THE ONCE AND FUTURE MILKY WAY

Data from the Gaia spacecraft are radically transforming how we see the evolution of our Galaxy.

BY ADAM MANN

Last April, Amina Helmi felt goose bumps while driving to work in the northern Netherlands. It had nothing to do with the weather — it was pure anticipation. Just days earlier, a flood of data had been released from Gaia, a European Space Agency (ESA) mission that has been mapping the Milky Way for five years. The University of Groningen astronomer and her team were racing to comb through the data for insights about the Galaxy before others got there first.

Working on fast-forward, unable to sleep from the excitement, Helmi and her colleagues sensed they were on to something. The team had spotted a set of 30,000 renegade stars. Unlike other objects in the main body of the Milky Way, which orbit in a relatively flat disk shape, these non-conformists were moving backwards, in orbits that were carrying them out of the Galactic plane.

Within weeks, the team had worked out that the luminous horde pointed to a long-hidden and especially tumultuous chapter in the Milky Way's history: a smash-up between the young Galaxy and a colossal companion[1]. That beast once circled the Milky Way like a planet around a star, but some 8 billion to 11 billion years ago, the two collided, massively altering the Galactic disk and scattering stars far and wide. It is the last-known major crash the Galaxy experienced before it assumed the familiar spiral shape seen today.

Although the signal of that ancient crash had been hiding in plain sight for billions of years, it was only through Gaia's

data set that astronomers were finally able to detect it. "It's just incredible to have been able to find such an important milestone in the history of the Milky Way," says Helmi.

Such monumental discoveries are becoming almost commonplace thanks to Gaia. The mission aims to catalogue more than 1 billion local stars, charting their brightness, temperatures, ages, locations and velocities. It is those last two properties that are particularly edifying for astronomers: before Gaia, scientists lacked high-precision measurements of the distance to many stars, as well as what's known as proper motion, or a star's movement across the sky. Using this crucial information, researchers can — as Helmi and her colleagues did — hunt for groups of objects travelling together in coordinated trajectories that point to a common history. Stellar velocities can also help astronomers to trace the influence of dark matter — the invisible and still-mysterious substance that constitutes most of the Galaxy's mass and bends the paths of stars with its gravity.

Hundreds of papers have been published since Gaia's April 2018 data release. They paint a picture of a Milky Way that is much more dynamic and complex than previously imagined. The Galaxy is teeming with surprises, including hints of dark-matter clumps that might eventually give scientists a better grasp of the shadowy material's properties. The early, easy-to-spot findings have already been transformational, says astronomer Vasily Belokurov at the University of Cambridge, UK, and yet they are merely a glimpse of what is to come: "How we see the Milky Way has clearly changed."

A DISRUPTIVE PAST

The Solar System sits on the outskirts of the Milky Way, some 8,000 parsecs (26,000 light years) from the Galactic Centre, on a secondary spiral arm known as Orion. It is from this perch, looking at the enormous starry band stretching across the night sky, that astronomers must map out the Galaxy's structure. By the mid-twentieth century, they had painted a broad-brush picture, determining that the Milky Way's stars are distributed in a central bulge, wrapped by serpentine stellar arms and surrounded by a thin, spherical halo. In the 1970s and 1980s, researchers deduced how this structure had built up over billions of years, beginning with a vast cloud of dark matter, gas and dust. The visible components collapsed into a disk-like structure, which then bulked up by devouring smaller, satellite galaxies. Astronomers later filled in the details by using terrestrial telescopes to repeatedly photograph the entire night sky. Such surveys allowed scientists to peer more closely at large-scale Galactic objects such as the stellar halo, where they found remnants of small galaxies that had been stretched out into star-studded debris streams.

But ground-based surveys give astronomers only so much information about the Milky Way's structure, mainly because blurring from Earth's turbulent atmosphere limits how accurately the distances to stars can be determined. And although the speed at which stars move towards or away from Earth can be measured by changes in colour, sorting out their proper motion — and so their full 3D velocity — is difficult because most objects move so little across the sky on human timescales. That problem has obscured the relationships between many stars — links that might be revealed by similarities in their movements.

The roughly €740-million (US$844-million) Gaia mission, which was approved in 2000 and launched 13 years later, was designed to fill these gaps. Orbiting the Sun slightly farther out than Earth does, the spacecraft snaps the same stars from different positions in its orbit. This allows astronomers to measure distance through a quantity known as stellar parallax — infinitesimal shifts in the apparent position of an object in the sky that accompany a change in perspective. ESA's Hipparcos satellite, which operated between 1989 and 1993, gathered similar parallax data. But Gaia's precision will ultimately be 100 times greater. And thanks to its sensitivity, it can probe deeper into the Galaxy: some 99% of the more than 1 billion stars it observes have never had their distances accurately determined.

