The Biggest Cosmic Map
Professor Chris Lintott
26 February 2025

On the 10th January, a little more than a month ago, the European Space Agency's *Gaia* satellite took the last of three trillion observations of the sky, completing a decade-long mission to make the largest, most complete and most accurate map of the our cosmic surroundings ever attempted. It includes the positions more than 2 billion separate objects and recording not only their locations on the sky and within the Milky Way but also their movements through the galaxy. More than 13000 scientific publications have already made use of *Gaia* data, and researchers will be working for years to produce the final version of its rich catalogue.

Mapping the night sky is perhaps the oldest astronomical activity. The Nebra Sky Disc dates back to the Bronze Age, and alongside a depiction of a star cluster usually associated with the Pleiades, has markers indicating the positions of the rising and setting Sun throughout the year. The Dunhuang star map from China – the oldest surviving complete map of the sky – was made in approximately 700 CE, containing 1300 stars, and was the result of a millennium of astronomical tradition. Almost every culture has made patterns out of the stars, and shared them – the great ship of Argo, for example, which seemed to sail along the Mediterranean horizon, may have had its roots in Indian astronomy.

The patterns were arbitrary, of course – consider the attempts of the cat-loving 18th century French astronomer Jérôme Lalande to add a constellation called Felis to the celestial bestiary, but over time, creating maps of the cosmos became a more scientific and systematic endeavour, with effort shared between international observatories. But well into the 19th century, these were two dimensional maps – maps of the sky, not of the Universe.

Measuring distances to stars had proved difficult. Making a set of heroic assumptions – most importantly, that all stars are equal in luminosity – William Herschel had managed to suggest that we lived in a pancake shaped Universe – but attempts to find the distance to individual stars had failed. Indeed, the lack of the expected parallax – a shift in the position of nearby stars compared to their more distant cousins – had been used as an argument against heliocentrism in the 16th century. Robert Hooke, while Gresham Professor of Geometry in 1669, used an instrument installed in the college itself which was 36 feet long to try and spot the parallax of gamma Draconis, the brightest star which passed overhead: he claimed to have measured a clear parallax, but negative results from others, including Picard, meant these results were quickly attributed to refraction and other atmospheric results. (Hooke's efforts did inspire the creation of larger transit telescopes, including one in the well-used by Flamsteed at Greenwich, and the Monument built by Wren in the City of London, though passing traffic rendered it useless as a scientific instrument).

Only in the 1830s did astronomers, most notably Friedrich Bessel, manage to measure a true parallax of the star 61 Cygni, otherwise known as Piazzi's Flying Star, which had been chosen because of its large proper motion (motion across the sky from year to year). Bessel announced his success, casually, in a letter to John Herschel, later read to and published by the relatively new Royal Astronomical Society.

That letter starts off casual ('Esteemed Sir,—Having succeeded in obtaining a long-looked- for result, and presuming that it will interest so great and zealous an explorer of the heavens as yourself, I take the liberty of making a communication to you thereupon') but quickly details the complex calculations needed to measure the change in position of 61 Cygni compared to two stars which are nearby on the sky.

61 Cygni was, thanks to sentimental astronomers, the final object observed by Gaia a month or so ago. It will take many more years for astronomers to complete their reduction of the data it gathered – we're

expecting a catalogue with around half of its bounty, that gathered in the mission's first 5.5 years, to be released next year – but what we have has already transformed astronomy.

The edge-on view of the Milky Way constructed from the observations, for example, shows not only that our galaxy is warped – something which has been hinted at in observations since the 1950s, but that the warp is wobbling on timescales of 700-800 million years. (For comparison, the Sun orbits the centre of the Milky Way in one galactic year, or about 225 million years). This surprisingly rapid motion suggests that it is being caused by an ongoing collision with a satellite galaxy, perhaps the recently identified Sagittarius dwarf.

Sagittarius is only 1/10000th of the mass of the Milky Way, but it has had an outsized influence. The smaller galaxy has smashed through our galaxy three times in the past, as its orbit takes it through the Milky Way's disk: first five or 6 billion years ago, then 2 billion years ago, then just a billion years ago. The ripples produced by these collisions still exist, and are visible in the Gaia data, and the timings seem to coincide with peaks of star formation in the galaxy's history, revealed by estimating the ages of nearby stars. This suggests that we might owe the Sun's formation to influence of this small galaxy which was only discovered in the 1990s. This first example shows how *Gaia* is revealing that the Milky Way's history is both more dynamic and more complex than we thought.

The major event in that history may have been revealed by the presence of 30,000 stars identified amongst the first 7 million mapped by Gaia, a group which surround us completely and which can be seen across the whole sky, but which move together through the Milky Way. They also stand out on the Hertzprung-Russell diagram which plots fundamental stellar properties, and have distinct chemical compositions revealed by spectroscopic surveys carried out from the ground.

These 30,000 stars are, in fact, interlopers from another galaxy, which must have merged with the Milky Way billions of years ago, and which the researchers responsible for its identification call Gaia-Enceladus[1]. It was also identified by a separate team studying how a large set of stars move; they called it 'sausage-like', and so the unwieldy name of 'Gaia-Enceladus-Sausage' is often used, in a low point for astronomical nomenclature. Given that 13 globular clusters – large cities of stars in the Milky Way's halo – seem to be moving with its constituent stars, it must have been a substantial galaxy in its own right, at least a tenth as large as the modern Milky Way. However, unlike the Sagittarius dwarf which persists as a separate system even after billions of years of interacting with its larger neighbour, the Sausage is now dissolved entirely into the larger galaxy.

