INSTITUT DE FRANCE
Académie des sciences

Comptes Rendus

Physique

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Gaia astrometry and exoplanetary science: DR2, (E)DR3, and beyond

https://doi.org/10.5802/crphys.152

Part of Special Issue: Exoplanets
Guest editors: Anne-Marie Lagrange (LESIA, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, Sorbonne Paris Cité, 5 place Jules Janssen, 92195 Meudon, France.) and Daniel Rouan (LESIA, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, Sorbonne Paris Cité, 5 place Jules Janssen, 92195 Meudon, France.)

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Centre Mersenne pour l'édition scientifique ouverte
www.centre-mersenne.org
e-ISSN : 1878-1535

Comptes Rendus
Physique
Published online: 8 June 2023
`https://doi.org/10.5802/crphys.152`

Exoplanets / *Exoplanètes*

Gaia astrometry and exoplanetary science: DR2, (E)DR3, and beyond

L'astrométrie par GAIA et la science des exoplanètes : DR2, (E)DR3, et au-delà

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Abstract. I review the recent impact of Gaia astrometry in the exoplanet field, both in terms of characterization of the orbits and masses of planetary systems and the properties of their host stars. I then discuss the newly published results in the third major data release (DR3), that begin to tackle exoplanetary science based on Gaia data alone. I conclude with a perspective look at the expectations for major contributions to our understanding of exoplanet demographics from future Gaia data releases.

Résumé. Je passe en revue l'impact récent de l'astrométrie fournie par la mission spatiale Gaia dans le domaine des exoplanètes, tant en termes de caractérisation des orbites et des masses des systèmes planétaires que des propriétés de leurs étoiles hôtes. Je discute ensuite des résultats récemment publiés dans la troisième livraison majeure des données (DR3), qui commencent à aborder la science des exoplanètes sur la base des seules données de Gaia. Je conclus par un regard prospectif sur les contributions majeures à notre compréhension de la démographie des exoplanètes, attendues à partir des futures publications de données Gaia.

Keywords. Extrasolar planets, Brown Dwarfs, Gaia satellite, Astrometry, Spectroscopy, Transit Photometry.

Mots-clés. Planètes extra-solaires, naines brunes, satellite Gaia, astrométrie, spectroscopie, photométrie de transit.

Note. Follows up on a conference-debate of the French Academy of Sciences entitled "Exoplanets: the new challenges" held on 18 May 2021, visible via
https://www.academie-sciences.fr/fr/Colloques-conferences-et-debats/exoplanetes.html.
Note. Fait suite à une conférence-débat de l'Académie des sciences intitulée « Exoplanètes : les nouveaux défis » tenue le 18 mai 2021, visible via
https://www.academie-sciences.fr/fr/Colloques-conferences-et-debats/exoplanetes.html.

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1. Introduction

It is now more than 20 years since the first prediction on the exoplanet yield of ESA's space astrometry mission Gaia was published [1]. Over the last two decades, a significant body of works has contributed to update and refine the expectations both across a variety of spectral types of the primaries and for specific object classes [2–8]. The convergent view emerging from all the above works entails the astrometric detection by Gaia, assuming a nominal 5-yr mission duration, of several thousands (possibly $10-20\times10^4$) giant planets with typical separations in the range $0.5-4$ au from the host stars (see e.g. [9, Figure 4]). These numbers could as much as triple should the full Gaia mission extension be granted. 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.

As a direct consequence of its unbiased census of tens of thousands of planetary systems, the impact of Gaia astrometry in exoplanetary science is expected to be broad and structured. For example, the Gaia data will (a) allow to test the fine structure of giant planet parameters distributions and occurrence rates (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; and (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 substellar 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.

The broad range of contributions of Gaia astrometry to the demographics of exoplanetary systems will provide ideal complements and strong synergies 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. Studies of exoplanet demographics will in particular benefit from the synergies between Gaia and transit, Doppler and direct imaging programs (see [9] for details).

