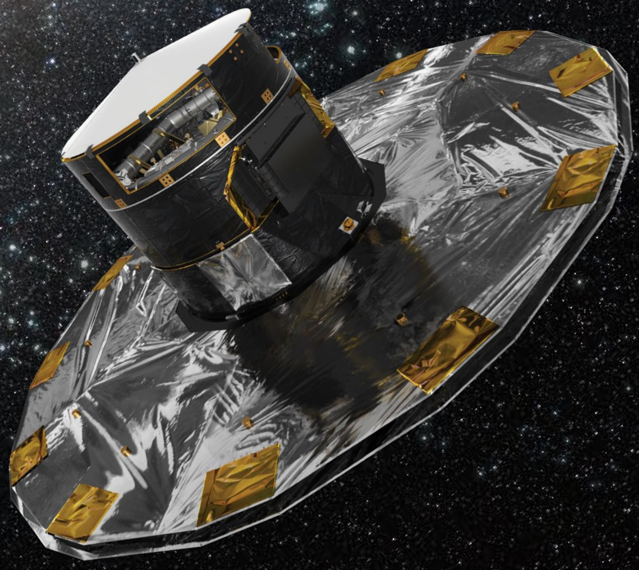
gaia

→ THE BILLION STAR SURVEYOR
GAIA DATA RELEASE 2

Media kit



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This document is available online at:
sci.esa.int/gaia-data-release-2-media-kit

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→ TABLE OF CONTENTS

1

Gaia – the billion star surveyor

→ GAIA – THE BILLION STAR SURVEYOR

Gaia's mission is to create the most accurate map of the Galaxy to date.

Gaia's first data release was published on 14 September 2016. It included the position and brightness for 1100 million (1.1 billion) stars, but distances and motions for just the brightest two million stars. Now Gaia's second data release is ready, opening a new era for astronomy. It provides sky positions and brightnesses for nearly 1.7 billion stars, distances, motions and colour information for 1.3 billion, and a number of additional parameters for smaller subsets of stars and other celestial objects.

Gaia is observing more than a billion stars, roughly one per cent of the total stellar content of our galaxy, the Milky Way. Eventually, this detailed inventory will include the positions and motions of stars to unprecedented precision, as well as the brightness and colour of each of them. In the process of discovering more about the Milky Way, Gaia observes celestial objects near and far, from our Solar System to extragalactic sources such as quasars. It will also detect new asteroids in our Solar System, discover planets around other stars, and even provide some tests of Einstein's theory of general relativity.

When we gaze up at stars in the night sky, we see them projected against the celestial tapestry. These stars appear equally far from us, and motionless with respect to one another. In reality, stars are located at a huge variety of distances from us, and each of them traces its own path around the centre of the Milky Way.

There are an estimated one or two hundred billion galaxies in the Universe, of various sizes and shapes. The Milky Way is a barred spiral galaxy, about 13 billion years old, and home to a few hundred billion stars, including our local star, the Sun.

The Milky Way's structure can be described as a flattened disc where the majority of stars are located, interspersed with a diffuse mixture of gas and cosmic dust, and a central bulge, where some of the Galaxy's oldest stars can be found. The Galactic Disc is about 100 000 light-years across, and the Sun is located about half way between the centre and periphery.

Beyond the disc and bulge is the stellar halo, a roughly spherical structure with a radius of about 100 000 light-years, containing isolated stars as well as many globular clusters – large, compact conglomerations of some of the most ancient stars in the Galaxy. On a grander scale, the Milky Way is embedded in an even larger halo of invisible dark matter. The Milky Way is part of the Local Group, together with the Andromeda galaxy, the nearest large galaxy to ours, and about 60 smaller galaxies.

Catalogues of stellar positions based on ground-based observations are limited in precision by the turbulence of Earth's atmosphere. Another limitation is that they cannot access the entire sky with a single telescope.

ESA's Hipparcos satellite, the first space mission dedicated to charting the sky, yielded a greatly improved catalogue with nearly 120 000 stars. Gaia has been extending this effort by cataloguing 10 000 times more stars and other celestial objects, while measuring additional parameters for each of these, too. With these data, astronomers will be able to investigate in extraordinary detail the past history, current status, and future evolution of our home galaxy.

2

Fast facts

→ FAST FACTS

Launch: 19 December 2013 at 09:12 UTC on a Soyuz rocket from Europe's spaceport in Kourou, French Guiana.

Launch mass: 2030 kg, including 710 kg of payload, a 920 kg service module, and 400 kg of propellant.

Spacecraft dimensions: The spacecraft body (payload and service module) is 4.3 m wide and 2.3 m high; the spacecraft is 10 m across when the sunshield/solar array assembly is deployed.

Payload: The payload comprises two identical optical telescopes/imaging systems, a radial velocity spectrometer, and blue and red photometers. The payload features a focal plane array (0.5 m x 1 m) with 106 CCD detectors containing nearly 1 billion pixels, making it the largest digital camera ever used in space.

Orbit: Gaia circles the Sun in a Lissajous-type orbit at the L2 Lagrangian point, 1.5 million km from Earth in the opposite direction with respect to the Sun.

Mission duration: Gaia was originally planned for a five-year nominal mission. ESA has already approved an indicative extension until the end of 2020, which is up for confirmation at the end of 2018.

Ground communications: ESA's ESTRACK stations at Cebreros (Spain), New Norcia (Australia), and Malargüe (Argentina) are used to communicate with the spacecraft.

Mission Operations: The mission is controlled from the European Space Operations Centre (ESOC) in Darmstadt, Germany. Science operations are conducted from the European Space Astronomy Centre (ESAC) in Villafranca del Castillo, Spain.

Data Processing and Analysis Consortium: The Gaia Data Processing and Analysis Consortium (DPAC) is formed by about 450 scientists and software experts, who have been entrusted with the task of converting the telemetry data into scientifically meaningful information and preparing the data releases, including the final Gaia Catalogue. Members of the DPAC come from twenty European countries (Austria, Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Netherlands, Poland, Portugal, Slovenia, Spain, Switzerland, Sweden, and the United Kingdom) as well as from further afield (Algeria, Brazil, Israel, and the United States). In addition, ESA makes a significant contribution to DPAC in the form of the Data Processing Centre at the European Space Astronomy Centre (ESAC) in Spain, which amongst other tasks and responsibilities, acts as the central hub for all Gaia data processing.

Industrial contributions: Gaia was designed and built by Astrium (now Airbus Defence and Space), with a core team composed of Astrium France, Germany and UK. The industrial team included 50 companies from 15 European states, along with firms from the US. Some 80 contracts were placed with European companies and three with those in the US. The spacecraft was launched by Arianespace on a Soyuz-ST-B Fregat-MT rocket. Between 2500 and 3000 people in all have been involved in the manufacturing of the spacecraft.

Mission name: Gaia was the acronym for Global Astrometric Interferometer for Astrophysics, the original name of the mission. This reflected the technique of optical interferometry that was first studied for use on the spacecraft. Although the acronym (written GAIA) is no longer applicable, the name (Gaia) remains to provide project continuity.

FIRST DATA RELEASE:

Date: 14 September 2016
Data time span: 14 months of observations
Contents:

- Celestial positions and Gaia 'G' magnitudes for 1.1 billion stars using only Gaia data;
- Positions, parallaxes (distances) and proper motions for more than two million stars using the Tycho–Gaia Astrometric Solution (TGAS);
- Light curves and characteristics for about 3000 variable stars;
- Positions and 'G' magnitudes for more than 2000 quasars – extragalactic sources used to define the celestial reference frame.

