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Gaia: the Galaxy in six (and more) dimensions

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Abstract

The ESA cornerstone mission *Gaia* was successfully launched in 2013, and is now scanning the sky to accurately measure the positions and motions of about two billion point-like sources of $3 \lesssim V \lesssim 20.5$ mag, with the main goal of reconstructing the 6D phase space structure of the Milky Way. The typical uncertainties in the astrometry will be in the range 30-500 μ as. The sky will be repeatedly scanned (70 times on average) for five years or more, adding the time dimension, and the *Gaia* data are complemented by mmag photometry in three broad bands, plus line-of-sight velocities from medium resolution spectroscopy for brighter stars. This impressive dataset is having a large impact on various areas of astrophysics, from solar system objects to distant quasars, from nearby stars to unresolved galaxies, from binaries and extrasolar planets to light bending experiments. This invited review paper presents an overview of the *Gaia* mission and describes why, to reach the goal performances in astrometry and to adequately map the Milky Way kinematics, *Gaia* was also equipped with state-of-the-art photometers and spectrographs, enabling us to explore much more than the 6D phase-space of positions and velocities. Scientific highlights of the first two *Gaia* data releases are briefly presented.

Keywords: The Galaxy, Astrometry, Astronomical surveys

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1. Introduction

Astrometry, one of the oldest branches of astronomy, is the science of measuring the positions and motions of objects on the celestial sphere. Besides providing the apparent motion of celestial objects, which is one of the ingredients for stellar kinematics and dynamics, astrometry answers two fundamental questions of astrophysics. The first concerns the definition of a reference system of celestial positions – astronomical coordinates are the most powerful tool to identify individual objects and to combine and compare large catalogues coming from observational surveys. The ICRF (International Coordinates Reference Frame, Arias et al., 1995; Fey et al., 2015) is the standard in the field, based on very long baseline interferometry (VLBI) of compact radio sources. The second ingredient is distance, an elusive but fundamental ingredient, without which it would be impossible to fully understand the universe. Astrometry, by measuring parallax – the reflection of the Earth’s motion around the Sun – is one of the few available techniques to provide direct estimates of distances, without assumptions on objects properties such as intrinsic luminosity. The more accurate and precise the astrometric measurement, the smaller the parallax that can be accurately measured, the larger the distance that can be reached.

Gaia (Gaia Collaboration et al., 2016b), is the ESA cornerstone astrometric mission, launched in 2013, whose main goal is to provide absolute astrometry, 100 times more accurate than its extremely successful predecessor (Hipparcos, Perryman et al., 1992) and to target much fainter objects, down to a magnitude of $V \simeq 20.5$ mag, thus providing a catalogue of two billion objects, covering the entire sky. The ambition of *Gaia* is to provide a homogeneous census of the phase space of positions and motions of as much as 1% of the stars in the Milky Way. *Gaia* is also equipped with a spectrograph, to measure line-of-sight velocities of millions of stars of various spectral types, down to $G \simeq 16-17$ mag¹. To give an idea of the improvement that *Gaia* is meant to provide, Figure 1 shows how astrometric measurement uncertainties have evolved through time: *Gaia*’s predecessor, Hipparcos, could obtain positions and parallaxes with uncertainties of the order of 1 mas, for 10^5 stars

¹The *Gaia* white-light magnitude is not too different from the Johnson V magnitude for stars with non-extreme colors. A full set of transformations between the *Gaia* photometry and widely used photometric systems can be found in Evans et al. (2018). The *Gaia* photometry is described more in detail in Section 2.2.

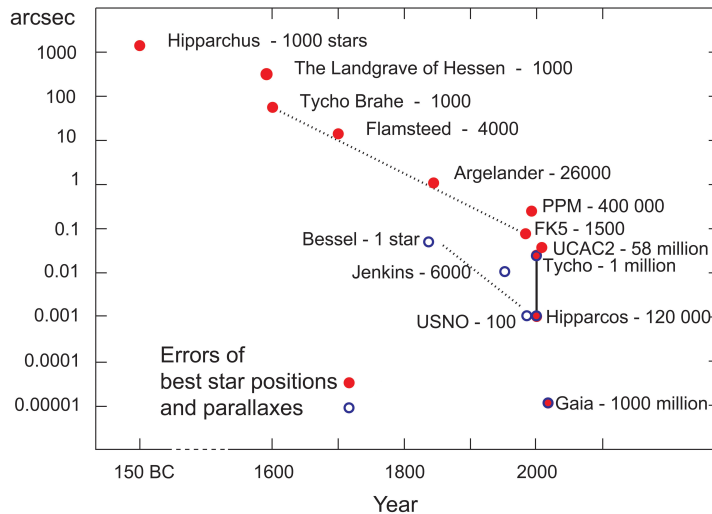


Figure 1: The improvements of astrometry measurements in the course of the centuries. Dotted lines show the rate of improvement for positions (red dots) and parallaxes (blue circles), while the vertical line shows the enormously accelerated improvement obtained in the last century. *Gaia*'s contribution to the field brings a further improvement of a few orders of magnitude compared to Hipparcos (see text). Image source: ESA.

down to $V \simeq 12$ mag. *Gaia*, on the other hand, will provide astrometry with uncertainties of the order of 0.01 mas, for 10^9 stars down to $V \simeq 21$ mag (at the end of the mission).

To be able to provide such high quality astrometry, however, *Gaia* will need also to collect exquisite photometry in three wide bands, which is necessary to correct for chromatic effects on the measurements of object's positions. *Gaia* will also provide time sampling: on average each object will be observed 70 times over the nominal mission duration of 5 years, to allow for accurate global astrometry and to break the degeneracy between proper motion and parallax. In substance, *Gaia*'s exquisite astrometry *requires* excellent photometry and spectroscopy, and the full catalogue will be unprecedented in optical astronomy in terms of the number of measured sources, characterized by (quasi-)simultaneous measurements with several different techniques. This is one of the reasons why *Gaia* is bringing a real revolution in many fields of modern astrophysics, from stellar structure and evolution, to the reconstruction of the Milky Way history and present day chemo-dynamical status; from the study of the motion of Solar System ob-

ject, to a wealth of data on distant, unresolved galaxies and QSO; from its planet-hunting capabilities, to the experiments of fundamental physics that it will enable. All *Gaia* released data can be obtained from various sources, like the ESA *Gaia* archive or the *Gaia* Partner Data Centers².

In this paper, I briefly describe the mission capabilities and performances, and I provide a few examples of the exciting results that have been obtained by the community using *Gaia* data coming from its first (DR1, Gaia Collaboration et al., 2016a) and second (DR2, Gaia Collaboration et al., 2018a) data releases. The paper is organized as follows: Section 2 presents the spacecraft, onboard instrumentation, and science performances; Section 3 presents the *Gaia* data releases and their content, and highlights some early results obtained with the first two releases; Section 4 summarizes the main points and concludes with a future outlook.