Gaia is now past its eighth year of scientific mission operations, started back in July 2014. The first two major data releases (DR2, [10]; EDR3, [11]) have provided data products for outstanding progress in our understanding of many an aspect of galactic astronomy and astrophysics. However, no direct binarity information was published at that time. The first catalog of non-single star solution, encompassing companions with masses in the substellar regime (brown dwarfs and planets) was published in June 2022 with Gaia DR3 [12]. I describe in turn the impact that these successive Gaia data releases have had on the science of extrasolar planets, concluding with a brief outlook on the expectations for Gaia DR4, slated to be published not before the end of 2025.

2. Gaia DR2 and EDR3

Gaia data release 2 (DR2) and early data release 3 (EDR3) delivered high-precision proper motions and parallaxes for ~ 1.3 billions and ~ 1.5 billions point sources, with a limiting magnitude of $G\approx 21$ and a bright limit of $G\approx 3$. The astrometric solutions were accompanied by quality indicators, such as the renormalized unit weight error (RUWE), and source image descriptors. This information has been extensively used for making important progress in crucial aspects of exoplanetary science even in absence of full-fledged orbital solutions for planetary-mass companions.

2.1. *Calibration of the hosts*

The availability of exquisitely precise direct distance measurements has allowed to significantly refine the properties of the class of transiting exoplanets. As a most notable example, Gaia precise and accurate parallaxes allowed to reduce typical uncertainties on the radius of stars in the original field of the Kepler mission [13] by up to a factor of 10. Using the improved knowledge of the stellar radii, [14] and [15] revisited the radius distribution of close-in ($P < 100$ days), small-size ($R_p \leq 4.0\ R_\oplus$) planets orbiting bright, unevolved F-G-K-type stars, unveiling its clear bimodality. The 'radius valley' is characterized by a suppression by a factor ~ 2 of the occurrence rate distribution in the range $1.5-2.0\ R_\oplus$. This "gap" splits the population of close-in small planets into two size regimes of nearly identical intrinsic frequency: super Earths with $R_p < 1.5\ R_\oplus$ and sub-Neptunes with $R_p = 2.0-3.0\ R_\oplus$. The physical interpretation for the existence of the radius valley and in-depth studies of these two classes of small planets are the objective of much of recent research in the field (for a review, see e.g., [16], and references therein).

2.2. *Constraints on the presence of companions*

Taking advantage of the long time baseline of ~ 25 yr between the Hipparcos mission ([17], see also [18]) and Gaia DR2/EDR3 position measurements it is possible to effectively determine mean long-term proper motion vectors of nearby stars with high accuracy. For binary systems, this can be considered as a close representation of the tangential velocity of the barycentre of the system. By subtracting this long-term proper motion from the quasi-instantaneous proper motions of the two catalogues, one obtains a pair of "proper motion difference", "astrometric acceleration", or "proper motion anomaly" values (i.e. $\Delta\mu$), which are assumed to entirely describe the projected velocity of the photocentre around the barycentre at the Hipparcos and Gaia DR2/EDR3 mean epochs. This approach was systematically implemented by [19, 20] and Brandt [21, 22], who constructed in this way Hipparcos-Gaia catalogs of astrometric accelerations.

The $\Delta\mu$ values can be used to test for the presence of anomalies that indicate the presence of an orbiting secondary body, as they explicitly depend upon orbital elements and companion masses. [19, 20] produced sensitivity limits to companions or given mass and orbital separation (averaging over all other orbital elements) that extend well into the planetary regime for the nearest stars, and used statistically significant $\Delta\mu$ values (at the $\geq 3-\sigma$ level) to verify the compatibility of the proper motion differences with the effects of known companions, such as those orbiting ϵ Eri, ϵ Ind, Ross 614 and β Pic.

2.3. *Dynamical mass measurements*

As they effectively constitute only a total of 4 measurements ($\Delta\mu$ components in right ascension and declination components at the mean Hipparcos and Gaia DR2/EDR3 epochs), astrometric accelerations cannot be used alone to derive an actual mass for a companion. Precise and accurate dynamical mass determinations are instead achievable when the $\Delta\mu$ technique can be combined with relative astrometry (direct imaging) and Doppler spectroscopy.

