DETECTION OF TRANSITING JOVIAN EXOPLANETS BY *GAIA* PHOTOMETRY—EXPECTED YIELD

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ABSTRACT

Several attempts have been made in the past to assess the expected number of exoplanetary transits that the *Gaia* space mission will detect. In this Letter, we use the updated design of *Gaia* and its expected performance and apply recent empirical statistical procedures to provide a new assessment. Depending on the extent of the follow-up effort that will be devoted, we expect *Gaia* to detect from a few hundreds to a few thousands of transiting exoplanets.

Key words: methods: statistical – planets and satellites: detection – surveys – techniques: photometric

Online-only material: color figures

1. INTRODUCTION

Gaia is a planned European Space Agency (ESA) mission, scheduled to be launched in 2013. It will perform an all-sky astrometric and spectrophotometric survey of pointlike objects between 6th and 20th magnitude. The primary goal of the telescope is to explore the formation, and dynamical, chemical, and star formation evolution of the Milky Way. The main science product of *Gaia* will be high-precision astrometry, backed with photometry and spectroscopy. It will observe about 1 billion stars, a few million galaxies, half a million quasars, and a few hundred thousands of asteroids (Lindegren 2010).

Gaia will operate in a Lissajous-type orbit, around the L2 point of the Sun–Earth system, about 1.5 million kilometers from Earth in the anti-Sun direction. It will have a dual telescope, with a common structure and common focal plane. During its five-year operational lifetime, the spacecraft will continuously spin around its axis, with a constant speed of 60 arcsec s^{-1}. As a result, during a period of 6 hr, the two astrometric fields of view will scan all objects located along the great circle perpendicular to the spin axis. As a result of the basic angle of 106°.5 separating the astrometric fields of view on the sky, objects will transit the two fields of view with a delay of 106.5 minutes. Due to the spin motion of a 6 hr period, and a 63 day period precession, the scanning law will be peculiar and irregular. This scanning law will result in a total of 70 measurements on average for each celestial object *Gaia* will observe (de Bruijne 2012).

Gaia will provide photometry in several passbands, the widest of which will be a "white" passband dubbed G, centered on $\lambda_0 = 673$ nm, with a width of $\Delta\lambda = 440$ nm. In what follows we use the apparent G magnitude as approximately equal to the apparent V magnitude. One can expect a millimagnitude precision in the G band for most of the objects *Gaia* will observe, down to 14th–16th G magnitude, and 10 mmag at the worst case of 19th magnitude objects (Jordi et al. 2010). The exact limiting magnitude for a 1 mmag precision depends on instrumental factors which are not yet "frozen" (de Bruijne 2012).

The 1 mmag precision of *Gaia* photometry naturally raises the question of whether it can be used to detect exoplanetary transits. While 1 mmag precision is nominally more than sufficient for the detection of Jovian transiting planets, the low cadence and the small number of measurements make the feasibility of this detection a nontrivial question. In the literature, there have been several conflicting estimates as to the number of transits detectable by *Gaia*, based on different assumptions.

Høg (2002) estimated the expected number of transit detections by *Gaia* at 250 for long-period planets with an orbital radius of 0.5 AU. According to Høg (2002), the expected yield of hot Jupiters (HJs) and very hot Jupiters (VHJs) with orbital radii of 0.1–0.01 AU was 6250 and 625,000, respectively. Høg (2002) based these estimates on some general assumptions. First, the planets' frequency was approximated as ∼1%, which already proved to be overestimated for HJs (Beatty & Gaudi 2008, hereafter BG). Second, Høg did not account for the stellar density and its variation due to galactic structure and neglected extinction by dust. He assumed that the number of stars *Gaia* will observe with 1 mmag precision (up to magnitude $G = 15.5$) is 10^9. Finally, he assumed that a transit detection can be made with only one transit observation per system, counting on *Gaia* astrometric observations to complement the transit observation.

