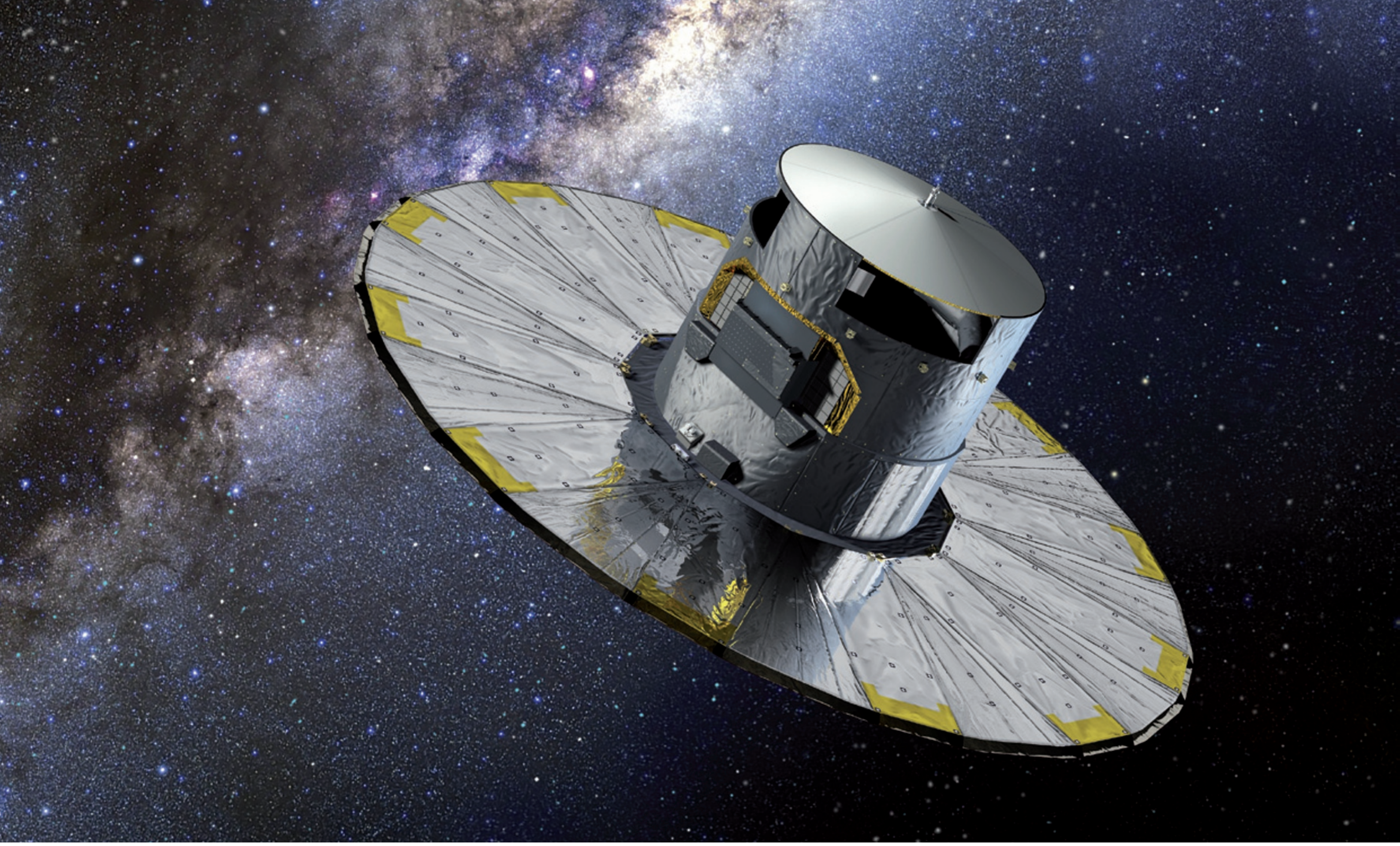


The Gaia mission (artist's impression) will pinpoint the locations of up to 1 billion stars.

EUROPE'S STAR POWER

The Gaia spacecraft will soon launch on a mission to chart the heavens in unprecedented detail.

BY DEVIN POWELL

The century-old brass telescope was broken in places and long past its useful life — but it captured Lennart Lindegren's heart.