Young, luminous, directly imaged companions in the brown dwarf and planetary regime (in particular, the companions in the β Pic and HR 8799 systems) have become targets of recent applications of this technique [23–32].

For companions without direct imaging information but well-determined spectroscopic orbital solutions, the combination with the Hipparcos–Gaia absolute astrometry can still be performed in two ways: 1) by directly carrying out a fit to both time-series, or 2) by exploring the ranges of the two orbital elements that only astrometry can determine (inclination i, longitude of the ascending node Ω) that are compatible with the measured $\Delta\mu$ values, with the remainder of the orbital parameters constrained by Doppler spectroscopy. In this way it is possible to remove the intrinsic uncertainty in the mass of the companion discovered by the radial velocity (RV) method, and determine its true mass rather than a minimum value. Recent, notable applications of this approach include: a) a preliminary astrometric mass for the super-Earth candidate orbiting at 1.5 au from the nearest star to the Sun, the M dwarf Proxima Centauri [33], which had been uncovered based on long-term RV time-series analysis [34]; b) true mass determinations for the long-period ($5 \leq P \leq 20$ yr) super-Jupiters ($1.5 \leq M_p \leq 10\ M_{\rm Jup}$) 14 Her b [35] and HD 83443 c [36], orbiting solar-mass primaries.

Finally, a most notable result based on the combined RV+absolute astrometry analysis concerns the π Mensae planetary system: known to host a Doppler-detected sub-stellar companion (minimum mass $M_b \sin i_b \sim 10\ M_{\rm Jup}$) on a long-period ($P_b \sim 2100$ days) and very eccentric ($e_b \sim 0.6$) orbit [37], it was found to also contain a transiting super-Earth (π Men c), the first transiting planet unveiled by the TESS mission [38]. [39] used long-term RV time-series to determine the true mass of π Men c, and the combination of RV and $\Delta\mu$ data allowed them to determine the dynamical mass of π Men b, which turned out to straddle the planet-brown dwarf boundary. As the inclination of π Men c was also known, it was then possible to measure the relative alignment between the orbits of the two planets, which turned out to be highly misaligned, with a mutual inclination of no less than ~ 50 deg. Similar findings were obtained by [40] and [41].

2.4. *New detections*

Evidence of statistically significant astrometric accelerations, indicating the likely presence of an intermediate- to wide-separation companion, can also be used to select targets for follow-up measurements with direct imaging instrumentation. This approach has been very successful in increasing the efficiency of detection of directly imaged companions. Direct-imaging discoveries and dynamical mass determinations for substellar companions orbiting accelerating stars were recently reported by e.g., [42–46].

3. Gaia DR3

3.1. *Overall statistics*

Gaia DR3 was published on June 13th, 2022. For the first time, it delivered non-single star (NSS) information gathered across its three observing channels. A total of $\sim 813\,000$ NSS solutions populated the Gaia DR3 archive (identified with a wide range of possible solution types), including $\sim 169\,000$ astrometric orbits, $\sim 187\,000$ spectroscopic orbits, and $\sim 87\,000$ eclipsing binary solutions. No information on higher multiplicity beyond the first companion is published in DR3. For details, we refer the reader to the main Gaia DR3 performance verification paper [47] accompanying the NSS release, processing papers on the processing of astrometric orbits [48, 49], and the relevant Chapter of the Gaia documentation [50].

Taken at face value, the numbers are astounding: based on the NSS analysis of a mere 0.3% of the full sample of sources observed by Gaia, the DR3 archive already contains ~ 45 times more spectroscopic orbits than the SB9 catalog [51], and ~ 300 times more astrometric orbits than the Orb6 catalog [52]. Binary companions are identified across the entire Hertzsprung-Russell diagram, including the white dwarf sequence. Binary mass ratios q encompass a very wide range, e.g., from $q < 0.001$ to $q < 1.0$. Orbital periods span the approximate range 0.2 – 3000 days, with most of the orbital solutions below 1000 days, reflecting the time-span of Gaia data used for DR3 processing. Figure 1 shows an example of a 'library' of astrometric orbits.

