COSMOS

THE SCIENCE OF EVERYTHING

Issue 91 **Winter 2021**

TIME TRAVEL

EARTH'S EPIC HISTORY AND THE FUTURE OF LIFE

+

New Ancestor?
DNA detectives on the hunt

Tetris and Telepathic Mice
Mind meld made real

High Revolution
Gaia telescope's galactic gaze

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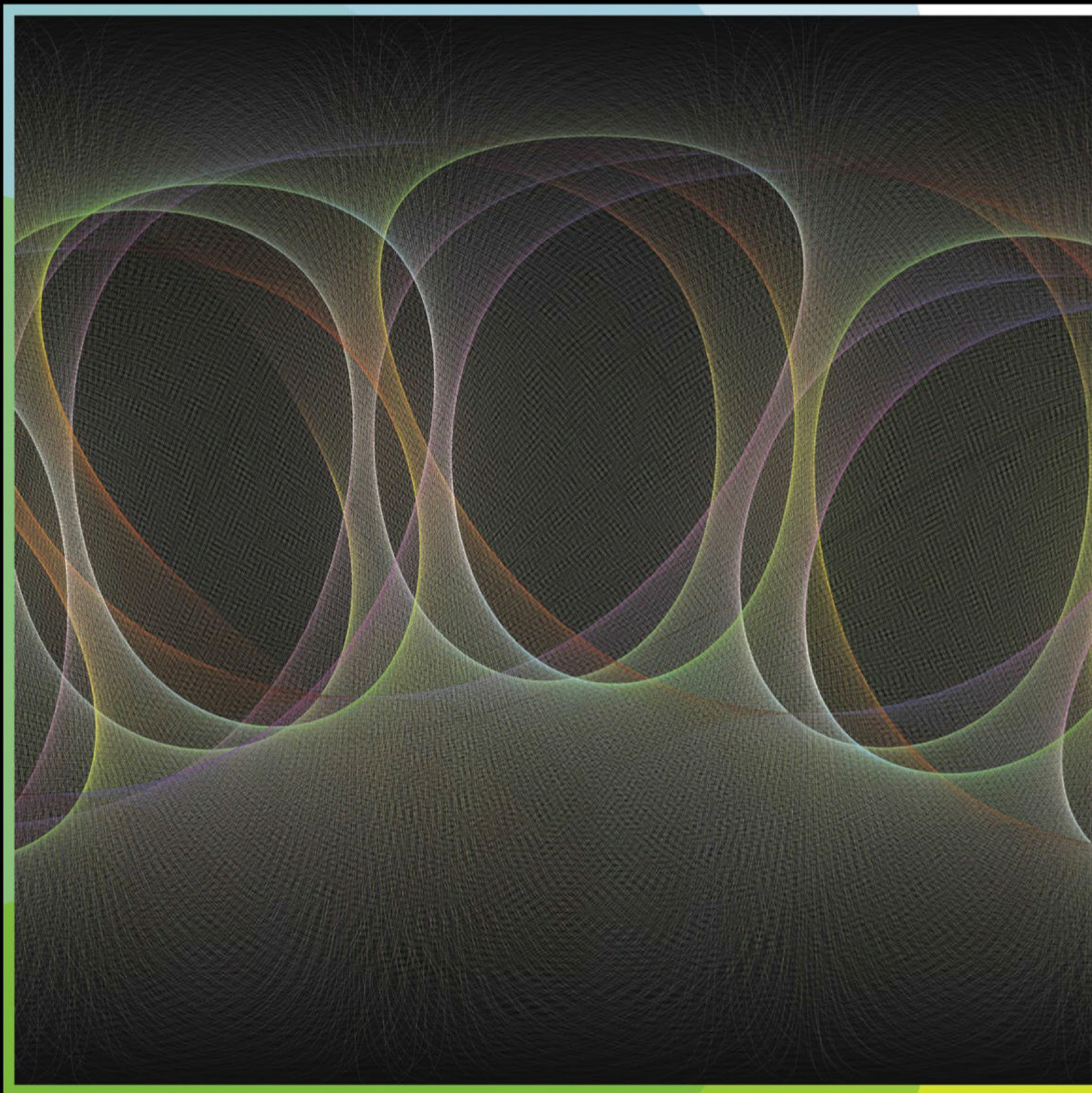
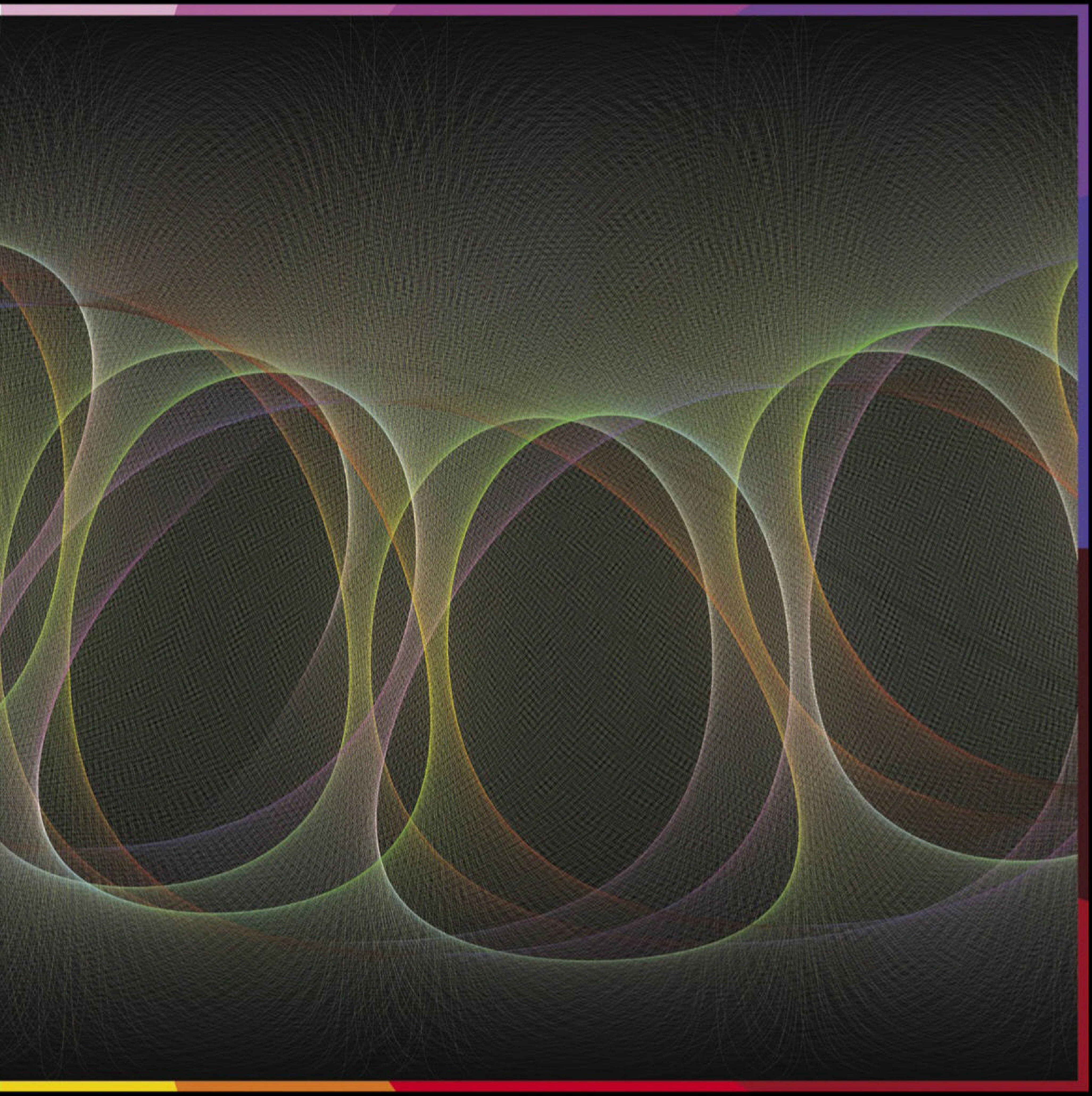


