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Gaia astrometry: a revolution in our knowledge of the Milky Way and beyond

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Abstract. Through careful and systematic observations of the sky, humans have long been building and refining their knowledge of the Universe and of themselves. The Gaia Space Mission has enabled us to make an unprecedented leap in gathering observational data, reaching levels that, until very recently, were beyond our imagination. This leap is mainly a direct consequence of the abundance of observational data, the variety of observed objects and the precision of astrometric measurements, particularly concerning stellar parallaxes, as well as the establishment of an "inertial" and highly accessible reference frame.
Around 35 thousands stellar parallaxes have been measured with great and unprecedented accuracy (relative error < 0.1%). On the other hand, a reference axis system has been established using more than 1.5 million quasars and 2 billion stars, as a secondary frame, with excellent astrometric quality.
With Gaia data, we can study and characterize, in detail and with an extremely high degree of confidence, billion of stars. The Gaia's astrometry precision has allowed to discover, for example, dormant black holes, gravitational lenses, binary asteroids, exoplanets, star clusters, and much more, dramatically changing our knowledge of the Milky Way in only a few years of observations.
Today, we have a more trustworthy understanding of the history of our galaxy, including the environment and mergers. In this lecture, my aim is to highlight astrometric measurements, especially their implications for solving millennia-old questions, such as determining how far celestial objects are and establishing a "fixed direction" to describe their movements, along with the underlying causes and consequences.

Resumo.

Keywords. Astrometry – Gaia Space Mission – Stellar Parallaxes – Reference System – Reference Frame – GaiaNIR

1. Introduction

At this meeting, where we celebrate the 50th anniversary of the Brazilian Astronomical Society (SAB), I had the honor of presenting the opening lecture, in which I wanted to pay tribute to the many astronomers, Brazilian or not, who dedicated their professional lives to measuring and studying the positions and movements of celestial bodies, as well as to developing theories primarily aimed at establishing an essential "fixed" direction.

There is not a better way to honor all these efforts than speaking about the Gaia Space Mission (Gaia Collaboration 2016a), one of the most ambitious and revolutionary projects of our times, and about the revolution that the Gaia astrometry is causing in many fields of the astronomy and other fields of scientific researches (Gaia Collaboration 2016b), (Gaia Collaboration 2018a), (Gaia Collaboration 2021), (Brown 2021) and (Gaia Collaboration 2023a).

As we know, astronomy's dependence on observations is so great that we could say that astronomy is the science that studies the light of celestial bodies. Naturally, the more abundant, precise, and accurate the observations are, the better. It is precisely in this regard that the Gaia Space Mission is revolutionary.

Today, we have at our disposal, thanks to the Gaia Mission, a superabundance of very high quality data that allows us to describe our galaxy and tell its story in ways we couldn't have dreamed of until recently. Beside of this, the Gaia astrometry is complemented by photometric, spectroscopic and spectrophotometric measurements for approximately 2 billion stars in our galaxy and in neighboring galaxies. Additionally, the Gaia satellite also observes hundreds of thousands of solar system objects and millions of distant and compact galaxies and quasars. The magnitude limit is around V~21 and the astrometric precision reaches the microsecond level.

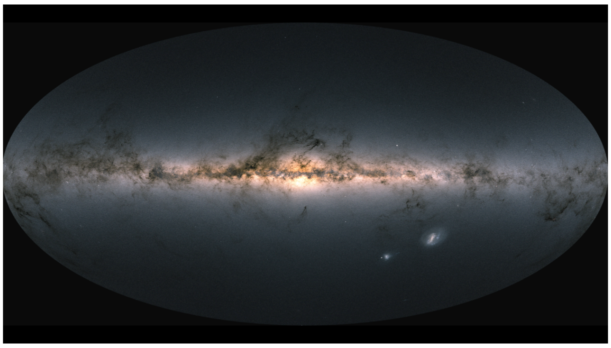

Figure 1. This is not a photo but a map where each pixel contains the flux of thousands of stars that are no longer anonymous: thanks to Gaia, today we know who they are, how much they shine, how old they are, what their masses are, where they came from, and where they are going. Credit: ESA/Gaia/DPAC.

I'm going to address here just a few of the many scientific impacts made possible by Gaia astrometry in some domains of astronomy, not necessarily the most evident or most important ones.

In Figure 1, we can see an iconic and most representative figure of the Gaia Space Mission showing the distribution in galactic coordinates of approximately 2 billion stars and beyond.

