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THE GAIA REV

The precise observations of Europe's prolific surveyor have enabled astronomers to map the universe and unravel the history of our Milky Way Galaxy.

Ask someone to name a revolutionary space telescope right now, and they will probably answer "James Webb." Ever since its launch on Christmas Day 2021, this versatile successor to the Hubble Space Telescope has been stealing the astronomical limelight. But operating from the same part of the solar system, some 1.5 million kilometers behind Earth's nightside, is a lesser-known instrument that is one of the most successful space science missions ever built: the European Space Agency's Gaia spacecraft.

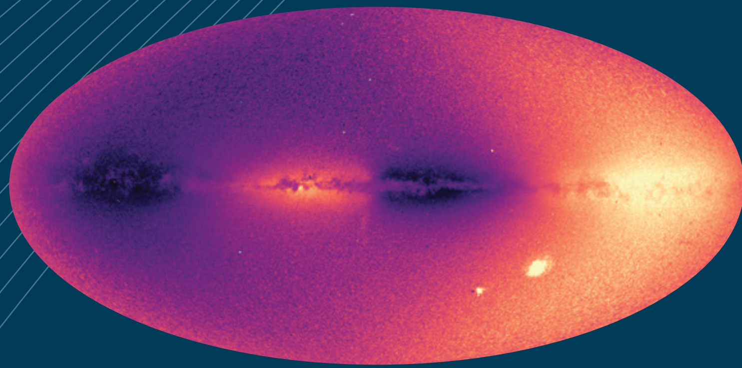
Gaia and Webb are very different. Whereas Webb is the instrument of choice to study selected astronomical objects in detail, Gaia is an all-sky surveyor. Its main mission: to collect precise data on positions, distances, motions, and compositions for almost 2 billion stars and extragalactic objects. It is the ultimate astronomical measuring machine.

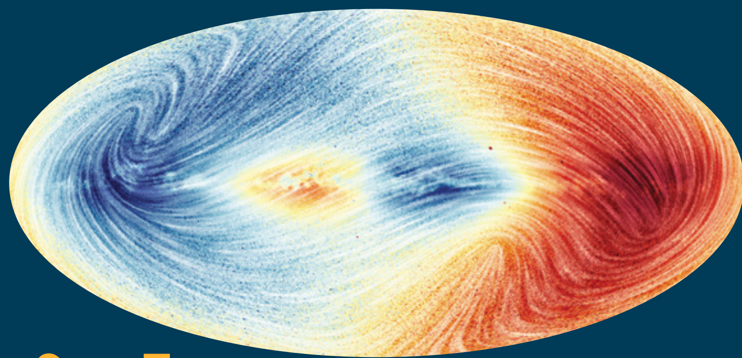
On June 13, 2022, ESA released the third batch of Gaia results (Data Release 3, or DR3), based on the first 34 months of observations. DR3 contains 10 terabytes of information, covering a whopping 1,811,709,771 distinct sources: Milky Way stars (including huge numbers of binaries and variable stars), galaxies and quasars, and small bodies in our solar system. It's the latest in a series of mission catalogs that are providing a tsunami of new results — as evidenced by the steady stream of a few scientific papers per day (on average) that are based on Gaia data.

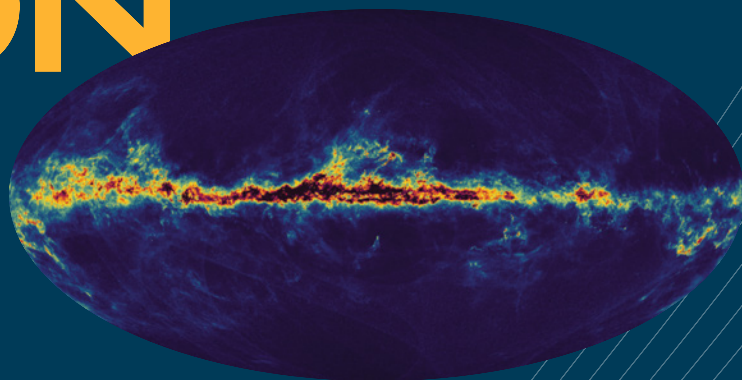
"There is probably no area where Gaia has not had an impact," says Richard Smart (Italian National Institute of Astrophysics). "It's totally awesome."