In a computationally intensive undertaking, Gaia researchers have built up a plot of the location of every star relative to every other star that the telescope sees. This has allowed the team to measure how fast stars seem to travel across the sky — their proper motion. Then, by measuring small shifts in the colour of the stars, astronomers can get an indication of how quickly the objects are moving towards or away from the satellite, along its line of sight. The combination of the two measurements, plus the distances calculated from Gaia, provides the stars' full 3D motion. Gaia can measure the line-of-sight motion for the brightest stars it sees, but ground-based telescopes will help to measure the remaining stars. Knowing where each star is and where it's going allows researchers to quickly tease out hidden Milky Way history.

Such was the case for the ancient collision investigated by Helmi and her colleagues (see 'Galactic shake-up'). In their work, evidence that the cohort of stars they spotted shared a common origin was bolstered by data from the ground-based Sloan Digital Sky Survey (SDSS) in New Mexico, which showed that the members of the ensemble all had a similar chemical composition. The team chose the name Gaia-Enceladus for the dwarf galaxy that is thought to have been the stars' home. Enceladus was a giant who descended from Gaia in Greek mythology.

As it so happened, Belokurov and his colleagues had also found evidence of the collision, using information from Gaia's preliminary data release in 2016. Those data did not include proper-motion readings, but by comparing stellar positions in that data set with SDSS observations taken about a decade ago, the team could see how stars had moved in the intervening time. They noticed a group of objects travelling together on eccentric orbits that should eventually take them from the centre of the Galaxy to the outskirts. These seemed to have originated from a single major crash, their shared history apparent because of similarities in metal content. Because the plotted velocities formed a sausage shape, the team dubbed the ancient dwarf galaxy that was once the stars' home the Gaia Sausage[2].

The double naming has led to some confusion in the community. But whatever the culprit is called, the ancient merger could be a clue to an abiding Milky Way mystery. The Galaxy's disk has two components — a thin inner disk containing gas, dust and young stars sits like the filling of an Oreo, inside a thick outer disk consisting almost entirely of older stars. Astronomers have debated whether the thick disk arose first, with gas and dust then condensing down to form a thinner core, or whether the structure began with a thin disk that was then partially puffed up. Because the Gaia-Enceladus-Sausage was a significant fraction of the Milky Way's size during the crash, it would have deposited a great deal of energy into the Galactic disk, heating and expanding it. Helmi's group sees this as a mark in favour of the puffing-up scenario, and evidence of a dramatic distortion to the Milky Way.

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KNOWLEDGE EXPLOSION

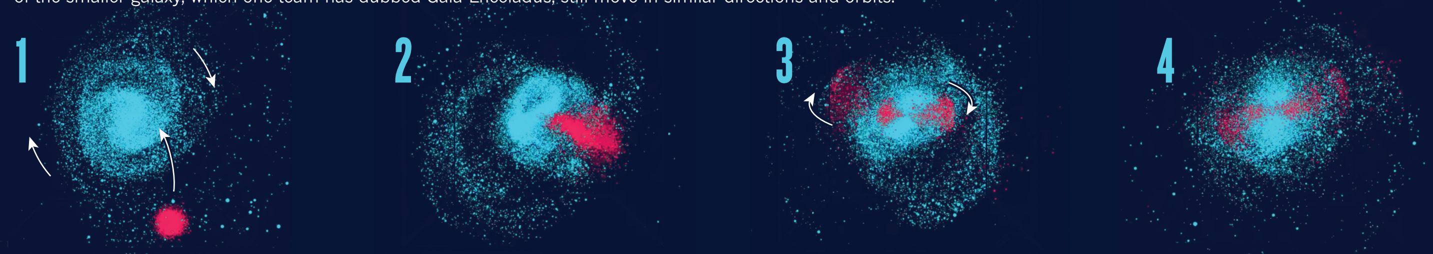
The speed at which such previously difficult insights can be made using Gaia data has astounded researchers. Astronomer Kathryn Johnston at Columbia University in New York City recalls the buzz over a paper posted the day after the April data release, showing how the motions of about 6 million stars near the Sun are all aligned in a peculiar spiralling pattern akin to a snail shell[3].

The pattern seemed to be a fingerprint, Johnston says, stamped by a small satellite galaxy known as Sagittarius. Every time Sagittarius swoops in close, it gravitationally disturbs Galactic stars, and this should generate wobbles and ripples in the disk. Researchers had previously conjectured

NEWS FEATURE

GALACTIC SHAKE-UP

Using data from the Gaia satellite, two teams have found stars that seem to have originated in a smaller galaxy that once orbited the Milky Way. Roughly 10 billion years ago, the pair collided, shaking up the structure of the Milky Way, in much the same way as seen in this simulation of a galactic merger. Remnants of the smaller galaxy, which one team has dubbed Gaia-Enceladus, still move in similar directions and orbits.



IMAGES FROM ESA

about such imprints, but the signature in the Gaia data seemed to be the first clear and compelling signal of Sagittarius's influence. "For me that was a stunning moment," says Johnston. "The spiral was so clean. It looked like a theoretical prediction from an idealized simulation, not a real data plot."

