PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

Gaia and exoplanets: a revolution in the making

Sozzetti, Alessandro

Alessandro Sozzetti, "Gaia and exoplanets: a revolution in the making," Proc. SPIE 10400, Techniques and Instrumentation for Detection of Exoplanets VIII, 104001E (12 September 2017); doi: 10.1117/12.2276987

Event: SPIE Optical Engineering + Applications, 2017, San Diego, California, United States

Invited Paper

Gaia and Exoplanets: A Revolution in the Making

Alessandro Sozzetti[a]

[a]INAF - Osservatorio Astrofisico di Torino, Via Osservatorio 20, I-10025 Pino Torinese, Italy

ABSTRACT

The Gaia global astrometry mission is now entering its fourth year of routine science operations. With the publication of the first data release in September 2016, it has begun to fulfil its promise for revolutionary science in countless aspects of Galactic astronomy and astrophysics. I briefly review the Gaia mission status of operations and the scenario for the upcoming intermediate data releases, focusing on important lessons learned. Then, I illustrate the Gaia exoplanet science case, and discuss how the field will be revolutionized by the power of micro-arcsecond (μas) astrometry that is about to be unleashed. I conclude by touching upon some of the synergy elements that will call for combination of Gaia data with other indirect and direct detection and characterization techniques, for much improved understanding of exoplanetary systems.

Keywords: Astrometry, Extrasolar Planets, Gaia, Parallaxes, Proper motions, Surveys, Methods: data analysis, Methods: numerical

1. INTRODUCTION

As of August 2017, the list of known extrasolar planets encompasses a total of 3,509 confirmed and validated systems. The wealth of high-quality data gathered over the 22 years since the discovery of the first Jupiter-mass companion to a solar-type star[1] is providing fundamental insights on the complex processes of planet formation and structural, atmospheric, and dynamical evolution (for a review, see e.g. Ref. 2, and references therein). The most ground-breaking observational results, that allow to characterize, for example the population of planetary systems across orders of magnitude in mass and orbital separation (Fig. 1), have been obtained thanks to the highly successful techniques of planetary transits (both from the ground and in space) and radial-velocity measurements. In particular, the regime of small radii ($R_p \leq 4\ R_\oplus$) and low masses ($M_p \leq 30\ M_\oplus$) of exoplanets has been made accessible only thanks to the revolutionary space-based photometry of the Kepler mission and to state-of-the-art high-resolution spectrographs achieving 1 m s^{-1} precision (e.g., HARPS@ESO-3.6m, HARPS-N@TNG, HIRES@Keck).

The astrometric technique has historically been the first to be adopted to search for planetary companions to stars other than the Sun. However, despite many decades of attempts, astrometry has yet to provide a firm detection (for a review of the troubled history of claims of see e.g. Ref. 3). A game-changer is now finally in sight. The tide is expected to begin turning soon, starting in 2018.

2. THE GAIA MISSION

ESA's Cornerstone mission Gaia[4] (http://www.cosmos.esa.int/gaia) was launched in December 2013 to collect data that will allow the determination of highly accurate astrometric parameters (positions, proper motions, and parallaxes) for > 1 billion sources brighter than $G = 20.7$ mag (Gaia's white-light photometric band). Gaia's exquisite astrometric sensitivity (complemented onboard by spectro-photometric and spectroscopic information) is set to surpass that of its predecessor Hipparcos[5,6] by two orders of magnitude, with a reference performance requirement of 24 μas accuracy on the parallax of a 15th magnitude solar-type star at the end of the nominal 5-yr mission lifetime. Gaia's all-sky survey will allow to unravel the early formation, and subsequent dynamical, chemical and star formation evolution of our Galaxy. The broad range of crucial issues in astrophysics that will be addressed by the wealth of the Gaia data is summarized by, e.g., Ref. 7.

Further author information: (Send correspondence to A. Sozzetti)
A. Sozzetti: E-mail: sozzetti@oato.inaf.it, Telephone: +39 011 8101923

Techniques and Instrumentation for Detection of Exoplanets VIII, edited by Stuart Shaklan, Proc. of SPIE
Vol. 10400, 104001E · © 2017 SPIE · CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2276987

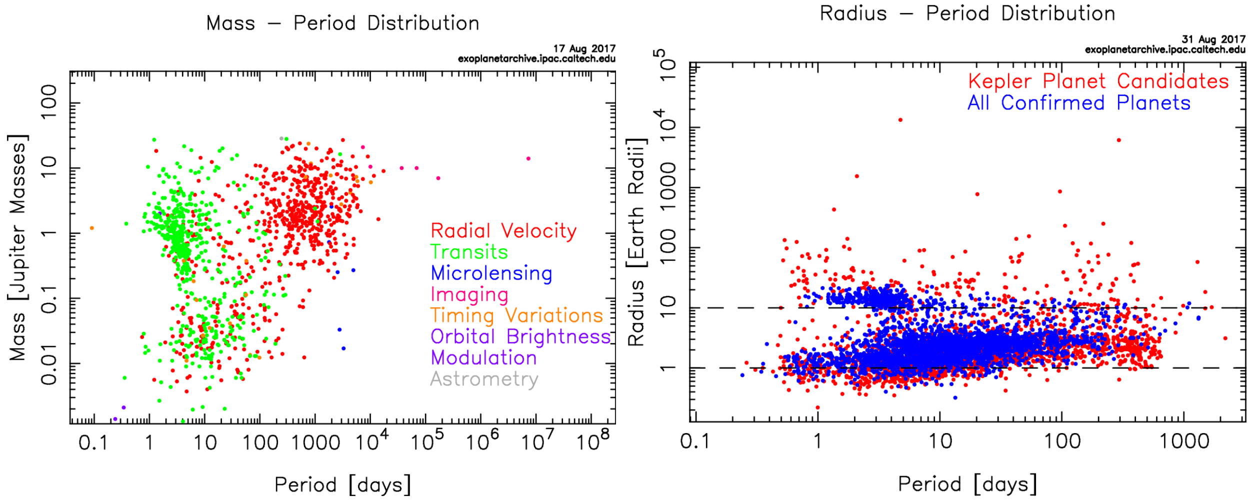

Figure 1. *Left:* The sample of known exoplanets in the mass - orbital period diagram (as of August 2017). Filled dots of different colors indicate objects detected with different techniques. *Right:* The sample of both candidate and confirmed transiting planets in the radius - orbital period diagram. Credits: NASA Exoplanet Archive.

2.1 Gaia Astrometry: Principles, Performance, and Lessons Learned

Gaia has adopted a mode of operations derived from the global-astrometry concept successfully demonstrated by its astrometric predecessor mission Hipparcos.[8] The slowly spinning satellite[9] continuously scans the sky (covering the whole celestial sphere in about six months) measuring the crossing times of targets transiting the focal plane. These observation times represent the one-dimensional, along-scan (AL) stellar positions relative to the instrument axes. All detected objects, irrespective of their magnitudes, are observed for the same amount of 28 time during each field-of-view crossing, with end-of-mission observing time mainly depending on ecliptic latitude. An astrometric global iterative solution (AGIS) process[10,11] effectively builds up the astrometric catalogue from a large number of such observations of transit times. The AGIS solution also involves a simultaneous reconstruction of the time-dependent spacecraft attitude, and a geometric calibration that consists in the optical mapping of the focal plane detector elements (pixels) through the spacecraft's two field of view (separated by a constant, large angle of 106.5 deg) onto the celestial sphere. The Gaia Data Processing and Analysis Consortium (DPAC) is in charge of the scientific processing of the Gaia data and production of the final Gaia catalogue to be released sometime in the 2022-2023 timeframe. The consortium lists $\sim$ 450 individual members in some 25 countries. Six data processing centers participate in the DPAC activities, which are organized in eight Coordination Units (CUs), each responsible for the development of one part of the data processing software (e.g., core astrometric processing, photometry). The ninth Coordination Unit (CU9) is in charge of the design and implementation of the Gaia archive. For details we refer the reader to the official presentation of the mission and its payload by Ref. 4.