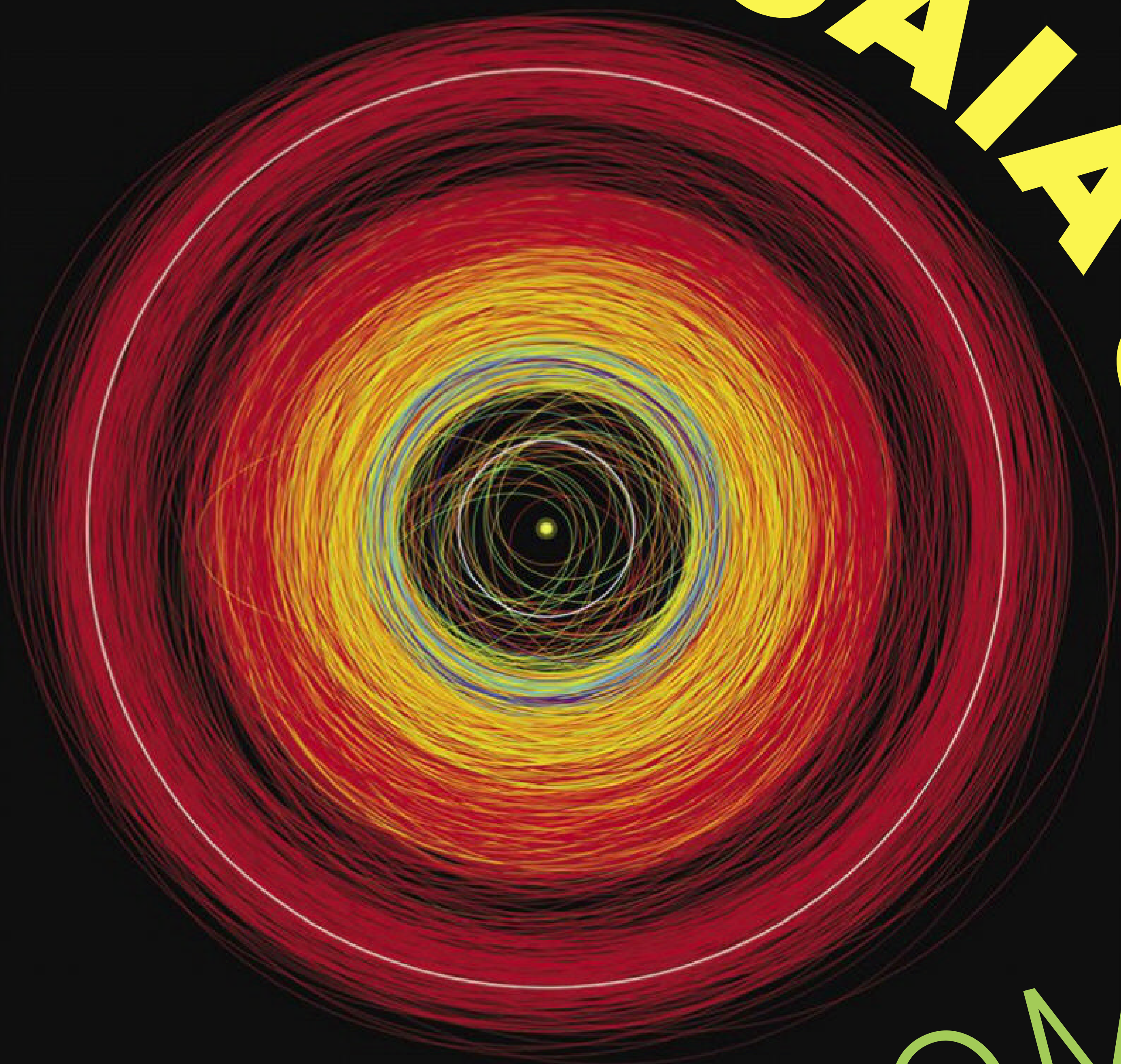
ESA / GAIA

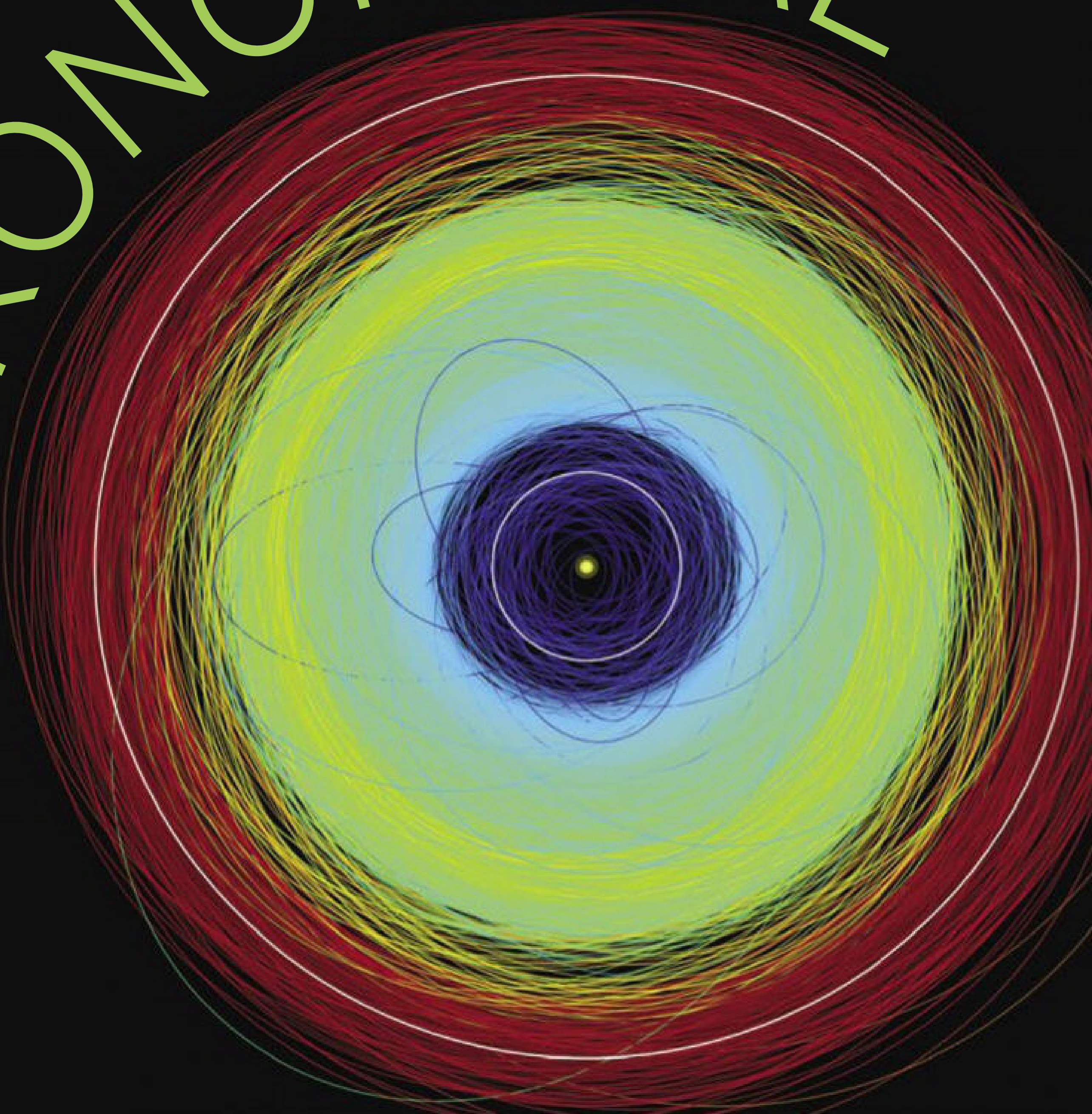


Where is Gaia looking?

This psychedelic swirl plots the viewing direction of the European Space Agency's Gaia space telescope as it maps our galaxy. The craft sweeps its two telescopes around in four rotations per day, while also changing the orientation of its spin axis over 63 days. The colour of each line of dots represents the direction of the scan with respect to north (top of image) – indicated by the border, where each block of colour spans 18°. Densely overlapping lines denote areas that have been scanned many times in many directions, but the gaps will close as Gaia continues its work. Read more about Gaia on page 66.

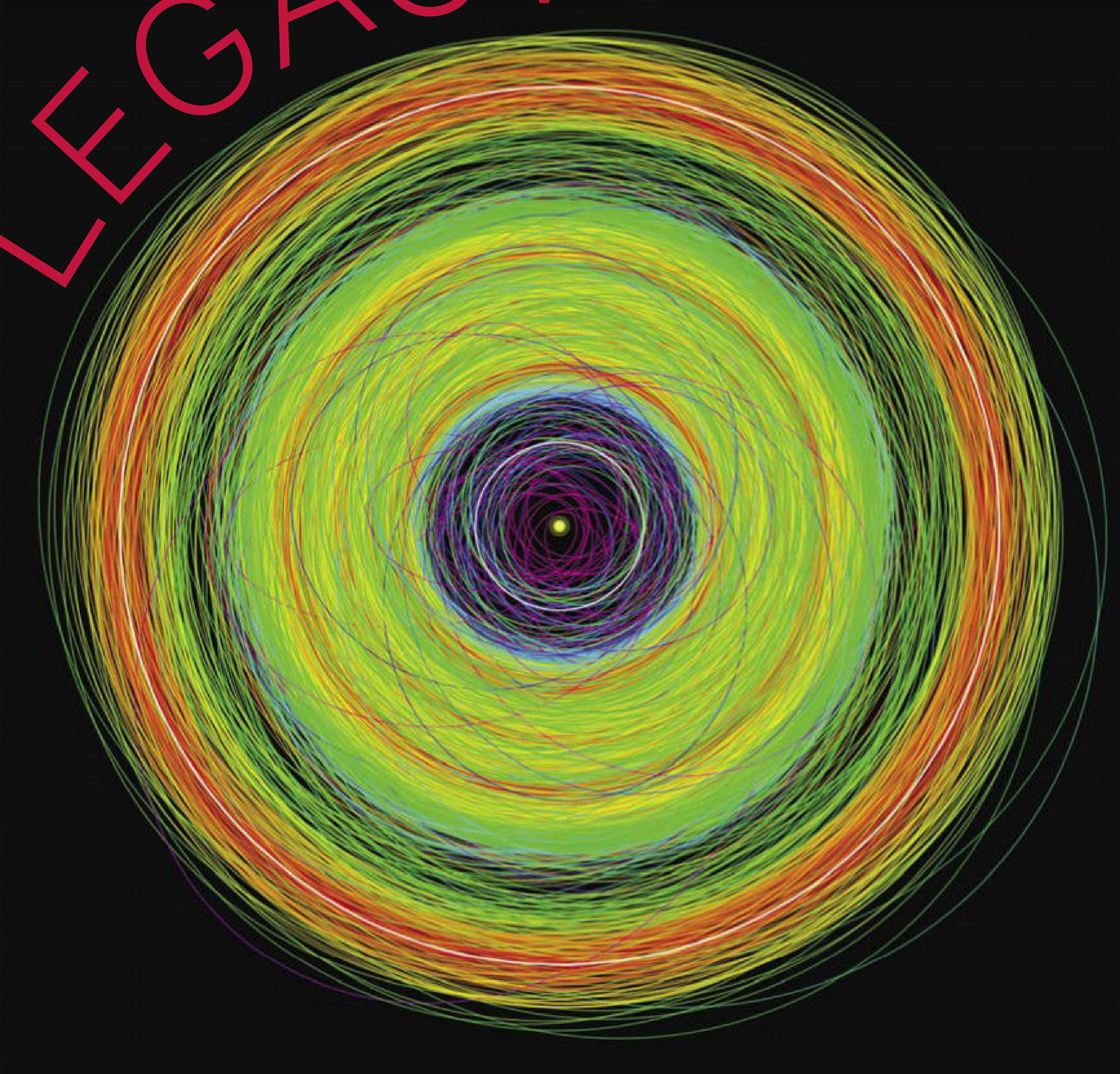
GAIA'S ASTRONOMICAL

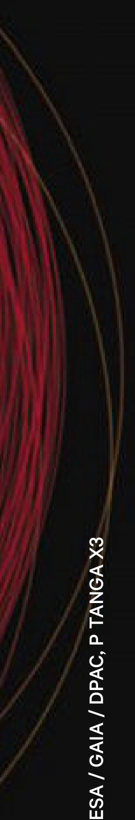




GAIA's plots of the 14,099 asteroids orbiting between the Sun and Jupiter show the Sun at the centre, Earth as the inner white circle and Jupiter as the outer white circle. Orbits coloured by albedo (above) – the "lightness" of an asteroid's surface –show dark asteroids (red) dominating the external regions, with the lightest bodies in the inner Main Belt. Orbits coloured by perihelion distance (right) – the minimum distance from the Sun – show the trajectories of Near-Earth in blue and those of Main Belt asteroids in green. Jupiter's gravitational perturbations are evident, except for Trojan asteroids (red) that precede and follow the planet in safe, stable regions. Coloured for their eccentricity (opposite), most asteroids' orbits are nearly circular (green), while others take eccentric paths that zip close to the Sun (purple).

LEGACY





ESA / GAIA / DPAC, P TANGA X3

The European Space Agency's peerless space telescope continues to break new ground in astrometry, and the best is likely yet to come. **Richard A. Lovett** reports.

Just over four centuries ago, the Dutch mathematician Willebrord Snellius measured the approximately 116 kilometres from Alkmaar, in North Holland, to Breda, in the country's south, by breaking it up into quadrangles built upon a chain of 33 carefully constructed triangles.

Snellius – better known in the English-speaking world as Snell (as in Snell's law, of light refraction) – underestimated the distance by 3.5%. Still, it wasn't a bad first effort in modern times to use triangulation as a survey method, especially because the quadrant he used (an instrument for measuring angles), although revolutionary for its time, was only accurate to tenths of a degree.

People improved on Snellius's work (largely by developing ever better methods of measuring angles) throughout the 18th and 19th centuries, eventually reaching a point of accuracy that was surpassed only when global navigation positioning systems became commonly used from the 1980s.

But GPS only works on Earth. If you want to look at and map objects much further out in space you need another method. European space telescope Gaia does this by going back to the future: it uses a process akin to how surveyors measure distances on Earth, but on a far grander scale.

"[Gaia] uses the Earth's orbit to provide a long baseline to triangulate [on stars and] relies on making very accurate measurements of positions," says Nick Rowell, a wide-field astronomer at the Royal Observatory of Edinburgh, Scotland.