2. *Gaia*

The idea for an astrometric mission that could improve on Hipparcos dates back to the 80s, and started appearing in international Journals of the field in 1994 (Lindegren et al., 1994), with an interferometric design that later was abandoned. The mission was formally approved by ESA in 2000, as part of its Horizon 2000 Plus program. Its main scientific goal is to study the structure, formation and evolution of our galaxy, the Milky way, by studying stars belonging to all its components and to the Local Group (Perryman et al., 2001). In 2006, after the Announcement of Opportunity by ESA, the *Gaia* Data Processing and Analysis Consortium (DPAC) was formed, to take care of all aspects of data treatment and to deliver the data to the community. At about the same time, the contract for the construction of *Gaia* was granted to Astrium (now Airbus Defence and Space). Launch occurred successfully in December 2013, and the satellite reached very smoothly its Lissajus orbit around L2, the unstable Lagrangian point of the Sun and Earth-Moon system, where it started its technical and scientific commissioning phase, and started nominal operations about six months later.

The nominal five years of *Gaia* observations were completed in July 2019, but the onboard fuel reserve is expected to keep *Gaia* operational until 2024. After a careful cost-benefit analysis, ESA formally approved the first mission

²<https://www.cosmos.esa.int/web/gaia/data-access>

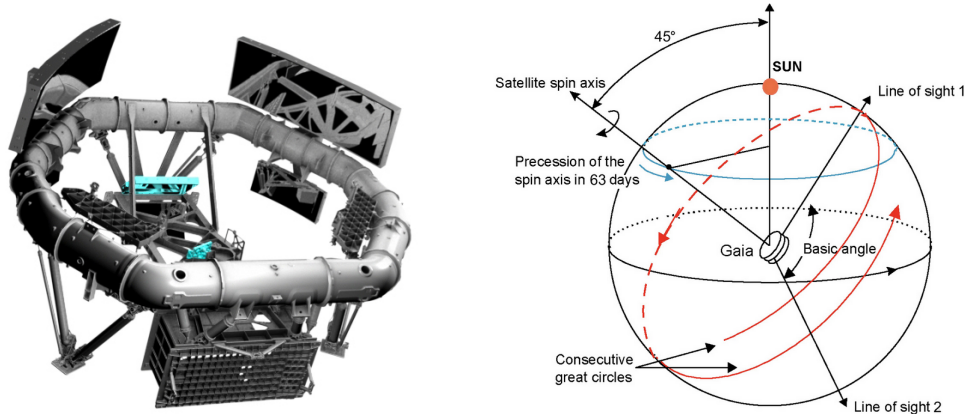


Figure 2: Left panel: Gaia payload. The two Gaia mirrors are mounted on the payload torus (top), observing two different lines of sight that are focalized through a series of mirrors (M4 and M5 are visible, in cyan) onto a single focal plane (its back side is visible at the bottom of the figure, see also Figure 3). Right panel: *Gaia* scanning the sky, by precessing its spin axis around the Sun direction. Images source: ESA.

extension of two years, on November 2018. This ensures that *Gaia* will receive support to operate until at least 2020. Contextually, a preliminary pre-approval of a further two-year extension was given, to be re-examined later, to keep on observing until 2022. The Gaia mission extension is expected to improve positions, parallaxes, photometry, and radial velocities by about 40% and to improve upon proper motions even more. The mission extension will also have a positive effect on the detection of exoplanets and asteroids as well as on the time-sampling of variable objects³.

2.1. Astrometry

Like Hipparcos, *Gaia* is one of the few missions designed to perform global astrometric measurements. To this aim, it is equipped with two telescopes observing two different lines of sight, separated by a wide angle – the basic angle of 106.5 deg – and whose light is then combined on a single focal plane (Figure 2, left panel) to allow for the simultaneous measurements of large angular differences between celestial objects. The satellite scans the whole

³More information on *Gaia* can be found in the official ESA webpages for the public (http://www.esa.int/Our_Activities/Space_Science/Gaia) and for scientists (<https://www.cosmos.esa.int/web/gaia/>).

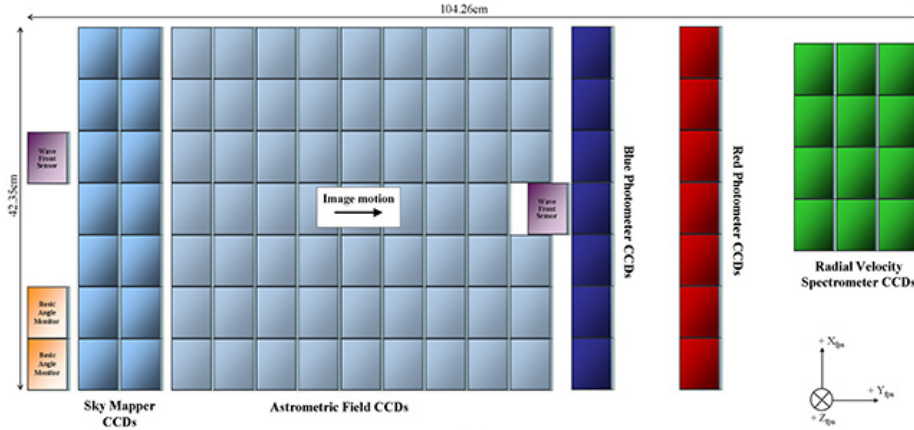


Figure 3: The Gaia focal plane. Each rectangle represents one CCD. Light passing through different instruments is collected by groups of CCDs marked in different colors, as annotated on the Figure. Thanks to *Gaia*'s continuous sky scanning, celestial objects appear on the focal plane on the left side and travel horizontally across it to exit on the right side. Image source: ESA, Alexander Short.

sky by slowly precessing its spin axis (Figure 2, right panel) and by doing so, it passes repeatedly on the same regions of the sky (on average 70 times) each time with a different orientation. The large basic angle, the repeated measurements, and the onboard metrology system (Mignard, 2011), provide global astrometric measurements and good control over the systematic uncertainties of the astrometry. Thanks to its design, *Gaia* can thus define its own kinematically non-rotating reference system (Mignard et al., 2016; Gaia Collaboration et al., 2018c), based on more than half a million Quasars, that are in part also observed with VLBI, thus allowing the axes of the reference system to be aligned with the ICRF (Fey et al., 2015).

As described more in details by Gaia Collaboration et al. (2016b), the light from the two telescopes reaches the focal plane, where 106 CCDs (Charge-Coupled Devices) gather the light and are read out continuously as *Gaia* scans the sky. From the point of view of the focal plane, thus, it looks as if celestial objects enter the focal plane on one side, travel across it at a speed that carefully matches the read-out speed (about 4 s per CCD), and then exit on the other side. To save telemetry bandwidth, objects are detected on board in the first two CCD columns (Sky Mapper CCDs, or SM, colored in light blue in Figure 3), and confirmed in the third column: only the charges accumulated

in little windows that follow the object on the focal plane are transmitted to the ground. The next set of 62 CCDs, the Astrometric Field (AF, colored in grey in Figure 3) collects photons in white light (300-1100 nm), to allow the PSF (Point Spread Function) modeling and accurate centroiding, that is the basis for the astrometric solution⁴.