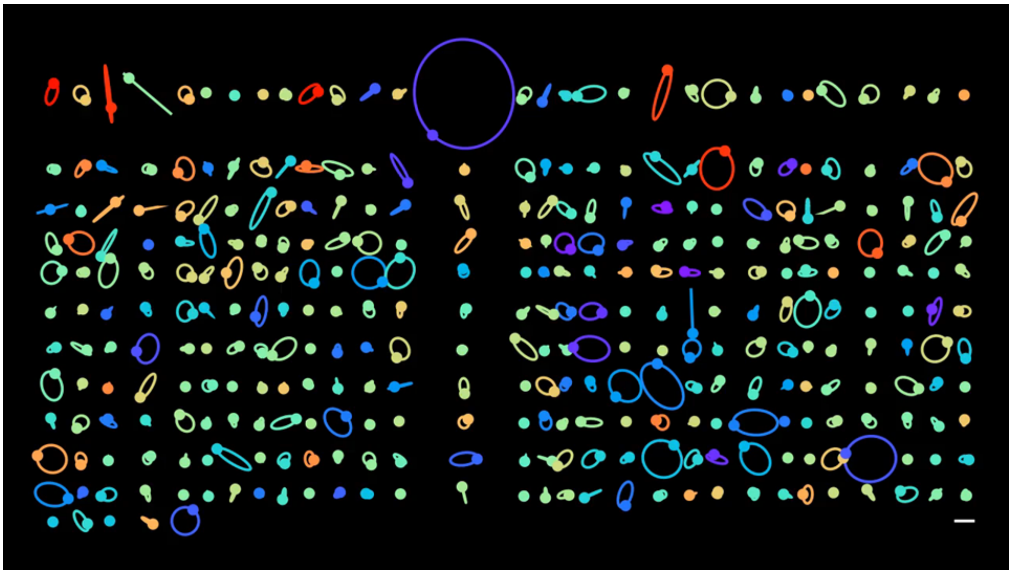

Figure 1. An 'orrery' of orbital solutions from Gaia DR3 astrometry. The wide range of shapes (from circular to highly eccentric orbits) and orientations (from edge-on to face-on orbits) is clear. Orbits are color-coded by the effective temperature of the primary (blue: hottest, red: coolest) *Credits: J. Sahlmann.*

3.2. *Validations checks, biases, and caveats*

The published solutions have received extensive validation efforts in order to minimize the fraction of spurious results. For example, in the case of astrometric solutions for bright stars also observed by Hipparcos, one would expect that massive companions on very long periods detected as acceleration solutions in Gaia DR3 also produce statistically significant proper motion anomalies. Indeed this is the case, with > 95% of acceleration solutions matched to $\Delta\mu$ values with $S/N > 3$ [47].

Even for bona-fide orbital solutions, some biases that are intrinsic to the NSS modeling approach adopted for DR3 were identified. For example, in the case of astrometry a pronounced suppression of edge-on orbits ($\cos i \approx 0.0$) was noted. The origin of the feature was understood (via simulations) in terms of the specific approach to orbit fitting with the partially linearized Thiele-Innes representation, in the presence of noisy data [47]. In the case of spectroscopy, a sizable fraction of low-amplitude, short-period signals are likely a variety of aliases of longer-period ones [47].

The NSS catalog is the result of a drastic selection process of sources. Still, the large sample of NSS solutions published in the DR3 archive is not free of contamination. As an example, in the low signal-to-noise regime [49] estimate that the fraction of spurious solutions could be in the ballpark range of 5%-10%. The impact of the successive selections at the level of the input list, during the data processing, and based on the posterior source filtering will have to be taken carefully into account in any statistical studies of the NSS sample.