And Gaia isn't just doing this for a few stars. Its latest data release, announced last December at a press briefing by the Royal Astronomical Society, now maps the positions, brightnesses, distances and motions of 1.8 billion stars.

The whole process is a testament to the advancement of computer technology, not just while Gaia was being built, but afterwards. "They are absolutely dependent on Moore's Law," says George 'Fritz' Benedict, a retired astrometer from the University of Texas, Austin (citing the famous computer-tech dictum that processing capabilities double every two years). "When they built this, the computers absolutely weren't fast enough to process the data. Now they can."

Even though it is still collecting data, Gaia is already making its mark on astronomy: as of April 2021, the Astrophysics Data System at Harvard University listed a whopping 5172 refereed Gaia-related studies.

"There is hardly a field of astronomy that isn't revolutionised by Gaia," says Dafydd Evans, a Gaia researcher at the University of Cambridge, UK.

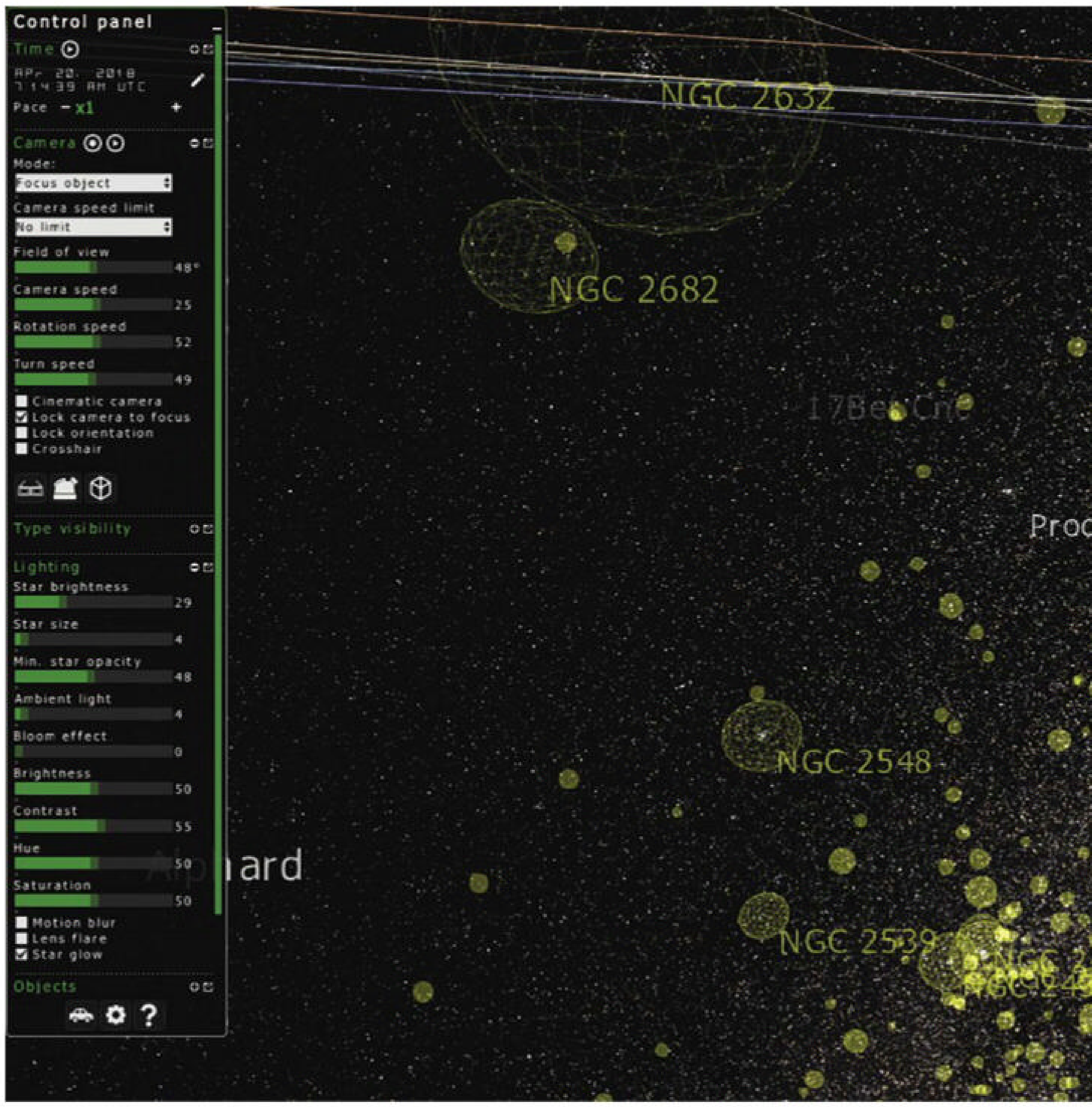
Martin Barstow of the University of Leicester, UK, calls it "a tsunami rolling through astrophysics. You'll be talking about astronomy before Gaia and after Gaia."

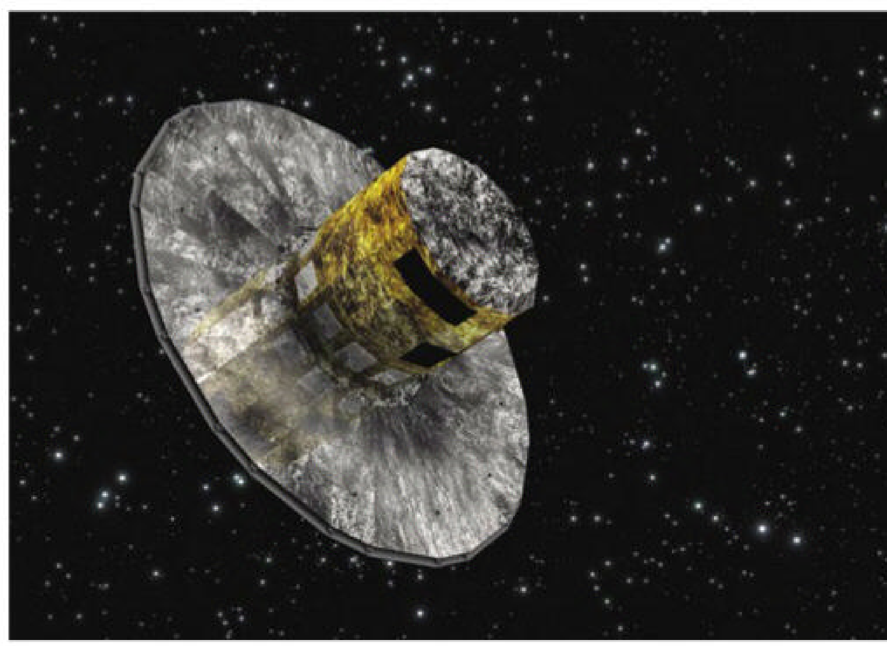
Eyes in the sky

Astronomy is best known for the spectacular images produced by the best telescopes. But it is a field with many subdisciplines, one of the earliest of which is astrometry.

Stripped to its basics, astrometry is nothing more than the making of sky maps. Google Earth for the heavens: a tabulation of the positions, brightnesses, and colours of the stars. Modern astrometers have also included distances and motions, but the idea goes back to the ancient Greeks, who by the time of Hipparchus (~190 BCE to ~120 BCE) had created a catalogue of nearly 1,000 stars. "It's one of the oldest sciences, ever," says Leanne Guy, data management project scientist for the US's Vera C. Rubin Observatory.

Such maps are, of course, incredibly important to backyard stargazers trying to figure out where to point their telescopes. But to the ancients they served





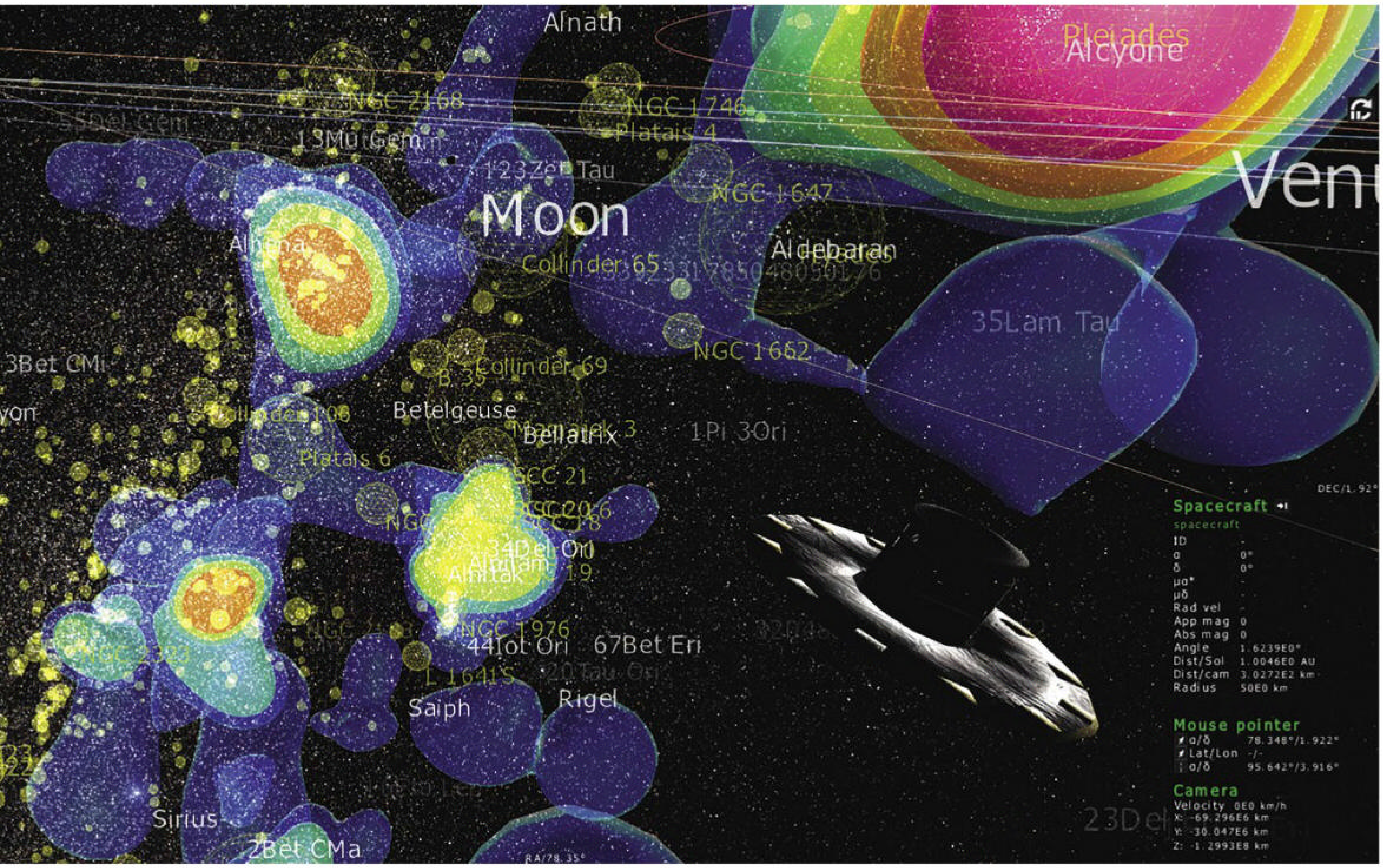
Gaia Sky (above) utilises the data from Gaia (right) to create an open-source simulation of our local stellar neighbourhood, complete with planets, dwarf planets, some satellites, moons, asteroids, trajectories, locations and more. It's used for both scientific and recreational purposes; anyone can download the map and data sets – including star clusters, nearby galaxies (NBG) or distant galaxies and quasars (SDSS) – and cruise round their favourite part of the Solar System and beyond.