Robichon (2002) performed transit simulations with the assumed *Gaia* photometry to estimate the number of detections, and concluded that *Gaia* will detect between 4000 and 40,000 transiting Jupiter-like planets. He assumed that the number of individual observations per star would be between 100 and 300 with an average of 130. He also used a galactic model (Haywood et al. 1997), and derived the probability distribution of the number of observations during transits using the *Gaia* scanning law. We suspect that these predictions are overestimated due to the fact that the currently planned scanning law of *Gaia* implies an average of 70 measurements per star and not 130. We will refer to Robichon's estimates in more detail in Section 3.

In this short Letter we present a new estimate, one that we believe is more realistic than the previous ones. It is based on the methodology of BG, which includes broad assumptions about the galactic structure, as well as implicit assumptions about the geometric transit probability and the effects of stellar variability, that rely on statistics from completed transit surveys. The field of planetary transits of HJs and VHJs seems to have come to a certain maturity from which we can draw some statistical assumptions. We feel this is not yet the case for transits of smaller planets ("Saturnian" and "Neptunian"), and we therefore do not address these issues here.

Providing more accurate and up-to-date predictions of the number of transiting planets detectable by *Gaia* is important for the ongoing effort of developing the *Gaia* analysis pipeline.

Moreover, detection of planetary transits requires considerable follow-up effort, which is also a reason for having a reliable estimate of this number. We took it upon ourselves to provide a somewhat more rigorous analysis, based on empirical statistics, simply because the estimates in the literature are too varied and inconsistent. At the time they were made, the field of transit surveys was too young and much had yet to be learned. The time has come to provide a more decisive estimate, based on the current more evolved understanding of the problem.

2. PREDICTING THE TRANSIT YIELD

BG presented a statistical methodology to predict the yield of transiting planets from photometric surveys. Their method takes into consideration the frequency of short period planets, variations in the stellar density due to the galactic structure, and also corrects for the extinction by dust.

Following the procedure suggested by BG, the average number of exoplanets that a photometric survey can detect is estimated by the product of the probability of detecting a transiting planet, the frequency of transiting planets, and the local stellar mass function. Obviously, this product should also be integrated over mass, distance, and the field of view:

$$\frac{d^6 N_{\text{det}}}{dR_{\text{p}}\, dp\, dM\, dr\, dl\, db} = \rho_*(r, l, b)\, r^2 \cos b\, \frac{dn}{dM}\, \frac{d^2 f(R_{\text{p}}, p)}{dR_{\text{p}}\, dp}$$
$$\times P_{\text{det}}(M, r, R_{\text{p}}, p), \qquad (1)$$

where $\rho_*(r, l, b)$ is the local stellar density as a function of heliocentric galactic coordinates (r, l, b), dn/dM is the present day mass function in the solar neighborhood, and $(d^2 f(R_{\text{p}}, p))/(dR_{\text{p}}\, dp)$ is the frequency of transiting planets (the probability that a given star harbors a transiting planet with radius R_{p} and period p). P_{det} is the transit detection probability, assuming there is indeed a transiting planet around the examined star.

Following BG, we consider detection of transits of VHJs with orbital periods of 1–3 days and HJs with periods of 3–5 days. For the probability that a star will harbor a transiting planet with radius R_p and orbital period p we assume the same form that BG used:

$$\frac{d^2 f(R_{\text{p}}, p)}{dR_{\text{p}}\, dp} = k(p)\, f(p)\, \delta(R_p - R_p'). \qquad (2)$$

The normalization factor $k(p)$ is an empirical number that can be deduced from completed surveys. It encapsulates many factors that are common to transit surveys looking for the same range of periods and more or less the same stellar populations. BG proposed using a normalization factor based on the results of Gould et al. (2006), who analyzed the statistics of the OGLE transit surveys. They suggested a value of $k(p) = 1/690$ for VHJs, and $k(p) = 1/310$ for HJs, and a locally uniform distribution of the period in the specified interval, $f(p) = 1$.

This planet frequency (Gould et al. 2006) is compatible with the frequency implied by *Kepler* results (Howard et al. 2012). Furthermore, *Gaia*'s low cadence makes it more similar to ground-based surveys, rather than to high-cadence space surveys. Moreover, *CoRoT* and *Kepler* results are not yet complete since they are still operating.