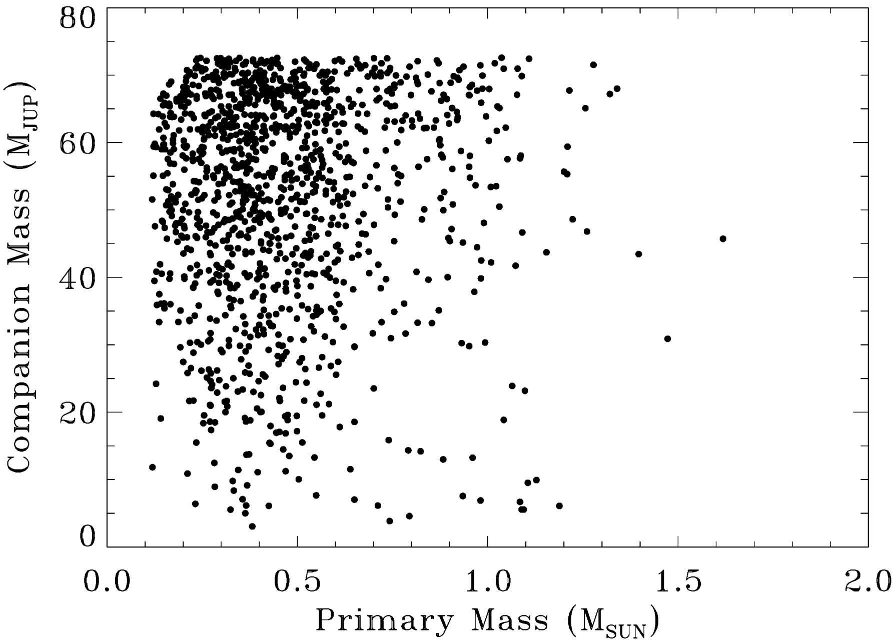

Figure 2. Companion mass vs. primary mass for the sample of orbital solutions in the substellar regime (see [47] for details)

3.3. *Substellar companions*

In [47] a catalog of masses of astrometrically and spectroscopically detected companions is presented, derived based on knowledge of the primary masses and under the assumption of null flux ratio (see more below). From astrometry alone, 1843 are identified as candidate brown dwarfs in the mass range $20 \leq M_c \leq 80$ M_{Jup}, while 72 are labeled as planet candidates with $M_c < 20$ M_{Jup}. A total of 10 brown dwarfs and 9 planets were already known, identified by ground-based Doppler surveys (see [47] for details). Astrometric orbital solutions are also published for 13 brown dwarf binaries, 7 of which had been known previously. A sample of 5723 spectroscopic companions is found to have $M_c \sin i < 80$ M_{Jup}, with ∼ 10% of these having $M_c \sin i < 20$ M_{Jup}. The vast majority of the radial-velocity detected substellar companions are found at very short periods ($P < 10$ days), and due to the above considerations on aliasing effects they should therefore be considered with caution (see [47] for additional details).

Finally, > 200 transiting exoplanet candidates are identified in photometry [53]. Of these, 173 are known transiting giant planets from ground-based photometric surveys. One of these, WASP-18b, is also identified with Gaia radial velocities, while two of the 41 new candidates were validated and confirmed with ground-based radial-velocity follow-up [54], and are dubbed Gaia-1b and Gaia-2b. The list of Gaia candidate exoplanets is maintained at https://www.cosmos.esa.int/web/gaia/exoplanets, and information on the orbital solutions is also found in the Extrasolar Planet Encyclopaedia (http://exoplanet.eu).