ABOVE: ESA / GAIA

more practical purposes, such as allowing sailors to navigate the ocean or farmers to track the seasons so they knew when to plant crops.

Today, GPS has replaced stars for navigation and astrometry has far outstripped the needs of people wanting to know where to point a telescope.

"The data is about 100,000 times more accurate than we need," says Oregon-based Jerry Oltion, an amateur astronomer, telescope-maker and columnist for *Sky & Telescope* magazine. But that doesn't mean astrometry is a relic of history.



At the heart of this is Gaia, launched in 2013. It's the successor to a prior ESA space telescope called Hipparcos, which orbited the Earth from 1989 to 1993. Hipparcos wasn't large as telescopes go – only 29 centimetres in diameter – but in space, free of the distorting effects of the Earth's atmosphere, it was able to collect the most accurate information then available on 118,000 stars, measuring their positions to an accuracy akin to spotting a $1 coin at a distance of 2,500 kilometres.

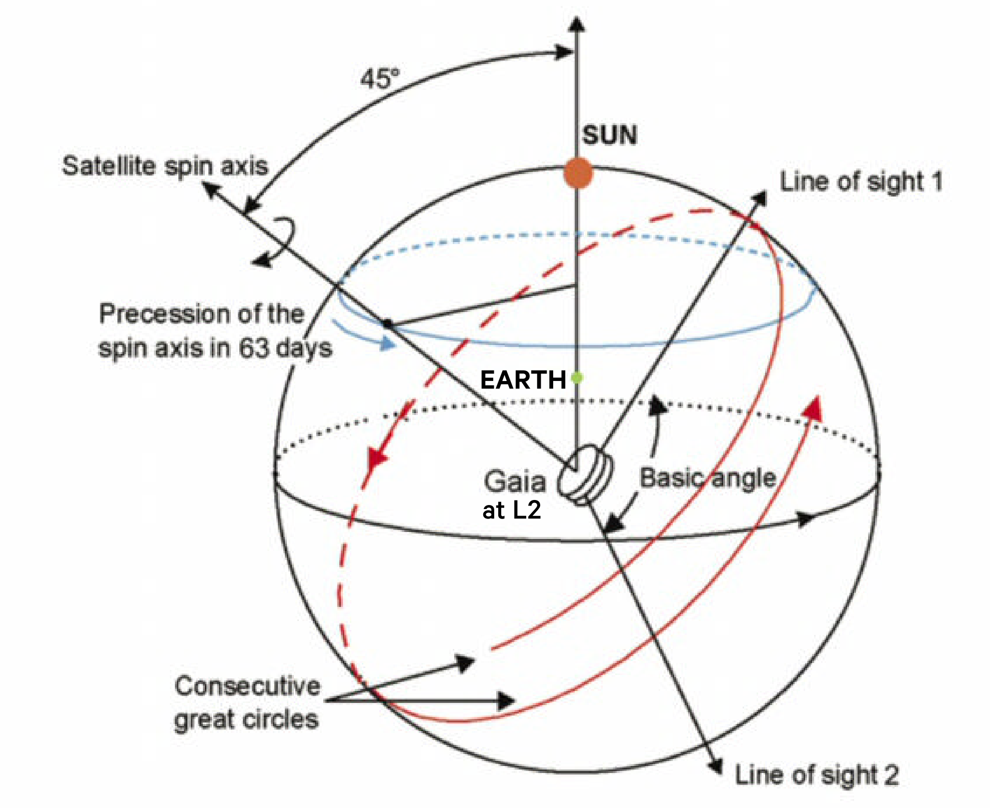
Gaia took that groundbreaking effort and raised it exponentially. Hipparcos was "pretty good," says Benedict. "Gaia is about 50 times better."

Gaia does its magic via a pair of rectangular telescopes each measuring 145 x 50 cm, substantially larger than the one on Hipparcos. Rather than being in Earth orbit, it is in a location called the L2 point, about 1.5 million km from Earth (see box at right). There, the balance of forces from the Earth and the Sun keeps it on station, while also holding it in an orbit where Earth never blocks its view. (NASA's upcoming James Webb Space Telescope, scheduled for launch on 31 October this year, will also be placed at L2.)

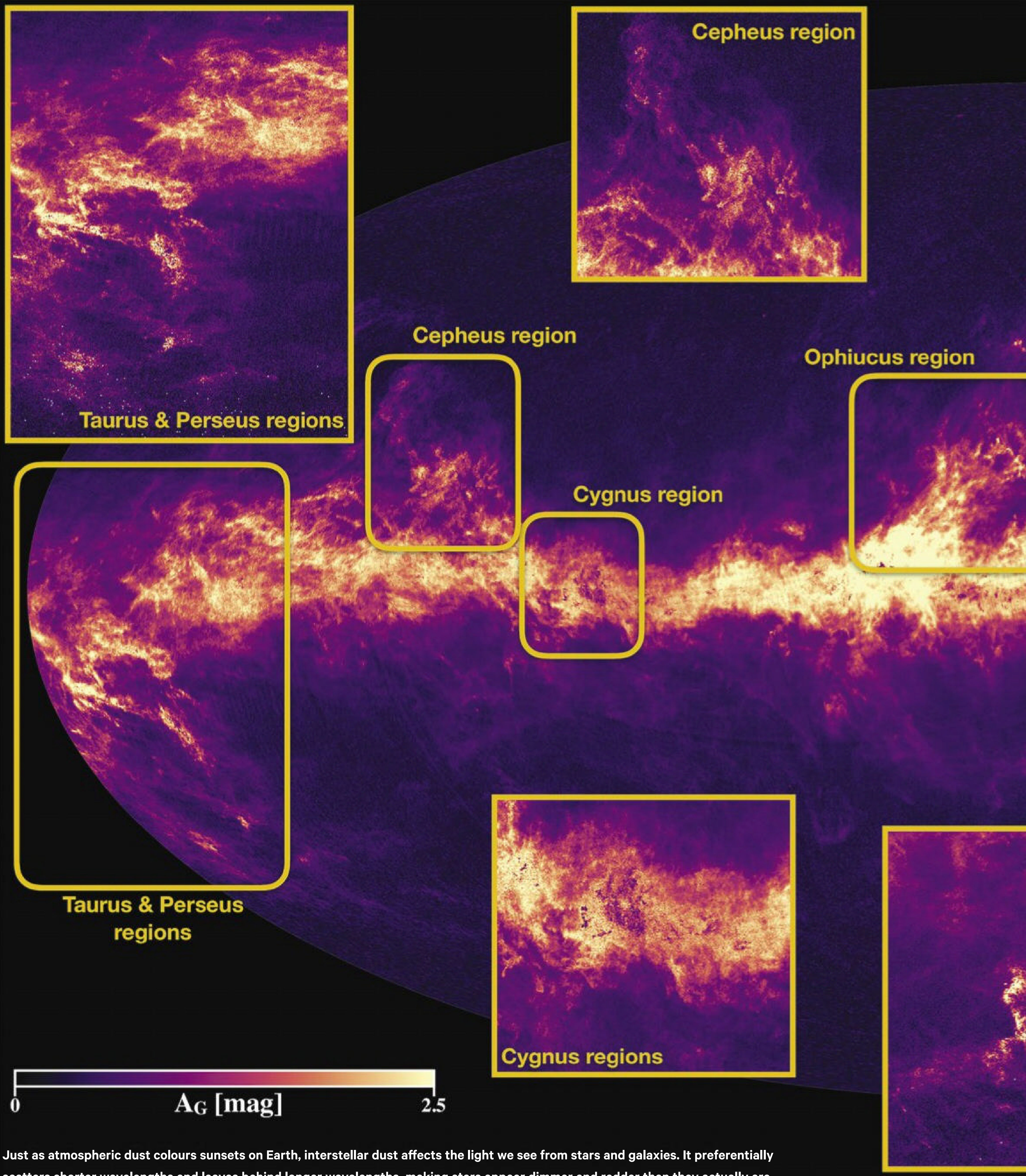
Gaia's twin mirrors focus starlight onto a one-billion-pixel camera, the largest such detector ever launched into space. It's so good that Gaia can do the

GAIA'S SPIN CYCLE

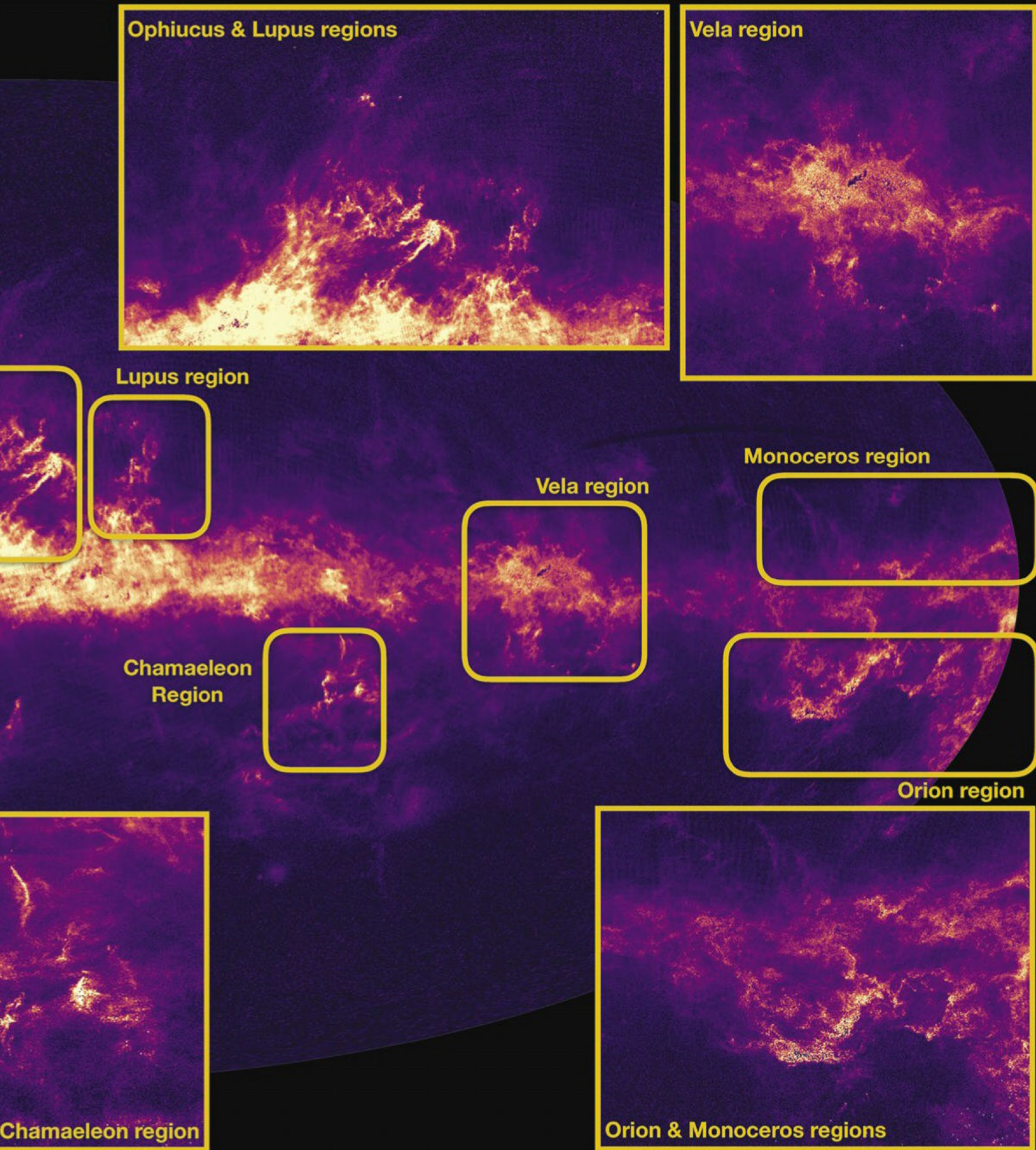
Gaia travels in a controlled orbit around the L2 Lagrange point – one of five positions where the competing gravitational pull of Earth and the Sun hold a satellite relatively stable. Gaia spins at a constant 60 arcseconds/second; each five years in space it will scan each object in view around 70 times.