To account for the stellar density in the solar neighborhood, we used the present-day mass function (PDMF). Reid et al. (2002) used data from the Palomar/Michigan State University

survey together with the *Hipparcos* data set to derive the PDMF:

$$\frac{dn}{dM} = \begin{cases} k_{\text{norm}} \left(\frac{M}{M_\odot} \right)^{-1.35} & \text{for } 0.1 \leqslant M/M_\odot \leqslant 1 \\ k_{\text{norm}} \left(\frac{M}{M_\odot} \right)^{-5.2} & \text{for } 1 < M/M_\odot \end{cases} \qquad (3)$$

where again we adopted the normalization suggested by BG, $k_{\text{norm}} = 0.02124 \,\text{pc}^{-3}$.

In order to convert absolute magnitudes to masses, we used the mass–luminosity relations, as derived by Reid et al. (2002). For lower main-sequence stars we used the mass–luminosity relation:

$$\log M = 10^{-3} \times \big(0.3 + 1.87 M_V + 7.614 M_V^2$$
$$- 1.698 M_V^3 + 0.06096 M_V^4\big), \qquad (4)$$

and for the upper main-sequence stars,

$$\log M = 0.477 - 0.135 M_V + 1.228 \times 10^{-2} M_V^2$$
$$- 6.734 \times 10^{-4} M_V^3, \qquad (5)$$

where M_V is the absolute visual magnitude of the star. The boundary between the calibrations is set at $M_V = 10$.

The last step of the procedure is integration of the stellar density over the entire field of view:

$$N_{\text{det}} = \int_0^\infty \int_{l_{\text{min}}}^{l_{\text{max}}} \int_{b_{\text{min}}}^{b_{\text{max}}} \rho_*(r, l, b)\, r^2 \cos b\, db\, dl\, dr. \qquad (6)$$

We now had to account for the variation in the stellar density due to the galactic structure, and also the effect of extinction due to interstellar dust. We incorporated into our calculations the galactic model of Bahcall & Soneira (1980), which is a simplified model that depends only on the distance from the galactic plane (z) and the disk-projected distance from the galactic center (d):

$$\rho_* = \exp\left[-\frac{d}{h_{\text{d},*}} - \frac{|z|}{H(M_V)} \right], \qquad (7)$$

where $h_{\text{d},*} = 2.5\,\text{kpc}$ is the scale length of the disk. The scale height, $H(M_V)$, depends on the absolute magnitude, and BG use the dependence:

$$H(M_V) = \begin{cases} 90 & \text{for } M_V \leqslant 2 \\ 90 + 200 \left(\frac{M_V - 2}{3} \right) & \text{for } 2 < M_V < 5 \\ 290 & \text{for } M_V \geqslant 5 \end{cases}. \qquad (8)$$

To account for the interstellar dust extinction, we used the expression suggested by Bahcall & Soneira (1980) for obscuration by dust. In their model the obscuration depends on the heliocentric distance and the galactic latitude:

$$A(r) = \begin{cases} 0 & |b| > 50^0 \\ 0.17 \left(1.2 + \tan |b|\right) \left[1 - \exp\left(-\frac{r \sin |b|}{h}\right)\right] \csc |b| & |b| \leqslant 50^0 \end{cases}, \qquad (9)$$

where h is a typical scale height with respect to the galactic plane, that is approximated by 100 pc (Bahcall & Soneira 1980).