The vast majority of substellar companions detected with Gaia DR3 astrometry is found to orbit cool M dwarfs, as shown in Figure 2. This is not unexpected: the calibration levels in the bright-star regime are still sub-optimal for Gaia DR3, and consequently relatively faint, low-

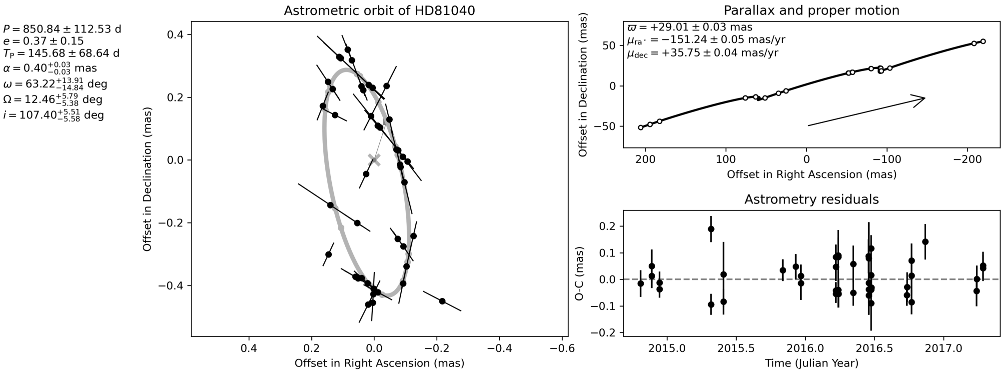

Figure 3. Left: Gaia astrometric orbit of the super-Jupiter companion HD 81040 b, initially detected with RV techniques [55]. The Gaia data are de-projected in the plane of the sky after removal of parallax and proper motion effects. The orientation of the error bars indicates the along-scan direction at the given epoch. Top right: The star's modelled parallax and proper motion. Bottom right: the post-fit residuals. The rms dispersion is 65 μas. The solution parameters and their uncertainties are shown by insets on the very left and in the top right panel. Figure from https://www.cosmos.esa.int/web/gaia/iow_20220131. *Credits: ESA/Gaia/DPAC.*

mass stars constitute the sample of primaries around which the chances of detecting substellar companions are maximized. In [47], under the assumption of maximum completeness and reliability, a first figure is provided for the occurrence rate of brown dwarf companions with $P < 1000$ days orbiting M dwarfs within 100 pc from the Sun. This number turns out to be $\sim 0.3\%$. The occurrence rate is likely underestimated, pending a detailed assessment of the numbers of missed companions vs. those of spurious solutions and incorrectly classified objects. Nevertheless, Gaia DR3 already provides critical constraints on the M dwarf binary fraction at close separations and very low mass ratios: the M dwarf sample in the Solar neighborhood for which Gaia is sensitive to substellar companions within a few au is orders of magnitude larger than those of all other spectroscopic surveys combined.

Detailed completeness and reliability studies of Gaia DR3 astrometry for the purpose of occurrence rate calculations will have to deal in particular with an intrinsic ambiguity in the interpretation of the nature of the companion that stems from the accessible information on its mass based on astrometry alone. The astrometric mass function:

$$f(\mathcal{M}) = (\mathcal{M}_1 + \mathcal{M}_2)\left(\frac{\mathcal{M}_2}{\mathcal{M}_1 + \mathcal{M}_2} - \frac{F_2/F_1}{1 + F_2/F_1}\right)^3 = \frac{(a_0/\varpi)^3}{(P/365.25)^2} \tag{1}$$

relates the mass ratio $q = \mathcal{M}_2/\mathcal{M}_1$ and the flux ratio F_2/F_1 to the angular size of the perturbation on the primary a_0, the parallax ϖ and the orbital period P. Small values of the mass function, e.g. $f(\mathcal{M}) < 0.001$, are realized in the case of negligible F_2/F_1 and small $\mathcal{M}_2$ but also when the mass ratio is similar to the flux ratio. A non-negligible fraction of the substellar detected astrometrically by Gaia could therefore be instead systems of a different nature. An instructive example is discussed in [49] for the case of the companion to HD 185501, which is detected by Gaia with a small perturbation size $a_0 = 0.48$ mas, with an inferred mass of a super-Jupiter or low-mass brown dwarf in case of $F_2/F_1 = 0$, but it was instead identified by means of ground-based spectroscopy and speckle imaging analysis to be an equal-mass binary with the same orbital period as the one detected by Gaia.