TOP: GAIA SKY. RIGHT: ESA / GAIA. NEXT SPREAD: ESA / GAIA / M FOUESNEAU / R ANDRAE / CAL BAILER-JONES / O CREEVEY



Just as atmospheric dust colours sunsets on Earth, interstellar dust affects the light we see from stars and galaxies. It preferentially scatters shorter wavelengths and leaves behind longer wavelengths, making stars appear dimmer and redder than they actually are. This 2D projection is a dust map of the whole sky, centred on the heart of the Milky Way. It was created using data from 88 million individual stars spied by Gaia, allowing astronomers to quantify the average "interstellar extinction" caused by dust – and therefore account for it in their measurements of stars and galaxies. A_G refers to the magnitude of extinction along the line-of-sight: the brighter the colour, the more strongly light is attenuated by dust. The map reveals many of the Milky Way's features, such as the disk of the galaxy and the fine structures of large dust clouds.


Ophiucus & Lupus regions
Vela region
Lupus region
Monoceros region
Vela region
Chamaeleon Region
Orion region
Chamaeleon region
Orion & Monoceros regions

equivalent of spotting a $1 coin on the Moon – an accuracy only expected to improve as Gaia continues to collect data. The ultimate goal, says Giorgia Busso, an astrophysicist at the University of Cambridge, UK, is to be able to do the equivalent of reading the title of a book on the Moon.

And that's just the tip of the Gaia iceberg. Gaia can also measure the motions of these stars. Some of these are radial motions – the stars' movements toward or away from us. These are measured by looking for Doppler shifts in key spectral lines. If they are shifted to the blue, the star is moving toward us. If they are shifted to the red, it's receding. Trickier are the stars' "proper motions" – their sideways movements across the sky – but Gaia's hyper-precise mapping ability allows these to be measured by tracking position changes over time. Put the two together with the star's distance and you have the star's motion in three dimensions.

To get the distance, Gaia measures how the star's apparent motion oscillates as viewed first from one side of the Earth's orbit, 150 million km to one side of the Sun and then, six months later, 150 million km to the Sun's opposite side, allowing astronomers to accurately triangulate stars tens of thousands of light years away.

In a dramatic demonstration of the power of Gaia's data, Busso and colleagues plotted the positions, distances, colours, and motions of 303,446 stars within 100 parsecs (326 light years) of the Earth.

Prior to Gaia, she said, there was only enough data to do that for slightly less than 6000 stars. Now, in one giant leap, it's expanded by a factor of more than fifty. "[Gaia] is going to improve the verisimilitude of all kinds of space shoot-em-up games!" Benedict laughs.

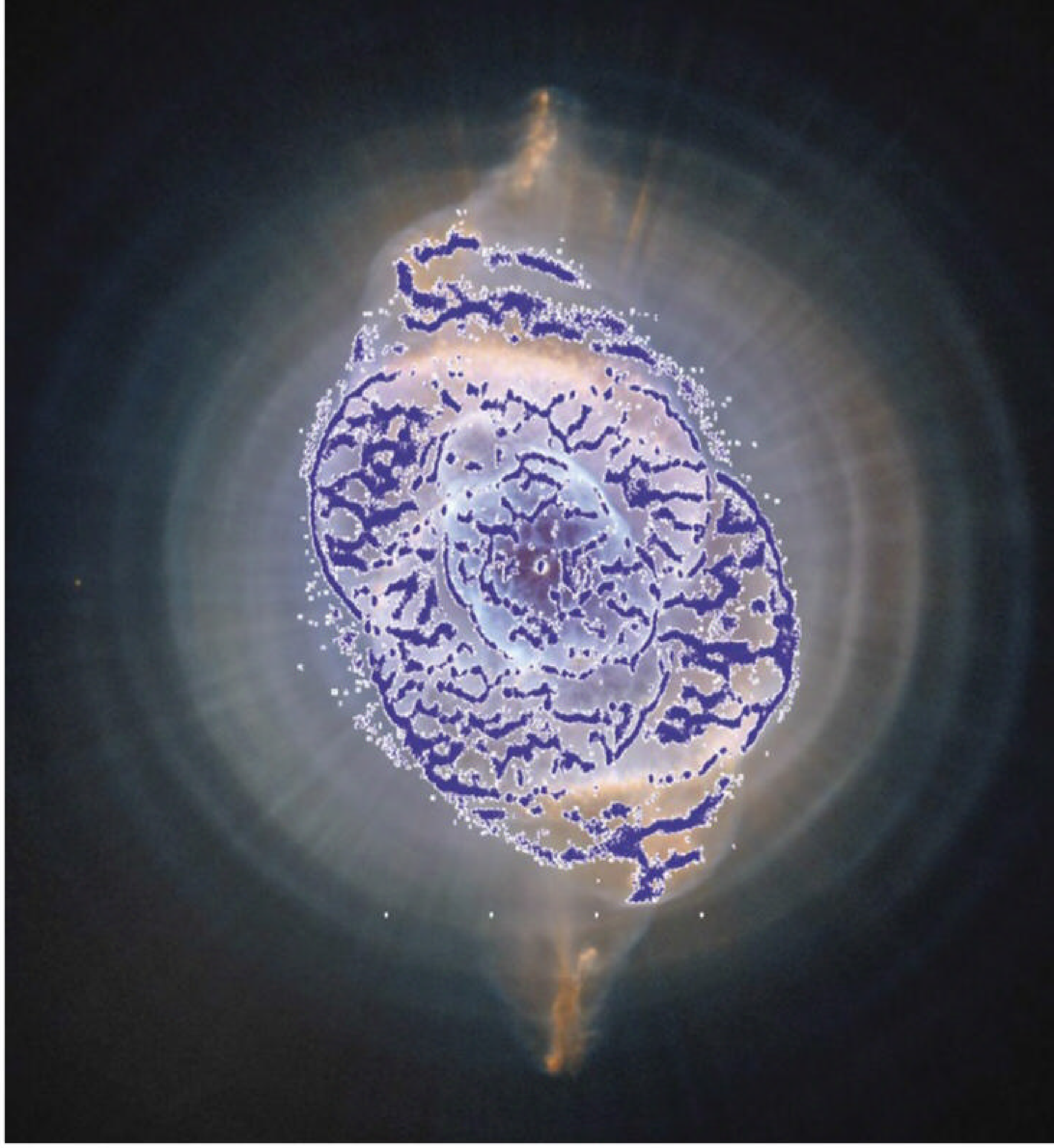
And that's just one trick you can do with that data. It's possible to project the positions of these stars millions of years into the future, or backwards to see how stars presently far apart might once have been more closely associated.

Greedy galaxies

Closer to home, Gaia is helping to reveal how our own galaxy has grown through mergers with smaller ones.

"The Sagittarius dwarf galaxy (65,000 light years away) has moved through the Milky Way on at least three occasions," says Guy. Models show that these have been occurring with increasing frequency as the Sagittarius dwarf galaxy moves toward eventual merger with the Milky Way. The first collision was 5–6 billion years ago. The next was two billion years ago. The most recent was one billion years ago.

That much had been previously known. But Gaia data suggest that the first of these collisions might have been responsible for the birth of the Sun. That's possible, because such collisions can disturb gas and dust clouds, which in turn can trigger bursts of star formation. Gaia can detect the timing of such bursts because, along with measuring the positions,



ESA / GAIA / DPAC / UB / IEEC

SEEING THE UNSEEN

Stars aren't the only things Gaia can detect. It can also help find dark matter, a mysterious substance that appears to make up the bulk of the Universe. "We have no idea what dark matter is," says Gerry Gilmore, of the University of Cambridge, UK. But even if it's invisible, Gaia can help determine where it is by measuring the effect of its gravity on things we can see.

One of these is the Sun.

Astronomers have long known that the Sun (and the Earth) orbit the galactic centre once every 230 million years, moving at a velocity of about 230 kilometres per second. But we're not going in a straight line. Rather, the galaxy's gravity is bending our movement, keeping us from wandering off into the intergalactic void. And now, Gaia has allowed us measure that rate of deflection to astonishing precision.

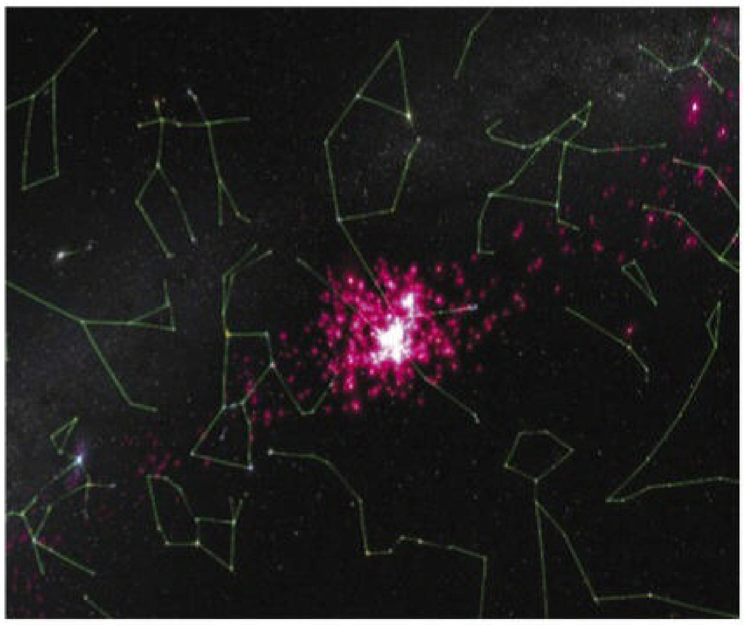
The number? About 7.3 km/second/million years, Gilmore and others reported recently in *Astronomy and Astrophysics*.

