GAIA (originally the acronym for Global Astrometric Interferometer for Astrophysics) is a mission of the European Space Agency (ESA) which will make the largest, most precise three-dimensional map of our Galaxy by an unparalleled survey of one per cent of the Galaxy’s population of 100 billion stars with the precision of microarcseconds (μas). This article will briefly review Gaia, the data releases (DR) and the possible implications of this mission. The reader will be introduced to the DR1 and DR2 data releases and the scientific outcomes of DR1 as a forerunner to the DR2 (released on 25 April 2018) of this one-of-a-kind mission. This article aims to summarize this great milestone in astronomy.

And those who were seen dancing were thought to be insane by those who could not hear the music.

– Friedrich Nietzsche

Introduction

Imagine you are on a dance floor where everyone is dancing to their own beat, own music, own style. And what appears to be insane movements are actually very ordered movements, each to a different beat. Space is the dark labyrinth, which makes us lose our perception of depth in its two-dimensional projection. What we need is to hear the music, and follow the dance steps of each dancer. That is exactly what Gaia is up to.

On 19 December 2013, Gaia was launched and put in a Lissajous-

*DOI: https://doi.org/10.1007/s12045-019-0796-2
type orbit, around the Lagrange point L2 of the Sun-Earth system, which is located 1.5 million km from the Earth in the anti-Sun direction. According to the Greek poet Hesiod, Chaos was the first thing to exist, but next (possibly out of Chaos) came Gaia. It is expected that Gaia will bring order at the Milky Way level to our understanding of the positions and motions of stars. In its expected lifetime of five years, Gaia will observe each of its one billion sources about 70 times, resulting in a time-based record of the brightness and position of each source over time. The photometry and spectroscopy will also provide the ages (for stars), chemical compositions and velocities of celestial objects. The scope of Gaia’s prospective discoveries makes the mission unique in scope and potential returns.

1. Astrometry

Astrometry is the branch of astronomy which deals with the accurate measurement of the positions and hence distances and motions of celestial objects including planets and other solar system bodies, stars within the Milky Way, other galaxies and quasars. Since observing and making catalogues of the positions of the stars and planets on the sky was important for time-keeping, navigation and agriculture, astronomy and astrometry were synonymous in earlier times.

Astrometry has applications ranging from validation of the heliocentric theory, to detection of the massive stellar black hole in the center of our Galaxy, to clues to the origin of the Universe. It provides basic information related to distance and motion of celestial bodies which is essential to convert apparent measured quantities to absolute, physical ones.

Distances to stars are really vast. If we were to scale the Sun to a marble one centimetre in size, the Earth would be a grain of salt one meter from it, Pluto would be at a distance of forty meters, and the closest stars Proxima and Alpha Centauri would be two hundred kilometres away. The simplest method of measuring distance is by parallax². An increase in baseline can be obtained
by measuring positions of stars six months apart. By definition, a parallax ($\pi$) of one arcsecond (1") is obtained for an object at a distance of 1 pc (3.26 light years) with a baseline of 1 AU.\(^3\) (Figure 1).

2. **Spacecraft**

Ground-based optical telescopes provide blurred images, degraded due to the atmosphere, as well as with a limiting resolution due to diffraction (0.1" for a 1 meter telescope in the visible). For precision astrometry, therefore, it is essential to go to space.\(^4\) Hipparcos (HIgh Precision PARrallax COllecting Satellite) was launched in 1989 to provide precision astrometry.

The Tycho Catalogue was one of the primary products of Hipparcos, which collected data for four years, from November 1989–March 1993 for one million stars to better than 25 milliarcseconds by observing them 130 times over the duration of the mission.

In addition to J2000 positions and proper motions, it included $B$ and $V$ magnitudes.\(^5\) Using a more advanced reduction technique, the subsequent Tycho-2 Catalogue was released for 2.5 million stars complete to a $V$ magnitude of 11.

Gaia is a major improvement to the Hipparcos mission in terms of the collecting area of the primary mirrors. It collects more than 30 times the light of its predecessor, and its parallax measurements

---

\(^3\) 1 AU is an astronomical unit, which is the mean distance of the Earth from the Sun or 149.6 million km.

\(^4\) Good sites and adaptive/active optics can give very good resolution, for example at the 10 m Very Large Telescope, the adaptive optics system achieves an angular resolution of about 50 mas.

\(^5\) Magnitude is a scale used to measure the brightness of an object in astronomy. A difference of 5 magnitudes corresponds to a factor of exactly 100 times in intensity. Brighter stars have smaller magnitude than fainter stars.
are of the order of μas. To maximize the collection of photons, it uses a broad $G$ band filter which centres at 5328Å and with a width of 440Å. For colour information, it uses two filters $G_{BP}$ and $G_{RP}$, that centre at 5320Å and 7970Å and with widths of 253Å and 296Å respectively. Figure 2 shows the evolution of precision astrometry in astronomical observations.

