometry is very precise. When combined with the simultaneous GAIA astrometry or ground-based radial velocities the scientific harvest is orbit, mass and mass density for hundreds of exoplanets. We have typically considered Jupiter-size planets at Earth-like distances from stars.

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1. Introduction

The transit of exoplanets across a stellar disk will often occur in GAIA observations. A safe detection of the slight dimming of the star can be made many hundred times, i.e. in cases where the star is sufficiently constant in intensity, and the photometry is very precise. The constancy can be be verified by analysis of all photometric measurements of the star.

The following sections contain a tentative estimate of the number of detectable photometric transits of planets at about one astronomical unit from a star. An estimate of the transits for exoplanets much closer to the star has been made by Robichon (see [1]).

2. Geometry of exoplanet transits

We define r_{st} : radius of star, r_{pl} : radius of planet, and the relative radius of the planet

$$R = r_{\mathrm{pl}}/r_{\mathrm{st}} \tag{1}$$

The relative dimming of a star during a transit is therefore $= R^2$. We adopt as standard example $R = 0.1$ giving a dimming of $0.01 = 0.01$ mag since this is considered to be detectable when GAIA obtains a precision of 0.001 mag per observation.

Table I. Probabilities P of transit for a random and for an eclipsing system, and duration T of a central transit.

$a_{\mathrm{pl}}/a_{\oplus}$	1.0	0.5	0.25	Radius of orbit
A	0.005	0.01	0.02	Relative radius of star
P_{ran}	0.0000062	0.000025	0.0001	Random system
P_{ecl}	0.0015	0.003	0.006	Eclipsing system
T	13	9.2	6.5	Duration

Considering the orbit we define a_{pl} : radius of (circular) orbit, and the relative radius of star to orbit:

$$A = r_{\mathrm{st}}/a_{\mathrm{pl}} \tag{2}$$

Simple geometric considerations lead to the following two probabilities for transits. Probability that a random planet is transiting the star at a random time is equal to the projected area of the star divided by the area of the sphere containing the planet

$$P_{\mathrm{ran}} = \pi r_{\mathrm{st}}^2/4\pi a_{\mathrm{pl}}^2 = 0.25A^2 \tag{3}$$

and the probability that an *eclipsing* system is transiting at a random time is approximately

$$P_{\mathrm{ecl}} = A/\pi \tag{4}$$

It follows from Kepler's third law that the duration of a central transit for the standard example of a Sun-like star is

$$T = 13 \times (a_{\mathrm{pl}}/a_{\oplus})^{0.5} \text{ hours} \tag{5}$$

where $a_{\oplus}$ is the radius of the Earth orbit.

This results in Table I of probabilities and durations of a central transit.

3. GAIA photometry in the astrometric fields

The astrometric fields in the two Astro telescopes collect light in the broad G-band, i.e. from the whole sensitivity range of the CCD. GAIA photometry in the G-band is thus obtained from all 16 astrometric CCDs of a field crossing, cf. [2] and [3]. This gives 1 millimagnitude precision per field crossing for the stars brighter than 14 mag. This is derived from the count rate of N = 5450 e-/CCD at G = 17.0, given in Table 8.1 of the GAIA Study Report [2].

There are about 130 such transits during a 5 year mission. They come in groups of about 4 crossings, each of the crossings 1 hour apart. We consider typically exoplanets at about 0.5 AU distance from a Sun-like star where the stellar transit takes about 9 hours. The 4 crossings can therefore be averaged and be used as one *group observation* in the detection of transits. The precision of a group observation is 1 millimag at $G = 14 + 1.5 = 15.5$ mag.

There are about 30 such groups per star during the mission. About 30 million stars exist with $G < 15.5$, according to Table 6.4 of [2]. The number of relevant group observations is therefore $N_{\rm group} = 1\ 10^9$.

Some stars have a planet with relative diameter $R \geq 0.1$, e.g. a Jupiter size planet in front of a Sun-size star. This gives a dimming larger than 1 per cent = 0.010 mag, which is for the present taken as the detection limit, corresponding to $S/N \geq 10$ for stars with $G \leq$ 15.5 mag.

Let a fraction F of stars be sufficiently constant and have planets which could give a dimming of 0.01 mag and having an orbital radius about 0.5 AU, then GAIA will give the number of detectable transits:

$$N_{\rm ecl} = F \times P_{\rm ran} \times N_{\rm group} \tag{6}$$

where $P_{\rm ran} = 0.000025$ according to Table 1.

A value $F = 0.01$ may be assumed giving $N_{\rm ecl} = 250$. This value of F is very uncertain since it has to take into account the constancy of stars and the frequency of exoplanets, their sizes and orbits. This uncertainty will not be lifted soon, and perhaps only by means of GAIA observations.

4. Discussion

The fraction $F = 0.01$ in Eq. 6 is not unreasonable considering that the observed probability is about 0.01 of a Sun-like star having a Jupiter-size planet with a period of revolution less than 10 days, according to Mayor (2001, priv. comm.). Perhaps a fraction 0.03 of all stars have a Jupiter size planet with period less than one year.

Our main conclusion is that many exoplanets with fairly long periods about one year can probably be found from transits in GAIA photometry.

The requirement on the accuracy of GAIA epoch photometry is here assumed to be 0.001 mag which is very stringent, but not impossible if the requirement is taken into account in the hardware design, and if all means for calibration of of CCD sensitivity are utilized (see e.g. Section 3 of [3]).

We believe that a planet can be detected from a single transit with GAIA because there are so many possibilities for verification of the reality and the cause of a dimming. Verification is possible by study of the consistency of the four transits in a group, each of which would have a $S/N \geq 5$. Constancy of the star throughout the mission can be verified from GAIA observations. The astrometric observations must be consistent with an eclipsing system. Finally, after the internal consistency of GAIA observation has been established ground-based radial velocities should be obtained, and new eclipses may be observed at times which can be predicted from the astrometric GAIA observations.

An orbit of the planet may be obtained from the simultaneous GAIA astrometry or from ground-based radial velocities, resulting in the planet mass. The planet diameter is obtained from the dimming. The scientific harvest is orbit, mass and mass density for hundreds of exoplanets.

The GAIA sample will comprise exoplanets of all spectral type stars, the sample covers all sky, and stars are closer to us than in other large surveys, the sample will have very well known selection functions. The possible stellar atmospheric activity may be monitored with the Ca-triplet observed in the high-dispersion spectrograph of GAIA, and with filter photometry of H_α. These features are important for the theoretical interpretation in terms of planetary systems formation.

References

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