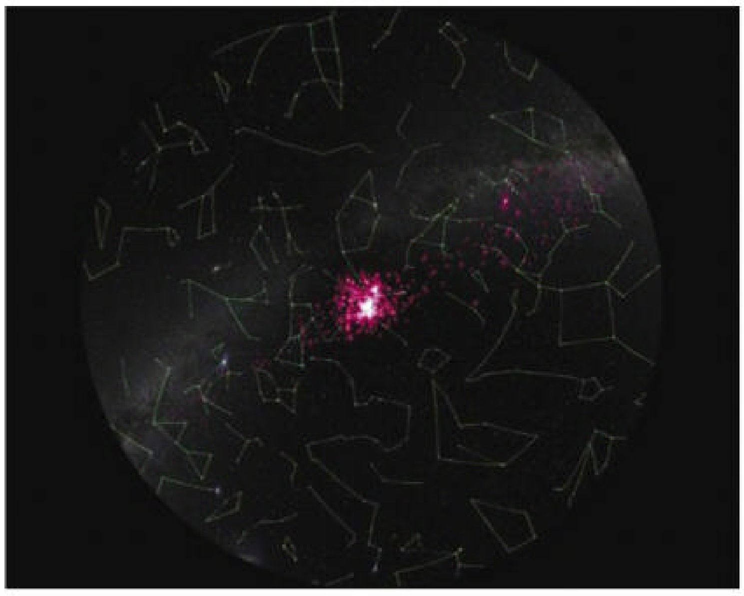
That sounds like a lot, but a million years is a long time. Reduced to human timescales it means the Sun's motion around the galaxy is being bent by gravity by a whopping 7.3 mm/year.

That's about the rate at which tectonic plates move here on Earth. But it's more than can be accounted for based on visible matter alone. "The immediate conclusion," Gilmore says, "is that roughly half the weight interior to the Sun is dark matter."

Other researchers are using Gaia data to try to find out whether dark matter is broadly dispersed or exists in clumps.

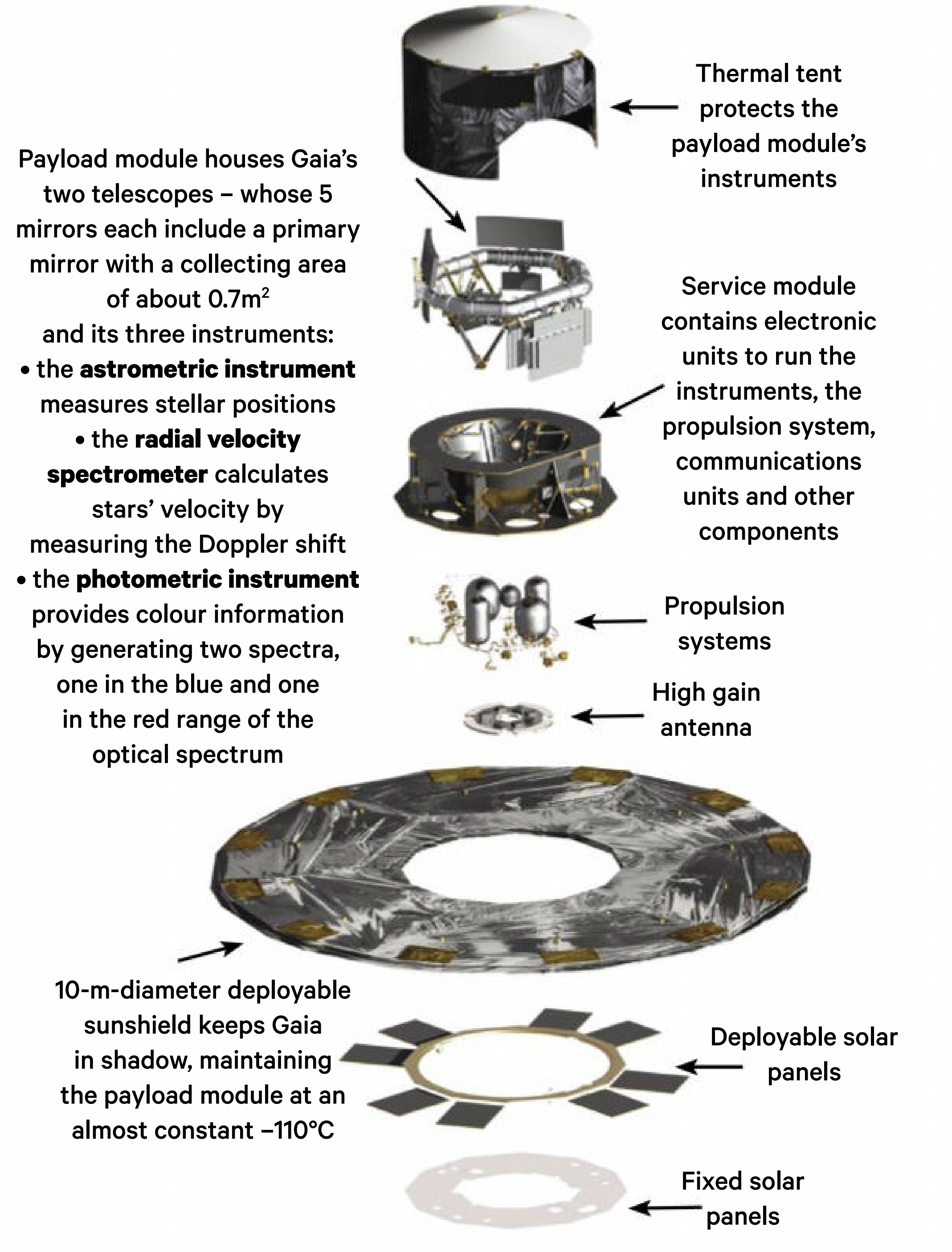
In a 2019 paper in *The Astrophysical Journal*, a team led by Ana Bonaca, of the Harvard-Smithsonian Center for Astrophysics, took a detailed look at a star stream called GD-1, far out in the Milky Way's halo. What they found was odd. "We see stars pulled out of this stream," Bonaca says. Best guess? Half a billion years ago, a ball of dark matter with a mass of about five million Suns ploughed through it, scattering stars like confetti in its gravitational wake.





HIGH AND MIGHTY

Gaia packs an impressive amount into its 3.5-metre-wide frame.



distances and motions of stars, it also measures their brightnesses and colours – measurements astrophysicists can use to calculate their ages.

In a 2020 paper in *Nature Astronomy*, a team led by Tomás Ruiz-Lara, an astronomer in the Instituto de Astrofisica de Canarias, Spain, did just this for millions of stars within 2,000 parsecs (6400 light-years) of the Earth, finding three major bursts of star formation coinciding with the three collisions, peaking 5.7, 1.9, and 1.0 billion years ago.

Did that collision create the Sun and, by extension, us? Who knows? The Sun came on the scene 4.6 billion years ago, close enough to the peak of the first Sagittarius stellar baby boom to be intriguing.

Other collisions are more ancient, such as the one that created a group of stars known as the Gaia Sausage. These are remnants of a fairly large dwarf galaxy that ploughed into the Milky Way about 10 billion years ago and was shredded in the process.

"While there have been many dwarf satellites falling onto the Milky Way over its life, this was the largest of them all," says Sergey Koposov, physicist at Carnegie Mellon University, Pittsburgh, Pennsylvania, and co-author of a 2018 paper about the collision in *Monthly Notices of the Royal Astronomical Society*.

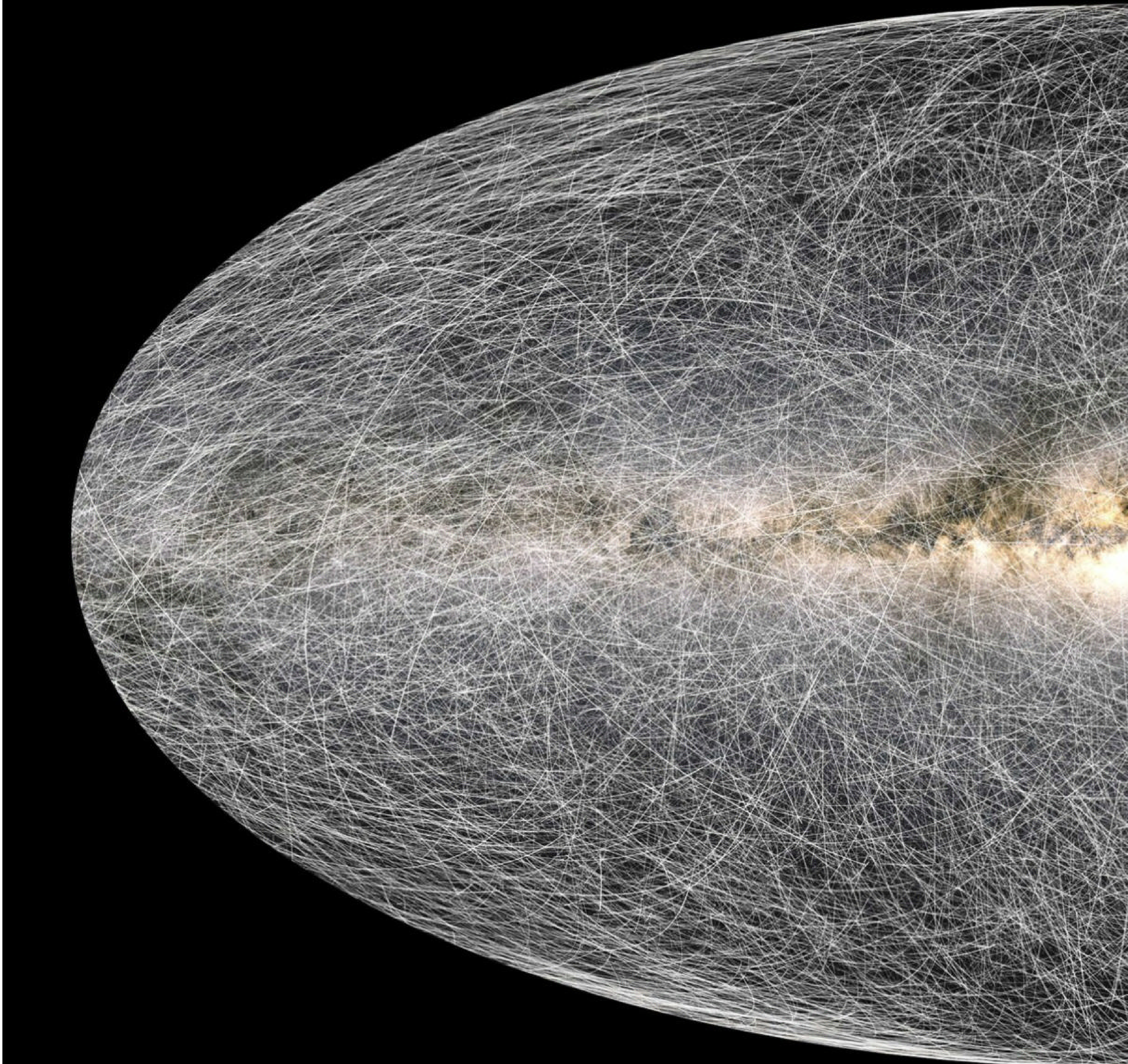
When Gaia data were used to plot the orbits of these stars, something that stood out was how elongated they were, says Koposov's coauthor, Wyn Evans of the University of Cambridge. "We plotted the velocities of the stars, and the sausage shape just jumped out at us. As the smaller galaxy broke up, its stars were thrown onto very radial orbits. These 'sausage stars' are what's left of the last major merger of the Milky Way."

Other researchers are peering farther back into the galaxy's history, looking for relics of older collisions. One of these is Timothy Beers, of the University of Notre Dame, South Bend, Indiana. "My stars can be all over the sky, but I can tell whether they were once part of a dwarf galaxy or globular cluster that got destroyed," he says.