The payload module also contains all necessary electronics for managing the instrument operation and processing the raw data [1].

The Gaia spacecraft is composed of the payload module, the service module and the deployable sunshield. It had a launch mass of around 2 tonnes. The payload module is built around a toroidal-shaped optical bench (about 3 m in diameter) which provides the structural support for the single integrated instrument that performs three functions – astrometry, photometry and spectrometry.

Originally Gaia was planned as an interferometric mission, but later the present optical telescope design was adopted which ensured the desired astrometry. Since observations started in July 2014, two identical TMA telescopes, with apertures of 1.45 m × 0.5 m simultaneously observe in two regions of the sky separated by the basic angle (106.5°). Gaia has three motions: rotation ev-
every 6 hours, precession every 63 days, and revolution around the Sun with L2, every year (Figure 3). It observes strips of the sky as it spins and records it on 106 CCD detectors with a total of almost 1 billion pixels.

With an accuracy of 24 μ as, we can accurately measure a distance of \( d \) (pc) = \( 1/\pi \) (arcsec) = \( 10^6/24 = 42 \) kpc. So with a galactic diameter of 30 kpc and the Sun being 8 kpc from the centre, we can accurately measure distances in the Galaxy and its close neighbourhood. Gaia will allow astronomers to study the velocities of stars in great precision. The space velocity can be found by combining the proper motion (which can be estimated from shifts in positions of stars over long baselines, thus providing the velocity as projected on the plane of the sky) with the radial velocity, which is perpendicular to the proper motion and can be found from the Doppler shifts of spectral lines observed by the spectrograph onboard Gaia. With this outstanding data set, astronomers will trace the past trajectories of stars in the Milky Way, thus studying the dynamical history of our Galaxy. By ‘rewinding the track of time’ in the stars’ paths, we will gain new insights into the formation of our Galaxy.

Also, with Gaia’s unique combination of astrometric, photomet-

---

**Gaia Instruments**

**Astrometry**: Two three-mirror anastigmatic (TMA) telescopes (distances and proper motions)

**Photometry**: Blue and Red photometers (BP/RP) (brightness and ages of stars)

**Spectrometry**: Radial-velocity spectrometer (RVS)(radial velocities, chemical compositions).

---

**Figure 3.** Gaia motions: rotation every 6 hours, precession every 63 days and revolution around the Sun with L2, every year (Image Credit: ESA)
ric and spectroscopic data, we can characterise stars and measure their physical parameters such as their masses, luminosities and their ages. This will be an unparalleled census of the Galaxy’s stellar population.

3. Issues

Forty million stars pass Gaia’s focal plane every day, leading to 40 Gigabytes of information per day, or 73 Terabytes over the full, nominal life of the mission. Astronomers are challenged with dealing with a flood of data since Gaia began its work in 2013. The ‘raw’ data transmitted by Gaia is processed here on Earth to turn it into a calibrated set of measurements that can be freely used by the astronomical community and citizens. The Gaia Data Processing and Analysis Consortium (DPAC) is responsible for processing the raw data, which will be published in the Gaia catalogue. ESA had to not only design and build the spacecraft itself, but they also had to develop new computer software that will ensure that the data can be processed efficiently once it is back on Earth.

During the commissioning phase, a number of unforeseen problems occurred with Gaia. These include contamination of the telescope optics due to ice, stray light (due to fibres on the edge of the sunshield) infiltrating the focal plane, micro-clanks (small mechanical vibrations arising from thermal effects) and larger-than-expected variations in the basic angle between the two Gaia telescopes. Detailed investigations by DPAC and prime contractor Airbus Defence and Space have identified means of diminishing these issues.

Gaia can detect and measure celestial objects down to magnitude 20.5, about 650,000 times fainter than an unaided eye can see. The precision of the measurements: astrometric, photometric, and radial velocity depends upon the type of object and its magnitude.

The measurements provided in the first Gaia Data Release (DR1) are substantially more precise than those in the existing cata-
logues. In the final Gaia catalogue, expected in the early 2020s, brighter objects (3–13 magnitudes) will have positions measured to a precision of 5 $\mu$as, parallaxes to 6.7 $\mu$as, and proper motions to 3.5 $\mu$as per year. For the faintest stars (magnitude 20.5), the equivalent numbers are several hundred $\mu$as.

The photometry measurements in the final catalogue is expected to be precise at the level of milli-magnitudes. For the subset of objects for which radial velocity measurements are obtained these will be measured with a precision of 15 km/s for the fainter stars and as precise as 1 km/s for the brighter stars.