SECOND DATA RELEASE:

Date: 25 April 2018
Data time span: 22 months of observations
Contents:

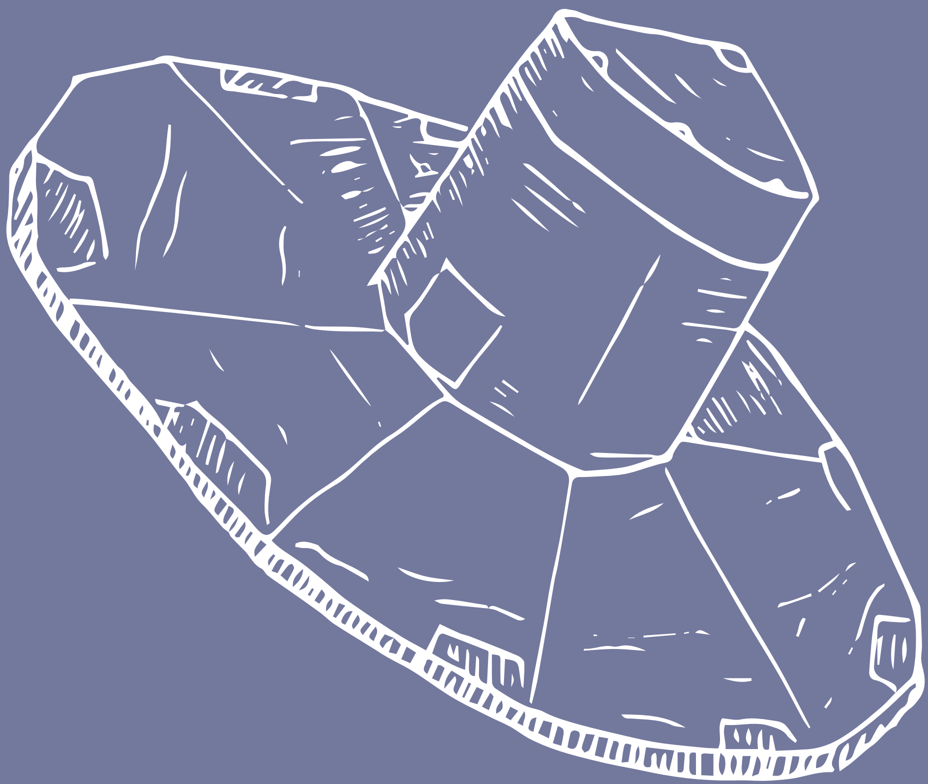
- Celestial positions and Gaia 'G' magnitudes for nearly 1.7 billion stars;
- Parallaxes (distances), proper motions and BP/RP (blue/red photometer) colours for more than 1.3 billion stars;
- Radial velocities for more than seven million stars;
- Astrophysical parameters such as surface temperature (161 million stars), extinction and reddening (a measure of the amount of dust along the line of sight to a star; 87 million stars), radius and luminosity (76 million stars);
- Light curves and classification for about 0.5 million variable stars;
- Positions and epoch of observation of 14 099 known Solar System objects – mainly asteroids – based on more than 1.5 million observations.
- Positions and 'G' magnitudes for more than 0.5 million quasars – which allows the celestial reference frame to be fully defined for the first time using optical observations of extragalactic sources.

Access: All data are available from the ESA Gaia Archive, which also provides visualisation tools, pre-computed cross-matches with other large catalogues, as well as comprehensive documentation to explore the data sets: http://archives.esac.esa.int/gaia

Data can also be accessed from the partner data centres:
- Centre de Données astronomiques de Strasbourg (CDS): http://cdsweb.u-strasbg.fr/gaia
- ASI Space Science Data Center (SSDC): http://gaiaportal.asdc.asi.it
- Astronomisches Rechen-Institut (ARI): http://gaia.ari.uni-heidelberg.de
- Leibniz-Institut für Astrophysik Potsdam (AIP): http://gaia.aip.de

3

Mapping the Galaxy with Gaia



→ MAPPING THE GALAXY WITH GAIA

The extraordinary data collected by Gaia throughout its mission will be used to eventually build the most accurate three-dimensional map of the positions, motions, and chemical composition of stars in our Galaxy. By reconstructing the properties and past trajectories of all the stars probed by Gaia, astronomers will be able to delve deep into the history of our Galaxy's formation and evolution.

The field of astronomy that deals with measuring the positions of celestial bodies in the sky is known as astrometry. Over the course of many centuries astronomers have relied on astrometry to compile ever more detailed maps of the heavens. By monitoring how the positions of stars and other astronomical objects vary over time, it is possible to infer their distances from us and their motions through space. Both of these are essential for investigating the physical nature of these distant bodies.

Tiny changes in the position of stars contain information about their distance – this is encoded in the parallax, an apparent annual shift of stars on the sky caused by Earth's yearly motion around the Sun. Over time, stellar positions also slowly change due to the stars' real movement through the Galaxy. The parallax of a star is the size of the ellipse it traces on the sky on a yearly basis. The distance to a star is inversely proportional to its parallax.

The associated motion perceived across the plane of the sky is termed the proper motion. Proper motion provides two of the three components of a star's velocity through the Galaxy; the third component – the radial velocity – can be inferred from the red- or blue- shift of the light in its spectrum.

Inside Gaia
Gaia has been performing its unique census of stars in the Galaxy using the billion-pixel camera at its heart, which collects the light focused by the satellite's dual telescope system. As the satellite spins, the two telescopes scan great circles on the sky. They feed three instruments: one for astrometry (to determine the positions and motions), one for photometry (to measure the colours of the stars), and one for spectroscopy (to measure their radial velocity and see what materials the stars are made of).

The astrometric instrument is the core element in the focal plane, providing input to determine the position of stars and other astronomical sources to unprecedented precision; in turn, the positions are used to derive stellar parallaxes and proper motions. This instrument also measures the brightness of all stars in the Gaia G-band, using a bandpass that covers the visible portion of the spectrum, between 330 and 1050 nm. This band was chosen to optimise the collection of starlight, which in turn maximises the precision of the measurements. It also matches the overall sensitivity of the Gaia astrometric instrument thus providing a measure of the brightness as seen by that instrument.

The photometric instrument separates the light from the stars into their constituent colours and does this over a short (blue; 330–680 nm) and long (red; 630–1050 nm) wavelength range. These measurements will in turn be used to determine the colour of each star – the portion of the spectrum where it emits most of its light – which is key to determine its temperature, age, and other properties.

Finally, the radial velocity spectrometer provides spectra for a subset containing the brightest 150 million stars observed by Gaia. These spectra are used to estimate the radial velocity of stars – their velocity along the line of sight with respect to Gaia. Radial velocities complement proper motions and in combination deliver three-dimensional velocities.

For each celestial object, all the information recorded by the instruments is compressed into data packets and stored on board. The data packets are transmitted to ESA's ground stations in Spain, Australia, and Argentina, and are then processed by the Data Processing and Analysis Consortium (DPAC), who are responsible for turning them into scientifically useful data.

At the core of this process is a mathematical procedure called AGIS – the Astrometric Global Iterative Solution. Put simply, this is the way to collate the billions of pieces of information that come from the satellite and convert these into the Gaia map of the Galaxy. It can be thought of like a giant jigsaw puzzle with hundreds of billions of pieces that have to be combined very accurately before the complete picture emerges.

The assembly of this gigantic picture is a complex process that needs to be performed over a number of years in order to reach Gaia's expected measurement goal: an accuracy of 0.00002 arcsecond in the parallax measurement for a magnitude 15 star. (An arcsecond is 1/3600 of a degree; a magnitude 15 star is about four million times fainter than Sirius, the brightest star in the night sky.)

In practice, Gaia's focal plane tracks the position where light from each star falls as it passes across the CCD detectors and records the time of each transit. To transform this information into astronomically useful quantities, namely measurements of stellar positions on the sky, scientists need to know where Gaia was pointing at each time, as well as its position with respect to the Sun and other planets in the Solar System. In addition, they also need to take into account the light bending caused by the Sun and the major planets as well as the exact position of each element in Gaia's optical system and focal plane.