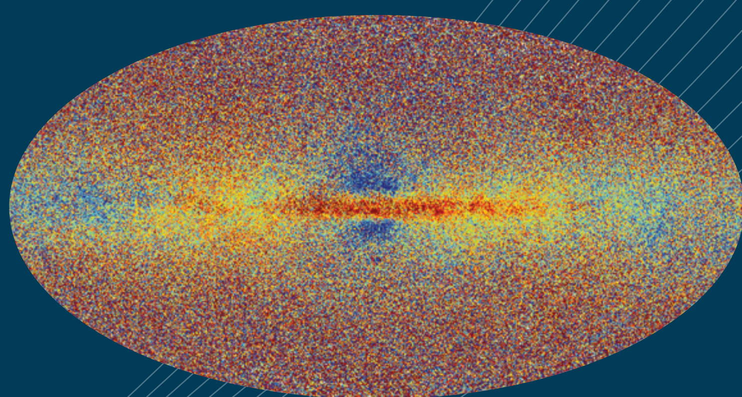
▲ **GAIA'S SKY** This all-sky map uses data from more than 1.8 billion stars observed by Gaia. Brighter regions represent denser concentrations of bright stars, and the colors are a combination of the total amount of light with the amount of blue and red light the spacecraft recorded in each patch of sky.

OLUTION









▶ **RADIAL VELOCITY** *First:* Our galaxy's rotation reveals itself in this map, which shows the speeds at which more than 30 million objects (mostly stars) are moving toward or away from us. Bright areas are moving away from us, dark areas toward. (Remember that we're in a rotating disk, and this map curves 360° around us.)

▶ **RADIAL VELOCITY PLUS PROPER MOTION** *Second:* Based on the movements of about 26 million stars, this map shows the parts of the sky where stars' average motion is toward us (blue) or away from us (red). The lines trace the stars' motions projected on the sky, which vary by galactic latitude and longitude.

▶ **INTERSTELLAR DUST** *Third:* Gaia's measurements also reveal the intervening dust that absorbs starlight. Dust concentrates along the galactic plane, with very little in the halo (dark blue regions).

▶ **CHEMISTRY** *Fourth:* Stars richer in elements heavier than helium (redder colors) lie in the galaxy's disk. These stars are relatively close, because interstellar dust blocks our view of farther stars. We have a clearer sightline to the old, metal-poor stars in the bulge and halo concentrated around the galactic center (blue). The high galactic latitudes show a rainbow because we see a mixture of nearby young, metal-rich stars and far-off old, metal-poor stars in the halo.

Mapping the Stars

Astrometry — finding out where the stars are and how they move — is the oldest and conceptually simplest part of astronomy. It all started with the first known star catalog by Greek astronomer Hipparchus of Nicaea (2nd century B.C.), which we think contained sky positions for just 850 stars. Later generations improved on this work. For instance, the three-volume monumental German *Bonner Durchmusterung*, published between 1859 and 1862 and based on many years of visual observations, listed 324,188 stars in the Northern Hemisphere sky down to magnitude 10, with a positional accuracy of a few arcseconds (one arcsecond is 1⁄3600 of a degree).

The field of astrometry changed dramatically with the 1989 launch of ESA's first star mapper, Hipparcos (High Precision Parallax Collecting Satellite). In 1997, the mission team produced a catalog of positions for more than 1 million stars, based on the full 3.5 years of observations. In a separate catalog, the brightest 118,218 stars had their sky positions measured to within the nearest 0.7 milliarcsecond, and astronomers precisely determined their distances on the basis of the stars' *annual parallax* (*S&T:* Oct. 2022, p. 12).