The complex data processing is described by Lindegren et al. (2016, 2018). Its heart is the Astrometric Global Iterative Solution (AGIS). Each time a new chunk of data comes in from the satellite and is preprocessed, AGIS is re-run on all the data available, using its previous solution as a starting point for the new solution. This happens approximately every 6 months. AGIS solves for the satellite attitude and for all five astrometric parameters: on sky positions (α and δ), proper motions (μ_α and μ_δ) and parallax (ϖ). To help pinpointing *Gaia*'s position in the sky, a network of medium-sized telescopes regularly observes it from Earth (the GBOT, Ground-Based Optical Tracking project, Altmann et al., 2014; Buzzoni et al., 2016). This is a novel approach for ESA: *Gaia* is the first mission that is tracked from the ground not only with radio tracking and ranging, but also with optical imaging. The volume of AF data processed is of tens of billions of measurements, and every AGIS cycle contains of course more data than the previous one, increasing the computational challenge. The satellite's attitude and Basic Angle monitoring on board and in post-processing from the ground is so accurate and sensitive that thermal changes and micro-meteoroid impacts in the L2 region produce jumps, oscillations, and the so-called micro-clancks, very well visible in the astrometric solution. Thus, they provide an entirely new insight into the space weather conditions at L2.

The expected end-of-mission performances of *Gaia* are presented and updated on the ESA webpages⁵. With DR2, that is based on roughly two years of data over the nominal five, *Gaia* is already approaching the exquisite quality expected at the faint end. This is because the mission is not optimized for bright stars ($V \lesssim 13$ mag), and more work and more data are required to improve the bright end. In spite of the preliminary nature of the released data, DR2 is already spawned numerous new discoveries in the first few weeks (Section 3).

⁴see also <https://www.cosmos.esa.int/web/gaia/astrometric-instrument>

⁵<https://www.cosmos.esa.int/web/gaia/science-performance>

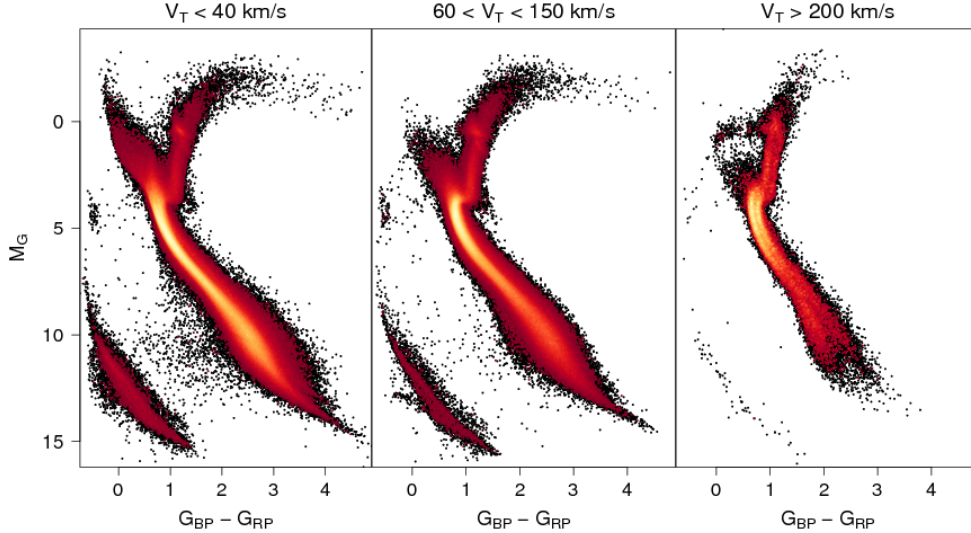


Figure 4: Gaia Hertzsprung-Russell diagrams, Gaia absolute magnitude M_G versus $G_{BP} - G_{RP}$ color, as a function of the stars tangential velocity (V_T), using Gaia DR2 with relative parallax uncertainty better than 10% and low extinction stars ($E(B-V) < 0.015$ mag), together with astrometric and photometric quality filters. The color scale represents the square root of the density of stars. Image source: ESA/Gaia/DPAC, Carine Babusiaux.

2.2. Photometry

To obtain the required quality in astrometric measurements, it is necessary to map extremely well the differential object displacement that occurs in different regions of the large *Gaia* focal plane, depending on the object intrinsic color. In other words, the blue light and the red light emitted by each celestial source travel through slightly different optical paths and end on slightly different positions on the focal plane. The net result is that cool or reddened stars and galaxies have systematically different centroid measurements than hot and blue objects.

With *Gaia*, we aim at 10-500 μs uncertainties in the absolute astrometry, and the chromaticity effects cannot be neglected. This is one of the reasons why – besides the white light magnitudes measured on the AF – *Gaia* is equipped with two low-dispersion spectrographs: the blue and the red (spectro-)photometers (hereafter, BP and RP). They produce spectra with a resolution ($R = \lambda / \delta\lambda$) varying between 20 and 100, each covering roughly

half of the optical range covered by *Gaia* SM and AF images⁶, the BP from 330 to 670 nm and the RP from 620 to 1050 nm.

The BP-RP color is obtained by extracting integrated magnitudes⁷ from the BP and RP spectra. The obtained three-band photometry of white light, integrated BP and RP magnitudes already in GDR2 contains 1.3 billion sources, down to $G \simeq 21$ mag and has internal uncertainties of the order of a few millimagnitudes. This constitutes a problem because none of the existing photometric catalogues has comparable uncertainties, and thus one cannot efficiently use external catalogues to fully validate *Gaia* photometry (Evans et al., 2018). The external (absolute) flux calibration is based on an extension of the CALSPEC set of spectro-photometric standard stars (Bohlin, 2014; Pancino et al., 2012), that provides external uncertainties of about 1% or better in flux, i.e., the best that can be done with current technology. The three-band color-magnitude diagram from the latest *Gaia* release (Figure 4) shows an impressive amount of detail, and has spawned new discoveries even in the relatively old field of stellar structure and evolution (see section 3).

Besides integrated magnitudes and colors, *Gaia* BP and RP spectra provide a wealth of additional astrophysical information. They can be used – together with the medium-resolution spectra described in the next section – to classify astrophysical objects, for example separating stars from galaxies or quasars. The spectra also provide accurate astrophysical parameters such as surface temperatures and gravities, metallicities, or interstellar reddening and extinction. A preliminary set of astrophysical parameters was provided with *Gaia* DR2 (Andrae et al., 2018), using solely integrated magnitudes. We expect significant improvement in the quantity and quality of the released astrophysical parameters in the upcoming releases.