A first detailed estimate of the end-of-mission science performance of Gaia has been published prior to launch in Ref. 14, based on CCD-level Monte Carlo simulations calibrated with measurements and then extrapolated to end-of-life conditions. The overall Gaia science performance was updated in Ref. 15, following the in-orbit commissioning phase of the mission. The commissioning phase lasted significantly longer than expected due to a number of unwanted surprises:

1. contamination of the optics by water ice, translating in transmission losses;
2. larger than expected variations of the basic angle between the two viewing directions of the two telescopes
3. significant straylight, which periodically varies with time;

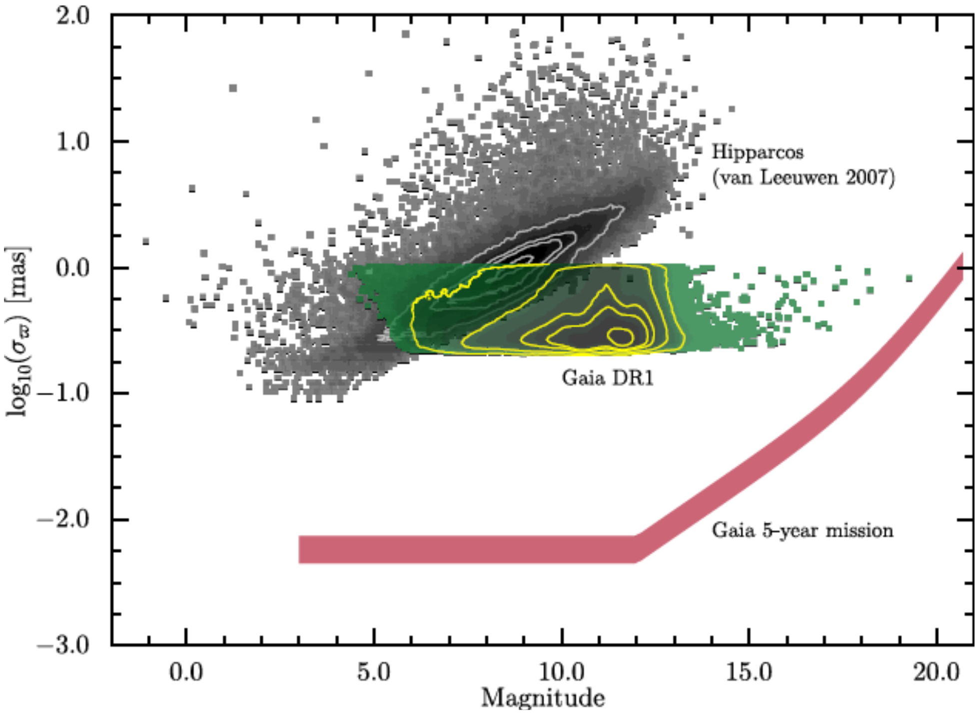

Figure 2. Parallax standard errors as a function of magnitude for Hipparcos[12] and the primary astrometric data set in Gaia DR1, compared to the predicted 5-year Gaia mission parallax standard errors. The band for the 5-year mission predictions indicates the expected variation as a function of celestial position. The colour coding for the Hipparcos and Gaia DR1 parallax error distributions indicates increasing numbers of sources from light to dark colours (logarithmic scale). For details, see Ref. 13.

4. frequent spikes in the spacecraft rotation rate (micro-clanks) due to sudden, minute structural changes within the spacecraft, and small, permanent changes in the spin rate of the spacecraft produced by micro-meteoroid hits.

The augmented noise levels associated with the increased straylight negatively impacts the performance on faint objects. As a consequence, the 2014 astrometric accuracy estimates are somewhat degraded compared to the 2012 values (as explained in Ref. 15). The other commissioning surprises are expected to have a fairly modest effect on the science output of the mission. First, the wavelength-dependent transmission losses are effectively dealt with by restoring the telescopes' throughput via successive payload decontamination campaigns. Second, micro-clanks and micro-meteoroid hits are easily identified from CCD-level transit data and are calibrated out in the preprocessing of the attitude data. Finally, the large, periodic fluctuations of the basic angle are accurately measured by the basic angle monitor (BAM) device, and subsequently added as knowledge in the astrometric global iterative solution. By looking at the the predicted, post-launch, sky-average, end-of-mission Gaia performance (`http://www.cosmos.esa.int/web/gaia/science-performance`) it is clear that the impact of the excess straylight levels becomes relevant in the astrometry only at faint magnitudes ($G \geq 17$ mag). This is good news as far as the the high expectations the mission has raised in the exoplanet field are concerned, since most of Gaia's exoplanet science is expected for brighter stars.

We show in Fig. 2 how the end-of-mission estimates of the parallax standard errors published in 2014 compare with the Hipparcos values[12] and the Tycho-Gaia Astrometric Solution (TGAS) parallax standard errors published in 2016 as part of Gaia Data Release 1(DR1).[13] The diagram clearly shows that DR1 accuracies are limited by systematic calibration errors. The typical uncertainty for sources in the primary astrometric dataset is about 0.3 mas, and a systematic component of ~ 0.3 mas should be added to the parallax uncertainties.[13] The reduction of attitude and calibration errors to negligible values will be a key challenge for DPAC in the production of DR2 and subsequent data releases. The task will not be a simple one, particularly at the bright end ($3 \leq G \leq 12$

mag) *. For these stars, saturation will be mitigated through the use of TDI gates, which are special structures on the CCDs that can be activated to inhibit charge transfer and hence to effectively reduce the integration time for bright sources.[4] Each TDI-gate configuration in use requires its own geometric calibration, the quality of which could in practice be compromised by the limited number of calibration targets in this magnitude range. In addition, residual errors in the calibrations of, for instance, basic-angle variations and chromaticity could also contribute to the total calibration budget of the brightest few million stars.

2.2 Gaia status and data release scenario

As of August 2017 Gaia science operations are proceeding nominally. While unwanted surprises have somewhat complicated the data processing and analysis scheme, one major source of concern that had been identified before launch, i.e. radiation damage of the CCD detectors, appears to be having a much smaller effect than predicted: extrapolations show that charge transfer inefficiency effects at end of mission will be approximately an order of magnitude less than predicted pre-flight.[17] In its first 1140 days of nominal life, Gaia has collected $\sim 85 \times 10^9$ transit measurements, subdivided in $\sim 830 \times 10^9$ billion astrometric CCD measurements, $\sim 170 \times 10^9$ billion photometric CCD measurements, and $\sim 15 \times 10^9$ spectroscopic CCD measurements. The nominal 5-year mission ends in July 2019. However, the cold gas of the micropropulsion attitude control system used to control the spin of the science mode could last till ∼2023–2024. In principle, therefore, the Gaia mission operations could be extended by up to five years. DPAC is currently pursuing approval by ESA's member states for a first extension (till end-2020).

In September 2016 DPAC released the first intermediate Gaia data release (DR1) was made public.[13] It contains a 'billion star atlas' of celestial coordinates[11] and magnitudes,[18] including ~ 2000 ICRF quasars,[19] time series photometry for ∼3000 selected RR Lyrae and Cepheid variable stars collected by Gaia during 28 days of ecliptic pole scanning law and 13 months of nominal scanning law operations,[20] and five-parameter astrometry for 2×10^6 sources in the Tycho-Gaia Astrometric Solution.[11]

The next data release, DR2, is planned for April 2018. Pending successful DPAC-internal validation, the Gaia DR2 will be consisting of *a*) five-parameter astrometric solutions for all sources with acceptable formal standard errors ($> 10^9$ anticipated), and positions (α, δ) for sources for which parallaxes and proper motions cannot be derived; *b*) G-band and integrated blue and red magnitudes for all sources; *c*) median radial velocities for sources brighter than $G \sim 12$ mag (a few million expected); *d*) estimates of the effective temperature and, where possible, line-of-sight extinction for stars brighter than $G = 17$ mag; *e*) Photometric data for a sample of variable star; *f*) epoch astrometry for a pre-selected list of $> 10,000$ asteroids.