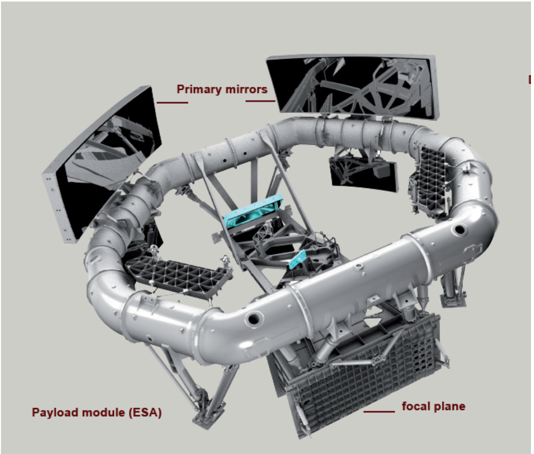

Figure 2. Gaia telescopes and overview of the observational system. Credit: ESA/Gaia/DPAC - EADS Astrium.

2. Gaia observations

The Gaia revolution is primarily based on astrometric, photometric, spectroscopic and spectrophotometric observations performed by the Gaia satellite, along with the big efforts of a team of approximately 400 professionals (technicians, engineers, researchers, etc.) who make up the Gaia Data Processing and Analysis Consortium (Gaia DPAC), responsible for transforming the data collected by the satellite (the data sent to Earth are not images, only numerical codes) into scientific information.

The observational setup is quite unique. In simple terms, it consists of two rectangular telescopes measuring $0.50m$ x $1.45m$ (0.6° x 1.7° on the sky) with focal length of $35m$, separated by a very stable angle of 106.5°, as shown in Figure 2.

In this configuration, like its predecessor HIPPARCOS – High Precision Parallax Collecting Satellite (ESA 1997), both telescopes simultaneously observe two distinct fields and share the same focal plane (Figure 2). This setup enables wide-angle astrometry, therefore allowing for the determination of absolutes positions, proper motions and parallaxes.

The Gaia telescopes do not point at predefined targets or at objects of specific interest. Instead, the satellite simply scans the entire sky from the Lagrange point L2, detecting objects with magnitudes up to $V \sim 21$ and measuring the positions, motions, brightness, colors, and spectra for all these objects.

The satellite has a rotational movement with a period of 6 hours, with its angular momentum perpendicular to the plane containing the two lines of sight and oriented at 45° from the direction of the Sun, as shown in Figure 3. In this configuration, a star transits through the telescope's field of view for approximately 10 seconds (Gaia Collaboration 2016a). The axis of rotation, in turn, precesses around the Sun with a period of 63 days, gradually changing the direction of the satellite's rotation. As the Sun moves along the ecliptic, the satellite's axis of rotation slowly traces loops around the Sun's direction, allowing it to complete a full sky scan approximately every 3 months (Gaia Collaboration 2021).

The detection system in the focal plane consists of a mosaic with 106 Charge-Coupled Devices (CCDs) operating in drift scan mode. As shown in Figure 4, four of these CCDs are used for technical controls, while the others are organized to perform scientific observations. Fourteen CCDs make up the Sky Mapper (SM), which "decides" whether an object should be observed or not.

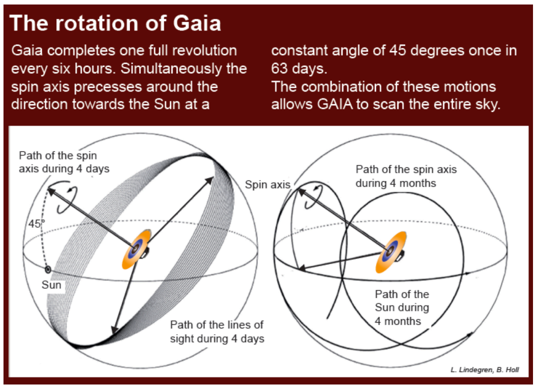

Figure 3. Gaia's scanning law. Credit: ESA/Gaia/DPAC - EADS Astrium.

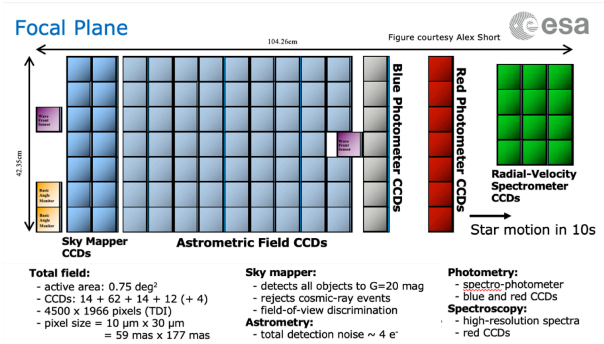

Figure 4. Mosaic of CCDs and their functions. Credit: ESA/Gaia/DPAC - EADS Astrium.