2.3. Spectroscopy

Gaia astrometry is designed to provide five of the six phase-space dimensions – the space of positions and motions – for roughly 2 billion stars: sky position (right ascension and declination, or α and δ), distance (through par-

⁶see https://www.cosmos.esa.int/web/gaia/iow_20180316

⁷The term *integrated magnitude*, widely used in the *Gaia* community, simply means that all photons collected in the white AF passband or in the BP/RP low resolution spectra, or in the RVS spectrograph, are summed and converted to a magnitude scale. For each instrument, respectively, the obtained integrated magnitudes are indicated as G , G_{BP} , G_{RP} , and G_{RVS} .

allax, or ϖ), and the on-sky motion (proper motion in α and δ , or μ_α and μ_δ). It cannot however provide information on the motion along the line of sight, also called radial velocity (RV hereafter). For this reason, *Gaia* is equipped with a medium resolution spectrograph that provides line-of-sight velocities based on the Doppler shift: the Radial Velocity Spectrometer or RVS (Cropper et al., 2018).

The spectra have a resolution $R \simeq 11\,500$ and cover the widely used region around the Calcium IR triplet (846–874 nm), which allows for accurate RV measurements for late type stars. For early type stars, the Paschen lines are well visible in this range and for very cool stars the molecular bands of TiO can be used for RV determination, albeit with lower performances compared to the Calcium triplet. The region is also rich in atomic lines belonging mostly to the iron-peak and α -elements, and can thus be used to accurately parametrize stars and to derive their chemical composition. Some diffuse interstellar bands are also present, for the independent determination of interstellar absorption.

The science performances depend on the spectral type and the brightness of the observed stars, where the expected limiting magnitude is brighter than the one of AF, BP, and RP: $G \simeq 16$ mag. For the brightest stars ($G \lesssim 13$ –14 mag) it is about 1 km/s or less, which is quite competitive with existing RV surveys⁸. For the less favorable cases of very blue and faint stars it can reach 15 km/s or more. All RV measurements are accurately calibrated using a set of more than 1000 RV standard stars (Soubiran et al., 2018). The currently released RV measurements constitute the largest available set of homogeneously and accurately measured RV in the literature to date, with more than 7 million stars in the DR2 catalogue.

2.4. Time coverage and variability

The last necessary ingredient to obtain extremely accurate astrometry is time coverage, i.e., repeated observations. One of the reasons why time coverage is necessary is the so-called parallax-proper motion degeneracy. The motion of a star on the plane of the sky is a combination of its actual motion (proper motion) with the reflection of the Earth’s orbit around the Sun (parallax). If an object is observed for less than one year, the measured (apparent) motion vector cannot be accurately separated into the two com-

⁸<https://www.cosmos.esa.int/web/gaia/science-performance>

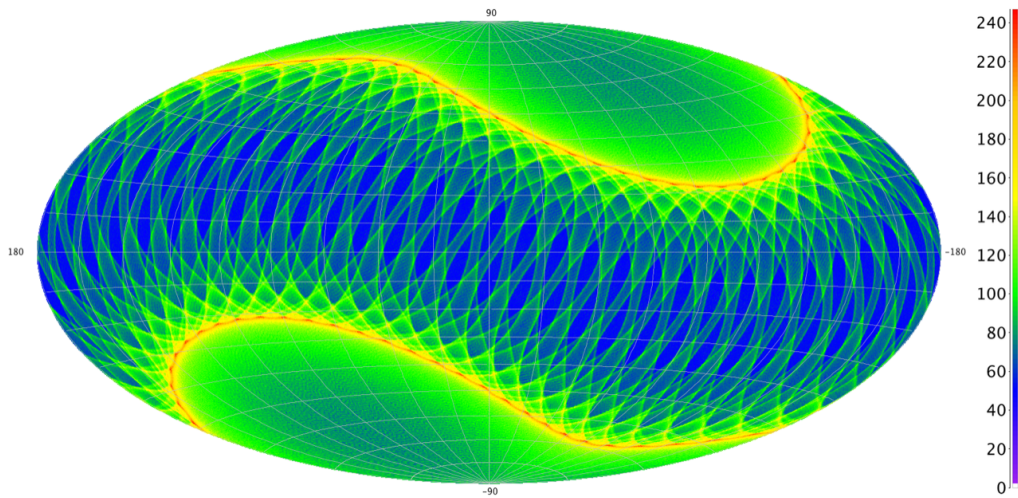


Figure 5: Gaia field-of-view transits for the five-year Nominal Scanning Law in ICRF coordinates. The Ecliptic plane is within the blue curved strip, while the number of passages is maximum on the two lines at ± 45 deg from it. Image source: Berry Holl.

ponents, while if observations are carried out for at least one full year, one full parallax ellipse will be covered, and the two components will be accurately disentangled. Another important reason is that *Gaia* is a complex instrument, with a scanning law that generally allows to cover the same region of the sky multiple times with different observations (Figure 5)⁹. Because the accuracy in position measurements is largest along the scanning direction and the combination of *Gaia*'s spin and spin axis precession provides many observations with a different scanning orientation, it is thus possible to reconstruct the 2D sources positions much more accurately, at the same time keeping systematic errors under control.

Gaia is therefore designed to observe each source on average 70 times over the five 5 years of its nominal operation timeframe. The RVS instrument, being designed differently, gathers about 40 different observations instead of 70, on average. This opens up a range of time-domain astrophysical studies based on photometry (light-curves), spectroscopy (RV curves), and astrometry (centroid motions), obtained quasi-simultaneously in case of bright sources (Gaia Collaboration et al., 2019). The repeated observations allow to study periodically varying objects such as variable stars or quasars (Gaia

⁹For more details: https://www.cosmos.esa.int/web/gaia/iow_20120312.

Collaboration et al., 2017; Hwang et al., 2019) or transient objects such as novae, supernovae, and microlensing events (Wyrzykowski, 2016). In addition repeated observations allow to detect planets through astrometric variability, opening a discovery window that is complementary to other techniques (Perryman et al., 2014). They also allow to fully model binary stars, which are a fundamental ingredient for understanding the formation and evolution of stars and stellar systems (Eyer et al., 2015): the first release containing non-single stars measurements will be DR3 (see Section 3.3).

3. Data releases and science highlights

Hundreds of scientists and engineers in Europe and in the world have contributed a significant fraction of their careers to designing, building, launching, and operating *Gaia*, but also to process, analyze, validate, and publish its data in a form that the community can use for their scientific research, for teaching, and for outreach activities and events. Two public data releases have taken place so far (Gaia Collaboration et al., 2016a, 2018a), and at least two more are foreseen¹⁰. Indeed, the analysis of *Gaia* data in the DPAC is subdivided in 9 different Coordination Units (CUs) that take care of various aspects such as: software and database infrastructures, data simulations, astrometric, photometric, and spectroscopic processing, time-series analysis of variable and peculiar objects, and the like. Closing the loops of communication, validation, and data exchanges among the CUs smoothly is a slow and careful process of growing complexity. Therefore, each data release presents more data products and improves on the quality of previously released products.

3.1. The first *Gaia* data release

The first *Gaia* data release, in 2016 (Gaia Collaboration et al., 2016a) contained: positions and G magnitudes of more than billion sources; the TGAS (Tycho-Gaia Astrometric Solution) catalogue, obtained by combining Hipparchos and Gaia positions and thus limited to $G \simeq 12$ mag; and light-curves for a few thousand variable stars at the ecliptic poles. It was thought as a demonstrational release, to show the *Gaia* mission's potential and to prepare the community for the upcoming releases. It was instead used intensively

¹⁰Official release scenario: <https://www.cosmos.esa.int/web/gaia/release>.

not only to test ideas and algorithms to use in future releases, but also to obtain many new and original scientific results in different research fields. The results were published in more than 1000 refereed papers, that cited the *Gaia* first release papers between 2016 and 2018 alone.