The AGIS procedure consists of combining all these elements together: an astrometric model for the stars, the orientation of the satellite as a function of time and the geometry of the focal plane and optics. The goal is to determine the many millions of unknown parameters of the models by seeking the best possible match between model predictions and the actual input from observations. This process is carried out in an iterative fashion, by repeatedly adjusting the parameters in small steps until the best possible solution has been found. Not all stars observed by Gaia need to be considered in this first step of the process, but only a subset. In the second data release, 16 million stars were used for this phase, whereas only two million were used in the first data release – those in common with the earlier Hipparcos and Tycho-2 catalogues. Then, the astrometric parameters for the majority of the remaining stars can then be computed via a simpler procedure.

The AGIS procedure does not take into account all possible parameters that are relevant for an accurate modelling of the observations. This includes, for example, the colour of a star as measured by the photometric instrument, which influences slightly the position of the image of the star in the focal plane. A full consideration of all relevant effects involves a series of additional steps, and extra iterations between these and AGIS. This will be included in subsequent data releases, as well as the addition of increasingly larger amounts of observations.

4

Gaia's second data release — the Galactic census takes shape

→ GAIA'S SECOND DATA RELEASE THE GALACTIC CENSUS TAKES SHAPE

For the field of astrometry — the discipline of measuring the positions of celestial objects — a new era is here. The data bounty that awaits us will be revealed on 25 April 2018, when ESA's Gaia mission publishes the second data release. It is based on observations taken by the satellite between 25 July 2014 and 23 May 2016.

This second public release of data is the first one that relies solely on Gaia measurements, and will be an extraordinary resource for astronomers. It includes the positions on the sky for approximately 1.7 billion stars, as well as a measure of their overall brightness at optical wavelengths.

Parallaxes (a measure of the distance) and proper motions (the motion of objects across the plane of the sky) are provided for 1.3 billion stars. This is a huge leap forward with respect to the two million parallaxes and proper motions of the first data release.

This unprecedented data release also contains four new elements: broad-band colour information in the form of brightness measurements in 'red' and 'blue' light for more than 1.3 billion stars; radial velocities for some seven million stars; for between 77 and 161 million stars estimates are provided of the stellar effective temperature, extinction and reddening (which quantify the amount of dust along the line of sight to a star), radius and luminosity; and the positions of 14 099 known Solar System objects — mainly asteroids.

Measurements of how the brightness and colour of about half a million variable stars change over time are also made public. This is one of the largest available catalogues of variable stars and the largest ever compiled scanning the entire sky.

Finally, the positions and brightness for more than 0.5 million quasars are published; these extragalactic objects are used to define a reference frame in which the celestial coordinates of all objects in the Gaia catalogue are expressed in. Conventionally, this is done at radio wavelengths but with Gaia's second data release this can now be achieved at optical wavelengths too.

This release provides astronomers with a comprehensive set of superb scientific data that can be used to make significant research progress in a wide range of space science fields.

From Hipparcos to Gaia

ESA has a rich history of producing stellar catalogues. The Hipparcos Catalogue was created from data obtained with the science instrument on ESA's Hipparcos satellite, the first space mission dedicated to astrometry, which operated from 1989 to 1993. The catalogue, published in 1997, contains the positions and parallax of more than 100 000 stars with a precision of 0.001 arcseconds, and proper motions with a precision of 0.001 arcseconds per year. At the time of publication these values were unprecedented. (One arcsecond is equivalent to the size of a Euro coin seen from a distance of about four kilometres.)

A few years later, the Tycho-2 Catalogue was produced, based on measurements from the star mapper on the Hipparcos satellite and on previous ground-based astrometric catalogues that relied on photographic observations made since the late nineteenth century. This catalogue is less accurate but much larger than the Hipparcos Catalogue, listing positions and proper motions of 2.5 million stars. The average accuracy in the Tycho-2 Catalogue is 0.06 arcseconds for positions – improving to 0.007 arcseconds for the brightest stars – and 0.0025 arcseconds per year for proper motions.

Two years ago, Gaia's first release included two million parallaxes and proper motions, estimated by combining Gaia's measurements (based on 14 months of observations) with the earlier Hipparcos and Tycho-2 Catalogues. This resource was twice as precise and contained almost 20 times as many stars as the Hipparcos Catalogue.

The second Gaia release greatly exceeds the size and accuracy of the first one, with parallaxes and proper motions of roughly 650 times as many stars and about ten times more precise, reaching uncertainties on position and parallax between 0.00002–0.00004 arcsecond (0.00007 arcsecond per year for proper motions) for bright stars and 0.002 arcsecond (0.003 arcsecond per year for proper motions) at the faint end of the surveyed star population.

In future years, there will be more data releases, and the final Gaia catalogue will be published in the 2020s. This will be the definitive stellar catalogue for the foreseeable future, playing a central role in many and varied fields of astronomy.

5

Caveats and future data releases

→ CAVEATS AND FUTURE DATA RELEASES

The second Gaia data release represents a major advance compared to the first one. It features new data types and a much expanded and improved data set with respect to the first release, which will enable unprecedented investigations and discoveries.

Nevertheless, this release is still intermediate. It is based on approximately 22 months of input data, and is still affected by some simplifications in the data processing, including the application of filters to select the final sample of stars and preliminary models used in the calibration, which can introduce small (and sometimes systematic) uncertainties in the results. A small number of stars in the catalogue are reported to have very large positive or negative parallaxes exceeding one arcsecond (for comparison, the parallax of the nearest star to the Sun, Proxima Centauri, is 0.77 arcsecond). These spurious values are caused by the close alignment of stars that are only resolved by Gaia in some observations, depending on the scan direction, and mainly occur in the observation of dense stellar fields. Generally, negative parallaxes are an unavoidable consequence of measurement uncertainties when observing far away objects.

The limitations of the second data release will gradually decrease in the further two releases of Gaia data planned for the coming years – one more intermediate release and then the final release of the data gathered in the nominal mission. These will be characterised by increasingly improving precision and additional parameters for the surveyed stars, as well as for other celestial objects – from Solar System bodies to galaxies beyond our Milky Way.

In late 2020, the third data release will bring another big increase in data and accuracy. It will consist of improved positions and brightnesses; object classifications, astrophysical parameters and spectra; the average velocity along the line of sight for a much larger set of stars; classifications for an extended set of variable star types. It will also include results for a much larger number of Solar System objects, including preliminary orbit calculations. Finally, a catalogue of binary and multiple stars will be included.

The final Gaia data release, based on data from the five-year mission, is currently planned for the end of 2022. It will contain full astrometric and photometric parameters for nearly two billion stars as well as extensive additional information including a classification of the sources and lists of variable stars, multiple stellar systems and exoplanet-hosting stars, and measurements of the radial velocity for more than 150 million stars. Producing this catalogue is a complicated endeavour that requires processing and analysing the entire five-year mission dataset. Possible mission extensions will then generate future data releases after this.

The second Gaia data release is an extraordinary census of our Galaxy that will redefine the fundamental reference frame used for all astronomical coordinate systems. Each subsequent release will be increasingly more powerful and complete, until reaching the greatest catalogue of astronomical sources that has ever been released. Unearthing Gaia's discoveries and unlocking its many secrets will keep astronomers busy for decades.