Forty years ago, when Lindegren was a graduate student at the Lund Observatory in Sweden, he fell in love with the elaborate, once cutting-edge technology that had allowed nineteenth-century astronomers to track and time the motion of the stars. The telescope had an ingenious mechanical stopwatch — originally invented to time race horses — and a large metal wheel that could adjust its angle. "I got so fascinated by the beauty of the instrument that I wanted to get it working again," says Lindegren, who is now on the Lund Observatory's staff.

He might as well have fallen in love with a sundial. Astrometry — mapping the locations and movements of celestial objects — was once a central concern in astronomy, with roots going back to ancient Babylon and China. But by the 1970s it had long fallen out of fashion. Astronomers had just about reached the limit for improving the precision of such measurements taken from the ground, and most had moved on to other questions. Astrometry, says Lindegren, "was not regarded as a field that would offer any great prospects for young scientists".

He eventually gave up on repairing the telescope, but never abandoned the idea of reviving astrometry. Better star maps, he argued, could help astronomers to answer some fundamental questions, from how the Milky Way evolved to what makes up the dark matter that accounts for most of the Universe's mass. All researchers would need to do would be to get their astrometric instruments into space, above Earth's turbulent atmosphere, which subtly distorts starlight and limits the precision of measurements.

In November, a proposal by Lindegren and like-minded scientists will bear fruit when the European Space Agency (ESA) launches Gaia: an astrometric mission that required many compromises and 13 years to complete, and will cost about €1 billion (US$1.4 billion). Gaia will make observations for the next 5 years; the results will extend the reach of high-precision maps from the roughly 2.5 million stars near Earth to at least 1 billion stretching to the edge of the Milky Way or beyond. For an estimated 10 million of those objects, Gaia's map will be fully

D. DUCROS/ESA

SOURCE: CSIRO

three-dimensional: the spacecraft will measure not just the stars' locations on the sky, but also their distances from Earth, accurate to less than 1%. For now, the distances to only a few hundred stars are known at this level of precision.

Michael Perryman, an astronomer at the University of Bristol, UK, and former project scientist for the mission, is optimistic. "Gaia will be tremendous and transformational, a huge leap forward both in terms of the number of stars measured and the accuracy of those measurements," he says.

STELLAR CARTOGRAPHY

The keen eyesight that will make this leap possible starts with Gaia's digital camera, which uses light-gathering sensors similar to those found in consumer cameras — but 106 of them, providing a resolution of more than 900 megapixels. By contrast, the main camera on NASA's Hubble Space Telescope has two sensors with a resolution of just over 16 megapixels.

Guiding starlight into the camera are two telescopes that point 106.5° apart, to take in a wide field of view. As the spacecraft spins, completing a full revolution once every 6 hours, that view will sweep across the same stars, month after month. Each star will be photographed about 70 times, producing roughly twice as much imaging data in 5 years as Hubble generated during its first 21 years in orbit.

When all the data have been analysed, they will provide a pair of coordinates for each star, pinpointing its position in the sky with an error as small as 6 microarcseconds — the size of a small coin sitting on the Moon as viewed from Earth. That is hundreds of times better than today's best catalogue, and millions of times better than the first known Western star atlas, compiled more than 2,000 years ago through naked-eye observations by the ancient Greek astronomer Hipparchus of Nicaea.

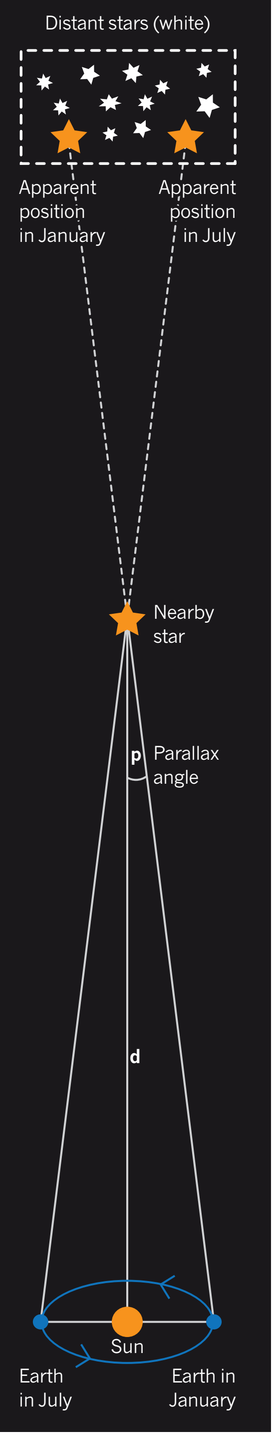
Finding a star's position in three dimensions will require further measurements. Because of a geometric phenomenon known as parallax (see 'The parallax effect'), stars appear to move from side to side as Earth orbits the Sun. The closer a star is to Earth, the larger its apparent movement, for much the same reason that trees on the side of a road seem to whiz past a speeding car, whereas a mountain in the distance barely seems to move at all. If astronomers can measure that side-to-side motion precisely, simple geometry will allow them to use the known size of Earth's orbit to calculate the star's distance.