Many projects were carried out to test the data and methods in view of DR2. The rotation of the Large Magellanic Cloud was studied with 29 TGAS stars (van der Marel and Sahlmann, 2016); a similar study was later carried out with DR2, using 8 million stars, and discovering for the first time rotation in the Small Magellanic Cloud (Gaia Collaboration et al., 2018b). The quality of TGAS parallaxes was compared with various catalogues, and a small bias was found in the comparison with eclipsing binaries and previously published astrometry, of $\simeq 2.5$ mas (Stassun et al., 2017; Jao et al., 2016), while other indicators like variable stars (Gaia Collaboration et al., 2017; Casertano et al., 2017) were found to be in good agreement. Finally, the problem of converting parallaxes into meaningful distances for individual stars was tackled using TGAS data (Astraatmadja and Bailer-Jones, 2016).

The modeling of the Milky using the new DR1 and TGAS data, one of the main goals of the *Gaia* mission, was carried out by various groups. I list here just some of the most cited works: the mass distribution and halo substructure with *Gaia*, RAVE, and APOGEE was studied in some detail (Helmi et al., 2017; Bonaca et al., 2017); the dynamics of the galactic bar and the Hercules stream were studied by (Monari et al., 2017); the galactic rotation was studied by (Bovy, 2017); and a 3D study of the Orion region revealed an age gradient in the OB-star population (Zari et al., 2017). *Gaia* DR1 and TGAS data were also used to study Galaxy dynamics and stellar structure and evolution, by compiling catalogues of comoving pairs and wide binaries (Oh et al., 2017; Andrews et al., 2017) or very cool stars (Smart et al., 2017), or by deriving fundamental relations such as the mass-radius relation for white dwarfs (Tremblay et al., 2017), or finally by testing and recalibrating various relations for pulsating variable stars (Gaia Collaboration et al., 2017).

Among the many scientific studies, a few received attention because they presented new results and were covered in various *Gaia* press releases, *Gaia* stories, or Images of the Week: (Koposov et al., 2017) discovered two new stellar clusters, one very close to Sirius, and thus difficult to study with more traditional instruments¹¹; the first supernova discovered by *Gaia* was

¹¹Although the discovery of the Sirius star cluster was presented by Koposov et al.

published by (Wyrzykowski, 2016) as part of the science alerts program and its ground-based follow-up network; RR Lyrae stars were used to discover a tidal bridge between the Large and Small Magellanic Clouds (Belokurov et al., 2017). *Gaia* DR1 was also used to observe new gravitationally lensed Quasars at high redshift (Lemon et al., 2017; Ostrovski et al., 2018).

3.2. The second *Gaia* data release

The second *Gaia* data release was issued in April 2018, and was a large improvement over the previous one. It was the first release to include: pure *Gaia* astrometry down to $G \simeq 21$ mag and $G_{\text{BP}} - G_{\text{RP}}$ colors for more than one billion sources; mean RV measurements for more than seven million sources; asteroid astrometry for 14 000 known objects; and astrophysical parameters (surface temperature and interstellar extinction) for approximately 100 million objects. *Gaia* DR2 data have such exquisite precision, that the internal structure of the data starts to be visible in the form of small systematic effects such as a parallax bias of 0.025 mas (ten times smaller than in DR1 TGAS, Lindegren et al., 2018; Gaia Collaboration et al., 2018b), or the G magnitude trend of 4 millimag per magnitude (Evans et al., 2018). These systematic effects are expected to decrease with each upcoming data release, as more data – with different characteristics – are processed and the processing pipelines are progressively refined.

At the time, more than 1800 refereed papers cite the second *Gaia* data release paper. According to the NASA ADS, the majority of the new publications are related to the fields of Galactic halo and disk studies (see below), but also to solar system studies (Cellino et al., 2007; Gaia Collaboration et al., 2018d), exoplanet and host star characterization (Kervella et al., 2019), characterization of variable or binary objects (Ziegler et al., 2018) and of objects with astroseismological data (Berger et al., 2018). Work was done also in the field of extragalactic studies, for example on Quasars variability (Hwang et al., 2019) or gravitational lensing (Wertz et al., 2019). *Gaia* DR2 data have even been used to search for a plausible home star for the interstellar object 'Oumuamua (Bailer-Jones et al., 2018), which recently was discovered transiting in the solar system¹². Summarizing such a huge and diverse body

(2017) as entirely new, a simple ADS search showed that the cluster was already known in the past (Auner et al., 1980). Nevertheless, *Gaia* is the only current instrument that allows to study such cluster in detail.

¹²<http://www.ifa.hawaii.edu/info/press-releases/interstellar/>

of literature in a fair and complete way is out of the scope of the present paper, so I will just present a few highlights of galactic and stellar science from the ESA *Gaia* press releases, in-depth stories, and Images of the Week.

On the Milky Way studies front, a lot of work has been done on stellar clusters, including a full census and dynamical characterisation of open clusters (with many new discovered clusters, Cantat-Gaudin et al., 2018, 2019) and globular clusters (Vasiliev, 2019), including the internal dynamics and substructure of individual clusters (Franciosini et al., 2018; Bianchini et al., 2018). An impressive study on the distribution of thousands of young clusters and OB association showed that they lie along filamentary structures across the galaxy disk, whose orientation changes systematically with age (Kounkel and Covey, 2019). New streams, kinematic substructures and past accretion events have been found (Helmi et al., 2017; Koppelman et al., 2018), from the inner galaxy to the outer halo, and studies of dwarf galaxies in the local group were carried out as well (Fritz et al., 2018). Various tracers were used to further explore the galactic structure, such as cepheids to trace the warp of the galactic disk (Ripepi et al., 2019).

Even relatively old research fields like stellar structure and evolution received a boost from *Gaia*: given the extremely large statistics and high precision of the of *Gaia* DR2 photometry, a new feature in the CMD of the galaxy was found (Jao et al., 2018), i.e., a gap along the main sequence that was predicted theoretically but never confirmed observationally¹³, caused by the transition of M stars from the fully convective to the partially convective regime. Similarly, the sequence of white dwarfs, now very populous in the *Gaia* DR2 data, showed for the first time its detailed substructure, not only the double sequence traced by different types of white dwarfs, but also the piling-up of white dwarfs towards the bottom of the cooling sequence, seen in *Gaia* data for the first time, and likely caused by internal processes of crystallization (Tremblay et al., 2019).