Sixty-two other CCDs are dedicated to the astrometric observations in the Astrometric Field (AF). Seven CCDs form the blue photometric spectrometer (BP), and another seven make up the red photometric spectrometer (RP). The remaining twelve CCDs compose the Radial Velocity Spectrometer mosaic (RVS).

In total, there are approximately 1 billion rectangular pixels, each measuring $10\mu m$ in the transit direction (along-scan – AL) and $330\mu m$ in the perpendicular direction (across-scan – AC), corresponding to $58,9mas$ x $176,8mas$ (mas = milli–arc–seconds).

Observational data from the Gaia Space Mission are released worldwide approximately every 2 years. The first release, Gaia DR1 containing the results of 14 months of observations, was made available in 2016 (Gaia Collaboration 2016b). The second release, based on 22 months of observations, was published in 2018 (Gaia Collaboration 2018a). The third Gaia data release, corresponding to 34 months, was divided into two parts: the first, called Early Gaia Data Release – EDR3, (Gaia Collaboration 2021), was released in 2020 and included mainly astrometric data, while the second part, Gaia DR3, was published in 2022 (Gaia Collaboration 2023a). In 2023, a special release, Focused Product Release (FPR), provided data on specific objects and structures that required special handling: diffuse interstellar bands (Gaia Collaboration 2023b), orbits of Solar System objects (Gaia Collaboration 2023c), radial velocities of long-period variables (Gaia Collaboration 2023d), extremely dense fields, in this case using images from the Sky Maper (Gaia Collaboration 2023e) and surroundings of quasars (Gaia Collaboration 2024a).

Naturally, the precision and abundance of data improved from one release to the next. In Figure 5, from Gaia Collaboration 2023a, we can see the behavior of the astromet-

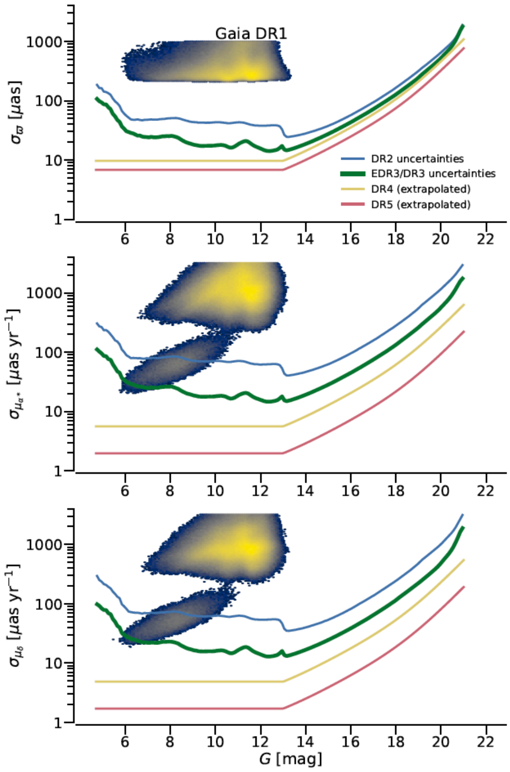

Figure 5. Astrometric precisions reached in each Gaia data release as a function of the G magnitude, including an estimate for Gaia DR4 and DR5 from (Gaia Collaboration 2023a)

ric measurement quality over time as a function of the Gaia G magnitude including an estimate for Gaia DR4 and DR5. For DR1 (top of the figure), the uncertainties refer to the Tycho-Gaia Astrometric Solution (Michalik et al. 2015) and are displayed as density maps, with lighter colors indicating a higher density of sources. The two elliptical regions for the Gaia DR1 proper motion uncertainties are due to stars for which the positions from HIPPARCOS and Gaia could be combined, allowing proper motions to be derived over a 24-year baseline. It is interesting to see that the proper motion uncertainties for Gaia DR3, based on only a 34-month baseline, are comparable to or even slightly better than those based on 24 years (Gaia Collaboration 2023a).

3. Galactic astrometry

From a more general perspective, we can say that the Gaia astrometry, combined or not with other quantities, in a very impressive manner, has radically impacted our view and understanding of the Milky Way and its surroundings in just a few years.

Today, in a much richer, more refined and reliable way, we can talk about its history, structure, and characteristics: the shape of the halo, the general structure of the central bar and spiral arms, Local Bulbe, interaction with neighboring galaxies and a better understanding of the formation of the disk warp, discovery of thousands of stellar clusters (more than what was previously known), invisible companions (as for example, exoplanets and dormant black holes), detection of different mergers: Sagittarius, Gaia-Sausage-Enceladus, Arjuna/Sequoia/L'itoi mergers, Cetus, LMS-1/Wukong, and Pontus, etc.