Special releases

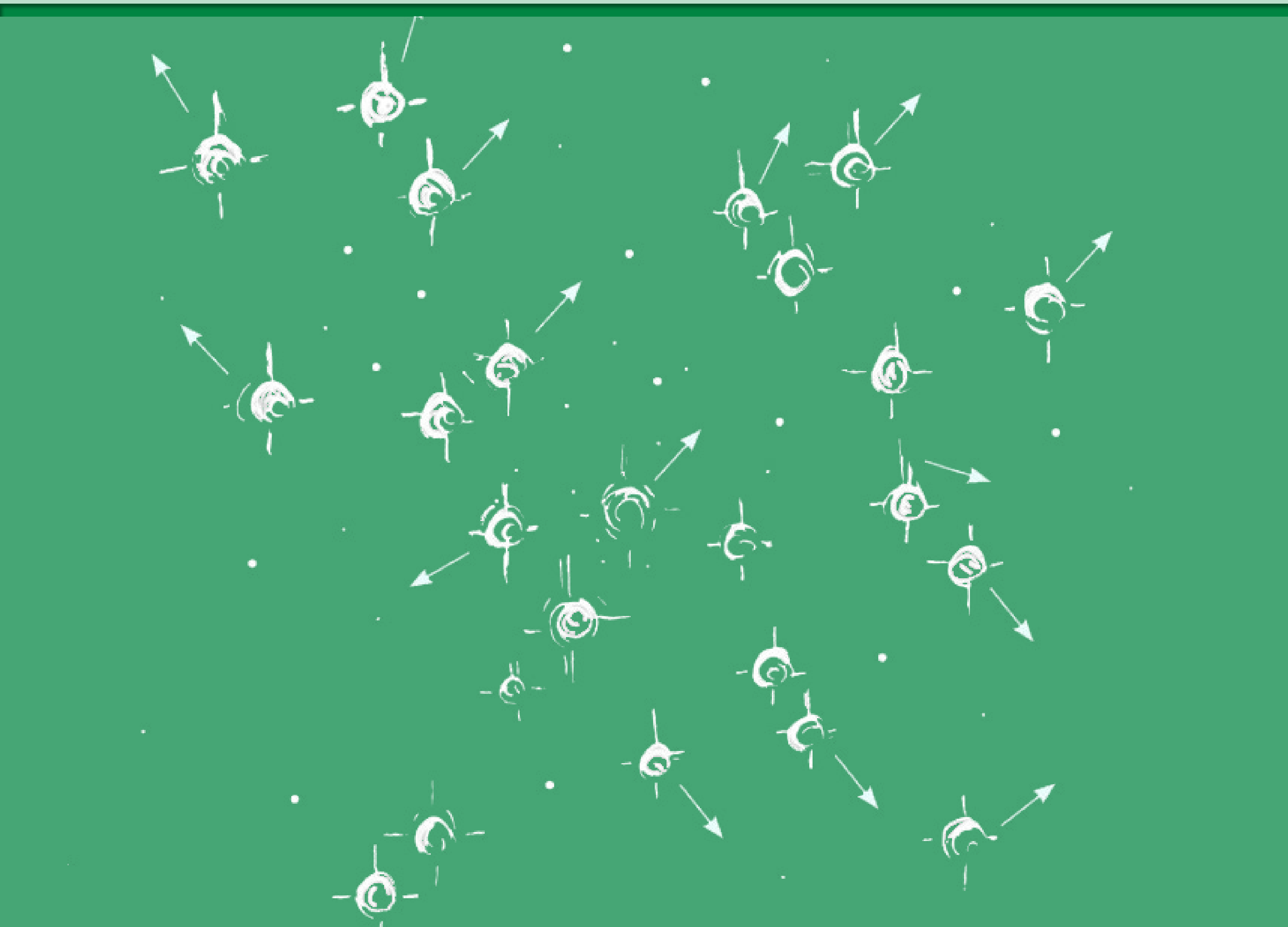
Besides the major data releases, special subsets of Gaia data are being made public to facilitate timely follow—up observations by the wider astronomical community. For example, the Science Alerts (http://gsaweb.ast.cam.ac.uk/alerts) – announcements to the scientific community about detected transient events such as supernovae and outbursting stars – and the Gaia Follow-Up Network for Solar System Objects (https://gaiafunsso.imcce.fr/), a similar resource for newly detected moving objects in the Solar System, are regularly issued.

In addition, Gaia coordinates for specific sets of stars have been made public in advance of data releases to support astronomical observations of rare stellar occultations, for example by dwarf planet Pluto in 2016 and by minor planet Chariklo and Neptune's moon Triton in 2017. In the case of Triton's occultation, the data were so accurate that the prediction of where to best observe the event could be refined: this led to the observation of an elusive 'central flash', confirming Gaia's pre-eminent data quality.

Preliminary stellar positions were also shared with the navigation team of NASA's New Horizons mission which, after its famous flyby of Pluto in 2015, is now heading towards another flyby in the unknown territories of the Kuiper Belt.

6

Science with Gaia’s new release



→ SCIENCE WITH GAIA'S NEW RELEASE

The second Gaia data release is a unique resource for astronomers. It is based on a homogeneous, high-precision scanning survey of the entire sky covering celestial objects near and far, from our Solar System to the stellar population of the Milky Way and beyond, and from our neighbouring galaxies to distant quasars.

Not only is it by far the best astrometric catalogue ever compiled to date, but it also complements the position, parallax and proper motion measurements with photometric and spectroscopic observations that have been performed by the same telescope and processed jointly in a consistent manner. As such, it offers immense possibilities to researchers interested in virtually any field of astronomy.

Astronomers worldwide are eagerly waiting for the release: some are after the precise distance and motion of one particular star, others will look for particular types of stars scattered across the sky or will focus their interest in one or more special regions of our Galaxy. There will be studies of stellar clusters, star-forming regions, and even of the invisible dark matter that underlies the distribution of stars.

It will be possible to investigate the motion and evolution of stars in regions of the Milky Way that could not be explored in such detail until now. Looking at the Sun's neighbourhood with Gaia's unprecedented accuracy might also reveal unexpected surprises.

Closer to home, the positions of Solar System objects will enable in-depth studies of asteroids and, jointly with Gaia's improved position and motion determinations of stars, support the prediction and observation of asteroids passing in front of distant stars in the future. The data will also be used for space navigation in the next generation of star trackers.

These are only examples of the impact that the second Gaia data release will have on selected areas of astronomy and space science. As with many surveys and experiments of the past, some of the most exciting discoveries will be the unexpected ones.

While the real science harvest of Gaia will only come once the data are made public, a series of scientific papers with preliminary investigations will be published alongside the release of the data. These studies have been conducted in order to validate the quality of the new data set and demonstrate the great potential of Gaia.

The subjects covered in these papers are:

- the new celestial reference frame based on Gaia's observations of more than half a million quasars
- the Hertzsprung-Russell diagram, which is a fundamental tool for astronomers to study stellar populations, their composition and evolution
- an analysis of the sample of Solar System objects included in the release – most of which are main-belt asteroids
- stellar velocities in the Galactic Disc
- the motions of globular clusters and dwarf galaxies around the Milky Way
- the properties of variable stars observed by Gaia

7

Science highlights from Gaia's first data release

→ SCIENCE HIGHLIGHTS FROM GAIA'S FIRST DATA RELEASE

ESA's Gaia mission published its first data release on 14 September 2016. It was based on observations taken by the satellite between 25 July 2014 and 16 September 2015. This first public release of data included the positions on the sky and brightness for more than one billion stars, as well as parallaxes and proper motions for a subset of two million based on the combination of Gaia data with the earlier Hipparcos and Tycho-2 catalogues.

One of the purposes of this first release was to prove that the observing strategy and the data processing 'pipeline' are working well. It demonstrated the high quality of the scientific data derived from the raw satellite observations and allowed some preliminary scientific investigations to take place.