With the experience gathered for the preparation of Gaia DR1 and while DR2 is being processed, DPAC has looked into releases thereafter. The major lesson learned is that for making a scientifically significant step forward, a reasonable time between releases is 2 rather than 1 year. The idea of the data releases is that each subsequent data release is based on a longer stretch of mission data and uses improved calibrations, such that the signal-to-noise ratio of the published results increases with time. In addition, fewer filters and more data products will be added in subsequent data releases, culminating with the publication of 'everything' in DR4 at the end of 2022 (see `https://www.cosmos.esa.int/web/gaia/release`). DR4 will contain an 'exoplanet list' and 'all epoch and transit data for all sources'. It will be based on all data collected during the nominal, 5-year mission. If the mission is extended, a final data release (DR5) will be added a few years after the end of spacecraft operations (∼2027).

2.3 Gaia Astrometric Orbits of Exoplanets

Gaia high-precision global astrometry is well poised to enable secure astrometric detections of planetary-mass companions. However, this is no easy task. There is in fact a variety of technical problems associated with the modeling of the astrometric signatures of planetary systems that must be carefully dealt with.[21] It is worth underlining that fitting astrometric orbit of exoplanets (particularly in the case of multiple companions) involves the adjustment of a large number of parameters, many of which nonlinear. The assessment of their

*For stars brighter than $G = 3$ mag, special observations, with associated non-trivial calibration challenges, are made which need dedicated, offline processing; see e.g., Ref. 16

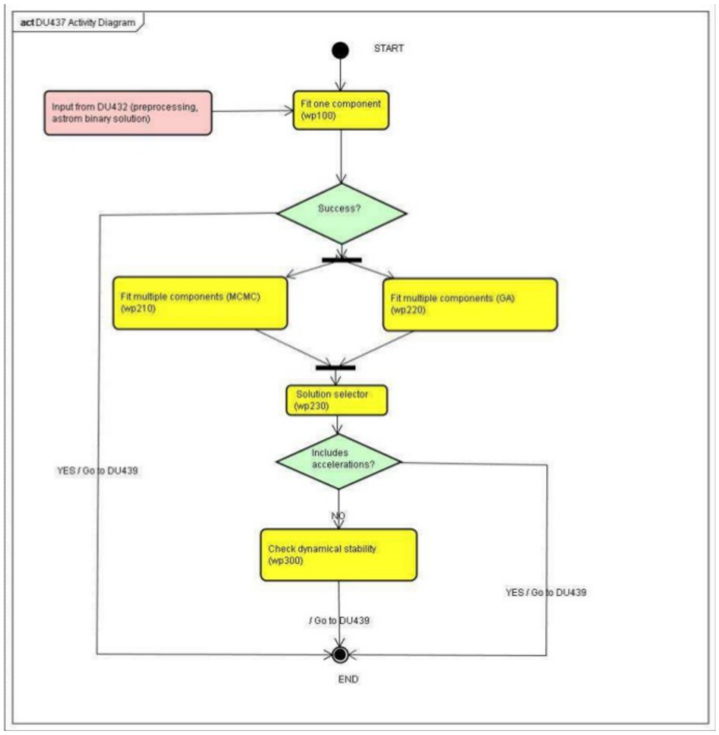

Figure 3. DU 437 Activity Diagram.

reliability and robustness (including meaningful error estimates on the fitted quantities) will be a nontrivial task, particularly in the limit of astrometric signals comparable in size to Gaias single-measurement uncertainties and/or limited redundancy in the number of observations with respect to the model parameters. For the above reasons, within the pipeline of Coordination Unit 4 (object processing) of DPAC a Development Unit (DU437) has been specifically devoted to the modelling of the astrometric signals produced by planetary systems around sources for which the single-star model with 5 astrometric parameters does not describe the data in a statistically satisfactory manner.[22] The DU is composed of several tasks, which implement multiple robust procedures for (single and multiple) astrometric orbit fitting (such as Markov Chain Monte Carlo and genetic algorithms) and the determination of the degree of dynamical stability of multiple-component systems.

Fig. 3 shows the activity diagram of DU437. The main feature of this software module consists of the use of two different solution algorithms for fitting astrometric orbits of planetary systems to Gaia transit data. In the tangent plane, Gaia position measurements in its sensitive (along-scan) direction are modeled as:

$$w = [\Delta\alpha_{\star 0} + (t-t_0)\mu_{\alpha_\star} + \sum_{j=1}^{n} B_j X_j(t) + G_j Y_j(t)] \sin\vartheta + [\Delta\delta_0 + (t-t_0)\mu_\delta + \sum_{j=1}^{n} A_j X_j(t) + F_j Y_j(t)] \cos\vartheta + f_w \pi \quad (1)$$

In Eq. 1, $\Delta\alpha_{\star 0}$ and $\Delta\delta_0$ are position offsets, $\mu_{\alpha_\star}$ and μ_δ are the two proper motion components, π and f_w are the parallax and along-scan parallax factor, t_0 the reference epoch, ϑ the position angle of the scan, A, F, B, G, X and Y are known functions of the orbital parameters in the Thiele-Innes elements representation,[23] and the sum is extended up to n planets. Note that the simplest star+planet solution has 12 parameters (5 astrometric parameters, 7 orbital elements) as opposed to a sky-averaged, end-of-mission number of field transits $N_{\rm fov} \sim 80$ (for $G < 16$ mag), and therefore the redundancy of the information is not very high.

The first algorithm is based on a hybrid Markov Chain Monte Carlo (MCMC) approach, that adopts a procedure for Bayesian parameter estimation based on a differential evolution MCMC algorithm[24] (DE-MC). Convergence of the solution is checked via the Gelman-Rubin test. The second orbital solution module implements

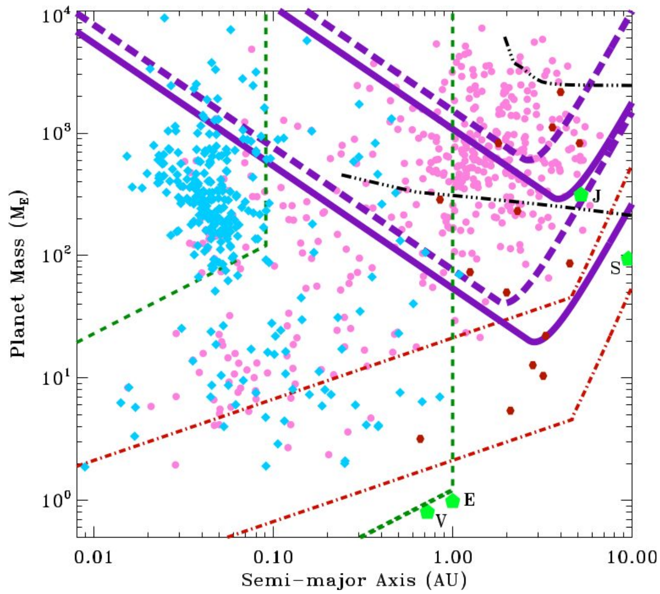

Figure 4. Gaia exoplanets discovery space (purple curves) compared to that of Doppler (red lines), transit (green curves), and direct imaging (black curves) techniques. Detectability curves are defined on the basis of a 3-σ criterion for signal detection, except for direct imaging for which a 5-σ criterion is adopted. The upper and lower purple long-dashed curves are for Gaia astrometry with $\sigma_{\rm A} = 20$ μas, assuming a 1-$M_\odot$ primary at 200 pc and a 0.4-$M_\odot$ M dwarf at 25 pc, respectively, and survey duration set to 5 yr. The two purple solid curves correspond to the expectations from a 10-yr extended Gaia mission. The RV curves (dashed-dotted lines) assume $\sigma_{\rm RV} = 1$ m s^{-1} (upper curve), typical of the state-of-the-art of the technique, and $\sigma_{\rm RV} = 10$ cm s^{-1} (lower curve), which is expected from ESPRESSO, $M_\star = 1$ $M_\odot$, and 10-yr survey duration. For visible-light transit photometry, the upper short-dashed curve reflects the sensitivity of ground-based programs, while the lower one is that appropriate for the Kepler mission. The upper dashed-dotted curve indicates the detection limits for SPHERE/VLT assuming a 250-Myr, J=8 mag primary at 30 pc, while the lower curve is for a more mature primary (1 Gyr) at the same distance observed by PCS/E-ELT. Three representative samples of observed planets are shown, as they were known at the end of 2015. The pink filled circles indicate the inventory of Doppler-detected exoplanets. Transiting systems are shown as light-blue filled diamonds. Red hexagons are planets detected by microlensing. Solar System planets are also shown (large green pentagons).

