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Exoplanetary transits as seen by Gaia

H. Voss[1,2], C. Jordi[1,2,3], C. Fabricius[1,2], J. M. Carrasco[1,2], E. Masana[1,2], and X. Luri[1,2,3]

[1] IEEC: Institut d'Estudis Espacials de Catalunya
[2] ICC-UB: Institut de Ciènces del Cosmos de la Universitat de Barcelona
[3] UB: Departament d'Astronomia i Meteorologia, Universitat de Barcelona

Abstract

The ESA cornerstone mission Gaia will be launched in 2013 to begin a scan of about one billion sources in the Milky Way and beyond. During the mission time of 5 years (+ one year extension) repeated astrometric, photometric and spectroscopic observations of the entire sky down to magnitude 20 will be recorded. Therefore, Gaia as an All-Sky survey has enormous potential for discovery in almost all fields of astronomy and astrophysics.
Thus, 50 to 200 epoch observations will be collected during the mission for about 1 billion sources. Gaia will also be a nearly unbiased survey for transiting extrasolar planets.
Based on latest detection probabilities derived from the very successful NASA Kepler mission, our knowledge about the expected photometric precision of Gaia in the white-light G band and the implications due to the Gaia scanning law, we have analysed how many transiting exoplanets candidates Gaia will be able to detect.
We include the entire range of stellar types in the parameter space for our analysis as potential host stars, as they will be observed by Gaia. We show statistics for expected distributions of the transiting exoplanets in planetary radius, orbital period and distance to the host star.
Additionally, we provide information about the expected distribution of the host star parameters stellar mass, radius and effective temperature. Combining all this information enables us to answer the most interesting question: Will Gaia be able to detect Super-Earths in the habitable zone of cool dwarfs?

1 Introduction

Gaia is a cornerstone mission of ESA with a planned launch date in the autumn of 2013. The satellite, to be launched by a Soyuz-Fregat launcher from the French Kourou spaceport, will be injected into a Lissajous orbit around the Sun-Earth Lagrange point L2. This kind of orbit allows nearly uninterrupted observations of regions in the sky pointing away from the Sun. Thus, Gaia will observe more than 1 billion sources up to 200 times with an average of 70 times during the planned mission duration of 5 years. The entire sky will be systematically monitored with astrometric, photometric and spectroscopic measurements down to white light G magnitude 20. Thereby, the mission concept is optimized to yield astrometrical results of highest quality.

The challenging task of the data reduction of the observations of more than 1 billion sources will be conducted by an international consortium of scientists and engineers (Data Processing and Analysis Consortium - DPAC) distributed all over Europe.

A more detailed description of the Gaia mission can be found in [8]. The expected photometric performance of Gaia is discussed in [4], and the challenges of the photometric calibration are outlined in [3]. Actual information about the Gaia mission can be found at the ESA website[1].

2 Exoplanets: Expected discoveries

As the Gaia mission is optimized for astrometric purposes it will be a great tool for the astrometric detections of extrasolar planets. It is expected that Gaia will detect astrometrically about 2000 single exoplanet systems and about 300 multi-planet systems by monitoring about 150 000 FGK dwarfs within a distance of 200 pc. For about 1000 of these systems orbits will be determined. The detected planets will mainly be giant planets with orbital periods smaller than 10 years. Furthermore, it is expected that up to 5000 transiting planets will be detected. All the infomration given above can be referenced in [2].

3 The photometric white light observations

The highest photometric precision is expected for the Gaia white light observations in the G band. As can be seen in Fig. 19 of [4] sub-mmag precision can be obtained for most of the single FoV observations of bright stars ($G < 14$). For fainter stars ($G < 17$) photometric precision of a few mmag is reached for single FoV transits. Note that a single FoV transit is composed of $8 - 9$ single astrometric field (AF) CCD transits as the stars are transiting $8 - 9$ AF CCDs in the focal plane during a single FoV transit. How the focal plane is built up can be seen in Fig. 1 of [3].

Gaia will observe with 2 telescopes separated by a field angle of 106.5 deg as can be seen in the schematic view of the Gaia scanning principle in Fig. 1. Due to the scan rate of the satellite a second FoV transit of the same source will be recorded with the second telescope 106.5 minutes later than the observation with the first telescope. The spin period of the satellite will be exactly 6 hours. It will depend on the actual precessional motion of the satellite if additional transits are recorded 6 hours after the first observation. In this way $1 - 5$ subsequent transits will be observed by Gaia before a gap of observations covering several weeks will occur. Obviously, this scanning law is not optimized for a search program for transiting exoplanets. It is optimized for astrometric purposes to result in an