Hundreds of scientific publications have appeared in the year and a half following the release. Some of the world class science results are summarised below:

Large Magellanic Cloud rotation
Within 24 hours of the release, Roeland van der Marel and Johannes Sahlmann reconstructed the rotation of a nearby galaxy, the Large Magellanic Cloud, from the proper motion of 29 of its stars.
Scientific paper: http://dx.doi.org/10.3847/2041-8205/832/2/L23

Galactic halo
Amina Helmi et al. published a study titled "A box full of chocolates" in which they revealed the rich structure of the Galaxy's stellar halo. The halo is the cloud of stars that surrounds the main disc of the Milky Way: its structure reveals the formation processes of the Galaxy. The investigation of this structure was one of the prime motivations for building Gaia in the first place. An immediate surprise was the discovery of a population of stars that orbit the Milky Way in the opposite direction to most stars. These stars probably came from a smaller galaxy that fell into the Milky Way.
Scientific paper: http://dx.doi.org/10.1051/0004-6361/201629990

New star cluster
Sergey E. Koposov et al. discovered a galactic star cluster that had been previously hidden from view because it was located near the bright star Sirius. From ground-based telescopes, the glare from Sirius outshone the light from the cluster.
Scientific paper: https://doi.org/10.1093/mnras/stx1182

Galaxy time machine
By combining the Gaia data with older sky surveys, Martin Altmann et al. have been able to derive the movements through space of 583 million stars, thus allowing us to project their orbits forwards and backwards in time. This allows preditcions of what the Galaxy looked like in the past, and what it will look like in the future. Of course, Gaia's second data release will greatly improve these proper motion estimates.
Scientific paper: http://dx.doi.org/10.1051/0004-6361/201730393

Bridging the gap
There were also some unexpected creative uses of the data. For example, by looking at the estimated errors in the brightness measurements, Vasily Belokurov et al. mapped out which Gaia sources were variable stars. Variable stars change their brightness by large amounts and these variations showed up in the Gaia data as measurement errors of the average brightness. By doing so, the astronomers revealed a bridge of variable stars between the Large and the Small Magellanic Clouds, two satellite galaxies of the Milky Way, showing that these systems are not completely separate.
Scientific paper: http://dx.doi.org/10.1093/mnras/stw3357

Speeding stars
The sheer size of Gaia's catalogue poses "big data" challenges for scientists who have to comb through the vast amounts of data in search of the proverbial needle in the Galactic haystack. Tommaso Marchetti et al. pioneered the use of machine learning to look for stars on high-speed trajectories from the centre of our Galaxy to its outskirts.
Scientific paper: https://doi.org/10.1093/mnras/stx1304

Searching for dark matter
Davide Massari et al. pushed their study beyond the visible stars, combining the data from Gaia's first data release with earlier observations from the NASA/ESA Hubble Space Telescope to investigate the distribution of dark matter in the nearby Sculptor dwarf galaxy.
Scientific paper: https://doi.org/10.1038/s41550-017-0322-y

More treasures

Other results showed previously undiscovered white dwarf stars, a map of the local interstellar medium in three dimensions, an inventory of the stars that had recently made (or will soon make) close encounters with the Sun, hints of fine structure in the evolution and movement of nearby stars, and powered searches for distant quasars whose light has been gravitationally lensed by foreground galaxies.

All of these topics and more are a teaser for the avalanche of discoveries and results expected following the second data release.

8

Making sense of it all – the role of the Gaia Data Processing and Analysis Consortium

→ MAKING SENSE OF IT ALL – THE ROLE OF THE GAIA DATA PROCESSING AND ANALYSIS CONSORTIUM

During the course of the nominal five-year mission, Gaia sweeps its gaze across the sky producing a continuous stream of data that is unintelligible in its raw format to the scientists who want to use it. The task of converting the raw data into scientifically useful products is entrusted to the 450 scientists and software experts who form the Gaia Data Processing and Analysis Consortium (DPAC).

The transformation of the raw measurements takes place within the DPAC Coordination Units, or CUs. Each unit is responsible for developing the scientific algorithms and software corresponding to particular, well-defined aspects of the data processing and analysis.

Two units provide development support for technical aspects such as defining the software architecture and strategy (CU1), and for the data simulations (CU2) that have been essential for preparing for the real mission data by allowing DPAC to test their software and rehearse the science operations.

Three units are responsible for basic data processing. The CU3 unit takes care of processing astrometric data, which provides the positions and motions of celestial bodies in the sky. Photometric data processing, which results in a measure of how much light is emitted by the objects, is the task of CU5. The spectroscopic data processing, carried out by CU6, produces a measure of the velocity with which an object is moving towards or away from us, and what the star is made of.

Three units examine particular aspects of the processed data, looking at Solar System objects, double stars, orbital binaries, exoplanets, and extragalactic objects (CU4); variable stars (CU7); and classification and astrophysical characterisation of all of the celestial objects observed by Gaia (CU8).

One unit (CU9) is responsible for the preparation, validation and distribution of the intermediate data releases and the final Gaia catalogue.

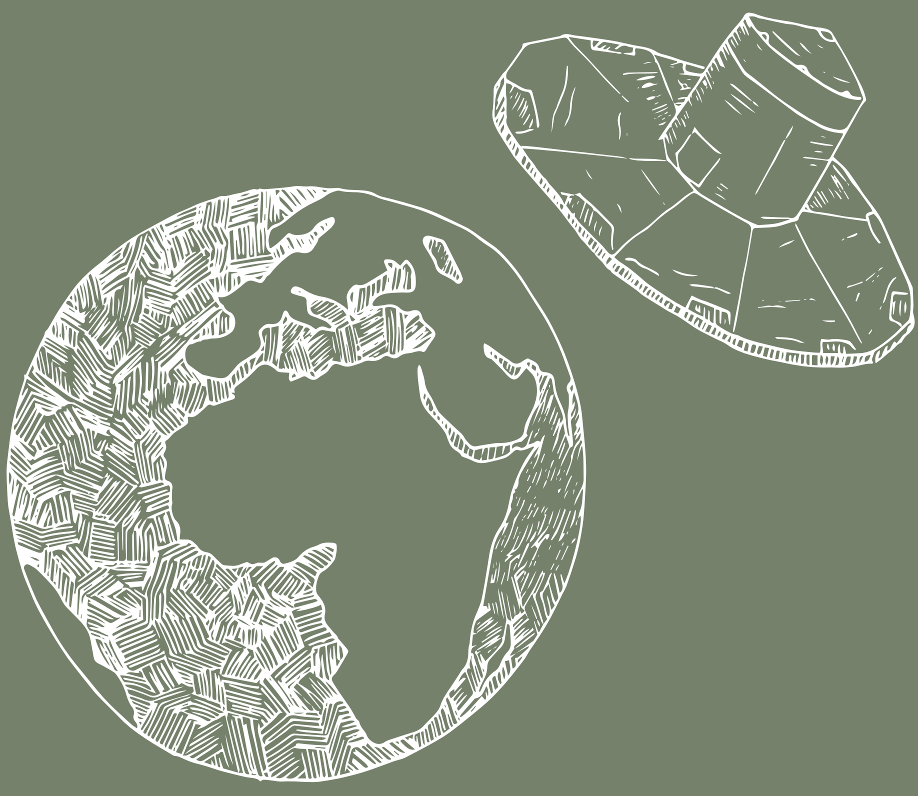
The software developed by each of the CUs is run in one of the six data processing centres located in France (Toulouse), Italy (Torino), Spain (ESAC, near Madrid; Barcelona), Switzerland (Geneva), and the United Kingdom (Cambridge). These centres host the computing hardware and provide software engineering expertise to support the CU software development work.

The DPAC is funded through national funding agencies of the participating ESA member states. Some funding agencies have signed a multilateral agreement with ESA that commits all parties to fund the DPAC effort up to the completion of the final Gaia catalogue, expected in the 2020s. In addition, ESA makes a significant contribution to DPAC in the form of the Data Processing Centre at the European Space Astronomy Centre (ESAC) in Spain, which amongst other tasks and responsibilities, acts as the central hub for all Gaia data processing.