3.3. Upcoming data releases

The third *Gaia* data release will occur in two stages in 2020 and 2021. The early release, EDR3, will contain new astrometry and integrated photometry based on the first 34 months of observations. The measurements uncertainties

¹³A search *a posteriori* in other survey data, such as 2MASS, indeed showed that the gap was present, but there was not enough statistics to confirm its reality.

in both astrometry and photometry will improve thanks to the increase in the number of observations for each source, and the refinements or the addition of various pipelines to produce the data (for example: crowding treatment, binary stars, and extended objects). This, in turn, will increase the number of sources that pass the quality filtering, bringing both the expected errors and the number of sources closer to the expected end-of-mission performances. Some internal systematics that were present in DR2, such as the parallax bias of about 0.03 mas (Lindegren et al., 2018; Gaia Collaboration et al., 2018b) and the trends seen in photometry of about 4 millmags/mag or the bright blue stars systematics (Evans et al., 2018) are expected to improve significantly.

The full EDR3 release, expected in 2021, will complement EDR3 with a wealth of additional data products obtained from the same 34 months of data. DR3 will improve incrementally on the quality of all DR2 data products (astrometry and integrated photometry will be those of EDR3), but will also include entirely new ones, such as: mean BP/RP spectra, non-single stars catalogues¹⁴, results for Quasars and extended objects, object classification and parametrization, and an additional data set, Gaia Andromeda Photometric Survey (GAPS), consisting of the photometric time series for all sources located in a 5.5 degree field centred on the Andromeda galaxy.

Expected presumably in 2023, DR4 will be the last release of the nominal five-year observations period. As such, it will contain all the obtained data, reaching the expected end-of-mission quality, and all connected data products, such as mean and epoch data from all instruments, and results from all pipelines. Finally, as mentioned in the introduction, the *Gaia* mission extension of two more years has been finally approved and observations are already ongoing, including a scanning law reversal period that will help in breaking the remaining degeneracies in the astrometric solution and will bring understanding of remaining systematic effects. A further extension of two more years, for *Gaia* operations until 2022 has also been pre-approved. The on-board fuel reserve is estimated to be sufficient to operate *Gaia* at least until 2024, thus more extensions are in principle possible, and data

¹⁴In particular, a full binary treatment is foreseen for all stars that show evidence of multiplicity, including full orbital solution when possible. The non-single-stars pipelines will be relatively simple in DR3, but as any other processing chain in DPAC (crowding treatment, extended objects, variables, and so on), they will improve and increase in detail and complexity from release to release.

releases beyond DR4 are to be expected.

4. Conclusions

To achieve the required quality in astrometric measurements, *Gaia* is also collecting high-quality photometry and spectroscopy, and repeatedly observing two billion point-like sources on the sky. The resulting dataset is huge, periodically released and available, to be freely explored not only by professional astronomers, but also by amateurs, outreach professionals, and teachers at all levels.

Among the published papers that cite *Gaia*, a trend has emerged of combining *Gaia* data with large existing datasets like asteroisismic studies, multiband photometry, or large spectroscopic surveys for the determination of stellar abundance ratios. This trend confirms that astronomy research is progressing towards a multi-dimensional kind of data exploration, that can simultaneously take into account a diversity of astrophysical properties, to gain a deeper insight. This is true both for large data samples, where data mining and machine learning techniques are employed to statistically decipher the collective behaviour of astrophysical sources prior to physical modelling, or for small data sets, where rare or new objects can be studied in depth. Astronomers are – necessarily – not specialized in *all* of the data analysis aspects and techniques involved, yet datasets like *Gaia* allow them to move beyond their specific expertise. Each *Gaia* release is accompanied by extensive documentation and various caveats that help researcher to use the data with care and profit.

Considering all this, together with the huge data volume, involving millions and billions of sources, *Gaia* is opening up a new path for astrophysics, providing a rich dataset that is not only producing many new discovery already, but can connect large existing surveys and enhance the scientific harvest of upcoming projects and facilities, like the James Webb Space Telescope, the Extremely Large Telescope, or the Large Synoptic Survey Telescope.

References

Altmann, M., Bouquillon, S., Taris, F., et al., 2014. GBOT: ground based optical tracking of the Gaia satellite, in: Observatory Operations: Strategies, Processes, and Systems V, p. 91490P. doi:10.1117/12.2056571.

- Andrae, R., Fouesneau, M., Creevey, O., et al., 2018. Gaia Data Release 2. First stellar parameters from Apsis. *A&A* 616, A8. doi:10.1051/0004-6361/201732516, arXiv:1804.09374.
- Andrews, J.J., Chanamé, J., Agüeros, M.A., 2017. Wide binaries in Tycho-Gaia: search method and the distribution of orbital separations. *MNRAS* 472, 675–699. doi:10.1093/mnras/stx2000, arXiv:1704.07829.
- Arias, E.F., Charlot, P., Feissel, M., Lestrade, J.F., 1995. The extragalactic reference system of the International Earth Rotation Service, ICRS. *A&A* 303, 604–608.
- Astraatmadja, T.L., Bailer-Jones, C.A.L., 2016. Estimating Distances from Parallaxes. III. Distances of Two Million Stars in the Gaia DR1 Catalogue. *ApJ* 833, 119. doi:10.3847/1538-4357/833/1/119, arXiv:1609.07369.
- Auner, G., Dengel, J., Weinberger, R., Hartl, H., 1980. A ghost image of Sirius as a hiding place for a new star cluster. *PASP* 92, 422–425. doi:10.1086/130689.
- Bailer-Jones, C.A.L., Farnocchia, D., Meech, K.J., et al., 2018. Plausible Home Stars of the Interstellar Object ‘Oumuamua Found in Gaia DR2. *AJ* 156, 205. doi:10.3847/1538-3881/aae3eb, arXiv:1809.09009.
- Belokurov, V., Erkal, D., Deason, A.J., et al., 2017. Clouds, Streams and Bridges. Redrawing the blueprint of the Magellanic System with Gaia DR1. *MNRAS* 466, 4711–4730. doi:10.1093/mnras/stw3357, arXiv:1611.04614.
- Berger, T.A., Huber, D., Gaidos, E., et al., 2018. Revised Radii of Kepler Stars and Planets Using Gaia Data Release 2. *ApJ* 866, 99. doi:10.3847/1538-4357/aada83, arXiv:1805.00231.
- Bianchini, P., van der Marel, R.P., del Pino, A., et al., 2018. The internal rotation of globular clusters revealed by Gaia DR2. *MNRAS* 481, 2125–2139. doi:10.1093/mnras/sty2365, arXiv:1806.02580.
- Bohlin, R.C., 2014. Hubble Space Telescope CALSPEC Flux Standards: Sirius (and Vega). *AJ* 147, 127. doi:10.1088/0004-6256/147/6/127.