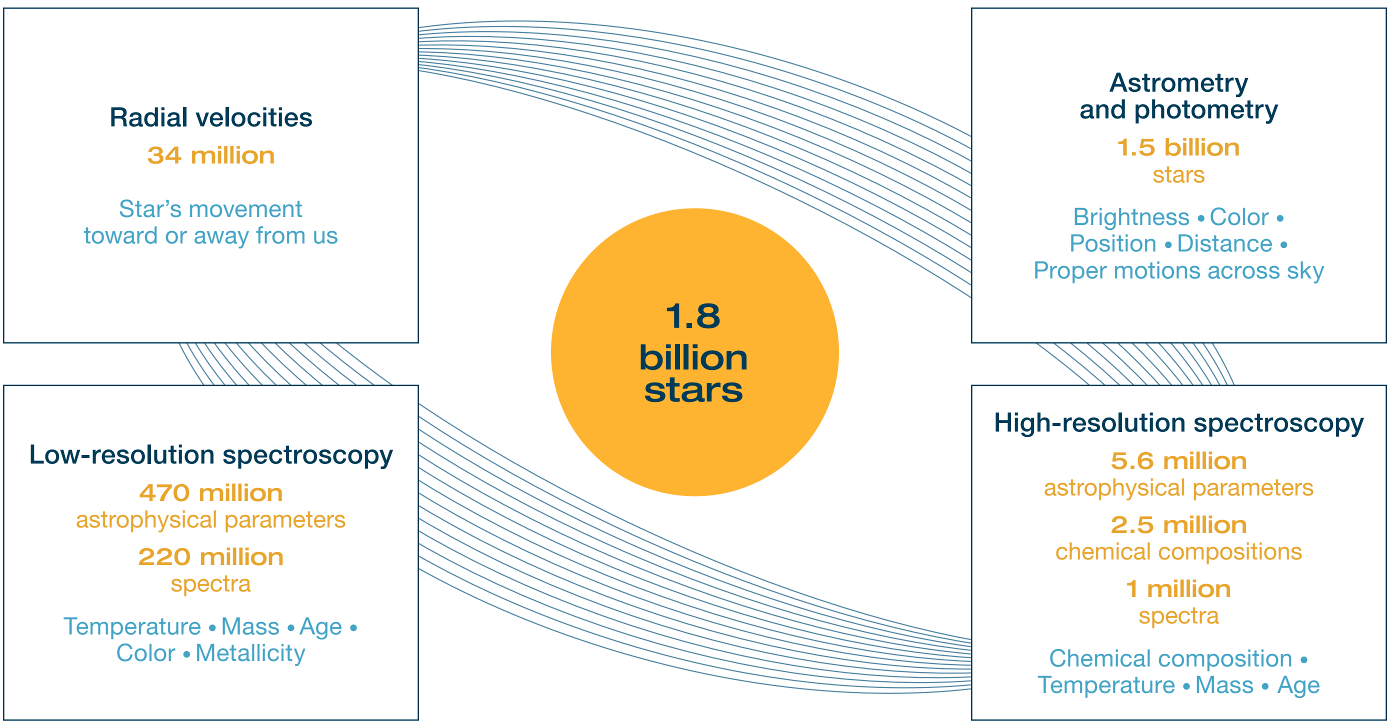
Gaia is Hipparcos's successor. Launched in 2013 from Europe's Spaceport in French Guiana, Gaia arrived in its halo orbit around the Lagrangian point L_2 soon after. It started observations in July 2014.

◀ **LOOKS CAN BE DECEIVING** Gaia's data show that several sparse groups of stars are not actually traveling together through space, including NGC 7772, shown here. Astronomers already thought at least one of the putative clusters was masquerading, but Gaia data cinched it.