The term $P_{\text{det}}(M, r, R_{\text{p}}, p)$ in Equation (1) deserves special attention. In their original formalism, BG followed the common wisdom and assumed that the detection probability is mainly
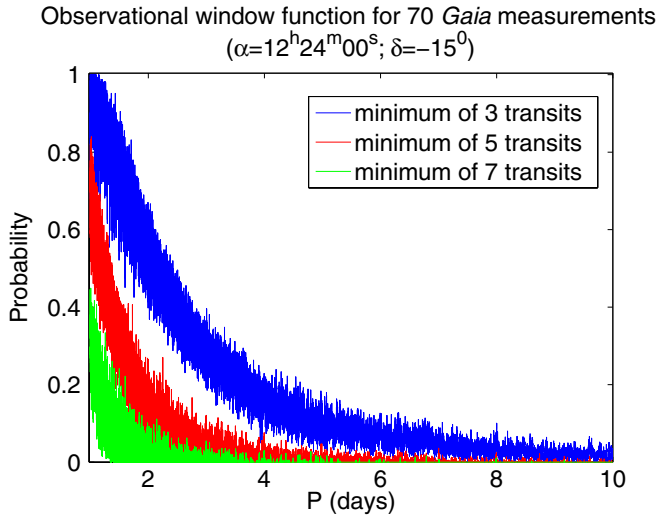
Observational window function for 70 *Gaia* measurements
(α=12^{h}24^{m}00^s; δ=−15^0)

Figure 1. Sample observational window function for a sky direction that *Gaia* is expected to observe 70 times, the average expected number of measurements over the entire mission. The detection probability is calculated for a transit duration of 2 hr, for a minimum of three, five, and seven observations in transit.

(A color version of this figure is available in the online journal.)

a function of the transit signal-to-noise ratio (S/N), which is usually defined by

$$S/N = \sqrt{n_{tr}}\frac{\Delta}{\sigma},\tag{10}$$

where n_{tr} is the number of observed transits, Δ is the transit depth, and σ is the photometric error. In BG's treatment, σ, and therefore the S/N, strongly depends on the stellar magnitude, which is obviously the case in most surveys.

However, unlike in most surveys, an important feature in the design of *Gaia* is a "gating" mechanism, that will cause most bright stars, certainly down to the 16th magnitude, to be measured with a precision of 0.001 mag, more or less (Jordi et al. 2010). Thus, the S/N in our case is mainly a matter of the number of observations that occurred during transits.

BG assumed that a planetary transit can be detected whenever the transit S/N exceeds a threshold. However, as opposed to high-cadence surveys, due to the small number of measurements that will sample the transits, Equation (10) does not represent the complete detection problem in our case. Even if the S/N does exceed a threshold value, we still cannot regard the signal we found as a periodic one. In fact, in our assumed parameters, using the S/N naively, even a single observation in transit can be considered a transit detection with an S/N of 10. Obviously, we have to use another indicator, which mainly depends on the number of points observed in transit, and abandon the S/N figure of merit for our purposes (that would not be the case for smaller planets, though, where an even more elaborate indicator will probably be needed). To put it differently, we assume the problem is not limited by the error bars of the individual measurements, but only by the scanning law and the temporal characteristics of the transit.

von Braun et al. (2009) calculated, for various ground surveys, the detection probability as a function of the period, which they dubbed the "observational window function." In our ideal case we assumed pure white noise and no outliers. We further assumed a certain transit duration, and a minimum number of points in transit that would constitute a detection (depending on the detection approach used). We then calculated for each period the fraction of configurations (namely, transit phases) which will result in detection, i.e., when the number of observations
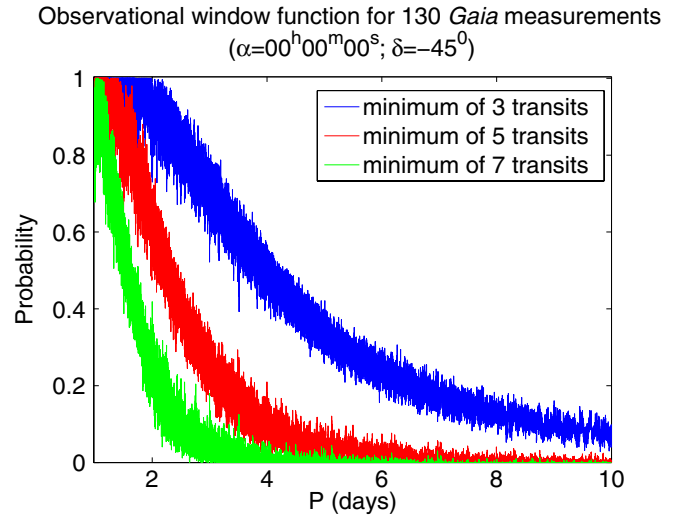
Observational window function for 130 *Gaia* measurements
(α=00^{h}00^{m}00^s; δ=−45^0)

Figure 2. Sample observational window function for an area that *Gaia* is expected to observe 130 times.