[1] `http://www.rssd.esa.int/index.php?project=GAIA&page=index`

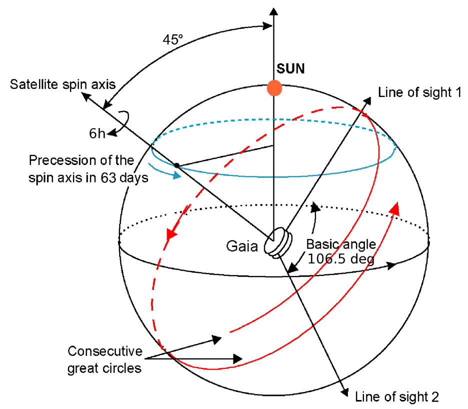

Figure 1: The Gaia scanning principle with a spin period of 6 hours and a scan rate of 1 arcmin s^{-1}.

all-sky coverage with enough observations per source to derive parallaxes and proper motions. Furthermore, this scanning law guarantees that on the average 70 transits per source will be observed during the 5 years of the nominal mission time. For sources close to the knots of the scanning law (ecliptic latitude 45°) up to 200 transits will be recorded by Gaia as can be seen in Fig. 2.

4 The exoplanet sample

The most complete sample of the transiting exoplanet candidates was published by the Kepler team in [1] after analysis of the first 16 months of Kepler observations. It consists of 2321 transiting exoplanet candidates found for the 156 000 target stars observed continuously by the Kepler space telescope. As these exoplanet candidates has passed already several confidence tests (for details please see [1]) the Kepler team is optimistic that at least 95% of the candidates are real exoplanets. The majority of the detected exoplanet candidates are Neptune-sized and Super Earth-sized planets.

For simplicity we assume that the sample is complete in detected planet sizes and orbital periods for our purpose to estimate how many of these planet candidates could be photometrically detected by Gaia. This assumption is well justified as the photometric precision of Gaia white light measurements will be lower than for Kepler measurements and the low number of Gaia observations per source will prefer exoplanets with short orbital periods to be detected.

5 The simulation of transit observation by Gaia

We have simulated 2.6 million lightcurves for stars with $G < 17$ with one transiting planet each. This magnitude limit was set for several reasons. As said already in Sect. 3 only FoV transit observations down to G magnitude 17 will have the photometric precision of a few

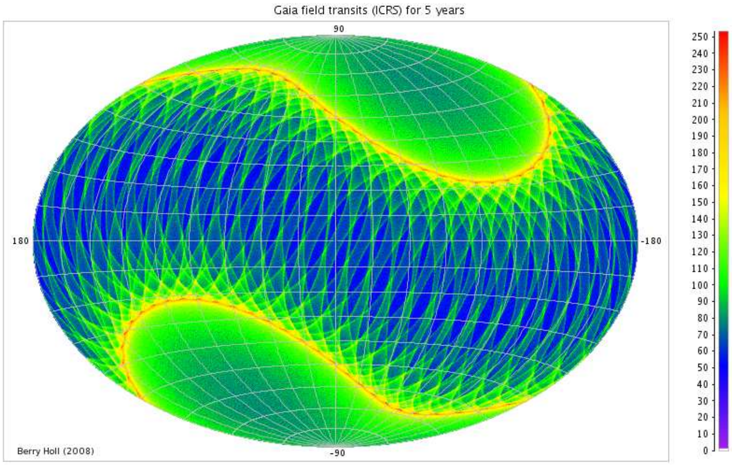

Figure 2: The number of transits that Gaia will observe during the 5 year mission vs. sky position given in equatorial coordinates.

mmag or better necessary to allow detections of signals of transiting exoplanets. Furthermore, necessary ground-based follow-up observation will be challenging for host stars of exoplanet candidates at these faint magnitudes. Additionally, there was simulated GASS (GAia System Simulator, an official DPAC simulator tool, [5]) data available with full stellar density down to magnitude 17. The stellar parameters are computed based on the Gaia Universe model described in [7]. The number of 2.6 million stars with transiting planets corresponds to about 200 million stars all over the sky that are expected to be observed by Gaia to the limiting magnitude of $G < 17$ assuming the observed frequency of Kepler. The lightcurves were simulated to contain typical noise like photon noise and RON. The noise was artificially increased by 20% to account for extra noise sources. Additional conditions for the simulations were set:

- One transiting planet from Kepler dataset in terms of sizes and orbital periods was randomly distributed to each star.
- The zero epochs for the transits were chosen randomly.
- The typical number of 70 Gaia observations were chosen based on the scanning law.