(I should note here that while the major result that the Milky Way has had a series of violent mergers with other galaxies seems well established, the details are hazy. Recent work seems to show that the orbits of many of the stars which were key to the original identification of the Gaia-Enceladus-Sausage event show features – 'wrinkles' – that seem to come from the structure of the original galaxy, but which should be washed out with time. That suggests that they are in fact from a more recent event, perhaps in the last few billion years. Arguments are also raging over the distant past, with perhaps as many as seven large systems, including a giant one named 'Kraken', interacting with the Milky Way over the last 11 billion years.

Gaia data is also rewriting history on smaller scales too. We have known for decades that the Sun is currently passing through a relatively empty region of the Milky Way, a feature known as the Local Bubble. Within the Bubble, which is a few hundred light-years across, there is a small amount of hot plasma, but it is surrounded by what seems to be a shell of cold, neutral gas and dust. New results show that the surface of the Bubble is host to most of the star-forming regions within 300 light-years or so of the Sun, and studying the motion of the stars seems to suggest that it's the result of a violent event 14 million years ago, perhaps a burst of supernovae from recently formed massive stars. The resulting shockwave has swept up material, triggering star formation even as it is carried away into the surrounding disk.

Gaia lifetime of more than a decade was nearly twice as long as originally planned. This extended mission has greatly extended the power of another mode of observing with the spacecraft, which involves watching the position of the stars it sees change over time. The hope is that many stars will be seen wobbling, pulled this way and that under the gravitational pull of hidden companions, most particularly planets. In the meantime, astrometric studies – measurements of position – have already identified the two nearest black

[1] Enceladus, most commonly used in astronomy for a moon of Saturn, was a giant in ancient Greek mythology who was the offspring of Gaia and Uranus. In legend, he was buried under Mount Etna, causing earthquakes: his galaxy namesake was similarly buried in the Milky Way.

holes to Earth, both in orbit around stars in the Gaia catalogue whose movements revealed the presence of hidden companions. The next data release, due in 2026, should double the number of exoplanets known, adding 4000-5000 to the total from astrometry alone.

Closer to home, Gaia has caught more than 150,000 asteroids and determined their orbits. Along with a large population of trojans, which share Jupiter's orbit, and plenty of main belt asteroids which exist between Mars and Jupiter, there are both trans-Neptunian objects – 24 of them – and Earth-crossing asteroids which may one day pose a threat to our planet. Luckily none of the 446 observed by Gaia seem to pose any threat in the near future.

With Gaia operations ceasing, we now have all of the data we need to make the best map of our stellar neighbourhood that will ever be required, at least until humanity ventures out amongst the stars. A final few months of technical testing and the spacecraft will be placed in a parking orbit where it will remain for ever. These tests have brightened the spacecraft, however, and amateur observers are enjoying tracking it – a thank you for the guide to the cosmos Gaia has given us.

Bibliography

For a discussion of the Nebra disk, and of early Western astronomy more generally see:
Garrow, Duncan; Wilkin, Neil (June 2022). The World of Stonehenge. British Museum Press. pp. 145–147.

The Dunhuang star map is described on the International Dunhuang Programme website:
https://idp.bl.uk/exhibition/chinese-astronomy/

For a history of mapping the sky, I recommend the *Song of Urania* podcast: https://songofurania.com/

Early measurements of parallax are given in Reid & Menten, Astronomische Nachrichten, 2020: https://arxiv.org/abs/2009.11913 and placed in context by Alan Hirshfield in 'Parallax: The Race to Measure the Cosmos', 2001, Palgrave Macmillan.

Bessel's letter to John Herschel can be read at Bessel, 1838, Monthly Notices of the Royal Astronomical Society, 4, 152 https://ui.adsabs.harvard.edu/abs/1838MNRAS...4..152B/abstract

Gaia Results:
Gaia's study of the Milky Way's 'warp': Poggio et al. Nature Astronomy, 2020, 4, 590 https://arxiv.org/abs/1912.10471
Influence of the Sagittarius dwarf on star formation in the Milky Way: Ruiz-Lara et al., 2020, Nature Astronomy, 4, 965, https://arxiv.org/abs/2003.12577

The discovery of the Gaia-Enceladus galaxy: Helmi et al., 2018, Nature, 565, 85: https://arxiv.org/abs/1806.06038

…and the first of the 'sausage' papers is Belokurov et al., 2018, MNRAS, 478, 611 https://arxiv.org/abs/1802.03414

For an argument that much of the structure is recent, see Donlon et al, 2023, MNRAS, 531, 1422: https://academic.oup.com/mnras/article/531/1/1422/7675507?login=false

The Gaia study of the Local Bubble is Zucker et al, 2022, Nature, 601, 334: https://arxiv.org/abs/2201.05124

Discovery of first Gaia Exoplanet : Stefànson et al. 2025, Astronomical Journal, 169, 107
https://iopscience.iop.org/article/10.3847/1538-3881/ada9e1cc