(A color version of this figure is available in the online journal.)

in transit will exceed the prescribed minimum. Once we had obtained the observational window function, we could integrate it over the required period range and obtain an estimate of the detection probability.

The minimum number of observations in transit required for detection is not clear at the moment. Tingley (2011) introduced an algorithm that requires a minimum number of seven to eight points in transit to secure detection. In an upcoming paper (Y. Dzigan & S. Zucker, in preparation), we show that we can detect transits with five points in transit, or use our "directed follow-up" approach (Dzigan & Zucker 2011) even for three points in transit. We therefore repeated our calculations here for a minimum number of three, five, and seven points in transits.

We divided the entire sky into rectangular patches, 15° × 15° (apart from the poles, obviously, where we simply used the remaining circular patch), and applied the proper scanning law for each patch, assuming the scanning law for the central point as representative of the entire patch. Figure 1 shows a sample observational window function for one of the patches, for three cases of minimum points in transit (three, five, and seven) and for a transit duration of 2 hr. This specific window function represents an area that *Gaia* is expected to visit 70 times. This is the average expected number of measurements over the entire mission (de Bruijne 2012).

For comparison we also present the window function for an area with 130 measurements in Figure 2. The comparison shows that the detection probability depends strongly on the number of observations that the telescope will perform, during the mission lifetime. For example, the probability to sample a minimum of three transits (for an orbital period of 3 days) increases from less than 30% for 70 measurements, to more than 60% in case the telescope should observe the star 130 times.

Since we neglected the dependence of the window function on the S/N and therefore on the stellar characteristics, it remains mainly a function of the period and the scanning law. We can therefore take it out of the integral sign in Equation (1), which we calculate separately for each patch. We also divided the apparent magnitude range ($G = 6$–16) into 1 mag bins and treated each bin separately. We multiplied the result with the detection probability we obtained from the window function only at the end of the integration.

Table 1
Gaia Expected Detections Down to a Limiting Magnitude

	Minimum Number of Points in Transit	$G = 14$	$G = 16$
$w = 1\,\text{hr}$	3	230	999
	5	42	178
	7	7	30
$w = 2\,\text{hr}$	3	596	2605
	5	209	902
	7	73	310
$w = 3\,\text{hr}$	3	720	3191
	5	364	1577
	7	156	669

Notes. The expected yield of HJs and VHJs from *Gaia* photometry, for three different transit durations, down to a limiting apparent magnitudes of $G = 14$ and $G = 16$.

3. RESULTS

Table 1 presents the resulting expected yield of transiting HJs and VHJs in *Gaia* photometry, down to stellar magnitudes 14 and 16, for which we expect *Gaia* to observe on the order of 1.5×10^5 and 6.8×10^5 stars, respectively. Obviously, the required minimum number of observations in transit strongly affects the results, as well as the assumed transit duration. In Figure 3 we present the transiting planets' yield for a minimum of five sampled transits, for a transit duration of 2 hr, divided into apparent magnitude bins from $M = 6$ to $M = 16$. Our results show that the *Gaia* photometry is expected to yield on the order of hundreds or thousands of new planets, depending on the detection strategy.

Given the large amount of stars that *Gaia* will measure, we must estimate the false-alarm rate. The probability that 1 mmag of purely white noise will produce a single "transit-like" outlier (with magnitude of 0.005–0.015 mag) is $\sim 3.5 \times 10^{-7}$, which amounts to $\sim 2 \times 10^{-15}$ for three outliers out of the average 70 measurements. This is a worst case estimate, as requiring the outliers to have a periodic pattern reduces this probability. Thus, under our nominal assumptions, it is obvious that the false-alarm rate is negligible.