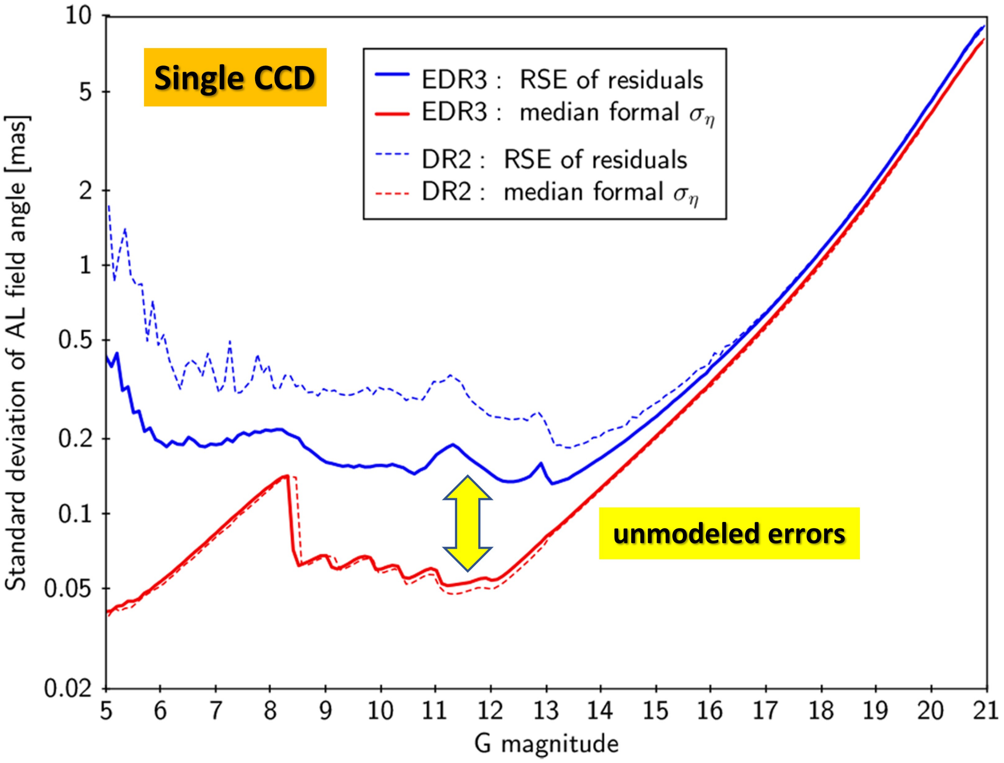

Figure 4. Precision of CCD-level Gaia astrometric measurements along the (sensitive) scan direction as a function of magnitude. Solid curves are for EDR3, dashed for DR2. The red (lower) curves show the median formal centroiding uncertainty; the blue (upper) curves are robust estimates of the actual rms of the post-fit residuals. The yellow thick arrow highlights the difference between the two solid curves for EDR3, which is mostly due to the still limited degree of calibration of the bright star sample ($G < 13$) mag approximately. *Figure adapted from [56].*

The sample of 10 brown dwarfs and 9 planets already known from Doppler surveys was identified in Gaia DR3 data based on a specific processing run targeting a sample of systems with known literature solutions. As described in detail in [49], this sample was defined for investigation of detectability of low signal-to-noise perturbations, and is composed of objects that were not selected for the main processing run based on a large RUWE value [48], exceeding the threshold (1.4) typically used to identify possible binarity. The angular semi-major axis of the orbits of the planetary companions is typically ≤ 0.5 mas, the record holder being HD 132406 b, with $a_0 \sim 150$ micro-arcseconds (μas). The Gaia-derived true mass estimates do not always scale from the minimum-mass values with $\sin i$, an effect that can be understood in terms of the limitations and biases described above [47].