For example, Gaia data revealed 30,000 stars with peculiar movements, significantly different from those of other Milky Way stars, leading to the conclusion that 10 billion years ago, the Milky Way merged with another galaxy, named Gaia-Sausage-Enceladus, and that this merger was decisive for the evolution and main characteristics of our galaxy (Helmi et al. 2018).

Another important discovery concerns the population of old stars in the core of the Milky Way devoid of heavy metals that would be formed only later in the life of the universe. These stars were identified by exploring two million bright giant stars in the inner regions of our galaxy (Rix et al. 2022). This discovery shows us that the center of the Milky Way harbors some of the oldest known stars.

Among the various quantities we deal to study our galaxy and the universe, the most important is undoubtedly the distance to celestial bodies. Only by knowing how far away they are we can transform the apparent (observed) into the absolute and further unravel the mysteries of the heavens. It is not very difficult to notice that the evolution of our knowledge about the universe progresses in line with our ability to determine distances.

Of course, it is not easy to determine stellar distances. It's done by a few strategies based on astrometric, photometric and spectroscopic observations and on some theoretical models. Each strategy allows us to go further, of course, with a loss of quality.

The first of these strategies, the most accurate and upon which the distance scale of the universe rests, is stellar parallax (trigonometric or annual parallax): a simple displacement of the star in the sky, describing a very tiny ellipse with an annual period as a consequence of Earth's orbital motion.

To quantify the Gaia revolution in terms of parallaxes, we can compare the situation before and after Gaia. The main source of parallaxes before Gaia was the first astrometric catalog of stars observed from space by HIPPARCOS, whose data for around 120,000 pre-selected stars were released in 1997 (ESA 1997) and (van Leeuwen 2007).

The number of highly precise parallaxes, with a relative error of less than 0.1%, was very small during the HIPPARCOS era, covering only a few stars (3-4 stars). This number increased to around $3.5x10^4$ stars in Gaia DR3, and it will be even greater in Gaia DR4 and DR5. Considering a relative error of up to 1.0%, we had approximately 700 stars, and now we have approximately $6x10^6$ stars. If we limit the relative error to 10%, which is quite reasonable for practical purposes, we increased from 30–40 thousands to 10^8 stars.

To illustrate the scope of these parallax measurements, we can think about the study of stellar evolution synthesized in an HR diagram. As a consequence of Gaia data, it is now possible, even when greatly restricting the sample to work only with the best data, to build such a diagram with millions of stars and with the various stellar populations oversampled, as shown in Figure 6.

This HR diagram was constructed with more than 4 million stars located less than 2 Kpc from us. The best we had before was limited to, at least, 100 times fewer stars. To get a better idea, we can look at the branch of white dwarfs. While before we had one or two dozen, in this diagram we have almost 40 thousands. Naturally, this scenario allows us to break down the large groups into subgroups and see details never before seen. Returning to the white dwarfs, with this data, it is easy, for example, to distinguish two large families: those rich in hydrogen and those dominated by helium (Gaia Collaboration 2018b).

Another very interesting advance thanks to Gaia parallaxes is related to the orbital solutions for binary systems. In the third data release, we had about 800 thousands of solved systems. As

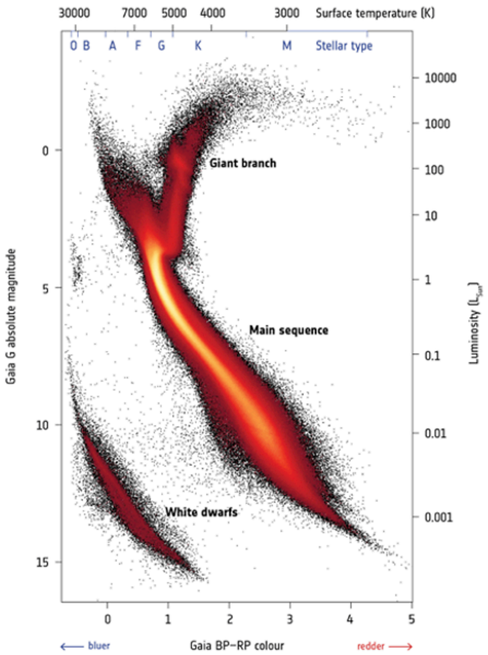

Figure 6. HR Diagram for 4.3 million objects closer than 5 thousands light-years from us (Gaia DR2). (Gaia Collaboration 2018b) – Copyright: ESA/Gaia/DPAC.