Gaia doesn't produce spectacular images of the night sky. Instead, its two rectangular concave mirrors, each measuring 1.45 by 0.5 meters, continually scan the celestial sphere as the spacecraft slowly rotates once every six hours (*S&T:* Mar. 2019, p. 20). By design, the two mirrors always look at parts of the sky that are 106.5° apart. They each focus light on a single CCD detector array (the largest ever flown in space, with almost 940 million pixels), which is mounted on the same ultra-stiff, silicon-carbide frame.

As stars from both patches of sky simultaneously drift across the detector, precise measurements of their crossing times yield the angular separation between pairs of stars. Zillions of such angular measurements constitute an elaborate all-sky trigonometric network, from which astronomers will eventually be able to derive sky positions with an accuracy of less than 10 *micro*arcseconds for those stars brighter than magnitude 14 — much more precise than Hipparcos could manage.

▼ **IN A NUTSHELL** Gaia's third data release includes information on some 1.8 billion Milky Way stars. For subsets of those stars, astronomers have different kinds of information (boxes).



NGC 7772: POSS-II / STSCI / CALTECH / PALOMAR OBSERVATORY; MEASUREMENTS GRAPHIC: TERRI DUBÉ / *S&T*, SOURCE: ESA

Since Gaia returns to each part of the sky many dozens of times over its extended 12-year mission, the ever-growing data archive not only contains full 3D information on the *locations* but also on the *motions* of some 1.5 billion stars. Parallax-based distance measurements reach out to many thousands of light-years, although the accuracy is lower for larger distances.

In addition to parallax and proper motion, Gaia registers brightness variations, using its sensitive dual (blue/red) photometric instruments, which even produce a crude spectrum. Meanwhile, the high-resolution Radial Velocity Spectrometer (RVS), used to measure an object's velocity along the line of sight, also provides detailed information on the chemical composition of many stars and galaxies. Data Release 3 includes low-resolution spectra for 220 million objects, 34 million radial-velocity measurements, and high-resolution spectra for 1 million targets.

All in all, Gaia is nothing less than an astronomer's dream. "Gaia is now providing the reference catalog of celestial sources," says Johannes Sahlmann (ESA). "The first question of an astronomer studying a particular star is now, 'What can Gaia tell me about it?'"

An Embarrassment of Stellar Riches

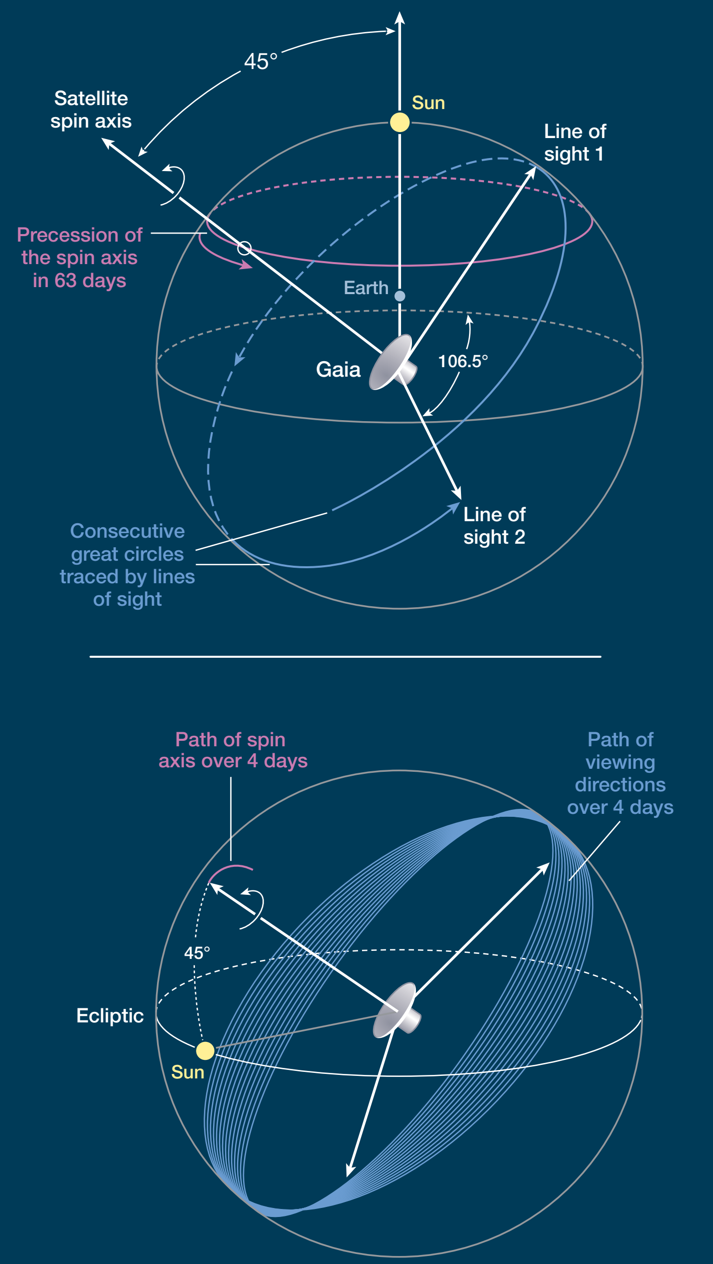
One important topic that Gaia can shed new light on is stellar characterization and evolution. Its spectroscopic observations not only reveal stars' compositions, but also their surface temperatures. If the distance to the star is known (from its parallax), the observed apparent brightness tells you the true luminosity, and it is relatively straightforward to derive the star's mass and age.