a method based on a genetic algorithm (GA) approach adapted from the existing RV fitting code YORBIT.[25] The last important element of the DU437 software module is constituted by its orbital stability analysis component. At present, a Hill stability criterion is applied.[26,27] This is sufficient to double-check dynamically pathologic (while potentially correct in a χ^2 sense!) solution sets (e.g., orbit-crossing due to $e \sim 1.0$) obtained by the De-MC and GA algorithms.

3. THE GAIA CONTRIBUTION TO THE EXOPLANET FIELD

3.1 Gaia Discovery Potential

The size of the astrometric perturbation induced on the primary by an orbiting planet (the astrometric signature) corresponds to the semi-major axis of the orbit of the primary around the barycenter of the system scaled by the distance to the observer: $\alpha = (M_p/M_\star) \times (a_p/d)$. With a_p in au, d in pc, and M_p and $M_\star$ in $M_\odot$, then α is evaluated in arcsec. At 10 pc, a $1-M_\oplus$ planet at 1 au from a $1-M_\odot$ star implies $\alpha = 0.3$ μas. As Gaia's best-achievable single-measurement astrometric precision is on the order of a few tens of μas, the discovery of terrestrial planets lies clearly beyond the realm of the mission's capabilities.

The sensitivity of Gaia astrometry to (single and multiple) giant planetary companions at intermediate separations around bright ($G \leq 13$ mag), nearby ($d \leq 200 - 300$ pc) F-G-K-type dwarfs has been quantified in the past.[28–30] More recent work[31,32] has revisited those early estimates based on improved (pre-commissioning) knowledge of the astrometric error budget and extending the studies to encompass a wider range of primary spectral types and limiting target magnitudes (down to $G = 20$ mag). The global figures on which all the above works converge speak of several thousands (possibly $10 - 20 \times 10^4$) astrometrically detectable giant planets at separations between typically 0.5 au and $4 - 5$ au from their parent stars. The global all-sky reservoir of stars around which Gaia will be sensitive to planetary-mass companions is likely in the range $10^6 - 10^7$. Finally, based on recent representations of the design of Gaia and its expected photometric performance, Gaia mmag-level photometry for $G \leq 16$ mag[14] should enable the detection of maybe $\approx 10^3$ transiting hot Jupiters around main-sequence solar-type stars.[33,34]

Recent studies have also focused on gauging the Gaia sensitivity to substellar companions around primaries with extreme spectral types as well as varied age, evolutionary, and multiplicity status, that will all be observed by Gaia in its fundamentally unbiased all-sky magnitude-limited survey. For example, thousands of detected ultra-cool dwarfs in the backyard of the Sun will have direct distance estimates from Gaia. For these, Gaia astrometry might be of sufficient precision to reveal any orbiting companions with masses even below 1 M_J.[35] The astrometric detection of massive (5-15 M_J) planets and mid-range (~ 50 M_J) brown dwarfs companions to white dwarfs with Gaia will also be possible out to 20-40 pc and 70 pc, respectively36. Finally, Gaia might discover hundreds of circumbinary giant planets in systems with F-G-K dwarf primaries within 200 pc of the Sun, assuming similar giant planet mass distribution and occurrence rates for tight binaries and single stars.[37]

3.2 The Gaia Legacy

Thanks to its unbiased census of tens of thousands of planetary systems, the actual impact of Gaia measurements in exoplanets science will be broad and structured. For example, the Gaia data will: **a)** allow to test the fine structure of giant planet parameters distributions and frequencies (including the transition region between giant planets and brown dwarfs), and investigate their changes as a function of stellar mass, metallicity, and age with unprecedented resolution; **b)** help crucially test theoretical models of the formation and migration of giant planets, study their impact on the formation scenarios for terrestrial planets, and establish a census of Solar-System analogs; **c)** achieve key improvements in our comprehension of important aspects of the formation and dynamical evolution of multiple-planet systems via direct measurements of their relative orbital arrangement; **d)** provide the first-ever statistically robust estimates of giant planet frequencies at intermediate separations around ultra-cool dwarfs and around stars in the final evolutionary states (e.g., white dwarfs), on the one hand supplying fundamental testing ground for the hypothesis that planet formation processes may not stop around sub-stellar mass primaries, and on the other hand lending crucial observational support for distinguishing between scenarios of post-main-sequence planetary systems evolution and second-generation planet formation processes.

3.3 The Extended Mission Opportunity

All the above simulation results were obtained assuming the nominal Gaia mission duration of 5 years. A significant extension of the mission, now actively pursued by DPAC, would significantly bolster the exoplanet science case for Gaia. Fig. 4 shows the sensitivity limits for Gaia in the $M_p - a_p$ diagram (see caption for details), compared to other detection techniques. In particular, the benefit of an extended, 10-yr Gaia mission is clear, in that it would make Gaia astrometry sensitive to Jupiter-like (i.e., $a_p \sim 5$ au, $M_p \sim 1$ M_J) companions around solar-type stars out to 150-200 pc, as well as cold Neptune-mass objects around the nearest ($d \leq 20$ pc) low-mass stars. In the former case it would then be possible to take full advantage of the recent expectations for a rise in occurrence rates of giant planetary companions as a function of orbital separation out to 10 au.[38] By accessing the range of orbital periods op to $P \simeq 10$ yr, preliminary estimates[32] indicate that the Gaia exoplanet sample might more than double. In the latter case, this is almost entirely uncharted territory (see Fig. 1), so the potential of Gaia astrometry could be potentially ground-breaking.

Furthermore, recent work[38,39] based on Doppler and direct imaging measurements has allowed to provide initial constraints on the occurrence rates of multiple systems containing two giant planets: the frequency of massive companions over the range $1 - 20$ M_J and $1 - 20$ au in known systems with one gas giant appears very high, on the order of 50%. By combining this information with the detection rates of Ref. 32 and with the expectations for accurate astrometric modeling of multiple-planet systems from Ref. 30, we would then expect maybe 2,000 systems with two giant planets to be detected by a 5-yr Gaia mission, and as many as 200-300 with accurate enough orbital solutions so as to allow for precise mutual inclination angle determination. Again, these numbers might more than double in case of a 10-yr extended Gaia mission.

4. GAIA AND EXOPLANETS: A PANDORA'S BOX OF SYNERGIES

The broad range of applications to exoplanets science is such that Gaia data can be seen as an ideal complement to (and in synergy with) many ongoing and future observing programs devoted to the indirect and direct detection and characterization of planetary systems, both from the ground and in space.

4.1 Synergies with direct imaging programs

Gaia data on long-period planets will inform direct imaging surveys and spectroscopic characterization projects about the epoch and location of maximum brightness of (primarily non transiting) exoplanets, in order to estimate their optimal visibility. Recent work[31] has shown that to directly image intermediate-separation giant planets with good orbital solutions from Gaia appears difficult for an instrument such as SPHERE, while the combination of Gaia astrometry for such systems might then become more effective with next-generation direct imaging devices on telescopes such as the E-ELT. This is clearly confirmed by looking at the overlap of the two techniques in Fig. 4.