The accuracy of the distances obtained by Gaia at the end of the nominal mission will range from 20% for stars near the centre of the Galaxy, some 30,000 light years away, to a remarkable 0.001% for the stars nearest to our solar system.

*Figure 4* shows the kind of results we expect to get from Gaia which range from rotation curves of the Galaxy at 15 kpc, proper motions in the LMC/SMC up to 2–3 km/s, the 20 kpc horizon within which we shall measure proper motions accurate to 1 km/s.
4. Data Release 1 (DR1)

On 14 September 2016, Gaia DR1 was released worldwide with positions \((\alpha, \delta)\) and \(G\) magnitudes for all 1 billion sources with acceptable formal standard errors on positions\(^6\).

Gaia DR1 is based on observations collected between 25 July 2014 and 16 September 2015 with 5–25 transits per star through Gaia’s focal plane. Figure 5 shows the first Gaia sky map released. To calculate the parallax and the proper motion (along the plane of sky), it is necessary to compare the observations of two different epochs.

The time baseline was not sufficient for the calculations of accurate parallaxes and hence distances and proper motions for DR1. Hence, DR1 uses the data for stars common in the Tycho-2 Catalogue (measured 24 years ago) and DR1 to find the five-parameter astrometric solution – positions, parallaxes, and proper motions for 2 million stars with a precision of 0.03 mas. This part of Gaia DR1 is based on the Tycho-Gaia Astrometric Solution (TGAS). Gaia Collaboration \textit{et al.} (2016, 2017) describes DR1 in detail and its applications along with performance, limitations, and future prospects. There were various issues with DR1 due to which

---

\(^6\)See https://www.cosmos.esa.int/web/gaia/release.
researchers eagerly awaited DR2 which promised a richer treasure of data.

Despite its limitations, there were more than 300 refereed papers from the first data release. Altmann et al. [2] derived the movements of 583 million stars through space by comparing the Gaia positions with those of existing catalogues to obtain the positions and proper motions of stars. This provided valuable data on their velocities and hence their positions in the past and future.

Helmi et al. [3] discovered a large population of stars that orbit the Milky Way in the direction opposite to most stars. These stars probably came from a smaller galaxy that was cannibalized by the Milky Way.

Bonaca et al. [4] combined the data with spectroscopic surveys obtained from the ground to investigate an interesting population of stars in the halo of the Milky Way. They found that these stars have formed in situ, rather than having been accreted from smaller galaxies, shedding light on the build-up history of our Galaxy. Oh et al. [5] found more than 13,000 new co-moving pairs of stars. They also found some larger associations of stars, all moving in the same direction, indicating that they were all born together in the same star cluster. DR1 also provided brightness measurements of more than 3000 variable stars where about 10% were newly discovered by Gaia and the positions and brightness of more than 2000 quasars, which are distant celestial objects used to define the coordinate system for astronomers to reference the sky.

5. Data Release 2

Gaia Data Release 2 was released on 25 April 2018. The five-parameter astrometric solution for more than 1.3 billion sources, with a limiting magnitude of $G = 21$ and a bright limit of $G \approx 3$ is expected based on roughly 22 months of data and unlike TGAS, with no priors needed.

Parallax uncertainties are in the range of up to 0.04 mas for sources
at \( G \leq 15 \), around 0.1 mas for sources with \( G = 17 \) and at the faint end, the uncertainty is of the order of 0.7 mas at \( G = 20 \). The corresponding uncertainties in the respective proper motion components are up to 0.06 mas yr\(^{-1} \) (for \( G \leq 15 \) mag), 0.2 mas yr\(^{-1} \) (for \( G = 17 \) mag) and 1.2 mas yr\(^{-1} \) (for \( G = 20 \) mag). The Gaia DR2 parallaxes and proper motions are based only on Gaia data; they no longer depend on the Tycho-2 Catalogue.

Median radial velocities will be available for more than 6 million stars with a mean \( G \) magnitude between about 4 and 13 and an effective temperature in the range of about 3550 to 6900 K. This leads to a full six-parameter solution – positions and motions on the sky with parallaxes and radial velocities, all combined with mean \( G \) magnitudes.

The photometry expected is \( G \) magnitudes for more than 1.5 billion sources, with precisions varying from around 1 milli-mag at the bright \( (G < 13) \) end to around 20 milli-mag at \( G = 20 \). Note that the photometric system for the \( G \) band in Gaia DR2 is different from the photometric system used in Gaia DR1. Epoch astrometry for more than 13,000 known asteroids based on more than 1.5 million CCD observations and light curves for more than 500,000 variable sources are also available.