- Bonaca, A., Conroy, C., Wetzel, A., et al., 2017. Gaia Reveals a Metal-rich, in situ Component of the Local Stellar Halo. *ApJ* 845, 101. doi:10.3847/1538-4357/aa7d0c, arXiv:1704.05463.
- Bovy, J., 2017. Galactic rotation in Gaia DR1. *MNRAS* 468, L63–L67. doi:10.1093/mnrasl/slx027, arXiv:1610.07610.
- Buzzoni, A., Altavilla, G., Galleti, S., 2016. Optical tracking of deep-space spacecraft in Halo L2 orbits and beyond: The Gaia mission as a pilot case. *Advances in Space Research* 57, 1515–1527. doi:10.1016/j.asr.2016.01.003, arXiv:1601.04719.
- Cantat-Gaudin, T., Jordi, C., Vallenari, A., et al., 2018. A Gaia DR2 view of the open cluster population in the Milky Way. *A&A* 618, A93. doi:10.1051/0004-6361/201833476, arXiv:1805.08726.
- Cantat-Gaudin, T., Krone-Martins, A., Sedaghat, N., et al., 2019. Gaia DR2 unravels incompleteness of nearby cluster population: new open clusters in the direction of Perseus. *A&A* 624, A126. doi:10.1051/0004-6361/201834453, arXiv:1810.05494.
- Casertano, S., Riess, A.G., Bucciarelli, B., Lattanzi, M.G., 2017. A test of Gaia Data Release 1 parallaxes: implications for the local distance scale. *A&A* 599, A67. doi:10.1051/0004-6361/201629733, arXiv:1609.05175.
- Cellino, A., Tanga, P., Dell’Oro, A., et al., 2007. Asteroid science with Gaia: Sizes, spin properties, overall shapes and taxonomy. *Advances in Space Research* 40, 202–208. doi:10.1016/j.asr.2007.03.011.
- Cropper, M., Katz, D., Sartoretti, P., et al., 2018. Gaia Data Release 2. Gaia Radial Velocity Spectrometer. *A&A* 616, A5. doi:10.1051/0004-6361/201832763.
- Evans, D.W., Riello, M., De Angeli, F., et al., 2018. Gaia Data Release 2. Photometric content and validation. *A&A* 616, A4. doi:10.1051/0004-6361/201832756, arXiv:1804.09368.
- Eyer, L., Rimoldini, L., Holl, B., North, P., Zucker, S., Evans, D.W., Pourbaix, D., Hodgkin, S.T., Thuillot, W., Mowlavi, N., Carry, B., 2015. The Gaia Mission, Binary Stars and Exoplanets, in: Rucinski, S.M., Torres,

- G., Zejda, M. (Eds.), *Living Together: Planets, Host Stars and Binaries*, p. 121. [arXiv:1502.03829](#).
- Fey, A.L., Gordon, D., Jacobs, C.S., et al., 2015. The Second Realization of the International Celestial Reference Frame by Very Long Baseline Interferometry. *AJ* 150, 58. doi:10.1088/0004-6256/150/2/58.
- Franciosini, E., Sacco, G.G., Jeffries, R.D., et al., 2018. The Gaia DR2 view of the Gamma Velorum cluster: resolving the 6D structure. *Astronomy and Astrophysics* 616, L12. doi:10.1051/0004-6361/201833815, [arXiv:1807.03621](#).
- Fritz, T.K., Battaglia, G., Pawlowski, M.S., et al., 2018. Gaia DR2 proper motions of dwarf galaxies within 420 kpc. Orbits, Milky Way mass, tidal influences, planar alignments, and group infall. *A&A* 619, A103. doi:10.1051/0004-6361/201833343, [arXiv:1805.00908](#).
- Gaia Collaboration, Brown, A.G.A., Vallenari, A., et al., 2016a. Gaia Data Release 1. Summary of the astrometric, photometric, and survey properties. *A&A* 595, A2. doi:10.1051/0004-6361/201629512, [arXiv:1609.04172](#).
- Gaia Collaboration, Brown, A.G.A., Vallenari, A., et al., 2018a. Gaia Data Release 2. Summary of the contents and survey properties. *A&A* 616, A1. doi:10.1051/0004-6361/201833051, [arXiv:1804.09365](#).
- Gaia Collaboration, Clementini, G., Eyer, L., et al., 2017. Gaia Data Release 1. Testing parallaxes with local Cepheids and RR Lyrae stars. *A&A* 605, A79. doi:10.1051/0004-6361/201629925, [arXiv:1705.00688](#).
- Gaia Collaboration, Eyer, L., Rimoldini, L., et al., 2019. Gaia Data Release 2. Variable stars in the colour-absolute magnitude diagram. *A&A* 623, A110. doi:10.1051/0004-6361/201833304, [arXiv:1804.09382](#).
- Gaia Collaboration, Helmi, A., van Leeuwen, F., et al., 2018b. Gaia Data Release 2. Kinematics of globular clusters and dwarf galaxies around the Milky Way. *A&A* 616, A12. doi:10.1051/0004-6361/201832698, [arXiv:1804.09381](#).

- Gaia Collaboration, Mignard, F., Klioner, S.A., et al., 2018c. Gaia Data Release 2. The celestial reference frame (Gaia-CRF2). *A&A* 616, A14. doi:10.1051/0004-6361/201832916.
- Gaia Collaboration, Prusti, T., de Bruijne, J.H.J., et al., 2016b. The Gaia mission. *A&A* 595, A1. doi:10.1051/0004-6361/201629272, arXiv:1609.04153.
- Gaia Collaboration, Spoto, F., Tanga, P., et al., 2018d. Gaia Data Release 2. Observations of solar system objects. *A&A* 616, A13. doi:10.1051/0004-6361/201832900, arXiv:1804.09379.
- Helmi, A., Veljanoski, J., Breddels, M.A., et al., 2017. A box full of chocolates: The rich structure of the nearby stellar halo revealed by Gaia and RAVE. *Astronomy and Astrophysics* 598, A58. doi:10.1051/0004-6361/201629990, arXiv:1611.00222.
- Hwang, H.C., Shen, Y., Zakamska, N., Liu, X., 2019. Varstrometry for Off-nucleus and Dual sub-Kpc AGN (VODKA): Methodology and Initial Results with Gaia DR2. arXiv e-prints , arXiv:1908.02292arXiv:1908.02292.
- Jao, W.C., Henry, T.J., Gies, D.R., et al., 2018. A Gap in the Lower Main Sequence Revealed by Gaia Data Release 2. *ApJL* 861, L11. doi:10.3847/2041-8213/aacdf6, arXiv:1806.07792.
- Jao, W.C., Henry, T.J., Riedel, A.R., et al., 2016. Distance-dependent Offsets between Parallaxes for Nearby Stars and Gaia DR1 Parallaxes. *ApJL* 832, L18. doi:10.3847/2041-8205/832/1/L18, arXiv:1611.00656.
- Kervella, P., Arenou, F., et al., 2019. Stellar and substellar companions of nearby stars from Gaia DR2. Binarity from proper motion anomaly. *A&A* 623, A72. doi:10.1051/0004-6361/201834371, arXiv:1811.08902.
- Koposov, S.E., Belokurov, V., Torrealba, G., 2017. Gaia 1 and 2. A pair of new Galactic star clusters. *MNRAS* 470, 2702–2709. doi:10.1093/mnras/stx1182, arXiv:1702.01122.
- Koppelman, H., Helmi, A., Veljanoski, J., 2018. One Large Blob and Many Streams Frosting the nearby Stellar Halo in Gaia DR2. *ApJL* 860, L11. doi:10.3847/2041-8213/aac882, arXiv:1804.11347.