However, the expectations for a large population of giant planets out to 20-50 au[38] imply that many of these objects will be seen by Gaia based on detection of astrometric accelerations of the primary stars. Valuable statistical information could then be obtained in the case of successful measurements of the angular separation of the such companions.[40] Work in progress[41] is focusing on the effectiveness of the combination of SPHERE/VLT direct detections of wide-separation giant planets and brown dwarfs with Gaia determinations of accelerations in the stellar motion due to the orbiting companions for improved constraints on the orbital architecture and mass, thereby helping in the modeling and interpretation of giant planets' phase functions and light curves.

4.2 Synergies with transit programs

Recent findings[31,32] indicate that Gaia might identify tens if not hundreds of potentially transiting intermediate-separation giant planets (i.e. with astrometric orbits compatible with $i = 90°$, within a few degrees). Such systems, in which planets might transit and/or be occulted by their relatively bright primaries would then become very interesting targets for follow-up photometry, to ascertain whether the prediction is verified or not. Work in progress (Giacobbe, Sozzetti et al. in preparation) is focusing on gauging the effectiveness of accurate ephemeris prediction of potentially transiting systems based on Gaia astrometry alone and in combination with RV follow-up campaigns from the ground. The possibility to study a sample of transiting cold (i.e., long-period) giant planets is certainly intriguing, for systematic comparison with their strongly irradiated, short-period counterparts in terms of mass-radius relationship and atmospheric characterization. Dedicated photometric follow-up efforts would also help discriminating among and improving the characterization of the many transiting hot Jupiter candidates expected from Gaia photometry.[33]

The availability of very accurate direct distance measurements (a few percent) to all bright stars in the sky will be a critically needed contribution to the definition of the input catalogues for space-borne photometric transit surveys such as those that will be carried out by TESS[42] and PLATO.[43] It will be in fact possible to define stellar samples of nearby solar-type main-sequence stars with negligible contamination from distant giant stars. Gaia parallaxes will also be instrumental in the improved determination of the fundamental physical properties (mass radius) of the hosts of (candidate and confirmed) transiting planets from Kepler, K2, TESS, CHEOPS, and PLATO, as well as ground-based transit surveys (such as WASP and HAT), thus allowing to improve the measurements of the planetary parameters themselves. Recent investigations[44] have shown that accuracies in masses and radii based on Gaia DR1 results are generally larger than previously published model-dependent precisions, but this is bound to change starting with Gaia DR2 in 2018.

4.3 Synergies with Doppler programs

There is a very strong, two-fold synergy potential between Gaia astrometry and high-precision radial-velocity (RV) measurements gathered with instrumentation operating at both visible (e.g., HARPS, HARPS-N, ESPRESSO, HIRES/E-ELT) and infrared wavelengths (e.g., GIANO, SPIROU, CARMENES, NIRPS) that either constitute the state-of-the-art of the Doppler technique or will come online during the next decade.[45] First, the combination of RVs of all bright ($V < 13$ mag), nearby ($d < 200$ pc) stars hosting planets and Gaia astrometric data will allow to a) characterize planetary systems across orders of magnitude in mass and orbital separation, and b) improve studies of the dynamical evolution of multiple systems with giant planets, including meaningful coplanarity analyses. Second, high-resolution, high-precision Doppler programs will cherry-pick on Gaia astrometric detections with the three-fold aim of 1) improving the phase sampling of the astrometric orbits determined by Gaia, 2) extending the time baseline of the observations (to put stringent constraints on or actually characterize long-period companions), and 3) search for additional, low-mass and/or short-period components which might have been missed by Gaia due to lack of sensitivity. As the sample of planetary systems for which most of the synergies between Gaia astrometry and high-precision RVs will be exploited is that orbiting bright stars, the synergy aspects between the two techniques will be maximized provided the expectations for single-measurement accuracies of a few tens of μas in the bright-star regime are met.

4.4 Synergies with Other Astrometric Programs

The possibility to take advantage of long time baselines ($20-30$ yr) for improved characterization of the outer regions of planetary systems will be a key synergy element between Gaia and existing astrometric planet detection programs, that from the ground have focused on (very) low-mass stars as primary targets,[46–49] while in space have been aimed at mass determinations of known systems identified with Doppler measurements (see Ref.,[50] and references therein). Gaia will also provide a fundamental catalog of systems for follow-up with future planned, proposed, and new concepts for space-borne observatories with ultra-high-precision astrometric capabilities, such as WFIRST,[51] Theia,[52] STEP,[53] and gaiaNIR.[54] The combination of Gaia astrometry with data from such programs would, for example, allow to characterize the mass function of giant planets at orbital separations typical of our Saturn, and would ease the interpretation and modeling of signals from close-in terrestrial planets in multiple systems with known outer gas giants.

5. SUMMARY

The Gaia all-sky survey will undoubtedly set the standards in high-precision astrometry for the next decade or two. Gaia's defining role in the exoplanet arena will be the largest compilation of new, high-accuracy astrometric orbits of giant planets, unbiased across all spectral types, chemical composition, and age of the primaries, as well as exquisitely precise parallaxes of bright stars with and without planets. The combination of Gaia data with ongoing and planned exoplanet detection and (atmospheric) characterization programs, both from the ground and in space, will establish strong synergies that will in turn allow to probe deeper into many aspects of the formation, physical and dynamical evolution of planetary systems. Twenty three years after the first mission proposal to ESA, and five years after launch, Gaia is finally about to deliver on its promise of revolutionary science in the field of exoplanets with μas-level astrometry, starting with DR2 in April 2018.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge useful discussions with Jos de Bruijne. This work was supported by the Italian Space Agency through Gaia mission contract: the Italian participation to DPAC, ASI 2014-025-R.1.2015 in collaboration with the Italian National Institute of Astrophysics.

REFERENCES

[1] Mayor, M. and Queloz, D., "A Jupiter-mass companion to a solar-type star," *Nature* **378**, 355–359 (Nov. 1995).

[2] Winn, J. N. and Fabrycky, D. C., "The Occurrence and Architecture of Exoplanetary Systems," *ARA&A* **53**, 409–447 (Aug. 2015).

[3] Sozzetti, A., "Detection and Characterization of Planetary Systems with μas Astrometry," *EAS Publications Series* **42**, 55–77 (Apr. 2010).

[4] Gaia Collaboration, Prusti, T., de Bruijne, J. H. J., Brown, A. G. A., Vallenari, A., Babusiaux, C., Bailer-Jones, C. A. L., Bastian, U., Biermann, M., Evans, D. W., and et al., "The Gaia mission," *A&A* **595**, A1 (Nov. 2016a).

[5] Lindegren, L., "Accuracy and Characteristics of the Hipparcos Catalogue," *ESA Special Publication* **1111**, 311 (June 1989).

[6] Perryman, M. A. C., Lindegren, L., Kovalevsky, J., Hoeg, E., Bastian, U., Bernacca, P. L., Crézé, M., Donati, F., Grenon, M., Grewing, M., van Leeuwen, F., van der Marel, H., Mignard, F., Murray, C. A., Le Poole, R. S., Schrijver, H., Turon, C., Arenou, F., Froeschlé, M., and Petersen, C. S., "The HIPPARCOS Catalogue," *A&A* **323**, L49–L52 (July 1997).

[7] Perryman, M. A. C., de Boer, K. S., Gilmore, G., Høg, E., Lattanzi, M. G., Lindegren, L., Luri, X., Mignard, F., Pace, O., and de Zeeuw, P. T., "GAIA: Composition, formation and evolution of the Galaxy," *A&A* **369**, 339–363 (Apr. 2001).

[8] Lindegren, L. and Kovalevsky, J., "Overview of the Data Acquisition and Reductions," *ESA Special Publication* **1111**, 1 (June 1989).

[9] Lindegren, L. and Bastian, U., "Basic principles of scanning space astrometry," *EAS Publications Series* **45**, 109–114 (Feb. 2011).