Thanks to Gaia's eyes, such perturbations are not only standing out, they are also telling a different story about the Milky Way's past. Previously, most astronomers presumed that whereas the outer halo of the Galaxy has endured a chaotic collisional history with smaller satellites, the main bulk has lived a fairly quiet life. Features such as the spiral arms and a bar of stars that is thought to cross the central bulge have generally been treated as products of the Milky Way's internal dynamics. But the wobbles that seem to be induced by Sagittarius suggest that external forces have a greater bearing on the Milky Way's shape than was previously recognized.

Gaia is forcing researchers to take a second look at some of the canonical assumptions that are used to simplify models, says astrophysicist Adrian Price-Whelan at Princeton University in New Jersey. "We knew those assumptions were wrong," he adds. "Gaia has now shown us how wrong they were."

PLOTTING THE DARK SIDE

Mapping the Milky Way's luminous objects could also shed light on dark matter, which might constitute as much as 90% of the Galaxy's mass. Theorists suspect that our Galaxy sits inside an enormous, roughly spherical halo of dark matter that, much like ordinary matter, has clumped together into smaller structures thanks to gravity. Cosmological simulations suggest that thousands of large dark-matter clumps orbit the Galaxy, occasionally getting eaten by a mass of dark matter at the centre, in a process akin to the Milky Way's consumption of its small visible satellites.

The vast majority of the dark-matter substructures are thought to contain few or no stars, making them difficult to detect. But Gaia might have found a hint of one in GD-1, a long stream of stars discovered in 2006 that stretches across half of the northern sky. This stellar stream is no stranger to scrutiny, but Gaia enabled Price-Whelan and astronomer Ana Bonaca at the Harvard-Smithsonian Center for Astrophysics in Cambridge, Massachusetts, to more confidently pick out true members of the group[4]. Last November, they and two other colleagues identified structural features, including a distinct gap, that could be the scars of an encounter with a massive object some 500 million years ago[5]. As the putative perturber sped past the stream, it might have separated the train of stars by gravitationally tugging on some, allowing them to pull ahead of their companions.

The most likely culprit seems to be a dense dark-matter clump, probably somewhere between 1 million and 100 million times the mass of the Sun, says Bonaca. That estimate could have implications for physical models of dark matter. A dark-matter particle's mass helps to dictate how fast it can move and, in turn, the size of clusters it is liable to form. The GD-1 perturber's size is in an interesting range, says Bonaca, that could eliminate hypothesized dark-matter candidates that are relatively low in mass.

Bonaca and her team are now interested in using Gaia data to determine the velocities of the disturbed stars in the stream, which might point to the orbit of the putative dark-matter clump. If they can ascertain where it could be found today, they might be able to detect its gravitational effects on other material. Or perhaps they could train γ-ray telescopes on the spot to look for evidence of dark-matter particles annihilating one another or decaying, processes that could emit energetic photons. Either technique could offer a more-direct probe of the invisible substance's physical properties.

Yet Price-Whelan says it is hard to infer too much from a single example. He hopes that systematic studies using the Gaia catalogue and future observatories — such as the ground-based Large Synoptic Survey Telescope in Chile, which is expected to begin gathering data in the early 2020s — will reveal fainter stars and other stellar streams. If some of those streams also show effects from encounters with dark-matter clumps, they could give astronomers a better idea of the abundance and size of such clusters, which would help to pin down the properties of dark matter.

Astronomers hope that Gaia's data on stellar motions will also help them to map out the general shape of the Galaxy's dark side. Depending on the type of particle it is built from, the Milky Way's dark-matter halo could have different levels of sphericality or symmetry. Belokurov expects that information from Gaia on local stellar orbits will be sufficient to trace out the overall mass and shape of the dark-matter halo in the next 2–4 years.

Such findings won't be confined to the Milky Way. The conclusions drawn about the Galaxy's history and dark-matter distribution will feed back into cosmological models that are used to explore how the Universe's large structures grew and changed. Gaia has already been granted its first mission extension to the end of 2020, and astronomer Anthony Brown at Leiden University in the Netherlands, who chairs the mission's data-processing and analysis consortium, thinks the satellite can continue to gather data until 2024, for a ten-year mission in total. He says that this extension should provide a factor-of-three improvement in the precision of Gaia's measurement of proper motion for the stars it currently tracks. And it could provide information about ever-more-distant stars.

Gaia's ultimate legacy has yet to be written, but all indications suggest it will be substantial. Data from all-sky surveys such as those conducted by the SDSS continue to provide fruitful discoveries about the Universe a decade or more after they were completed. Helmi is looking forward to further rewinding the Milky Way's history as Gaia's catalogue gets bigger and more detailed. "One of the things that I find most exciting," she says, "is that we just started really digging into the past." ■

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