For the detection of a transiting exoplanet a total detection threshold of 5σ was assumed for three or more independent intra-transit measurements. An intra-transit measurement was classified as independent if the next detection follows after 6 hours or more. This avoids to classify a transit signal re-detected in the subsequent observation from the other FoV as an independent signal, because they do not contribute to gain information about the orbital period of the transiting exoplanet. Three or more independent intra-transit observations yield the desired orbital period information.

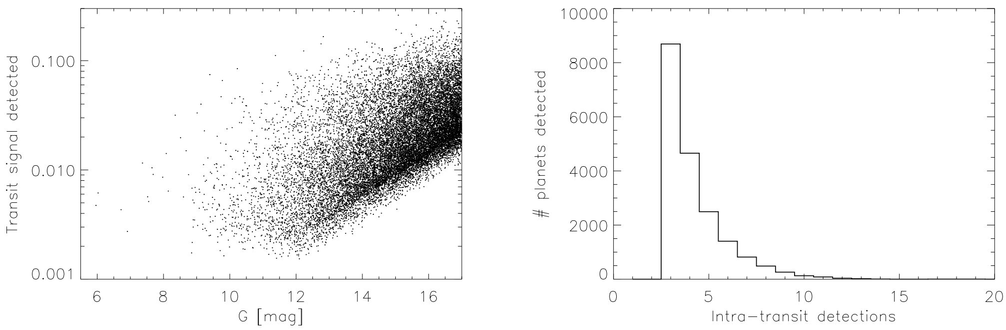

Figure 3: Properties of the 19000 transiting planets detected in the simulations. *Left panel:* detected transit signal depth vs. the G magnitude of the host stars. *Right panel:* the number of detected transiting planets is given per observed independent intra-transit signal.

6 Results from the simulations

The simulations as performed give an upper limit of the number of transiting exoplanets that Gaia will be able to detect. We found the following:

1. Gaia will be able to detect up to 19 000 transiting exoplanets all over the sky.
2. Signals down to 2 mmag depth are detectable (Fig. 3, left).
3. The majority of detected transiting exoplanets shows only $3-5$ observed transit signals (Fig. 3, right).
4. Planets with short orbital periods of a few days are preferred for detection (Fig. 4, left).
5. Most transiting planets detected are Jupiter- or Neptune-sized (Fig. 4).
6. The majority of the host stars are G and K dwarfs (Fig. 4, right).
7. Neptune-sized planets are mainly found orbiting K or M dwarfs (Fig. 4, right).
8. A very few Super-Earths are detected on short period orbits around M dwarfs (Fig. 4, right).

Thus, Gaia can provide a nearly unbiased sample of short period Jupiter- and Neptune-sized exoplanets. Only a weak bias will be included from the not perfectly even distribution of the number of observations over the sky. This can easily be corrected for.

7 The influence of stellar variability

We have only indirectly accounted for the influence of the stellar variability on the detectability of signals from transits. Transiting planets not detectable with Kepler due to stellar vari-

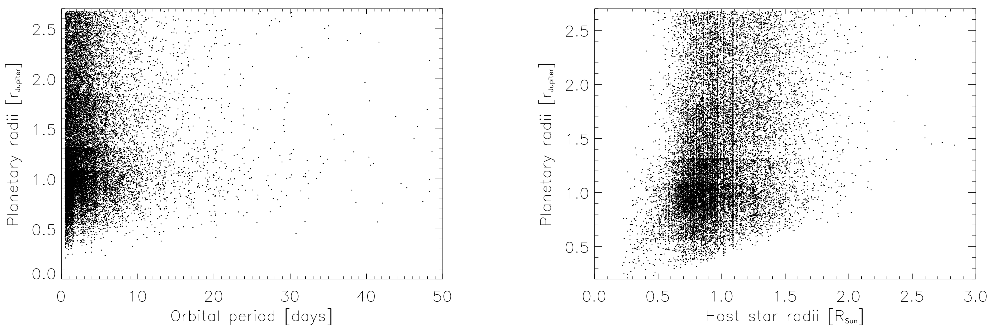

Figure 4: Properties of the detected transiting exoplanets and their host stars. *Left panel:* radii of the detected transiting planets vs. their orbital period. *Right panel:* radii of the detected planets vs. radii of their host stars.

ability are also not detectable by Gaia. Analysis of 1 month of Kepler observations in [6] shows that about 40% of all Kepler targets are less variable than the Sun. For longer observational periods this fraction may decrease further. For the internal photometric calibration of Gaia data it is generally assumed that only about 10% of the stars are non-variable. Therefore it does not seem to be unreasonable to assume that $10 - 40\%$ of all stars show a variability low enough that exoplanetary transits can be detected in Gaia white light photometry. Thus, $1900 - 7600$ transiting exoplanets will be detectable by Gaia during the 5 year mission.

Acknowledgements

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