[10] Lindegren, L., Lammers, U., Hobbs, D., O'Mullane, W., Bastian, U., and Hernández, J., "The astrometric core solution for the Gaia mission. Overview of models, algorithms, and software implementation," *A&A* **538**, A78 (Feb. 2012).

[11] Lindegren, L., Lammers, U., Bastian, U., Hernández, J., Klioner, S., Hobbs, D., Bombrun, A., Michalik, D., Ramos-Lerate, M., Butkevich, A., Comoretto, G., Joliet, E., Holl, B., Hutton, A., Parsons, P., Steidelmüller, H., Abbas, U., Altmann, M., Andrei, A., Anton, S., Bach, N., Barache, C., Becciani, U., Berthier, J., Bianchi, L., Biermann, M., Bouquillon, S., Bourda, G., Brüsemeister, T., Bucciarelli, B., Busonero, D., Carlucci, T., Castañeda, J., Charlot, P., Clotet, M., Crosta, M., Davidson, M., de Felice, F., Drimmel, R., Fabricius, C., Fienga, A., Figueras, F., Fraile, E., Gai, M., Garralda, N., Geyer, R., González-Vidal, J. J., Guerra, R., Hambly, N. C., Hauser, M., Jordan, S., Lattanzi, M. G., Lenhardt, H., Liao, S., Löffler, W., McMillan, P. J., Mignard, F., Mora, A., Morbidelli, R., Portell, J., Riva, A., Sarasso, M., Serraller, I., Siddiqui, H., Smart, R., Spagna, A., Stampa, U., Steele, I., Taris, F., Torra, J., van Reeven, W., Vecchiato, A., Zschocke, S., de Bruijne, J., Gracia, G., Raison, F., Lister, T., Marchant, J., Messineo, R., Soffel, M., Osorio, J., de Torres, A., and O'Mullane, W., "Gaia Data Release 1. Astrometry: one billion positions, two million proper motions and parallaxes," *A&A* **595**, A4 (Nov. 2016).

[12] van Leeuwen, F., "Validation of the new Hipparcos reduction," *A&A* **474**, 653–664 (Nov. 2007).

[13] Gaia Collaboration, Brown, A. G. A., Vallenari, A., Prusti, T., de Bruijne, J. H. J., Mignard, F., Drimmel, R., Babusiaux, C., Bailer-Jones, C. A. L., Bastian, U., and et al., "Gaia Data Release 1. Summary of the astrometric, photometric, and survey properties," *A&A* **595**, A2 (Nov. 2016b).

[14] de Bruijne, J. H. J., "Science performance of Gaia, ESA's space-astrometry mission," *Ap&SS* **341**, 31–41 (Sept. 2012).

[15] de Bruijne, J. H. J., Rygl, K. L. J., and Antoja, T., "Gaia Astrometric Science Performance - Post-Launch Predictions," *EAS Publications Series* **67**, 23–29 (July 2014).

[16] Martín-Fleitas, J., Sahlmann, J., Mora, A., Kohley, R., Massart, B., L'Hermitte, J., Le Roy, M., and Paulet, P., "Enabling Gaia observations of naked-eye stars," *Proc. SPIE* **9143**, 91430Y (Aug. 2014).

[17] Crowley, C., Kohley, R., Hambly, N. C., Davidson, M., Abreu, A., van Leeuwen, F., Fabricius, C., Seabroke, G., de Bruijne, J. H. J., Short, A., Lindegren, L., Brown, A. G. A., Sarri, G., Gare, P., Prusti, T., Prod'homme, T., Mora, A., Martín-Fleitas, J., Raison, F., Lammers, U., O'Mullane, W., and Jansen, F., "Gaia Data Release 1. On-orbit performance of the Gaia CCDs at L2," *A&A* **595**, A6 (Nov. 2016).

[18] van Leeuwen, F., Evans, D. W., De Angeli, F., Jordi, C., Busso, G., Cacciari, C., Riello, M., Pancino, E., Altavilla, G., Brown, A. G. A., Burgess, P., Carrasco, J. M., Cocozza, G., Cowell, S., Davidson, M., De Luise, F., Fabricius, C., Galleti, S., Gilmore, G., Giuffrida, G., Hambly, N. C., Harrison, D. L., Hodgkin, S. T., Holland, G., MacDonald, I., Marinoni, S., Montegriffo, P., Osborne, P., Ragaini, S., Richards, P. J., Rowell, N., Voss, H., Walton, N. A., Weiler, M., Castellani, M., Delgado, A., Høg, E., van Leeuwen, M., Millar, N. R., Pagani, C., Piersimoni, A. M., Pulone, L., Rixon, G., Suess, F. F., Wyrzykowski, Ł., Yoldas, A., Alecu, A., Allan, P. M., Balaguer-Núñez, L., Barstow, M. A., Bellazzini, M., Belokurov, V., Blagorodnova, N., Bonfigli, M., Bragaglia, A., Brown, S., Bunclark, P., Buonanno, R., Burgon, R., Campbell, H., Collins, R. S., Cross, N. J. G., Ducourant, C., van Elteren, A., Evans, N. W., Federici, L., Fernández-Hernández, J., Figueras, F., Fraser, M., Fyfe, D., Gebran, M., Heyrovsky, A., Holl, B., Holland, A. D., Iannicola, G., Irwin, M., Koposov, S. E., Krone-Martins, A., Mann, R. G., Marrese, P. M., Masana, E., Munari, U., Ortiz, P., Ouzounis, A., Peltzer, C., Portell, J., Read, A., Terrett, D., Torra, J., Trager, S. C., Troisi, L., Valentini,

G., Vallenari, A., and Wevers, T., "Gaia Data Release 1. The photometric data," *A&A* **599**, A32 (Mar. 2017).

[19] Mignard, F., Klioner, S., Lindegren, L., Bastian, U., Bombrun, A., Hernández, J., Hobbs, D., Lammers, U., Michalik, D., Ramos-Lerate, M., Biermann, M., Butkevich, A., Comoretto, G., Joliet, E., Holl, B., Hutton, A., Parsons, P., Steidelmüller, H., Andrei, A., Bourda, G., and Charlot, P., "Gaia Data Release 1. Reference frame and optical properties of ICRF sources," *A&A* **595**, A5 (Nov. 2016).

[20] Clementini, G., Ripepi, V., Leccia, S., Mowlavi, N., Lecoeur-Taibi, I., Marconi, M., Szabados, L., Eyer, L., Guy, L. P., Rimoldini, L., Jevardat de Fombelle, G., Holl, B., Busso, G., Charnas, J., Cuypers, J., De Angeli, F., De Ridder, J., Debosscher, J., Evans, D. W., Klagyivik, P., Musella, I., Nienartowicz, K., Ordóñez, D., Regibo, S., Riello, M., Sarro, L. M., and Süveges, M., "Gaia Data Release 1. The Cepheid and RR Lyrae star pipeline and its application to the south ecliptic pole region," *A&A* **595**, A133 (Nov. 2016).

[21] Sozzetti, A., "Astrometric Methods and Instrumentation to Identify and Characterize Extrasolar Planets: A Review," *PASP* **117**, 1021–1048 (Oct. 2005).

[22] Pourbaix, D., "Screening and modelling the double and multiple stars observed by Gaia," *American Institute of Physics Conference Series* **1346**, 122–133 (July 2011).

[23] Green, R. M., [*Spherical astronomy*], Cambridge and New York: Cambridge University Press (1985).

[24] Eastman, J., Gaudi, B. S., and Agol, E., "EXOFAST: A Fast Exoplanetary Fitting Suite in IDL," *PASP* **125**, 83 (Jan. 2013).

[25] Ségransan, D., Mayor, M., Udry, S., Lovis, C., Benz, W., Bouchy, F., Lo Curto, G., Mordasini, C., Moutou, C., Naef, D., Pepe, F., Queloz, D., and Santos, N., "The HARPS search for southern extra-solar planets. XXIX. Four new planets in orbit around the moderatly active dwarfs HD 63765, HD 104067, HD 125595, and HIP 70849," *A&A* **535**, A54 (Nov. 2011).