The final Gaia catalogue, to be produced by DPAC and ESA, will contain positions, distances, and motions for more than one billion celestial objects. For each of these objects Gaia will tell us the temperature, where it is in its lifecycle, the composition, and how much dust lies between us and that object. There will be stars from every phase of the stellar lifecycle, as well as asteroids in our Solar System and planets around other stars. There will also be objects located beyond the realm of the Milky Way, such as other galaxies and quasars.

9

Where is Gaia and why do we need to know?



→ WHERE IS GAIA AND WHY DO WE NEED TO KNOW?

Gaia is one of the most demanding of the 14 spacecraft operated by the European Space Operations Centre (ESOC) at Darmstadt in Germany. Situated 1.5 million km from us, the location of the spacecraft must be known to within 150 m every day of the nominal five-year mission, and the time on the spacecraft must be known to within two microseconds. At times, the amount of data that needs to be downloaded to Earth exceeds the capacity of all three ESA ground stations.

The location of the spacecraft feeds into the data analysis and the accuracy with which this position is measured has a direct impact on the precision needed to reconstruct the positions, motions and distances to the stars.

To determine the distance to a spacecraft from Earth, ESOC performs two-way ranging measurements, which are accurate to 5 m. The speed at which the spacecraft is moving towards or away from us is obtained from Doppler measurements, which are accurate to 0.1 mm/s. These measurements are routinely carried out to check that Gaia is in the correct orbit and if not, to calculate and monitor the manoeuvres that are made to place the spacecraft back on track.

The location of Gaia on the plane of the sky is obtained using two widely separated antennas to simultaneously track the location of a transmitter on the spacecraft – this is the delta-differential one-way ranging (DDOR) method. DDOR can provide measurements accurate to about 22 m for Gaia, but since it requires the regular use of two of the three ground stations that are shared by all science missions another method is also used.

Daily tracking of the spacecraft is carried out by the Gaia Ground-Based Optical Tracking (GBOT) programme, organised by the Gaia Data Processing and Analysis Consortium (DPAC) using the European Southern Observatory's VLT Survey Telescope in Chile. Additional observations are obtained with the Liverpool Robotic Telescope in La Palma, Spain, and occasionally the facilities of the Las Cumbres Observatory in Hawaii, US, are also used. These measurements will provide the location of Gaia to within 150 m, which is sufficient for the science needs. Initially, only DDOR positions are used to determine the actual orbit of Gaia to high accuracy but once the Gaia data is available, GBOT will routinely produce daily measurements of the location of the spacecraft to the accuracy needed.

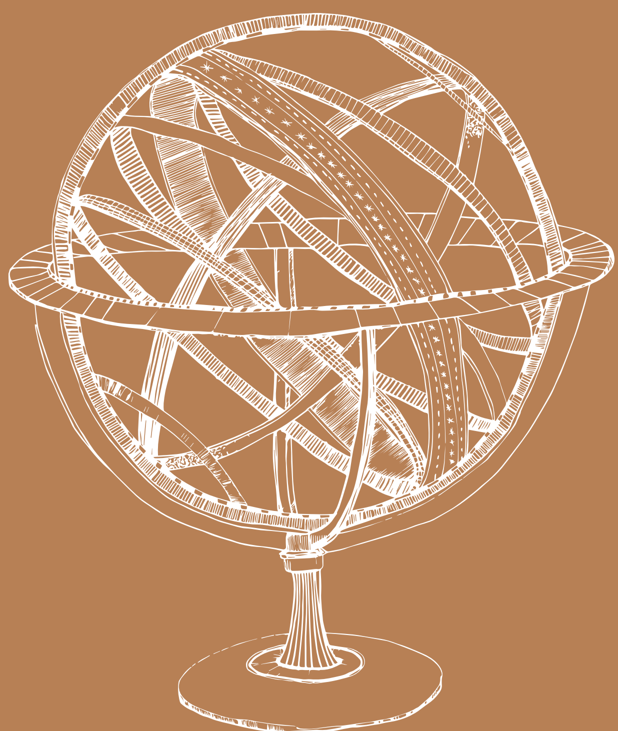
Some of Gaia's other operational requirements have meant it was necessary to enhance some operational practices. At the ground stations, ESA upgraded the infrastructure to support a high data rate which allows more data to be downloaded during each period of ground station contact.

Even with this high data rate – the highest of any science mission to date – Gaia is still the biggest user of ESA's large 35 m network. To optimise this use as much as possible, operators came up with a scheme that accurately predicts how much station time is needed. The sky is not uniformly dense with stars and this is reflected in the amount of data that is recorded by Gaia. Knowing where Gaia will be scanning the sky in future allows the amount of time needed per day to be predicted. Most of the time all the data can be downloaded to Earth using the three ground stations at Cebreros (Spain), New Norcia (Australia) and Malargüe (Argentina). However, when scanning the densest regions of the sky, such as the Galactic Centre, even the high rate and all three stations are not sufficient, and an intelligent onboard scheme selects the least important data types to be deleted.

The communication protocols that are used to transmit data from the ground stations to the space operations centre also had to be adapted to cater to the demands imposed on time accuracy: ESOC must timestamp the data received on ground to an accuracy of better than 2 microseconds. This accuracy is needed to be able to reconstruct the orbits of near-Earth asteroids.

10

From ancient star maps to precision astrometry



→ FROM ANCIENT STAR MAPS TO PRECISION ASTROMETRY

Astrometry, the science of charting the sky, is one of the oldest branches of astronomy.

The first documented records of systematic astronomical observations date back to the Assyro-Babylonians around 1000 BCE, and the oldest known stellar catalogue was compiled in the second century BCE by the Greek astronomer Hipparchus of Nicaea.

Hipparchus's catalogue lists the positions of 850 stars with a precision of one degree – twice the angular size of the full Moon – determined using only naked-eye observations and the few instruments available at the time: gnomons, astrolabes, and armillary spheres.

One and a half millennia later, in the fifteenth century, Ulugh Beg of the Timurid dynasty created a catalogue of 994 stars with a precision slightly better than that of Hipparchus, using an enormous sextant with a radius of 36 metres in Samarkand, located in present-day Uzbekistan.

The next major step was made in the late sixteenth century by Danish astronomer Tycho Brahe who measured the positions of around 1000 stars with a precision of about one arcminute, using large quadrants and sextants at the Uraniborg observatory on the island of Hven (in present-day Sweden). His catalogue was completed in 1598 and published in 1627. Not long before, in 1543, Polish astronomer Nicolaus Copernicus had proposed the revolutionary heliocentric system, in which Earth revolves around the Sun.

This revived the debate about measuring the distance to the stars using parallax – the apparent movement of a foreground object with respect to its background owing to a change in the observer's position. Astronomers had tried to apply this method, also known as triangulation, to determine stellar distances, but no baseline on Earth was big enough to detect parallaxes because of the immense distances involved. In a heliocentric system, however, they could exploit the much larger baseline offered by Earth's annual motion around the Sun.

Tycho Brahe himself tried to measure the parallax of stars but without success. It would take the invention of the telescope, in the early seventeenth century, and some two hundred years of diligent astronomy before the first distance to a star could be measured.

Meanwhile, in 1718, English astronomer Edmond Halley was the first to discover that stars are not fixed but actually move through space. When comparing contemporary catalogues with those from almost 2000 years earlier, he noticed a displacement in the position of many stars. This displacement corresponds to the projection of the star's velocity in the plane of the sky and is known as proper motion.

In 1725, English astronomer John Flamsteed published the first stellar catalogue compiled with the aid of a telescope, listing the positions of almost 3000 stars with a precision of 10–20 arcseconds. French astronomer Jérome Lalande published an even greater catalogue with the position of 50 000 stars and a precision of around three arcseconds, in 1801.