The sample of known Doppler planets with true masses from Gaia includes some well-known companions, such as GJ 876 b, one of the two giant planets in a resonant configuration orbiting a mid-M dwarf in the backyard of the Sun (d = 4.67 pc), one of the first to be discovered with the radial velocity method [57], and the first to have had a preliminary astrometric mass determination based on HST/FGS data [58]. Figure 3 shows an example of astrometric orbit for the known Doppler-detected giant planet HD 81040 b that Gaia confirmed to have a true mass in the planetary regime. Some of the known companions with $M_c \sin i$ in the planetary regime instead turn out to have much higher true mass estimates from Gaia. A most notable example is that of HD 114762 b: it was determined by [59], via radial velocity variations, to have a mass close to the Deuterium-burning threshold ($M_c \sin i \simeq 11$ $\mathrm{M_{Jup}}$), the Gaia DR3 orbital solution matches the period of the Doppler data, but the orbit size $a_0 = 1.8$ mas translates into a companion mass $M_c = 0.21$ $\mathrm{M_\odot}$, which establishes the companion to be a low-mass M dwarf rather than a substellar object. Finally, the sample of new planetary-mass candidates from Gaia DR3 is dominated by companions orbiting low-mass M dwarfs, as we have already shown in Figure 2. Notable cases that do not fall into this category include a) a close-in super-Jupiter orbiting the nearby metal-polluted white dwarf WD 0141-675, b) super-Jupiters around the solar-type stars HD 12800 and HIP 28193, and c) a companion straddling the Deuterium-burning threshold around the young star HD 3221 (see [47] and [49] for additional details)

4. Outlook: Gaia DR4

Gaia DR2/EDR3 allowed to use a) parallaxes to improve accuracy and precision of stellar and planetary parameters, and b) proper motions in a clever way to improve knowledge of existing and find new substellar companions. Gaia DR3 is wetting our appetite for exoplanet discoveries and is already a gold mine for studies focused on brown dwarf companions. Indeed, Gaia DR3 has provided the first-ever full orbital solutions for a number of known exoplanets and brown dwarfs, and it has delivered the first, precious sample of previously unknown planetary-mass companions based on astrometric data alone. This should be regarded by no means a small feat, as no planet detection by Gaia was initially forecast to be included in DR3.

The prospects for DR4 to deliver on the promises of thousands of new astrometrically detected giant exoplanets (based on performance figures from the nominal or extended mission) are intact, but this will not be a trivial task. Figure 4 shows a comparison between the Gaia CCD-level positional uncertainties (from photon statistics) of individual along-scan angular measurements and the actual scatter of the post-fit residuals in the astrometric solution [56]. Formal uncertainties are virtually unchanged between DR2 and EDR3, while the actual residual scatter (rms) is reduced by a factor ~ 2 between the two data releases in the bright-star regime $G \leq 13$ mag. However, there is still an important factor, about 3 – 4, to gain in order to bring the actual positional rms down to the level of photon noise. Critically important efforts will be made in order to further improve calibration models for bright stars in future releases, starting with DR4. This step is crucial, as the sample of planetary mass companions identified by Gaia around bright stars is the one that maximizes the synergy potential with other planet detection and characterization programs. Improvements in orbit modeling algorithms in pipeline processing will also be needed, for example to minimize the number of spurious solutions and to deal effectively with increased complexity of the planetary signals, as with the 66-months baseline of DR4 and improved positional precision higher-multiplicity systems will start being detectable.

Conflicts of interest

The author has no conflict of interest to declare.

Acknowledgements

This work is dedicated to the memory of Dimitri Pourbaix, a key contributor to the Gaia mission and astrometry, and the inspiration behind the production of the first astrometric catalog of binary solutions published in Gaia DR3. He will be greatly missed. This work has made use of data from the European Space Agency (ESA) mission *Gaia* (https://www.cosmos.esa.int/gaia), processed by the *Gaia* Data Processing and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the *Gaia* Multilateral Agreement.

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