Beers has spent much of his career painstakingly searching such groups out, based on what can be determined from ground-based telescopes. "I've done that for tens of thousands of stars, looking for clustering in orbits," he says.

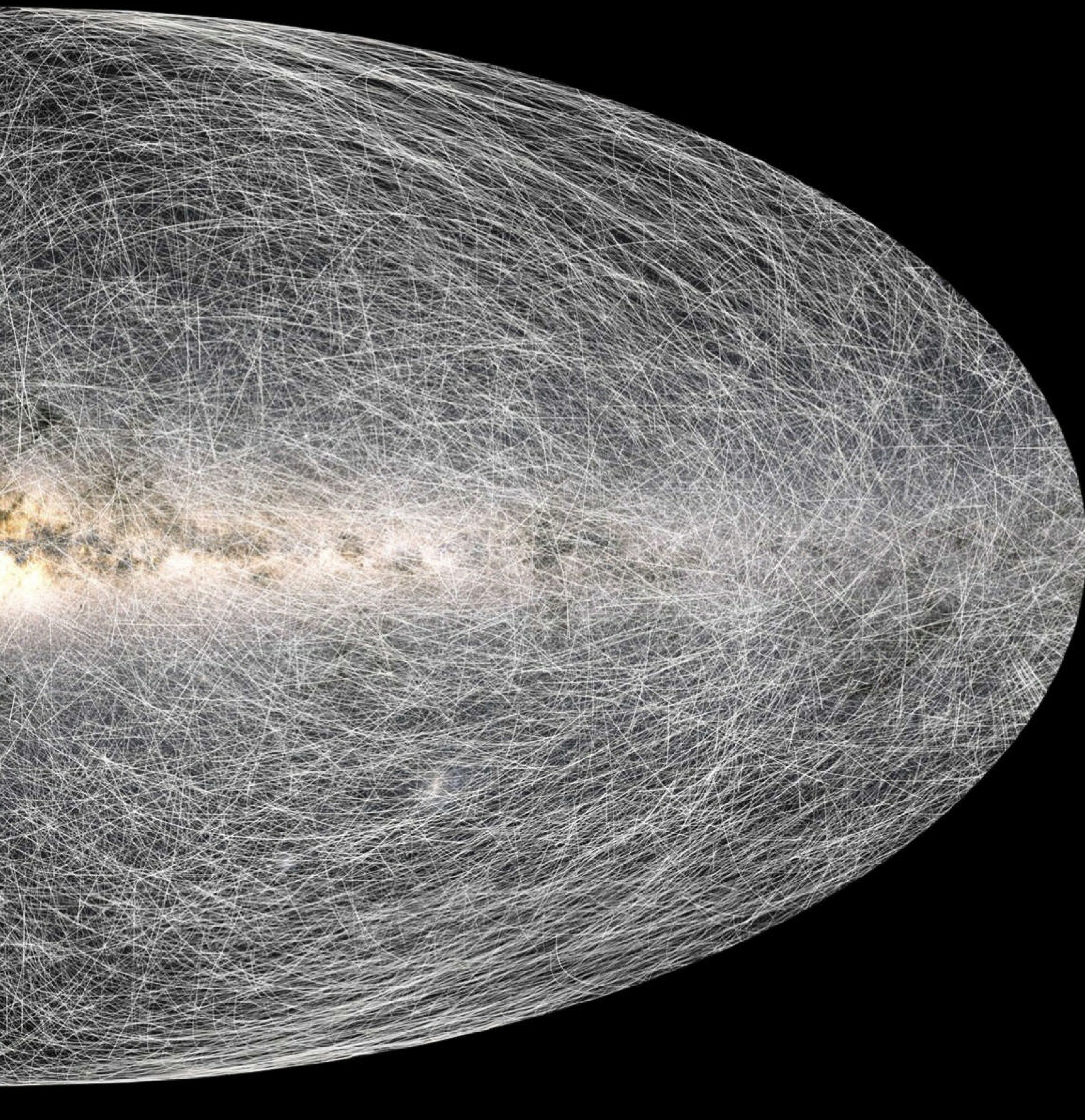
In a test run before official mission start, Gaia scanned the Cat's Eye Nebula (opposite top; image by the Hubble Telescope) over four weeks. Its data trace the central star's gaseous filaments; leading scientists to believe it's actually a binary star. Gaia has since also revealed the Hyades star cluster (above left) is being disrupted by a massive unseen structure. Stars (in pink) extend out from the cluster's heart in two "tidal tails". If this continues, Hyades will slowly merge with the background stars of the Milky Way (green).

ABOVE: ESA / GAIA / DPAC, S JORDAN, T SAGRISTA X2. RIGHT: ESA / ATG MEDIALAB



The stars are in constant motion. To the human eye this movement, known as proper motion, is imperceptible – but Gaia is measuring it with more and more precision. The trails on this image show how 40,000 stars, all located within 100 parsecs (326 light-years) of the Solar System, will move across the sky in the next 400,000 years.

ESA / GAIA / DPAC

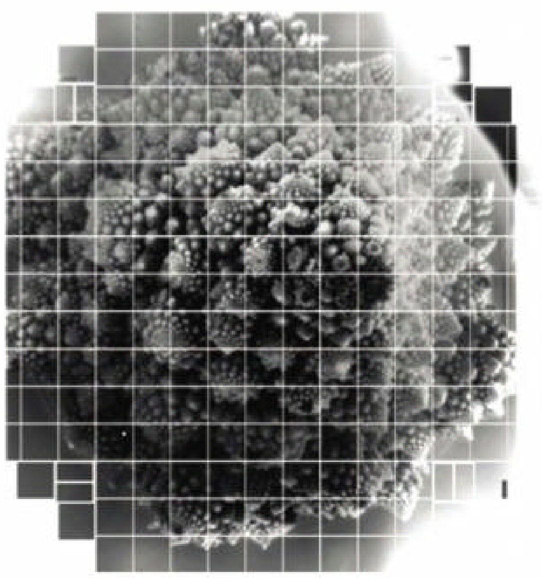


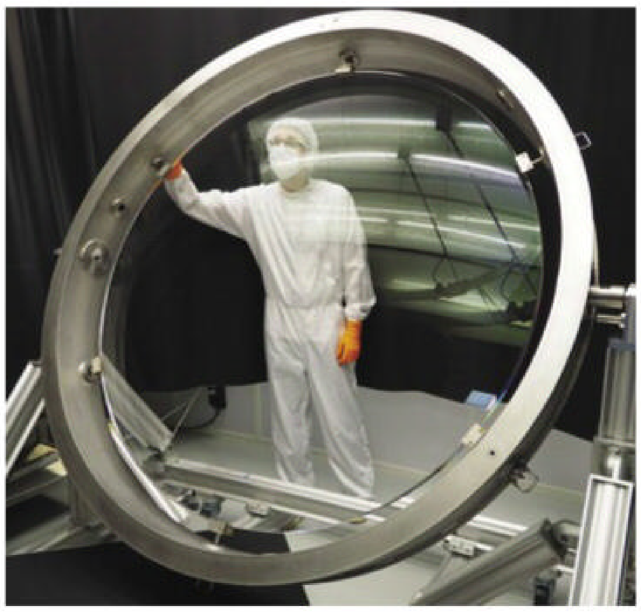
OPEN-ACCESS DATA

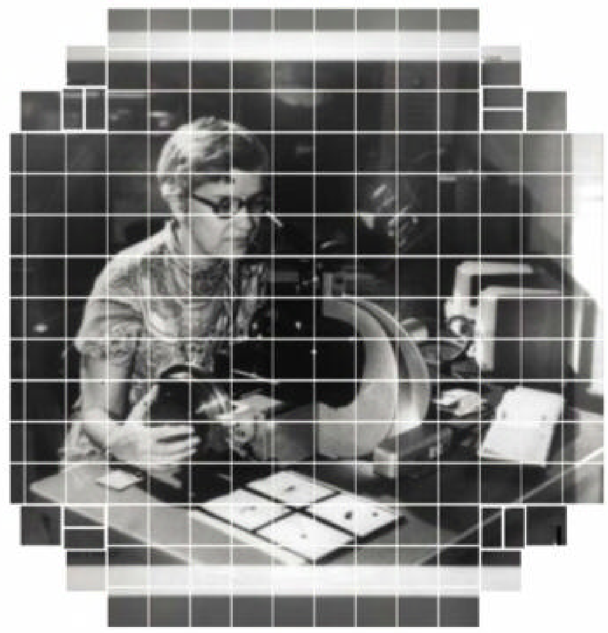
By the time it completes its final catalogue (possibly in 2025), Gaia will have cost the European Space Agency nearly €740 million (about $1.145 billion) to build, launch and operate, plus another €250 million ($387 million) to convert its raw data into usable form.

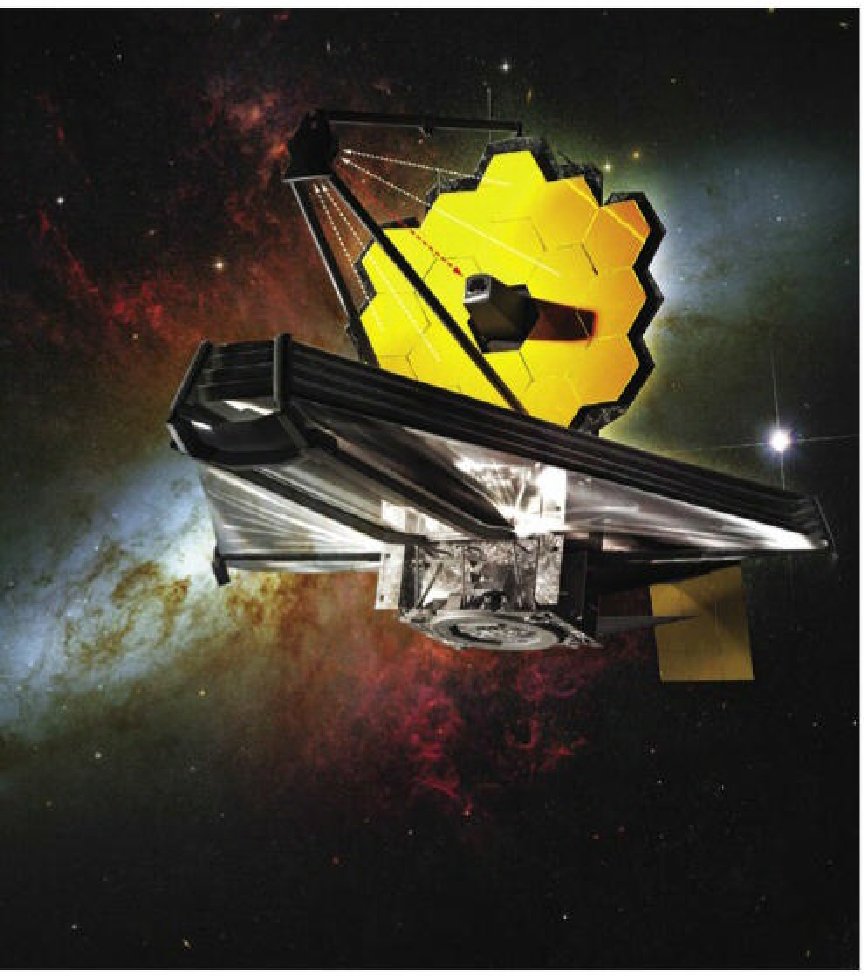
But once that processing is completed for each batch of data, ESA will make it open access – instantly available to every scientist in the world.