Shortly after that, in 1838, German astronomer Friedrich Bessel was the first to publish a reliable measurement of parallax, for the star 61 Cygni. Amounting to 0.314 arcseconds, this placed the star at a distance of about 10 light-years. Two more astronomers, the German Wilhelm Struve and Englishman Thomas Henderson, also successfully measured parallaxes in the late 1830s.

Knowledge of astronomical distances finally allowed astronomers to calibrate their observations and to estimate physical parameters of stars, such as their luminosity and size.

From the 1850s onwards, the application of photography to astronomical observations transformed the practice of charting the sky. With this method, Dutch astronomer Jacobus Kapteyn started measuring the parallax of hundreds of stars in the early 1900s.

In 1924, American astronomer Frank Schlesinger published a catalogue with the parallaxes of almost 2000 stars, probing stellar distances out to a few dozen light-years from Earth. His catalogue was extended to over 8000 stars by 1995, but the flickering effect caused by Earth's atmosphere prevented astronomers from reaching a precision better than about 0.01 arcseconds.

The onset of the space age brought astrometry firmly back to centre stage in astronomy. ESA's Hipparcos mission, operating from 1989 to 1993, was the first space telescope devoted to measuring stellar positions.

The Hipparcos catalogue, released in 1997, contains the position, parallax and proper motion of 117 955 stars with a precision of 0.001 arcseconds, allowing astronomers to probe stellar distances out to over 300 light-years.

The larger but less precise Tycho-2 catalogue, published in 2000, lists positions and proper motions of 2.5 million stars, combining data from the star mapper instrument Hipparcos with previous ground-based astrometric catalogues.

The Hipparcos mission has had a profound influence on many fields in astronomy, from studies of stellar interiors and evolution to the dynamics of stars. Beyond the Milky Way, stellar distances based on Hipparcos data have allowed cosmologists to refine the calibration of the cosmic distance ladder.

ESA's Gaia mission is astrometry for the twenty-first century and beyond. It builds on the legacy of Hipparcos to chart more than one billion stars – roughly one per cent of the content of our Galaxy – measuring their position and parallax with astrometric precisions of down to 0.00001 arcseconds and possibly even better for the brightest stars observed.

Read more in the History of Astrometry series: sci.esa.int/gaia/history–of–astrometry

APPENDIX 1

Resources

Gaia online

Gaia is on social media channels:

@ESAGaia

www.facebook.com/ESAGaiaMission/

Information about the mission can be found on the following websites:

www.esa.int/gaia – mission summaries and news for the general public
sci.esa.int/gaia – detailed information for interested readers
cosmos.esa.int/gaia – web pages for the Gaia scientific community
archives.esac.esa.int/gaia – the Gaia mission data archive

A listing of other Gaia websites can be found here:
www.cosmos.esa.int/web/gaia/links

Pictures, illustrations and animations

A variety of photographs, illustrations and animations are available for non-commercial use.

All Gaia images and videos:
sci.esa.int/gaia-gallery

Artist's impressions of the mission and related science:
sci.esa.int/gaia-mission-illustrations

Illustrations of Gaia science:
sci.esa.int/gaia-science

Photographs from the construction and testing phase:
sci.esa.int/gaia-construction-and-testing-photos

Photographs from launch:
sci.esa.int/gaia-launch-campaign-photos

Photographs of the focal plane array and CCDs:
sci.esa.int/gaia-focal-plane-and-ccds-photos

Photographs of the mirrors:
sci.esa.int/gaia-mirrors-photos

Photographs of the Basic Angle Monitor:
sci.esa.int/gaia-basic-angle-monitor-photos

Photographs of the sunshield:
sci.esa.int/gaia-sunshield-photos

Photographs of the payload module:
sci.esa.int/gaia-payload-module-photos

Photographs of the service module:
sci.esa.int/gaia-service-module-photos

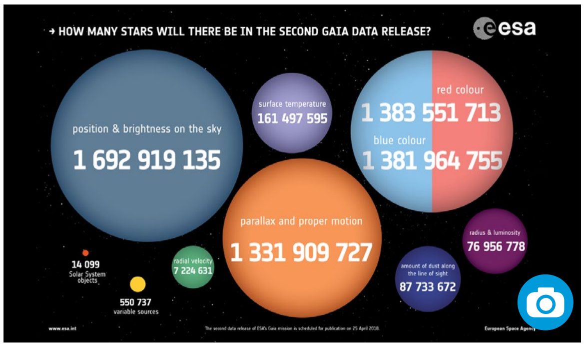
Photographs of people:
sci.esa.int/gaia-people

Selected images and videos

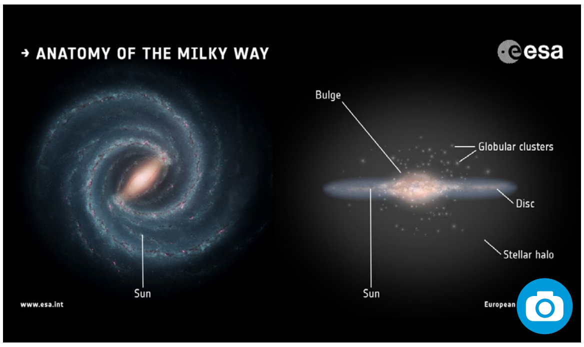
Gaia's sky in colour
http://sci.esa.int/gaia/60169

Gaia's new map of star density in the sky
http://sci.esa.int/gaia/60170

Gaia's view of dust in the Milky Way
http://sci.esa.int/gaia/60171

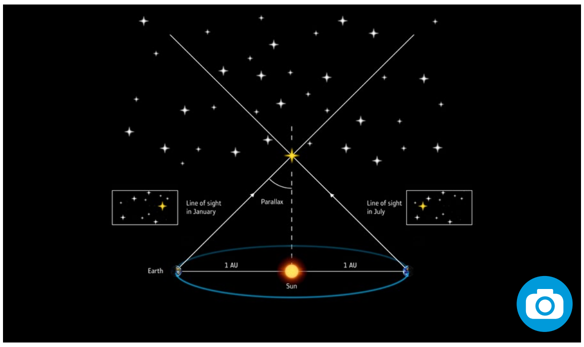


How many stars to expect in Gaia's second data release http://sci.esa.int/gaia/60146

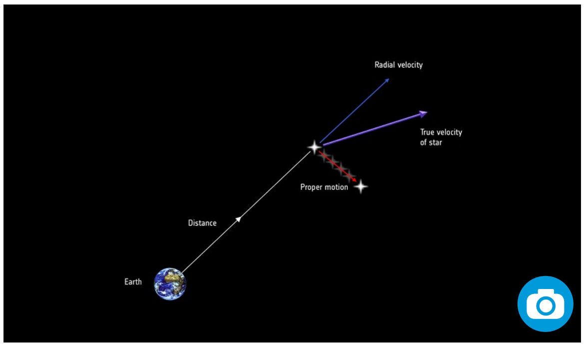


Anatomy of the Milky Way
http://sci.esa.int/gaia/58206

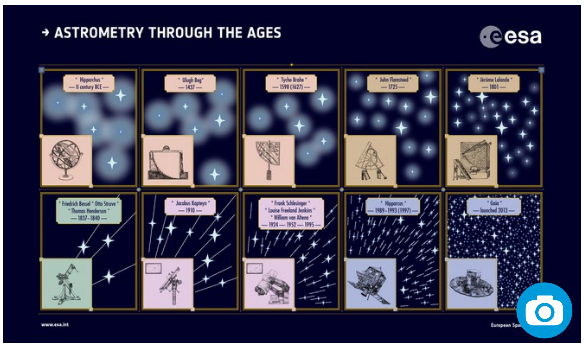
A journey through the Galaxy
http://sci.esa.int/gaia/58215