- Kounkel, M., Covey, K., 2019. Untangling the Galaxy. I. Local Structure and Star Formation History of the Milky Way. *AJ* 158, 122. doi:10.3847/1538-3881/ab339a, arXiv:1907.07709.
- Lemon, C.A., Auger, M.W., McMahon, R.G., et al., 2017. Gravitationally lensed quasars in Gaia: I. Resolving small-separation lenses. *MNRAS* 472, 5023–5032. doi:10.1093/mnras/stx2094, arXiv:1709.08976.
- Lindgren, L., Hernández, J., Bombrun, A., et al., 2018. Gaia Data Release 2. The astrometric solution. *A&A* 616, A2. doi:10.1051/0004-6361/201832727, arXiv:1804.09366.
- Lindgren, L., Lammers, U., Bastian, U., et al., 2016. Gaia Data Release 1. Astrometry: one billion positions, two million proper motions and parallaxes. *A&A* 595, A4. doi:10.1051/0004-6361/201628714, arXiv:1609.04303.
- Lindgren, L., Perryman, M.A., Bastian, U., et al., 1994. GAIA: global astrometric interferometer for astrophysics, in: Breckinridge, J.B. (Ed.), *Amplitude and Intensity Spatial Interferometry II*, pp. 599–608. doi:10.1117/12.177278.
- Mignard, F., 2011. A few metrological aspects of the Gaia mission. *Advances in Space Research* 47, 356–364. doi:10.1016/j.asr.2010.05.020.
- Mignard, F., Klioner, S., Lindgren, L., et al., 2016. Gaia Data Release 1. Reference frame and optical properties of ICRF sources. *A&A* 595, A5. doi:10.1051/0004-6361/201629534, arXiv:1609.07255.
- Monari, G., Kawata, D., Hunt, J.A.S., et al., 2017. Tracing the Hercules stream with Gaia and LAMOST: new evidence for a fast bar in the Milky Way. *MNRAS* 466, L113–L117. doi:10.1093/mnrasl/slw238, arXiv:1610.05342.
- Oh, S., Price-Whelan, A.M., Hogg, D.W., et al., 2017. Comoving Stars in Gaia DR1: An Abundance of Very Wide Separation Comoving Pairs. *AJ* 153, 257. doi:10.3847/1538-3881/aa6ffd, arXiv:1612.02440.
- Ostrovski, F., Lemon, C.A., Auger, M.W., et al., 2018. The discovery of a five-image lensed quasar at $z = 3.34$ using PanSTARRS1 and Gaia. *MNRAS* 473, L116–L120. doi:10.1093/mnrasl/slx173, arXiv:1709.08975.

- Pancino, E., Altavilla, G., Marinoni, S., et al., 2012. The Gaia spectrophotometric standard stars survey - I. Preliminary results. *MNRAS* 426, 1767–1781. doi:10.1111/j.1365-2966.2012.21766.x, arXiv:1207.6042.
- Perryman, M., Hartman, J., Bakos, G.Á., et al., 2014. Astrometric Exoplanet Detection with Gaia. *ApJ* 797, 14. doi:10.1088/0004-637X/797/1/14, arXiv:1411.1173.
- Perryman, M.A.C., de Boer, K.S., Gilmore, G., et al., 2001. GAIA: Composition, formation and evolution of the Galaxy. *A&A* 369, 339–363. doi:10.1051/0004-6361:20010085, arXiv:astro-ph/0101235.
- Perryman, M.A.C., Hog, E., Kovalevsky, J., et al., 1992. In-orbit performance of the HIPPARCOS astrometry satellite. *A&A* 258, 1–6.
- Ripepi, V., Molinaro, R., Musella, I., et al., 2019. Reclassification of Cepheids in the Gaia Data Release 2. Period-luminosity and period-Wesenheit relations in the Gaia passbands. *Astronomy and Astrophysics* 625, A14. doi:10.1051/0004-6361/201834506, arXiv:1810.10486.
- Smart, R.L., Marocco, F., Caballero, J.A., et al., 2017. The Gaia ultracool dwarf sample - I. Known L and T dwarfs and the first Gaia data release. *MNRAS* 469, 401–415. doi:10.1093/mnras/stx800, arXiv:1703.09454.
- Soubiran, C., Jasiewicz, G., Chemin, L., et al., 2018. Gaia Data Release 2. The catalogue of radial velocity standard stars. *A&A* 616, A7. doi:10.1051/0004-6361/201832795, arXiv:1804.09370.
- Stassun, K.G., Collins, K.A., Gaudi, B.S., 2017. Accurate Empirical Radii and Masses of Planets and Their Host Stars with Gaia Parallaxes. *AJ* 153, 136. doi:10.3847/1538-3881/aa5df3, arXiv:1609.04389.
- Tremblay, P.E., Fontaine, G., Fusillo, N.P.G., et al., 2019. Core crystallization and pile-up in the cooling sequence of evolving white dwarfs. *Nature* 565, 202–205. doi:10.1038/s41586-018-0791-x, arXiv:1908.00370.
- Tremblay, P.E., Gentile-Fusillo, N., Raddi, R., et al., 2017. The Gaia DR1 mass-radius relation for white dwarfs. *MNRAS* 465, 2849–2861. doi:10.1093/mnras/stw2854, arXiv:1611.00629.

- van der Marel, R.P., Sahlmann, J., 2016. First Gaia Local Group Dynamics: Magellanic Clouds Proper Motion and Rotation. *ApJ* 832, L23. doi:10.3847/2041-8205/832/2/L23, arXiv:1609.04395.
- Vasiliev, E., 2019. Proper motions and dynamics of the Milky Way globular cluster system from Gaia DR2. *MNRAS* 484, 2832–2850. doi:10.1093/mnras/stz171, arXiv:1807.09775.
- Wertz, O., Stern, D., Krone-Martins, A., et al., 2019. Gaia GraL: Gaia DR2 gravitational lens systems. IV. Keck/LRIS spectroscopic confirmation of GRAL 113100-441959 and model prediction of time delays. *A&A* 628, A17. doi:10.1051/0004-6361/201834573, arXiv:1810.02624.
- Wyrzykowski, L., 2016. First year of the Gaia Science Alerts, in: Róžańska, A., Bejger, M. (Eds.), 37th Meeting of the Polish Astronomical Society, pp. 65–68. arXiv:1601.02827.
- Zari, E., Brown, A.G.A., de Bruijne, J., Manara, C.F., de Zeeuw, P.T., 2017. Mapping young stellar populations toward Orion with Gaia DR1. *A&A* 608, A148. doi:10.1051/0004-6361/201731309, arXiv:1711.03815.
- Ziegler, C., Law, N.M., Baranec, C., Morton, T., Riddle, R., De Lee, N., Huber, D., Mahadevan, S., Pepper, J., 2018. Measuring the Recoverability of Close Binaries in Gaia DR2 with the Robo-AO Kepler Survey. *AJ* 156, 259. doi:10.3847/1538-3881/aad80a, arXiv:1806.10142.