Plotting hundreds of millions of Gaia stars in a temperature-luminosity diagram (also known as a Hertzsprung-Russell diagram) reveals many evolutionary subtleties, as stars of a certain mass move erratically through the diagram as they age. As an example, Anthony Brown (Leiden University, The Netherlands) points to the roughly 500,000 white dwarfs that the telescope has observed. The HR diagram reveals a weak concentration of white dwarfs at a certain luminosity, as if their evolution is slowing down for a while. According to Brown, this is most likely due to the crystallization of their slowly cooling cores, which temporarily slows their cooling rate — a key process that is almost impossible to study otherwise.

Gaia's spectroscopic observations constitute a "wealth of information on Milky Way stars," according to Alejandra Recio-Blanco (Côte d'Azur Observatory, France). The spacecraft's RVS instrument is collecting about 100 high-resolution spectra per second. "For 5.5 million stars, we now have detailed information on their chemical composition," Recio-Blanco said during the presentation of DR3 in June.

Since every star-forming region has a slightly different chemical makeup, Gaia can discern stars that share a common origin. For instance, studying both the chemical compositions and the spatial motions of stars makes it possible to identify members of open star clusters, even if they have started to disperse. Such work with Gaia's previous data release revealed distant members pulled from the well-known, nearby Hyades star cluster in the constellation Taurus, the Bull. Its two S-shaped *tidal tails* together stretch almost 800 light-years and across most of the sky.

So far, Gaia has observed more than 2,000 other open star clusters, many hundreds of which astronomers didn't know about before. These collections include a number of small, dispersed groups in the solar neighborhood, and one relatively old cluster that had never been recognized before because its



GAIA'S DANCE The spacecraft turns around its axis 1° per minute, scanning the sky simultaneously along two lines of sight that trace great circles on the celestial sphere. The rotation axis also precesses as the craft orbits the Sun, enabling Gaia to observe long, overlapping strips of sky.

S&T ILLUSTRATION, SOURCE: ESA

sky location is very close to the bright star Sirius. Then again, Gaia also confirmed that four sparse "clusters" (NGC 1252, 6994, 7772, and 7826) are actually chance projections of unrelated stars on the sky.

By returning to the same part of the sky every month, Gaia also registers brightness variations and transient phenomena. The space observatory has harvested data on countless Cepheids, RR Lyrae stars, and other types of variables. It discovered a number of unusual supernovae as well, including Gaia17biu, one of the nearest *superluminous supernovae* known to date. In 2021, no less than 17 galactic novae were discovered, and Gaia astronomers are compiling the largest ever catalog of cataclysmic variables, which are probable progenitors of Type Ia supernovae. Precise data on Cepheids and Ia's help to improve astronomers' cosmic distance ladder (*S&T:* Oct. 2022, p. 12).