Atmospheric turbulence so compromises such efforts that even the best modern ground-based visible-light telescopes can see parallaxes up to only about 100 parsecs (a few hundred light years). Radio telescopes are less affected, so they can see much farther — but only for objects that emit strong radio waves. From its place outside the atmosphere, Gaia, which is destined for a stable orbit that will remain fixed relative to both the Sun and Earth, should be able to obtain parallax measurements for stars up to about 10,000 parsecs away.

The same precision should let it measure a star's 'proper motion' across the sky at even greater distances. Proper motion — the result of a star's actual movement through space perpendicular to the line of sight — will show up as a steady sideways drift in the star's position, superposed on its annual side-to-side motion.

THE PARALLAX EFFECT

As Earth travels around the Sun, nearby stars seem to move back and forth relative to distant ones. Using simple geometry, the known size of Earth's orbit and a measurement of the parallax angle (p), astronomers can determine the star's distance (d). For an angle of 1 arcsecond, the distance is 1 parsec (3.26 light years.) Smaller angles mean larger distances.



Finally, Gaia should be able to use changes in the spectrum of light emitted by each star to measure the star's velocity towards or away from Earth. The result will be a complete portrait of the star's position and velocity in three-dimensional space.

ASTROMETRY REBORN

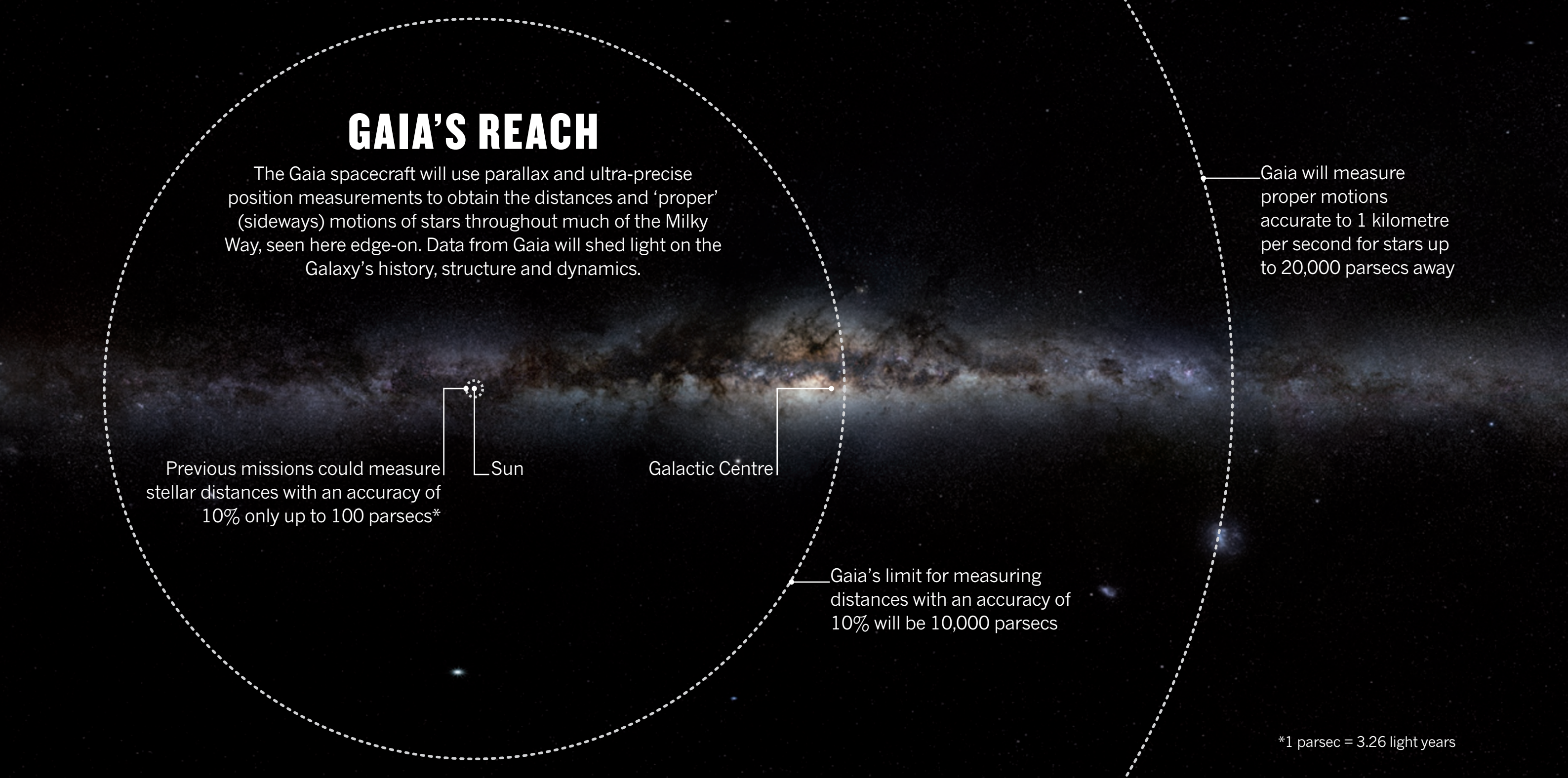
Gaia is not the first high-precision space-astrometry instrument. The feasibility of the exercise was demonstrated two decades ago by Gaia's predecessor, ESA's High Precision Parallax Collecting Satellite (Hipparcos). Launched in 1989, the €580-million spacecraft ran into trouble almost immediately, when a failed booster rocket left it in the wrong orbit. But even so, it worked: by the time the mission ended in 1993, Hipparcos had provided the distances to about 118,000 stars. Of those, some 400 were measured with an error of 1%. Only 50 had been measured so well from the ground. The Hipparcos star catalogue is still the best one available.