6. Further Data Releases

To know the 3D structure of the Galaxy, we need to know the positions and space velocities of objects in the Galaxy very precisely. The final Gaia catalogue will have complete astrometric, photometric, and radial-velocity catalogues as well as all available variable-star and non-single-star solutions. It will also provide colour-information as well as spectroscopic data of the chemical compositions of objects, thus correlating objects with common positions, velocities, ages (for stars) and chemistry. This will reveal important clues about the composition, formation and evolution of the Galaxy, that is, the ‘archaeology’ of the Galaxy. It will also provide source classifications (probabilities) plus multiple astrophysical parameters (derived from photometry and as-
trometry) for stars, unresolved binaries, galaxies, and quasars. There will also be an exoplanet list and all epoch and transit data for all sources.

There are various ground-based spectroscopic surveys to complement Gaia data like the RA dial Velocity Experiment (RAVE), APO Galactic Evolution Experiment (APOGEE), Galactic Archaeology with HERMES (GALAH), GAIA-ESO (European Southern Observatory) which already have some of their data available. On-ground, proper motion surveys like UKIRT Infrared Deep Sky Survey (UKIDSS) and Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) complement Gaia data.

Various tools have been developed to aid astronomers use data like the Gaia Observation Forecast Tool (to find out when their targets will be observed by Gaia), Gaia Sky (real-time, 3D, astronomy visualisation software), Gaia Ground-based Observational Service for Asteroids (Gaia-GOSA, to support observers in planning photometric observations of asteroids), Gaia Ground-based Optical Tracking (GBOT, interactive tools for tracking Gaia), Gaia Universe Model Snapshot (GUMS), etc. The reader is advised to have a look at their individual websites for further information.

Various projects will be possible with the data at different stages. Galaxies like our Milky Way undergo dramatic dynamic changes due to gravitational interactions and merging with smaller galaxies in its neighbourhood. Gaia will provide not only positions and motions of stars but also ages and chemical compositions of stars. Thus, we can study the evolution of our Galaxy over time scales of billions of years, which is also termed as ‘archaeology’ of the Galaxy.

Gaia will also measure distances to extragalactic objects, exoplanets and even objects like comets and asteroids in our solar system. Stellar moving groups, clusters and streams can be identified using this information. Vital data on membership of stars in clusters and their kinematics can be well studied [6]. Gaia will significantly expand our knowledge of the Universe from small

---

**Future Data Releases**

**2020:**
Improved astrometry and photometry,
Object classification and astrophysical parameters, BP/RP spectra and/or RVS spectra,
Mean radial velocities
Variable-star classifications,
Solar-system results,
Non-single star catalogues,

**2022:** Full astrometric, photometric, and radial-velocity catalogues,
All available variable-star and non-single-star solutions,
Source classifications (probabilities) plus multiple astrophysical parameters (derived from BP/RP, RVS, and astrometry) for stars, unresolved binaries, galaxies, and quasars,
An exo-planet list,
All epoch and transit data for all sources.
Additional Data and Tools:
Spectroscopic surveys: RAVE, APOGEE, GALAH, GAIA-ESO
On-ground proper motion surveys: UKIDSS, Pan-STARRS.

Gaia tools:
Gaia Observation Forecast Tool
Gaia Sky, Gaia-GOSA, GBOT, GUMS

scales to very large scales and has a huge potential in outreach activities [7]. It shall be a major repository of information for at least the next 50 years.

Following DR2, there has been a very heavy cascade of articles based on this data. New and interesting projects can be planned to meet this excitement! All the best! Prepare and enjoy exploring Gaia!

Acknowledgements

The author would like to thank the referee for her/his valuable comments that helped improve the content of the article.

Suggested Reading

[1] G Gilmore et al., Messenger, Vol.147, 25, 2012.
[2] M Altmann, S Roeser, M Demleitner, U Bastian, F Schilbach, A&A, 600, L4, 2017.
[3] A Helmi, J Veljanoski, M A Breddels, H Tian, L V Sales, A&A, 598, A58, 2017.
[4] A Bonaca, C Conroy, A Wetzel, P F Hopkins, D Kereš, ApJ, 845, 101, 2017.
[5] S Oh, A M Price-Whelan, J M Brewer, D W Hogg, D N Spergel, J Myles, ApJ, 854, 138, 2018.
[6] E Moraux, EAS Publications Series, Vol.80–81, 73, 2016.
[7] K S O’Flaherty, J Douglas, T Prusti, IAUS, Vol.248, 535, 2008.
[8] Gaia Collaboration et al., A&A, Vol.601, A19, 2017.
[9] Gaia Collaboration et al., A&A, Vol.595, A1, 2016.