As soon as a new unexpected event is discovered in the Gaia data (usually by automated software), the mission's Data Processing and Analysis Consortium (DPAC) issues a science alert to other astronomers who can carry out follow-up observations. "Since we started the science-alert program, transient astronomy has become ever more exciting," says Simon Hodgkin (University of Cambridge, UK), who is a DPAC member. "Because of Gaia's scanning mode, we are not always the first to detect new events, but even if we are late, we still provide extremely accurate positions."

Exoplanets and Asteroids

Gaia serves an an exoplanet finder, too. After all, a tiny, slow, periodic wobbling of a star's position could reveal the existence of a massive planet or brown dwarf in a wide orbit. Gaia should eventually discover and characterize thousands of giant exoplanets, says ESA's Sahlmann, but it takes time and patience — astronomers really need many years of data.

Nevertheless, the third data release already contains

▲ **GAIA 1** Hidden in Sirius's glare lies the cluster Gaia 1, its stars essentially invisible to the eye (astronomers found it thanks to a computer algorithm). In this image it sits at center, around where the orange, loop-shaped artifact appears left of Sirius. The cluster spans roughly 15 arcminutes — half the size of the full Moon — but its stars are at least 13 magnitudes fainter than the Dog Star at its western edge.

169,000 *astrometric binaries*, in which a companion reveals its existence by tugging on the primary star. Most of those consist of an invisible white dwarf orbiting a main-sequence star. But so far, Gaia has also found some 1,800 brown dwarf companion candidates and tens of new exoplanet candidates, making DR3 "substellar science candy," Sahlmann says.

And there's much more to come. "The real avalanche will come with the fourth and fifth data releases," says Smart.

Another major contribution to exoplanet science is Gaia's ability to better characterize the planets' host stars. Estimates of an extrasolar planet's mass and diameter (and thus its density and composition) rely on knowledge about the mass