[26] Marchal, C. and Bozis, G., "Hill Stability and Distance Curves for the General Three-Body Problem," *Celestial Mechanics* **26**, 311–333 (Mar. 1982).

[27] Giuppone, C. A., Morais, M. H. M., and Correia, A. C. M., "A semi-empirical stability criterion for real planetary systems with eccentric orbits," *MNRAS* **436**, 3547–3556 (Dec. 2013).

[28] Lattanzi, M. G., Spagna, A., Sozzetti, A., and Casertano, S., "Space-borne global astrometric surveys: the hunt for extrasolar planets," *MNRAS* **317**, 211–224 (Sept. 2000).

[29] Sozzetti, A., Casertano, S., Lattanzi, M. G., and Spagna, A., "Detection and measurement of planetary systems with GAIA," *A&A* **373**, L21–L24 (July 2001).

[30] Casertano, S., Lattanzi, M. G., Sozzetti, A., Spagna, A., Jancart, S., Morbidelli, R., Pannunzio, R., Pourbaix, D., and Queloz, D., "Double-blind test program for astrometric planet detection with Gaia," *A&A* **482**, 699–729 (May 2008).

[31] Sozzetti, A., Giacobbe, P., Lattanzi, M. G., Micela, G., Morbidelli, R., and Tinetti, G., "Astrometric detection of giant planets around nearby M dwarfs: the Gaia potential," *MNRAS* **437**, 497–509 (Jan. 2014).

[32] Perryman, M., Hartman, J., Bakos, G. Á., and Lindegren, L., "Astrometric Exoplanet Detection with Gaia," *ApJ* **797**, 14 (Dec. 2014).

[33] Dzigan, Y. and Zucker, S., "Detection of Transiting Jovian Exoplanets by Gaia Photometry – Expected Yield," *ApJ* **753**, L1 (July 2012).

[34] Dzigan, Y. and Zucker, S., "Directed follow-up strategy of low-cadence photometric surveys in search of transiting exoplanets - II. Application to Gaia," *MNRAS* **428**, 3641–3647 (Feb. 2013).

[35] Sozzetti, A., "Gaia, non-single stars, brown dwarfs, and exoplanets," *Mem. SAIt* **85**, 643 (2014).

[36] Silvotti, R., Sozzetti, A., Lattanzi, M., and Morbidelli, R., "Detectability of Substellar Companions Around White Dwarfs with Gaia," *Astronomical Society of the Pacific Conference Series* **493**, 455 (June 2015).

[37] Sahlmann, J., Triaud, A. H. M. J., and Martin, D. V., "Gaia's potential for the discovery of circumbinary planets," *MNRAS* **447**, 287–297 (Feb. 2015c).

[38] Bryan, M. L., Knutson, H. A., Howard, A. W., Ngo, H., Batygin, K., Crepp, J. R., Fulton, B. J., Hinkley, S., Isaacson, H., Johnson, J. A., Marcy, G. W., and Wright, J. T., "Statistics of Long Period Gas Giant Planets in Known Planetary Systems," *ApJ* **821**, 89 (Apr. 2016).

[39] Knutson, H. A., Fulton, B. J., Montet, B. T., Kao, M., Ngo, H., Howard, A. W., Crepp, J. R., Hinkley, S., Bakos, G. Á., Batygin, K., Johnson, J. A., Morton, T. D., and Muirhead, P. S., "Friends of Hot Jupiters. I. A Radial Velocity Search for Massive, Long-period Companions to Close-in Gas Giant Planets," *ApJ* **785**, 126 (Apr. 2014).

[40] Torres, G., "Substellar Companion Masses from Minimal Radial Velocity or Astrometric Information: a Monte Carlo Approach," *PASP* **111**, 169–176 (Feb. 1999).

[41] Sozzetti, A., Bonavita, M., Desidera, S., Gratton, R., and Lattanzi, M. G., "Gaia: The Astrometry Revolution," *IAU Symposium* **314**, 264–269 (Jan. 2016).

[42] Ricker, G. R., Winn, J. N., Vanderspek, R., Latham, D. W., Bakos, G. Á., Bean, J. L., Berta-Thompson, Z. K., Brown, T. M., Buchhave, L., Butler, N. R., Butler, R. P., Chaplin, W. J., Charbonneau, D., Christensen-Dalsgaard, J., Clampin, M., Deming, D., Doty, J., De Lee, N., Dressing, C., Dunham, E. W., Endl, M., Fressin, F., Ge, J., Henning, T., Holman, M. J., Howard, A. W., Ida, S., Jenkins, J., Jernigan, G., Johnson, J. A., Kaltenegger, L., Kawai, N., Kjeldsen, H., Laughlin, G., Levine, A. M., Lin, D., Lissauer, J. J., MacQueen, P., Marcy, G., McCullough, P. R., Morton, T. D., Narita, N., Paegert, M., Palle, E., Pepe, F., Pepper, J., Quirrenbach, A., Rinehart, S. A., Sasselov, D., Sato, B., Seager, S., Sozzetti, A., Stassun, K. G., Sullivan, P., Szentgyorgyi, A., Torres, G., Udry, S., and Villasenor, J., "Transiting Exoplanet Survey Satellite (TESS)," *Proc. SPIE* **9143**, 914320 (Aug. 2014).

[43] Rauer, H., Catala, C., Aerts, C., Appourchaux, T., Benz, W., Brandeker, A., Christensen-Dalsgaard, J., Deleuil, M., Gizon, L., Goupil, M.-J., Güdel, M., Janot-Pacheco, E., Mas-Hesse, M., Pagano, I., Piotto, G., Pollacco, D., Santos, Ċ., Smith, A., Suárez, J.-C., Szabó, R., Udry, S., Adibekyan, V., Alibert, Y., Almenara, J.-M., Amaro-Seoane, P., Eiff, M. A.-v., Asplund, M., Antonello, E., Barnes, S., Baudin, F., Belkacem, K., Bergemann, M., Bihain, G., Birch, A. C., Bonfils, X., Boisse, I., Bonomo, A. S., Borsa, F., Brandão, I. M., Brocato, E., Brun, S., Burleigh, M., Burston, R., Cabrera, J., Cassisi, S., Chaplin, W., Charpinet, S., Chiappini, C., Church, R. P., Csizmadia, S., Cunha, M., Damasso, M., Davies, M. B., Deeg, H. J., Díaz, R. F., Dreizler, S., Dreyer, C., Eggenberger, P., Ehrenreich, D., Eigmüller, P., Erikson, A., Farmer, R., Feltzing, S., de Oliveira Fialho, F., Figueira, P., Forveille, T., Fridlund, M., García, R. A., Giommi, P., Giuffrida, G., Godolt, M., Gomes da Silva, J., Granzer, T., Grenfell, J. L., Grotsch-Noels, A., Günther, E., Haswell, C. A., Hatzes, A. P., Hébrard, G., Hekker, S., Helled, R., Heng, K., Jenkins, J. M., Johansen, A., Khodachenko, M. L., Kislyakova, K. G., Kley, W., Kolb, U., Krivova, N., Kupka, F., Lammer, H., Lanza, A. F., Lebreton, Y., Magrin, D., Marcos-Arenal, P., Marrese, P. M., Marques, J. P., Martins, J., Mathis, S., Mathur, S., Messina, S., Miglio, A., Montalban, J., Montalto, M., Monteiro, M. J. P. F. G., Moradi, H., Moravveji, E., Mordasini, C., Morel, T., Mortier, A., Nascimbeni, V., Nelson, R. P., Nielsen, M. B., Noack, L., Norton, A. J., Ofir, A., Oshagh, M., Ouazzani, R.-M., Pápics, P., Parro, V. C., Petit, P., Plez, B., Poretti, E., Quirrenbach, A., Ragazzoni, R., Raimondo, G., Rainer, M., Reese, D. R., Redmer, R., Reffert, S., Rojas-Ayala, B., Roxburgh, I. W., Salmon, S., Santerne, A., Schneider, J., Schou, J., Schuh, S., Schunker, H., Silva-Valio, A., Silvotti, R., Skillen, I., Snellen, I., Sohl, F., Sousa, S. G., Sozzetti, A., Stello, D., Strassmeier, K. G., Švanda, M., Szabó, G. M., Tkachenko, A., Valencia, D., Van Grootel, V., Vauclair, S. D., Ventura, P., Wagner, F. W., Walton, N. A., Weingrill, J., Werner, S. C., Wheatley, P. J., and Zwintz, K., "The PLATO 2.0 mission," *Experimental Astronomy* **38**, 249–330 (Nov. 2014).