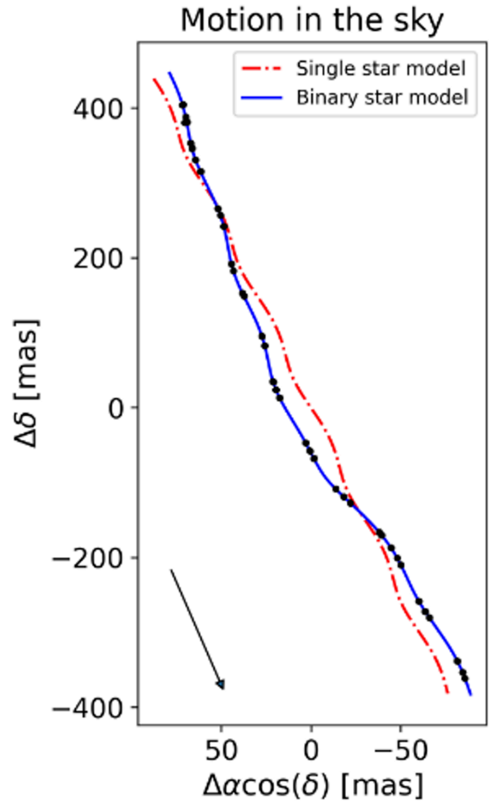

Figure 7. The displacement of the visible companion of the dormant black-hole BH3 with 33 solar mass. The red corresponds to a non disturbed trajectory and the blue is the same disturbed by BH3. The black points correspond the fit of the movement of the visible companion. (Gaia Collaboration 2024b) – Copyright: ESA/Gaia/DPAC.

a consequence, in addition to a huge number of stellar masses, it had discovery of dormant black holes in our galaxy, including the exceptional Gaia BH3 (Gaia Collaboration 2024b).

A dormant black hole is not detected by the radiation emitted from matter accelerated from a nearby stellar companion into it: only the perturbation in the movement of a companion can reveal its presence.

In this way, the Gaia satellite with its very high precise astrometry has proven to be a discoverer of dormant black holes in our galaxy formed from the collapse of giant stars. The Gaia BH1, BH2 and BH3 were discovered, and its mass was determined based on Gaia's astrometry, including the parallaxes of the companion stars.

The Gaia BH3 is the third stellar-origin black hole discovered by Gaia in our galaxy. It is located 2,000 light years from Earth and has an exceptional mass of over 30 solar masses. This discovery raises the question of how such massive black holes originating from stars can exist.

In Figure 7, we show the theoretical undisturbed modeled trajectory (red color) of the stellar companion of Gaia BH3, which is a superposition of its proper motion and parallax. In contrast, in blue color, we have the modeled disturbed trajectory by Gaia BH3, and in black the observed positions.

Alongside all improvements, the fourth release, expected in 2026, is projected to reveal thousands of confirmed and candidate exoplanets discovered via Gaia astrometry.

4. Solar System Objects

Once again, the Gaia mission, with its highly precise astrometry, proves to be extremely important for advancing our understanding of the dynamics, history, and evolution of the Solar System through the observations of small Solar System objects and discovery of new asteroids and, mainly, the characterization of their orbits and physical properties.

Around 160,000 orbits have been traced, including those for many NEOs (Near-Earth Objects) and PHAs (Potentially Hazardous Asteroids) based on 66 months of observations (Gaia Collaboration 2023c). With this vast amount of precise orbital data, and spectrophotometric (BP/RP) measurements many significant advances in our understanding of their dynamics and origins are expected.

The precise orbits, mainly those of the NEOs and PHAs are crucial for space exploration and for predicting possible future close approaches, thereby contributing to the protection of Earth.

Additionally, Gaia has discovered new asteroids that had not yet been cataloged and hundreds of binary asteroids, helping to expand our knowledge of the population of these objects in the Solar System.

Gaia also observed a sample of period comets, a few dozen natural planetary satellites and trans-Neptunian bodies.

In Figure 8, we can see a sample of asteroid orbits between the Sun and Jupiter, coded by perihelion distance, as published in Gaia DR2. In blue we have those which perihelions are closer to the Sun, including the more eccentric NEOs. In green, we have the asteroids of the main belt and in red those more distant, the Trojans.