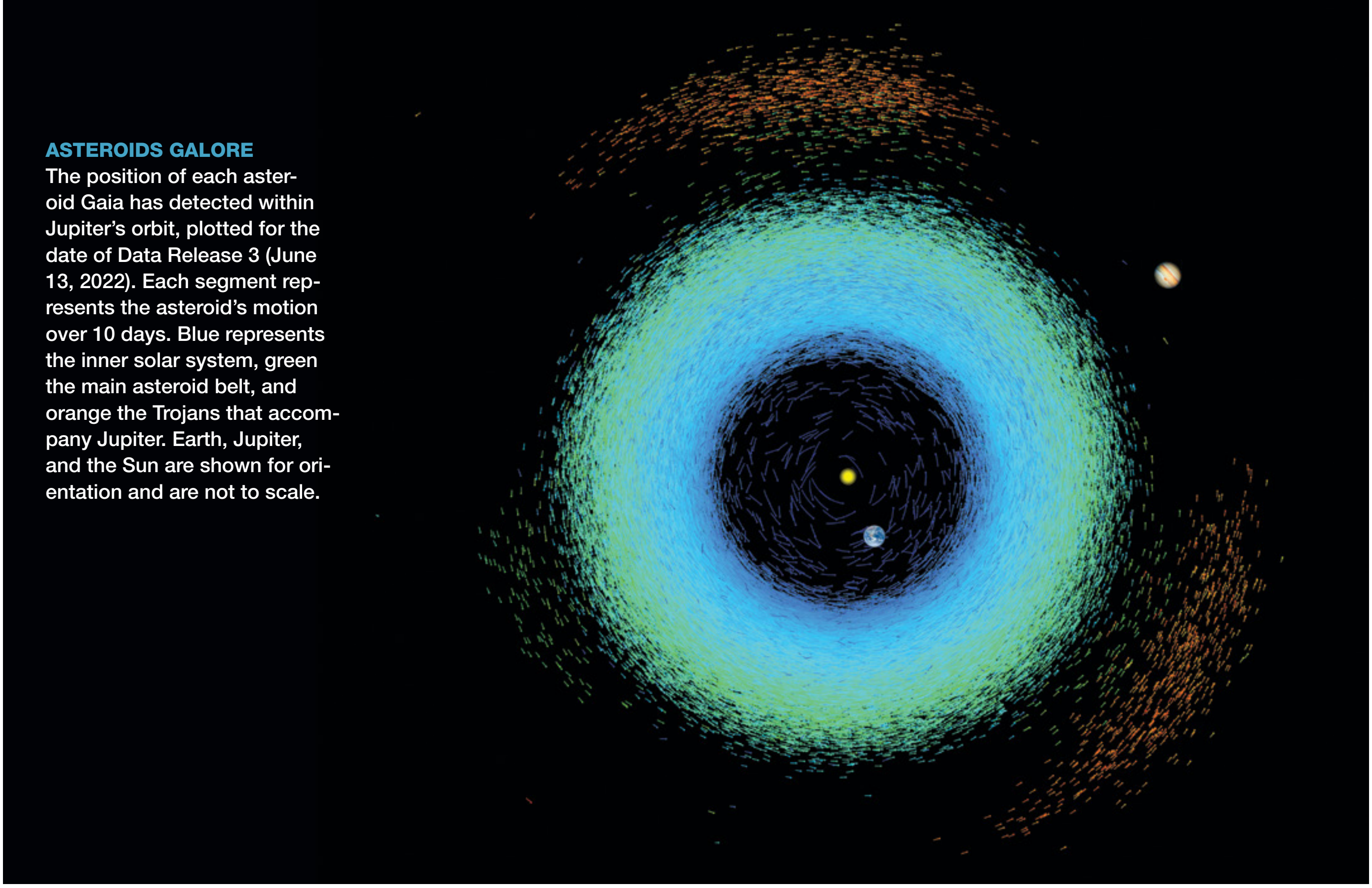
Total number of sources 1.8 billion (mostly stars)	Binary star systems	Variable stars	White dwarfs	Star clusters	Solar system objects	Quasar candidates	Galaxy candidates
	813,000	10 million	500,000	2,500	158,000	6.6 million	4.8 million

OUTSIDE THE MILKY WAY

When you're surveying between 1 and 2 billion stars, you can't help bagging numerous galaxies and quasars, too. Quasars are the luminous cores of remote galaxies, powered by supermassive black holes. They are found all over the sky, and since they don't exhibit parallax or proper motion, Gaia uses a selection of 1.6 million quasars as a reference frame — a coordinate system against which it measures stellar positions.

But of course, quasars are interesting by themselves, just like the many galaxies studied by Gaia. DR3 includes two separate catalogs of extragalactic sources, containing 6.6 million quasar candidates and 4.8 million galaxy candidates, respectively. For millions of those objects, astronomers have also determined redshifts, providing the distances. "The quality and homogeneity of the data are exceptional," says Christine Ducourant (University of Bordeaux, France).

One particularly interesting part of DR3 is the Gaia Andromeda Photometric Survey (GAPS) — a 34-month photometric data set on 1.2 million sources within a 5.5-degree radius centered on the Andromeda galaxy. Among other things, this survey will enable astronomers to study the variability of the brightest stars in our galactic neighbor, including Cepheids.



ASTEROIDS GALORE
The position of each asteroid Gaia has detected within Jupiter's orbit, plotted for the date of Data Release 3 (June 13, 2022). Each segment represents the asteroid's motion over 10 days. Blue represents the inner solar system, green the main asteroid belt, and orange the Trojans that accompany Jupiter. Earth, Jupiter, and the Sun are shown for orientation and are not to scale.

and diameter of the parent star. Thanks to Gaia, it has been possible to derive much more precise data on the physical properties of many known exoplanets.