However, the mission focused on relatively nearby stars, says Shrinivas Kulkarni, an astrometer at the California Institute of Technology in Pasadena, so the Hipparcos catalogue was more an evolution in the science than a revolution. "It showed us that our basic understanding of stars was sound," he says. As a proof of principle, says Erik Høg, an emeritus astronomer at the Niels Bohr Institute in Copenhagen who drew up the first blueprints for the mission, "Hipparcos's success was really invigorating for astrometry. People could gather around this project."

What they could not do, until now, was get a worthy successor off the ground. One after another, advanced astrometry missions were proposed and then failed because they overran their budgets. One of the most spectacular examples was NASA's Space Interferometry Mission (SIM). It had a deliberately narrow focus: it would have concentrated on pinning down the positions and movements of a mere 10,000 stars located fairly nearby. The trade-off was that SIM could have detected wobbles in those stars caused by the gravitational pull of orbiting planets as small as Earth. But the project was postponed several times, and its original $600-million budget ballooned. After NASA had already spent hundreds of millions of dollars on development, projections suggested that the mission would need a further $1.2 billion and SIM was cancelled in 2010. "The money just wasn't there," says Michael Shao, an astronomer at NASA's Jet Propulsion Laboratory in Pasadena and formerly project scientist for SIM.

Some researchers argue that Gaia will succeed where SIM and others failed because of Europe's style of building spacecraft. "In the European system," says Ken Seidelmann, an astronomer at the University of Virginia in Charlottesville, "the scientists write down the specifications they want, and the contractors come up with cheaper ways of doing things" — ways that sometimes involve cutting back the mission's capabilities. "In the United States, the scientists tend to stay more involved," he adds — and if they refuse to compromise on the objectives, costs can skyrocket.

In Gaia's case, keeping close to the budget set when ESA approved the mission in 2000 required a series of downgrades that substantially reduced the capabilities of the original design, mainly by halving the expected



PICTURE: S. BRUNIER/ESO; GRAPHIC SOURCE: ESA

accuracy of its parallax measurements. The cuts meant that some of the problems that Gaia had intended to tackle were now out of reach. For example, the mission would no longer be able to track potentially hazardous near-Earth objects such as asteroids well enough to predict their motion for the next century — a goal that had been named a top priority by a task force led by the UK minister of science. The downgrades led Perryman to quit the project in 2006, after six years as leader of the scientific team. "I was enormously frustrated by the decision to de-scope this project, which was not made on scientific grounds," he says.