In some years, we will have results based on 66 months of observations (the data are already on the ground), ensuring much greater coverage of the orbits for twice the number of objects compared to now. This will further improve both precision and accuracy. With this trend, Trojan orbits are expected

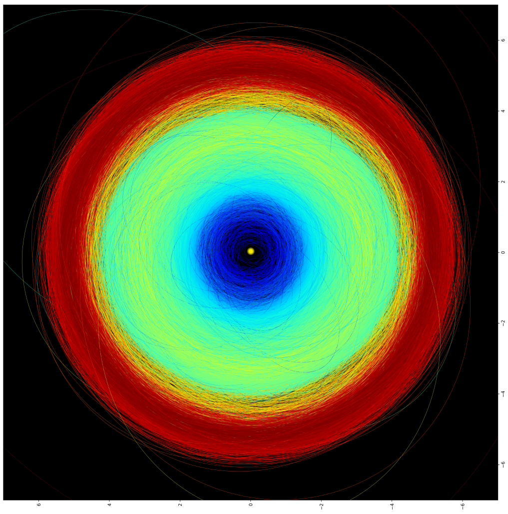

Figure 8. Asteroides orbits in Gaia DR2 codified according to the perihelion distance. Copyright: ESA/Gaia/DPAC.

to be as good as those of the main-belt asteroids are today (Gaia Collaboration 2023c).

5. Extragalactic Astronomy

The Gaia Space Mission was conceived with a primary focus on stars of our galaxy and on point-like sources in general, including quasars. However, the Gaia satellite also detects extended objects, such as Solar System bodies as we saw, planetary nebulae and galaxies.

The morphological parameters of a large number of galaxies and quasar host galaxies distributed throughout the sky constitute an important contribution to the study of their formation and evolution, the role of merges, cosmological evolution, mass distribution in the universe, dark matter, the relationship between supermassive black holes and host galaxies, among other topics.

Extended objects observed by Gaia satellite, require specific processing, and it was in this context that the Extended Object (EO group - Development Unit 470 - CU4) was created, similar to other groups, with the aim to explore the observations of galaxies and quasar-host galaxies to extract information about their brightness profile.

In Gaia DR3, we have 1.9 million quasars with redshifts measured using spectrophotometers and in addition some few million candidates. For 60,000 of these quasars, it was possible to detect the host galaxies and for 15,000 of them, morphological characteristics were determined. On the other hand, 2.9 million galaxies were observed and for 800,000 of them it was possible to obtain a solution for their brightness profiles and morphological parameters (Gaia Collaboration 2023f) and (Gaia Collaboration 2023g).

The spacial distribution of the galaxies and quasars for which it was obtained, at least, an acceptable solution, is shown in Figure 9.

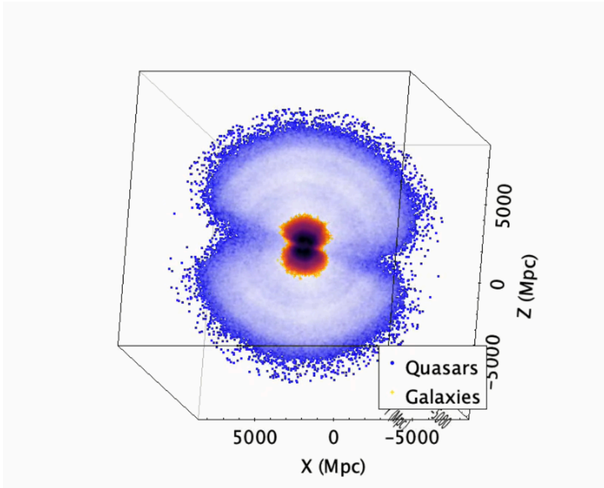

Figure 9. Spacial distribution of the quasars and galaxies treated by Gaia Extended Object group. Copyright: ESA/Gaia/DPAC.

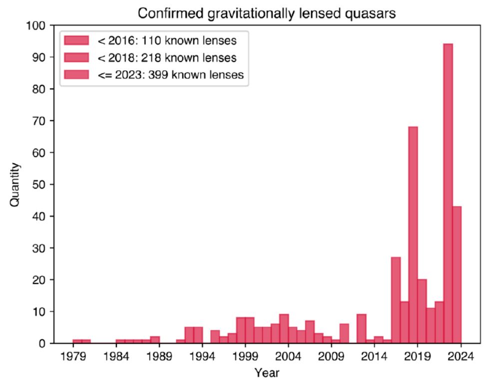

Figure 10. Histogram illustrating the increase in the discovery rate of quasar gravitational lenses following the Gaia data releases. Copyright: Pedro H. V. Cunha (IAG-USP)

Another interesting point, based on both the quality of Gaia astrometry and the quantity and variety of observed celestial bodies, is the discovery of gravitational lenses. In particular, the discovery rate of strong gravitational lenses of quasars has changed a lot, from about 3 to around 40 new lenses per year.

The histogram in Figure 10 illustrates this new era in strong gravitational lens of quasars discovering.