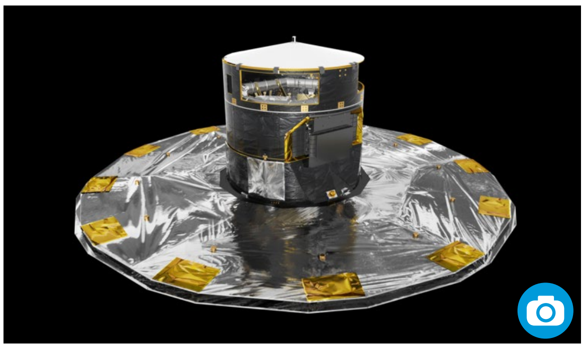
Parallax concept
http://sci.esa.int/gaia/53278



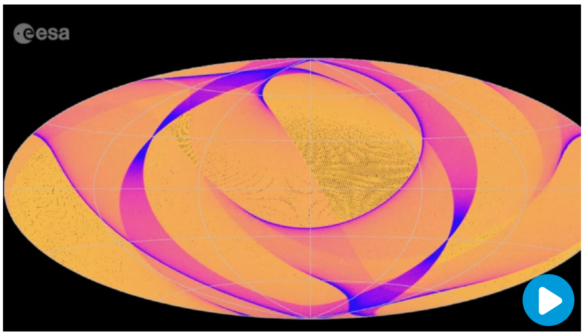
Stellar motion concept
http://sci.esa.int/gaia/53279



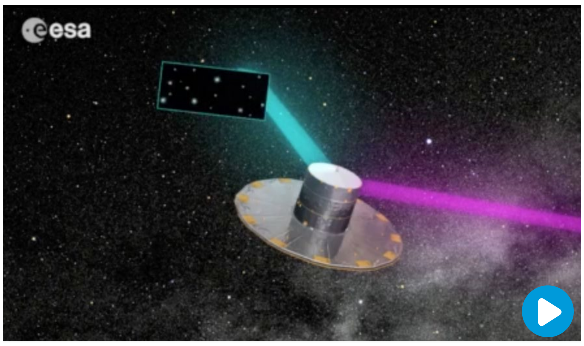
Astrometry through the ages
http://sci.esa.int/gaia/58212



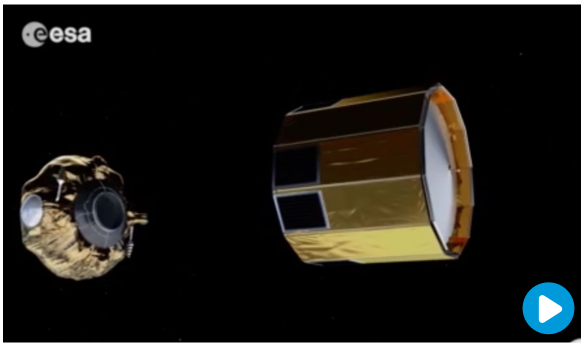
Gaia spacecraft (artist's impression)
http://sci.esa.int/gaia/55638



Mapping the Galaxy
http://sci.esa.int/gaia/58214



Inside Gaia's billion pixel camera
http://sci.esa.int/gaia/53560

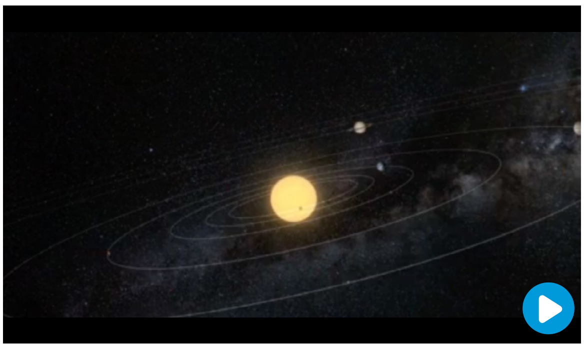


From launch to orbit
http://sci.esa.int/gaia/53280

Gaia launch: time-lapse of preparation and launch http://sci.esa.int/gaia/58063

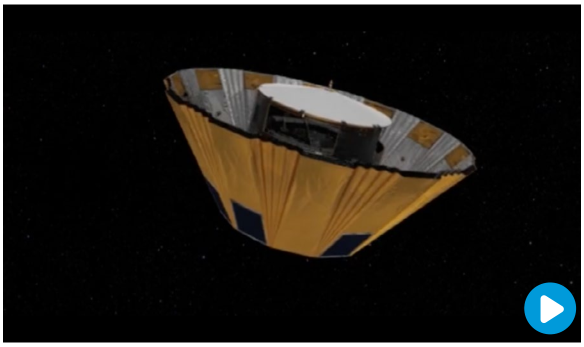
Gaia launch 19 December 2013
http://sci.esa.int/gaia/53539

Guide to our Galaxy
http://sci.esa.int/gaia/53147

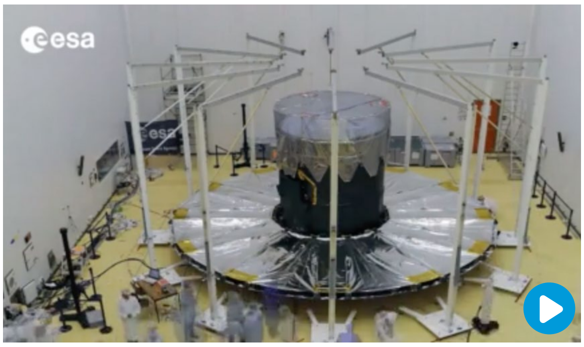


Gaia – building on the legacy of Hipparcos
http://sci.esa.int/gaia/53273

Participation in DPAC
http://sci.esa.int/gaia/56839

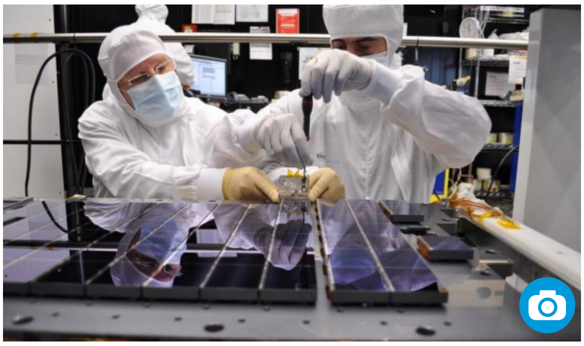


Sunshield deployment (artist's impression) http://sci.esa.int/gaia/53375



Sunshield deployment (time-lapse, during integration) http://sci.esa.int/gaia/53113

The Gaia torus during installation of one large mirror http://sci.esa.int/gaia/58208



Gaia's CCDs http://sci.esa.int/gaia/48887

Gaia primary mirror http://sci.esa.int/gaia/47690

Basic Angle Monitor http://sci.esa.int/gaia/58139

A series of 360-degree videos and other Virtual Reality visualisation resources based on data from Gaia's second release will be made available at sci.esa.int/gaia-vr

APPENDIX 2

Information about the press event

The press event about the Gaia Data Release 2 is being organised by ESA at the ILA Berlin Air and Space Show in Germany on Wednesday 25 April 2018, 11:00–12:15 CEST.

The event will be streamed live at: www.esa.int/live

Photographs, names and titles of the speakers at the press event:

Johann-Dietrich Wörner
ESA Director General

Josef Aschbacher
ESA Director of Earth Observation

Günther Hasinger
ESA Director of Science

Anthony Brown
Gaia Data Processing and Analysis Consortium
Leiden University
The Netherlands

Antonella Vallenari
Gaia Data Processing and Analysis Consortium
INAF, Astronomical Observatory of Padua, Italy

Also present at the press event:

Timo Prusti
Gaia Project Scientist
European Space Agency

Jos de Bruijne
Gaia Deputy Project Scientist
European Space Agency

Uwe Lammers
Gaia Science Operations Manager
European Space Agency

Sergei Klioner
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Lohrmann Observatory, Dresden, Germany

Nicholas A. Walton
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Gonzalo Gracia
Gaia Data Processing and Analysis Consortium project coordinator

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APPENDIX 3

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