Third data release from Gaia spacecraft maps 1.8 billion stars in the Milky Way

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Astronomers from the Gaia Data Processing and Analysis Consortium have made public the first part of the third major data release from the European Space Agency's Gaia spacecraft. The findings, published or being reviewed in a series of papers in the journal *Astronomy & Astrophysics*, accurately mapped the position of 1,811,709,771 stars in our Milky Way galaxy, including the distances from Earth and relative motions of 1,467,744,818 of those stars.

In short, the Gaia mission has provided the best map of the Milky Way to date, a tool which will be used in every field of astronomy. The spacecraft has provided both a trove of data that will be studied for years, as well numerous jumping off points for further research.

The specific findings of this data release were to explore the edge of the Milky Way, measure shifts in the Solar System's orbit around the center of the galaxy, provide an updated census of nearby stars, and further characterize the two satellite galaxies of the Milky Way, the Large and Small Magellanic Clouds. The third release also improves the accuracy and precision of the measurements over the second release.

Gaia was designed by the European Space Agency (ESA) and is operated by a team of more than 2,500 people from 15 countries. It launched on December 19, 2013 from the Guiana Space Centre in French Guiana and sits at the Earth-Sun Lagrange point 2, a point behind Earth from the perspective of the Sun where the gravitational forces of the two bodies are canceled out. This creates a very stable location for a space-based observatory to do precision work, a requirement for Gaia.

The orbit has the added benefit of minimizing fuel usage. The spacecraft is expected to run out of propellant to adjust itself as needed in late 2025, the effective end to its mission.

The latest Gaia release maps almost double the 1 billion stars of the mission's original goal, roughly 1 percent of all stars in our galaxy. To do this, Gaia was designed to be able to pinpoint object that are 400,000 times fainter than can be seen with the human eye. To make their measurements as accurate as possible, researchers made at least 70 observations of presumed stars before including them in their data.

The mission is the successor to the ESA Hipparcos mission, which operated from 1989 to 1993. The spacecraft name is an acronym (HIgh Precision PARallax COllecting Satellite) but also a reference to Hipparchus of Nicaea, the ancient Greek astronomer who is credited with founding trigonometry and incidentally discovering the precession, or change, in Earth's spin axis. Hipparcos was the first satellite dedicated to the field of astrometry, the accurate measurement of the position and motion of astronomical objects. The final Hipparcos Catalogue was published in 1997 and contained positions and distances for more than 118,200 stars.

Gaia was first proposed during the last year of the Hipparcos mission, given that a follow-up study would be necessary to further probe the Milky Way. It took another 13 years before the project was finally authorized, and another seven before it was built and launched. Overall, the mission has, during the 15 years since it was approved, cost about €740 million, one-fiftieth of the current annual military budget of Germany alone.

To understand the importance of mapping the Milky Way today, an analogy can be made to the importance of mapping Earth over the course of hundreds of years. Exploratory voyages such as those undertaken by Ferdinand Magellan (1519–1522) and James Cook (1768–1799) revolutionized the understanding of Earth, bringing distant civilizations closer together. Today, highly accurate maps of our planet from orbiting satellites provide invaluable knowledge about the past, present and future of our home world.

Similarly, the difficult but seemingly mundane task of mapping stars provides a wealth of knowledge from the physical signatures that hide in such data. There are three main characteristics of a star, position, distance and color, from which these signatures emerge.

The position and color of a star are in principle relatively easy to record. If one can overcome the blurring effects of Earth's atmosphere on a telescope and keep the temperature and gravitational forces on the optics constant, all of which are achieved by putting a telescope in space, one can get extraordinarily precise measurements of stellar positions. Gaia was designed to overcome terrestrial limitations, and in doing so has produced its latest map of more than 1.8 billion stars.

In the same vein, a spectrometer, which finds the colors of light (the wavelengths) being emitted from a given object, is much more accurate when boosted above Earth's atmosphere on a satellite. Once the wavelengths of light being emitted are known, one can derive a star's temperature and mass. Of the 1.8 billion stars it mapped, Gaia measured the brightness in red and blue light of more than 1.5 billion.

Distance and motion are much harder to calculate given how far away these stars are. Astronomers use the parallax method,

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measuring the change in the position of astronomical objects as compared to their background when Earth is on opposite sides of its orbit around the Sun. By observing these minuscule shifts, and employing the trigonometry of Hipparchus, one can determine the distance to an object without needing to travel interstellar distances. (This effect can be observed by holding up a finder against a static background, and using first one eye, then the other.)