6. Reference Frames

Since its beginnings, astronomy as a science has been concerned with the positions and movements of celestial bodies, which depend on the adopted reference system. In other words, determining the position of a celestial body anywhere in the universe essentially depends on the definition of a spatial reference system and on our ability to materialize them. So, the construction of a spatial reference system (definitions and materialization) is, consequently, one of the oldest focus of astronomy and an important and big task of the astrometry.

The materialization of a reference system by a reference frame represents the most practical (observational) aspect of its construction. The difficulties associated with materialization stem from the desire to have a reference system as close as possible to an inertial one relative to which we can obtain the precise coordinates of any celestial body, at any moment and from any location. In other words, this means that the reference system can be accessed independently of the observed object and the location of the observer. It must be available across the entire sky and be the same in any region of the sky. The materialization occurs through a catalog of positions and, when applicable, motions of fiducial points, along with any and all other information necessary to access the system of axes at any time.

The word "catalog" in Astrometry, therefore, goes far beyond a list of objects with positions, motions, and other characteristics: it signifies the materialization of a reference system. An astrometric catalog of absolute positions (absolute catalog) defines and materializes a reference system, whereas a catalog of relative positions (relative catalog) only secondarily materializes the reference system that served as its basis.

Until a few years ago, both the reference system and its materialization were carried out through a series of so-called Fundamental Catalog, the last of which was the FK5 (Fricke et al. 1988). This catalog with its complement, contained approximately 5 thousand stars with unknown or poorly known parallaxes and errors in proper motions compromised the inertiality. At the same time, the low number of fiducial points compromised the accessibility to this system, among many other difficulties.

In 1991, the International Astronomical Union (IAU) opted to build a barycentric reference system based on quasars (parallaxes and proper motions null) that is much closer to an inertial one than the previous ones. It also decided to align this new system with the old one and eliminate the ecliptic from the definition of the right ascension origin (x-axis).

Initially, the International Celestial Reference System (ICRS) was materialized by the International Celestial Reference Frame – ICRF (Ma et al. 1998), based on extremely precise VLBI observations of compact extragalactic radio sources. In total, there were just over 200 defining sources, and now, ICRF3 (Charlot et al. 2020) has just over 300 sources. Given this very low number of defining sources, the ICRF had and still has to be extended by secondary reference frames based on stars observed in the visible frequency. The first stellar representation of this system is the HIPPARCOS catalog, which is not dense enough. Therefore, the extension relies on other catalogs, always with some loss of quality.

Here too, the Gaia Space Mission was revolutionary completely transforming the scenario and providing a reference frame that meets all requirements – such as inertiality, availability, accessibility, homogeneity and rigidity – with an unprecedented level of precision and accuracy. Thanks to Gaia, today, the International Celestial Reference System is materialized primarily by approximately 1.5 million quasars and secondarily by nearly 2 billion stars with excellent and comprehensive astrometric data (Gaia Collaboration 2018c) and (Gaia Collaboration 2022).

Despite all the qualities of the Gaia frame, the link with the radio system (ICRF) through common sources is of lower quality than that of each reference frame within its own domain, since the centers of radio and visible emission may differ. Consequently, it was decided to maintain both solutions through IAU Resolution B3, adopted in 2021, which grants both the same fundamental status (Mignard 2024) by stating that:

"From 1 January 2022, the fundamental realization of the International Celestial Reference System (ICRS) shall comprise the Third Realization of the International Celestial Reference Frame (ICRF3) for the radio domain and the Gaia-CRF3 for the optical domain"

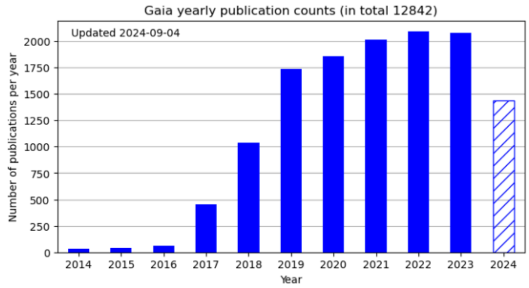

Figure 11. The annual number of peer-reviewed scientific articles talking about Gaia Space Mission or using Gaia data Copyright. Credits: ESA/Gaia/DPAC, CC BY-SA 3.0 IGO.

7. Considerations and future

As we have seen, the abundance and quality of data from the Gaia Space Mission are impressive and represent, on one hand, the spectacular overcoming of numerous problems and challenges, and on the other, the origin of new and exciting questions and researches. The volume of Gaia data is so impressive that it is not an exaggeration to think that much of astronomy in the coming decades will rely on these data.