[44] Stassun, K. G., Collins, K. A., and Gaudi, B. S., "Accurate Empirical Radii and Masses of Planets and Their Host Stars with Gaia Parallaxes," *AJ* **153**, 136 (Mar. 2017).

[45] Fischer, D. A., Anglada-Escude, G., Arriagada, P., Baluev, R. V., Bean, J. L., Bouchy, F., Buchhave, L. A., Carroll, T., Chakraborty, A., Crepp, J. R., Dawson, R. I., Diddams, S. A., Dumusque, X., Eastman, J. D., Endl, M., Figueira, P., Ford, E. B., Foreman-Mackey, D., Fournier, P., Fűrész, G., Gaudi, B. S., Gregory, P. C., Grundahl, F., Hatzes, A. P., Hébrard, G., Herrero, E., Hogg, D. W., Howard, A. W., Johnson, J. A., Jorden, P., Jurgenson, C. A., Latham, D. W., Laughlin, G., Loredo, T. J., Lovis, C., Mahadevan, S., McCracken, T. M., Pepe, F., Perez, M., Phillips, D. F., Plavchan, P. P., Prato, L., Quirrenbach, A., Reiners, A., Robertson, P., Santos, N. C., Sawyer, D., Segransan, D., Sozzetti, A., Steinmetz, T., Szentgyorgyi, A., Udry, S., Valenti, J. A., Wang, S. X., Wittenmyer, R. A., and Wright, J. T., "State of the Field: Extreme Precision Radial Velocities," *PASP* **128**, 066001 (June 2016).

[46] Anglada-Escudé, G., Boss, A. P., Weinberger, A. J., Thompson, I. B., Butler, R. P., Vogt, S. S., and Rivera, E. J., "Astrometry and Radial Velocities of the Planet Host M Dwarf GJ 317: New Trigonometric Distance, Metallicity, and Upper Limit to the Mass of GJ 317b," *ApJ* **746**, 37 (Feb. 2012).

[47] Sahlmann, J., Lazorenko, P. F., Ségransan, D., Martín, E. L., Queloz, D., Mayor, M., and Udry, S., "Astrometric orbit of a low-mass companion to an ultracool dwarf," *A&A* **556**, A133 (Aug. 2013).

[48] Sahlmann, J., Lazorenko, P. F., Ségransan, D., Astudillo-Defru, N., Bonfils, X., Delfosse, X., Forveille, T., Hagelberg, J., Lo Curto, G., Pepe, F., Queloz, D., Udry, S., and Zimmerman, N. T., "The mass of planet GJ 676A b from ground-based astrometry. A planetary system with two mature gas giants suitable for direct imaging," *A&A* **595**, A77 (Nov. 2016).

[49] Boss, A. P., Weinberger, A. J., Keiser, S. A., Astraatmadja, T. L., Anglada-Escude, G., and Thompson, I. B., "Astrometric Constraints on the Masses of Long-Period Gas Giant Planets in the TRAPPIST-1 Planetary System," *ArXiv e-prints* (Aug. 2017).

[50] Benedict, G. F., McArthur, B. E., Nelan, E. P., and Harrison, T. E., "Astrometry with Hubble Space Telescope Fine Guidance Sensors – A Review," *PASP* **129**, 012001 (Jan. 2017).

[51] Spergel, D., Gehrels, N., Baltay, C., Bennett, D., Breckinridge, J., Donahue, M., Dressler, A., Gaudi, B. S., Greene, T., Guyon, O., Hirata, C., Kalirai, J., Kasdin, N. J., Macintosh, B., Moos, W., Perlmutter, S., Postman, M., Rauscher, B., Rhodes, J., Wang, Y., Weinberg, D., Benford, D., Hudson, M., Jeong, W.-S., Mellier, Y., Traub, W., Yamada, T., Capak, P., Colbert, J., Masters, D., Penny, M., Savransky, D., Stern, D., Zimmerman, N., Barry, R., Bartusek, L., Carpenter, K., Cheng, E., Content, D., Dekens, F., Demers, R., Grady, K., Jackson, C., Kuan, G., Kruk, J., Melton, M., Nemati, B., Parvin, B., Poberezhskiy, I., Peddie, C., Ruffa, J., Wallace, J. K., Whipple, A., Wollack, E., and Zhao, F., "Wide-Field InfrarRed Survey Telescope-Astrophysics Focused Telescope Assets WFIRST-AFTA 2015 Report," *ArXiv e-prints* (Mar. 2015).

[52] The Theia Collaboration, Boehm, C., Krone-Martins, A., Amorim, A., Anglada-Escude, G., Brandeker, A., Courbin, F., Ensslin, T., Falcao, A., Freese, K., Holl, B., Labadie, L., Leger, A., Malbet, F., Mamon, G., McArthur, B., Mora, A., Shao, M., Sozzetti, A., Spolyar, D., Villaver, E., Albertus, C., Bertone, S., Bouy, H., Boylan-Kolchin, M., Brown, A., Brown, W., Cardoso, V., Chemin, L., Claudi, R., Correia, A. C. M., Crosta, M., Crouzier, A., Cyr-Racine, F.-Y., Damasso, M., da Silva, A., Davies, M., Das, P., Dayal, P., de Val-Borro, M., Diaferio, A., Erickcek, A., Fairbairn, M., Fortin, M., Fridlund, M., Garcia, P., Gnedin, O., Goobar, A., Gordo, P., Goullioud, R., Hambly, N., Hara, N., Hobbs, D., Hog, E., Holland, A., Ibata, R., Jordi, C., Klioner, S., Kopeikin, S., Lacroix, T., Laskar, J., Le Poncin-Lafitte, C., Luri, X., Majumdar, S., Makarov, V., Massey, R., Mennesson, B., Michalik, D., Moitinho de Almeida, A., Mourao, A., Moustakas, L., Murray, N., Muterspaugh, M., Oertel, M., Ostorero, L., Perez-Garcia, A., Platais, I., de Mora, J. P. i., Quirrenbach, A., Randall, L., Read, J., Regos, E., Rory, B., Rybicki, K., Scott, P., Schneider, J., Scholtz, J., Siebert, A., Tereno, I., Tomsick, J., Traub, W., Valluri, M., Walker, M., Walton, N., Watkins, L., White, G., Evans, D. W., Wyrzykowski, L., and Wyse, R., "Theia: Faint objects in motion or the new astrometry frontier," *ArXiv e-prints* (July 2017).

[53] Chen, D., "Step mission: high-precision space astrometry to search for terrestrial exoplanets," *Journal of Instrumentation* **9**(04), C04040 (2014).

[54] Hobbs, D., Høg, E., Mora, A., Crowley, C., McMillan, P., Ranalli, P., Heiter, U., Jordi, C., Hambly, N., Church, R., Anthony, B., Tanga, P., Chemin, L., Portail, J., Jiménez-Esteban, F., Klioner, S., Mignard, F., Fynbo, J., Wyrzykowski, Ł., Rybicki, K., Anderson, R. I., Cellino, A., Fabricius, C., Davidson, M., and Lindegren, L., "GaiaNIR: Combining optical and Near-Infra-Red (NIR) capabilities with Time-Delay-Integration (TDI) sensors for a future Gaia-like mission," *ArXiv e-prints* (Sept. 2016).