"This was not an easy choice," says Jos de Bruijne, an ESA support scientist for Gaia. But it was a lesson learned from Hipparcos. There, the data was held proprietary for one year and doled out to researchers whose proposals were accepted. Doing this, he says, turned out to be a "non-negligible" task, fraught with all kinds of internal politics. "Not having proprietary data rights simplified things a lot," he says.









The US's Vera C Rubin Observatory (top), in Chile, will be fitted with a 3.2 gigapixel camera (lens, above centre); it's due to start snapping shots from late 2022. The tests – of a Romanesco broccoli, above left, and of a 1948 snap of Vera Rubin at work, above right – would need 378 4K ultra-high-definition TV screens to display at full size and resolution. The James Webb telescope (left) is scheduled for launch in October to the same location as Gaia. Its 25m^2 primary mirror will search for the first galaxies formed after the Big Bang.

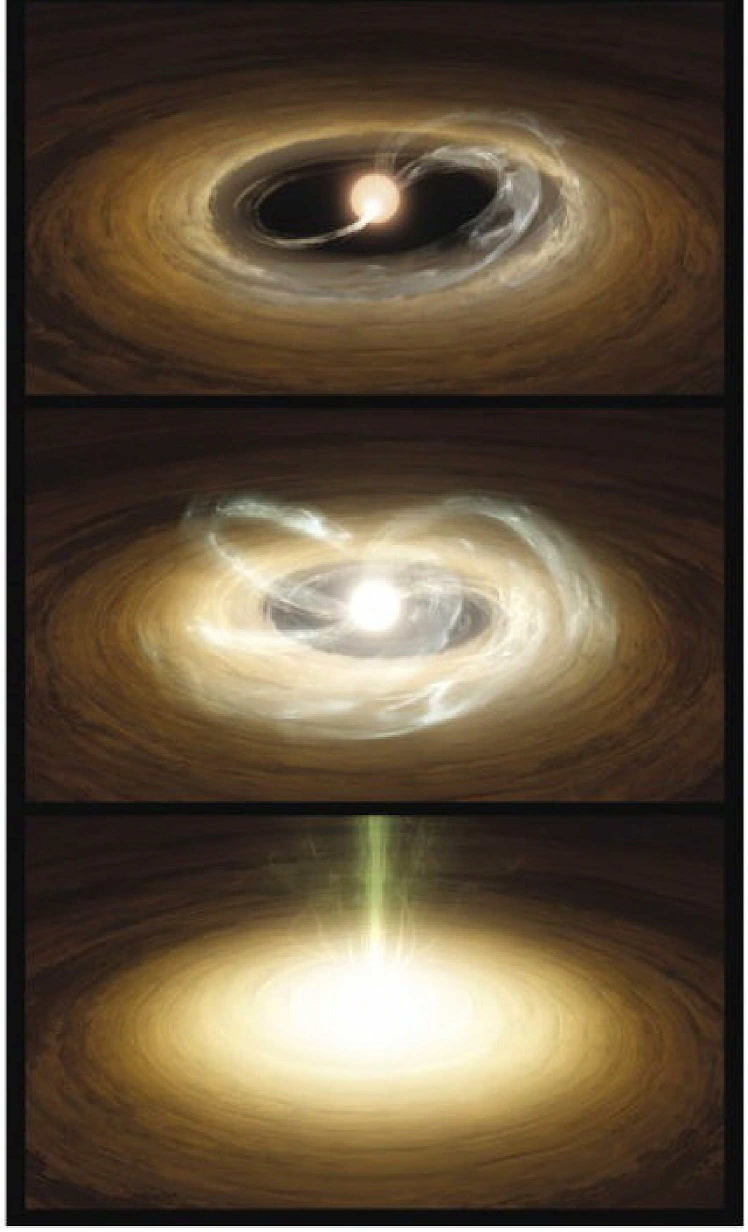
TOP: RUBIN OBSERVATORY / NSF / AURA X4. LEFT: NASA / JPL

Gaia makes the process vastly easier. "It's almost like a magic trick," Beers says. In a 2020 paper in *The Astrophysical Journal*, he and a team of international colleagues found 57 such groups, some associated with previously known structures, like the Gaia Sausage, but 20 never before observed.

Of particular interest, he says, are ones that are low in elements astronomers call "metals", meaning anything heavier than hydrogen and helium.

These stars are the most ancient of the ancient, born early in the history of the universe, before astrophysical processes had enriched the gas clouds from which they condensed with heavier elements. "The lower the content of metals, the more ancient we figure the star is," Beers says.

Traditionally, identifying them was a slow and laborious process, involving large ground-based telescopes and spectroscopy. "I've published papers with a couple thousand stars it took 25 years to find," Beers says. But again, Gaia has come to the rescue, because its colour measurements, Beers has found, can be used to create a colour index that can be



In 2018 Gaia captured an "outburst" from a FU Orionis star – a type of young, near-infant variable star that displays extreme changes in magnitude and spectral type. An illustration of an FU Orionis undergoing a growth spurt (above left) shows material from the star's debris disk (orange) and hot gas (green) flowing into the star. As more material enters, the inner disk heats up and the star bursts, with gas (yellow) flowing outwards. Astronomers think these outbursts are how these young stars acquire their mass.

combined with other data to produce a "reasonably accurate" estimate of the metal content of each and every star in the Gaia catalogue.

Grounding Gaia

In Greek mythology, Gaia was the mother of all life. And while the space telescope that bears her name isn't spawning anything other than vast quantities of data, it is indeed helping astronomers peel back the veil of history into the origins of our entire galaxy.

And, as Beers discovered by correlating Gaia's red/blue colour index to metallicities, astronomers may be just beginning to figure out all the ways in which its data can be used. "It's like a tool that's waiting for the right question to be asked," says Benedict.

Meanwhile, Gaia's days for producing new data are numbered. Sometime in the next few years, it will run out of manoeuvring fuel and be unable to keep itself precisely on station.

But by that time, the Vera C. Rubin Observatory, now under construction on a mountaintop in northern Chile, should be online. As a ground-based telescope, it has certain disadvantages compared to Gaia. To begin with, it can only see in certain directions. "A space telescope can see 360 degrees," says Guy. "We will see roughly half the sky, up to 20 degrees north." Also, even at 2682 metres in altitude, the Vera C. Rubin isn't free of distortion from the Earth's atmosphere, so it can't do astrometry at Gaia's level of precision.

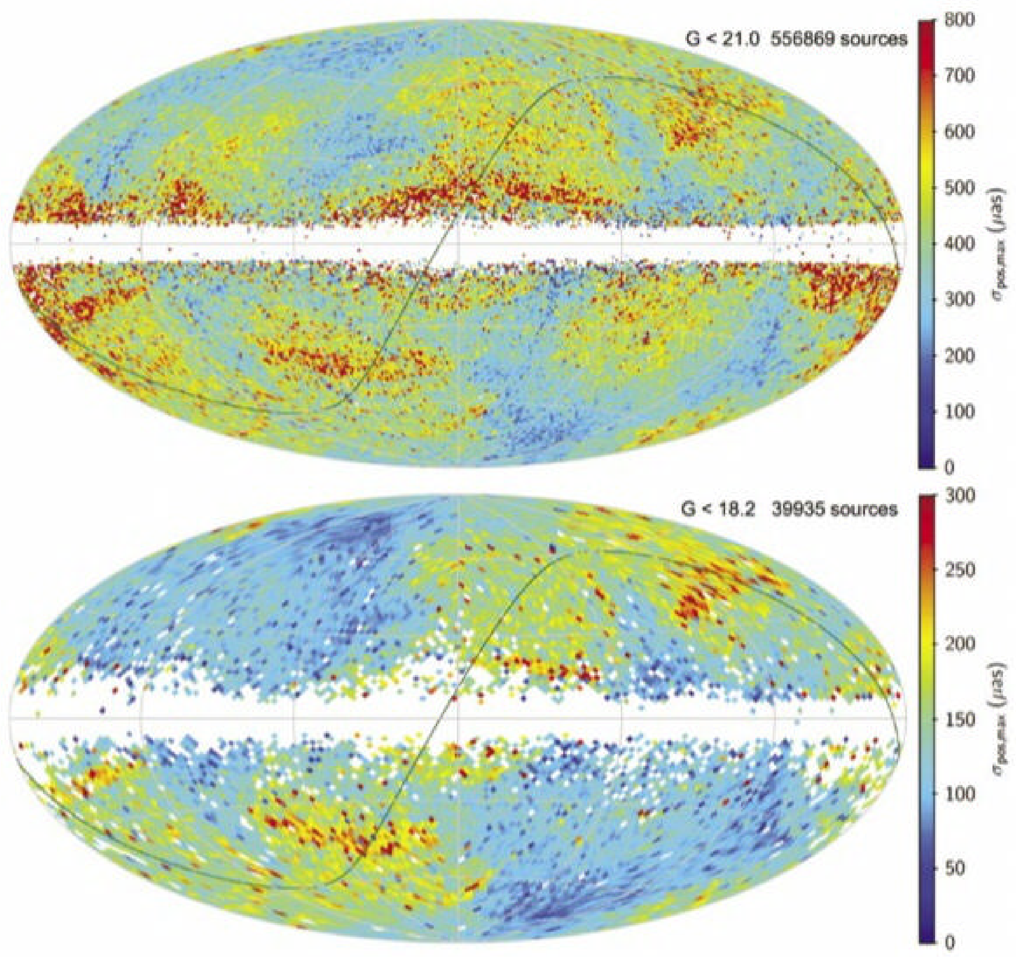
What it can do is use a much bigger mirror – an 8.4m primary that allows it to see stars hundreds of times fainter than those visible to Gaia. That, Guy says, will let it see 17 billion stars, a 10-fold improvement over Gaia, and about one-sixth of all the stars in the Milky Way. (It will also be able to see an estimated 20 billion distant galaxies, though those are much too far away to measure their distances by triangulation.)

And unlike Gaia, which only looked at any given star twice a year, it will be able to scan the visible parts of the southern sky every few days, allowing astronomers to look for much more subtle stellar movements. "Over the course of 10 years, every [star] position will be observed roughly 825 times," Guy says.

That will allow it to detect not only the motions of stars, but to spot asteroids, Kuiper Belt objects, and interstellar interlopers such as the object known as Oumuamua, which zipped through our Solar System in 2018. It might even find the mysterious Planet 9, thought to lie at the far fringes of our Solar System.

All of which means that astrometry continues to be on a roll. "It's better than a golden age," Benedict says. "It's a platinum age." ⊙

QUEST FOR QUASARS



Gaia's second data release precisely mapped 556,869 quasars. Astronomers used this information to create a celestial reference frame: a fixed but imaginary grid against which everything else moves, comparable to Earth's lines of longitude and latitude. Since the planet spins and wobbles, such a frame is important to not only guiding where we point telescopes but also keeping GPS systems working accurately. This image shows the formal position uncertainty of the quasar sources across the whole sky, which averages less than 0.2 milli-arcseconds.

RICHARD A. LOVETT is a science and science fiction writer based in Portland, US. His most recent story, about lithium, appeared in the last issue.

ABOVE: ESA / CALTECH / T PYLE (IPAC). TOP RIGHT: ESA / GAIA / DPAC