A look at the literature shows us how significantly the Gaia Space Mission has made its mark. In Figure 11, the annual number of peer-reviewed scientific articles talking about Gaia or using Gaia data can be seen. This amounts to an average of around 5 articles published per day.

In the near future, January 2025, the Gaia satellite will stop collecting astronomical data. A little later, 2026, it should be published the fourth data release (Gaia DR4), based on 66 months of observations (60 months of the nominal mission plus 6 months of the extension), containing all the data planned in the original mission. In a more distant future, we will have Gaia DR5 based on 120 months of observations, along with the publication of all information collected throughout the mission.

Naturally, after the success of HIPPARCOS and Gaia, the astronomy community is asking about and considering possible new satellites and space missions. There are already some proposals underway and submitted. Among them, the one that attracts me the most and may end up combining the others is the so-called GaiaNIR (Gaia Near Infra-Red), aiming, mainly, for high-accuracy astrometry in the near-infrared. In summary, it would be a kind of Gaia-II working on the TDI-mode observations, but in the infrared instead of the visible spectrum (GaiaNIR CDF Study Report: CDF-175(C)). With this mission, we would access the dark regions of the Milky Way, observe approximately 10 billion objects, and obtain proper motions 15-20 times more precise for common stars, among many other observational advances.

Although, for philosophical reasons mainly, I avoid making direct comparisons, when I reflect on the impact of the Gaia Space Mission on astronomical knowledge, I can not avoid to think of other monumental milestones in astronomy, such as the advent of telescopes, precise clocks, photographic plates and digital cameras, among others.

For me, the Gaia data already released, together with those expected from future, combined with data from other current and future space missions and large ground-based telescopes, as well as with the advanced processing and analysis capabilities, inspire high expectations for ground-breaking discoveries and transformative changes in the not-too-distant future.

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References

Brown A. G. A., 2021, ARA&A, 758, 59.
Charlot P., Jacobs C. S., Gordon D., Lambert S., de Witt A., et al. 2020, A&A, 644, A159.
ESA Publications Division, 1997, vol. 1200, ESA Special Publication: the HIPPARCOS and TYCHO catalogues.
Fricke W., Schwan H., Lederle T., Bastian U., Bien R. et al., 1988, Veroeff. Astron. Rechen-Inst., Vol. 32.
Gaia Collaboration, (Prusti, T. et al.) 2016a, A&A, 591, A1.
Gaia Collaboration, (Brown, A. G. A. et al.) 2016b, A&A, 595, A1.
Gaia Collaboration, (Brown, A. G. A. et al.) 2018a, A&A, 616A, 1G.
Gaia Collaboration, (Babusiaux, C. et al.) 2018b, A&A, 616, 10G.
Gaia Collaboration, (Mignard, F. et al.) 2018c, A&A, 616, A14.
Gaia Collaboration, (Brown, A. G. A. et al.) 2021, A&A, 649, A1.
Gaia Collaboration, (Klioner, S. A. et al.) 2022, A&A, 667, A148.
Gaia Collaboration, (Vallenari A. et al.) 2023a, A&A, 674, A1.
Gaia Collaboration, (Schultheis, M. et al.) 2023b, A&A, 680, A83.
Gaia Collaboration, (David, P. et al.) 2023c, A&A, 680, A37.
Gaia Collaboration, (Trabucchi, M. et al.) 2023d, A&A, 680, A36.
Gaia Collaboration, (Krone-Martins, A. et al.) 2023e, A&A, 680, A35.
Gaia Collaboration, (Ducourant, C. et al.) 2023f, A&A, 674, A11.
Gaia Collaboration, (Bailer-Jones, C.A.L. et al.) 2023g, A&A, 674, A41.
Gaia Collaboration, (Krone-Martins, A. et al.) 2024a, A&A, 685, A130.
Gaia Collaboration, (Panuzzo, P. et al.) 2024b, A&A, 686, L2.
Helmi, A., Babusiaux, C., Koppelman, Helmer H., Massari, D. et al., 2018, Nature, 563, 7729.
Krone-Martins, A., Ducourant, C., Teixeira, R., Galluccio, L., Gavras, P. et al., A&A, 556, A102.
van Leeuwen F., 2007, A&A, 474.
Ma C., Arias E. F., Eubanks T. M., Fey, A. L., Gontier A. -M. et al., A&A, 556, A102.
Michalik D., Lindegren L. and Hobbs D., 2015, A&A, 574, A115.
Personal communication.
Rix H.W., Chandra V., Andrae R., Price-Whelan A.M., Weinberg D.H., 2022,ApJ, 941, 45R.