Nevertheless, the analysis might be complicated by stellar red noise. If the red noise does not possess a periodic or quasi-periodic nature, then the low-cadence sampling simply renders it "white," effectively reducing the S/N. According to McQuillan et al. (2012), we estimate that roughly half of the stars have a microvariability larger than 2 mmag. This results in an increased false-alarm rate. However, in our upcoming paper (Y. Dzigan & S. Zucker, in preparation) we show that our prioritization process in the directed follow-up approach effectively eliminates them.

In any case, *Gaia* will provide the astrometric and spectroscopic data needed for further classification. These data will help to exclude false positives, such as background eclipsing binaries, and to distinguish between periodic variability of the stellar source and planetary transits. Thus, we can conclude that we do not foresee a significant false-positive rate, as long as we focus our analysis on HJs.

Our results seem to differ considerably from those of Robichon (2002). We suspect that the main cause for the discrepancy is the different scanning law we used, which implied 50–200 observations per star, with a mean of 70, compared with 100–300 with a mean of 130, which Robichon used. This reflects changes in the mission design during the years that elapsed since

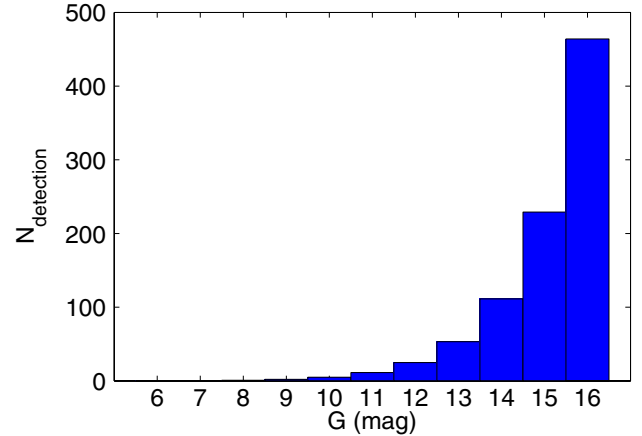Expected HJ and VHJ detections in *Gaia* photometry for a minimum of 5 sampled transits

Figure 3. Expected yield broken into apparent magnitude bins. This yield was calculated for a minimum of five sampled transits and a transit duration of 2 hr.
(A color version of this figure is available in the online journal.)

2002. Figures 1 and 2 hint at the significant effect this change had on the observational window function.

It is important to stress again that the analysis we present did not consider smaller planets. Their detection will be more difficult; moreover, the required follow-up, either photometric or spectroscopic, will be more complicated. This topic will require a much more elaborate and careful analysis.

The analysis we present in this Letter is a rough estimate that is based on general assumptions. We obviously made some approximations on the way, but at the level of accuracy needed at this stage we feel they are justified. The most important conclusion is that it will be worthwhile to develop detection algorithms that are tailored to *Gaia* photometry and that will be incorporated into the pipeline. This may reduce the minimum number of points in transit required for detection, which will immensely affect the yield. In addition, establishing a follow-up network that will be able to respond to alerts will also have a crucial effect, again, through this reduction in the number of required observations in transit (e.g., Wyrzykowski & Hodgkin 2012).

A significant feature one can notice while examining Table 1 and Figure 3 is the very strong dependence of the yield on the limiting apparent magnitude. Extending the analysis to fainter magnitudes will require introduction of the S/N into the analysis. This effort will be useless unless high-precision radial velocities of such faint targets will be feasible. Extremely large telescopes such as the E-ELT may enable this kind of observation. The enormous increase in the number of planets detected with *Gaia*, if fainter stars are considered, may serve as a justification for building high-precision radial velocity spectrographs for those telescopes.

Gaia will undoubtedly revolutionize astronomy in many aspects. Nevertheless, its contribution to the field of transiting exoplanets is usually expected to be marginal. The expected transiting planet yield is the key factor to establish whether this field will benefit considerably from *Gaia*. Usually, transit surveys focus on dense fields to maximize the chances of detecting transits and effectively using their high cadence. *Gaia*, on the other hand, will be an all-sky, low-cadence survey. These kinds of surveys are usually considered irrelevant for transit searches. The estimate we present here shows that *Gaia* will also have a valuable and significant contribution in this field,

mainly due to its high photometric precision, and in spite of its low cadence.

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