But Gaia survived and is now scheduled for launch as early as 20 November. With a bit of distance and a graveyard of space astrometry missions to reflect on, Perryman now expects big things from the mission.

GAIA GOES GALACTIC

To start with, the cosmic census begun by Hipparcos will continue and expand. Millions of new binary stars are expected to show up, as are tens of thousands of brown dwarfs: 'failed' stars too small to ignite by fusing hydrogen. Gaia should also discover 1,000 Jupiter-sized planets — or, rather, the wobbles these objects cause in nearby stars. Closer to home, the spacecraft will get at least some data on the hundreds of thousands of Solar System asteroids expected to cross its field of view.

Where Gaia will really shine, however, will be in extending astrometry across the Milky Way (see 'Gaia's reach'). "Our unique science goal is to unravel the structure and dynamics and history of our Galaxy," says Jos de Bruijne, a systems scientist at ESA's European Space Research and Technology Centre in Noordwijk, the Netherlands, and Gaia's deputy project scientist.

Astronomers already know the basics, he says. The Milky Way is shaped something like a fried egg, with a bulge of stars in the middle surrounded by a flat stellar disk that tapers at the edges and contains the Galaxy's spiral arms. Around the disk is a diffuse sphere of old stars called the halo. But astronomers are not certain how these structures formed, or in what order (see *Nature* **490,** 24–27; 2012). Gaia will provide one important set of clues by measuring stellar composition and brightness — data that will reveal for the first time when many stars formed, and will help astronomers to work out the ages of the Galaxy's different parts.

Another set of clues will come with Gaia's measurements of stellar movements, which astronomers can extrapolate back in time to find out how the Galaxy has evolved. Typically this is difficult because tiny errors quickly accumulate into large uncertainties. "Exactly how far back we can get is very much an open question," says Lindegren. But the high precision of Gaia's measurements will certainly take the extrapolation much further than before.

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For more about the structure and history of the Milky Way, see:
go.nature.com/di7phk

The measurements will also help to illuminate the many episodes of violence in the Milky Way's history. The Galaxy has grown by cannibalizing other, smaller galaxies; when they got too close, the Milky Way's gravity ripped them apart into long streams of stars that were then pulled towards the galactic centre at various angles. One such stream, torn from a dying object known as the Sagittarius dwarf galaxy billions of years ago, was found in 2002. "There are other streams out there that encode information about how the Galaxy has been developing," says Andrew Gould, an astronomer at the Ohio State University in Columbus. "Gaia will discover those streams" — and use its measurements of stellar motions to reveal how the dismemberments unfolded.

Knowing precise stellar movements should also help researchers to map out the distribution of invisible dark matter, which permeates the whole Galaxy. Dark matter emits no light, but it exerts a gravitational pull on stars, causing perturbations that should reveal themselves in Gaia's data. Those will allow astronomers to test how clumpy the dark matter is and whether it forms into disks, as theorists have proposed.

Whatever Gaia finds, one thing seems certain: its star catalogue, due to be published in 2021, will remain unsurpassed for decades. ESA is considering a planet-hunting spacecraft similar to SIM for a future mission but has yet to choose a successor to carry on Gaia's astrometric work. "We have to start thinking about it now if we want to realize something in 15 years," says Lindegren. "But we don't really know what exactly is the best way to proceed." Boosting the precision significantly would be an enormous technological challenge. An easier path would be to fly another Gaia mission with the same specifications in 20 years, after the stars have moved noticeably, to better pin down their positions and velocities.

Another proposed follow-on mission would examine parts of the Milky Way to which Gaia will be blind. Dust will obscure the Galaxy's bulge and some far-away parts of its disk from Gaia's visible-light gaze — but would pose no problem to an instrument looking for infrared radiation.

Or perhaps Gaia itself will upend the whole discussion. As astrometry sharpens its focus, there is always the exciting possibility that something wholly unexpected could be found. "Science often progresses by making detailed measurements," says Kulkarni. "Sometimes you see a deviation — something that turns out to be profound." ■

Devin Powell *is a freelance writer currently based in Singapore.*