This process is further complicated by the fact that every celestial body is always in motion, and as such there is no such thing as a truly "static" background. To compensate, the spacecraft also collected light from 1.6 million extragalactic sources to provide multiple "absolute" frames of reference, using very bright and distant objects known as quasars. In doing so, Gaia found the distances from Earth and motion through the Milky Way of more than 1.4 billion of the stars it mapped.

As an added benefit, this map of quasars is the largest ever produced. Quasars are a form of active galactic nuclei in which much of their energy is generated from the accretion of matter by supermassive black holes in their centers. Because so much of their energy is emitted in such a small area, they serve as very pinpoint distant beacons to calibrate any mapping scale. The quasar data published in the third data release, three times the amount from the second data release, is being used to study these supremely energetic objects.

Quasars aside, with the position, distance and temperature of a star, a great deal of physics and astronomy can be done, the most important of which is calibrating what is known as the cosmic distance ladder.

There are many methods one can use to estimate the distances to certain objects. Parallax is the only known direct method, and thus the basis for all other measurements. Other indirect measurements generally look for ways to infer the absolute brightness of a star, compare that to the apparent brightness, or magnitude, as seen from Earth, and then derive a distance. RR Lyrae variables and Cepheid variables, for example, are stars which periodically change brightness, and have a well defined relationship between their luminosity and how often their brightness changes. Type Ia supernovae are the result of white dwarf stars accreting matter up to a very specific mass, then exploding with known intrinsic luminosity in a spectacular event that can be seen across the cosmos.

Because the brightness of the variable stars and type 1a supernovae can be known without knowing the distance to these stars, they are known as "standard candles." The term was coined by astronomer Henrietta Swan Leavitt for all astronomical objects that have a known intrinsic brightness, from which the distance to them can be determined.

Another method is to use the different wavelengths of light emitted from a star to estimate its mass, age and composition, which in turn can be used to estimate a given star's actual brightness. This method is most often used on the Hyades cluster, which appears in the constellation Taurus. The Hyades are a group of about 100 stars, all gravitationally bound to each other and with roughly the same age, place of origin and chemical composition. Thus astronomers can use the light from each individual star to estimate the distance to the cluster as a whole, which has been calculated to be about 153 light years away.

And since the Hyades are the closest cluster to Earth, they have long been a target for parallax measurements, though the uncertainty in those measurements was very high. Such errors were reduced to 6 percent by Hipparcos and reduced by a further two orders of magnitude by Gaia, confirming that the Hyades are 153 light years away.

Such correlations form the rungs of the cosmic distance ladder. The light from Cepheid variables in a distant galaxy can be compared to the light from a type Ia supernova in that same galaxy. A type Ia supernova in a closer galaxy can be compared to the light from RR Lyrae stars in that second galaxy. And RR Lyrae stars in the Milky Way can be compared to the Hyades, or perhaps directly measured by parallax.

Thus, distances across the cosmos are known if the parallax to nearby stars can be measured. In that sense, the Gaia spacecraft is not just a tool to map the Milky Way galaxy, as impressive as that is: it also provides a new and immensely improved baseline for mapping the entire Universe.

Such a map is necessary for many fields of research in astrophysics and cosmology. Cepheid variables, for example, are not just one way to measure distances to galaxies, they are also used to measure the speed at which galaxies are moving apart from each other. Detailed knowledge of the distance and temperature of so many stars provides a better understanding of the history of the Milky Way, which in turn informs our knowledge of how stars and galaxies everywhere evolve.

Gaia also measured the bending of starlight of thousands of stars that passed, from the spacecraft's perspective, behind the Sun. Like Arthur Eddington in 1919, astronomers used Gaia to test Albert Einstein's general theory of relativity. Gaia's observations have again confirmed that general relativity correctly describes the structure of spacetime.

There have been many other achievements of the Gaia mission: measuring the orbits and inclinations of extrasolar planets, revealing that stars are being pulled from the Small Magellanic Cloud to the Large Magellanic Cloud, showing the orbits of nearby stars around the galaxy, uncovering the origin of the warped shape of the Milky Way, and finding which stars were born at the same time and place, even after they have been flung out to different parts of the galaxy, just to name a few. The curious reader is greatly encouraged to explore the full spectrum of what the Gaia team has studied.

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