Much closer to home, Gaia is revolutionizing asteroid research. DR3 contains data on 158,152 asteroids, Kuiper Belt objects, and planetary satellites, including spectra of 60,518 of these small solar system bodies. "This is simply the largest spectroscopic survey ever published," says Paolo Tanga (Côte d'Azur Observatory). "I am sure that many discoveries will come from this: on the composition of ancient planetesimals fragmented by collisions into asteroid families, on the formation of the asteroid belt, and maybe on asteroid satellites that can be found through astrometry." According to Federica Spoto (Center for Astrophysics, Harvard & Smithsonian), Gaia's "ultra-accurate asteroid positions" are about 100 times more precise than earlier ground- or space-based measurements. "It's really a new way to see the solar system," she said at the presentation of DR3.

Galactic Archaeology

Some of the most exciting Gaia results to date are related to the evolution of our Milky Way Galaxy. Over time, the Milky Way has grown to its present bulk by "consuming" smaller satellite galaxies and globular clusters. But even after hundreds of millions or even billions of years, stars that share a common origin have similar orbital energies and angular momenta, both of which are so-called *conserved quantities*, explains Amina Helmi (University of Groningen, the Netherlands). So astronomers can reconstruct the Milky Way's complicated formation history by precisely mapping the motions and compositions of its constituent stars (*S&T:* Mar. 2020, p. 34).

In April 2018, within hours of Gaia's second data release, Helmi and her collaborators discovered the telltale dynamical fingerprint of a massive galaxy merger that occurred some 10 billion years ago. They nicknamed this galaxy Gaia-Enceladus, after the mythological giant (and son of the Earth goddess Gaia) who was buried under Sicily's Mount Etna, driving its volcanic activity. Likewise, the merger with Gaia-Enceladus produced an eruption of star formation in the Milky Way.

The stars from Gaia-Enceladus (sometimes now called Gaia-Sausage-Enceladus, or GSE) are found throughout our galaxy and in its halo. But more recent mergers have left elongated streams of stars with similar dynamical properties and compositions. More than 20 years ago, Helmi had already found such *stellar streams* in data from the earlier Hipparcos mission. While these so-called Helmi streams were recognized on the basis of just 13 individual stars, Gaia's much greater sensitivity has revealed similar streams of many hundreds of stars, some of which extend over tens of degrees of sky.

"We are now able to find the remains of much smaller and more recent mergers," says Helmi. "Dwarf galaxy streams have typical widths of hundreds of light-years, but we've also discovered streams that are less than 10 light-years wide — the tidally disrupted remains of globular clusters." Eventually, Helmi hopes to use these streams to fully reconstruct the Milky Way's formation history.

Studying stellar streams — which usually extend well into the Milky Way's halo — may also shed light on the mystery of dark matter. According to computer simulations, the galactic halo should be home to countless invisible *subhalos* of dark matter. If they incidentally passed through a stellar stream, they could leave telltale "holes" and other gravitational disturbances. No such signatures have been confirmed so far. Moreover, studying the dynamics of stellar streams could provide information on the overall mass distribution in the Milky Way, which is thought to be dominated by dark matter.

Quiet Revolution

Over the next few years, many new results on a wide variety of astronomical topics will be published on the basis of Gaia DR3 data. But this release is only one third of Gaia's eventual astrometric harvest. "Around 2025, we plan to release the fourth batch of data, based not on 34 but on 66 months of observations," says Brown, who is the chair of the Data Processing and Analysis Consortium. "With DR4, for the first time, we will also publish all individual observations. Five years later, the final data release of 126 months is expected."

The spacecraft's micro-propulsion fuel is expected to run out in early 2025. But scientists and engineers are already drawing up plans for a successor to Gaia that operates at near-infrared wavelengths. GaiaNIR, proposed as part of ESA's Voyage 2050 scientific program, would be able to peer through most of the absorbing dust in the plane of our Milky Way and map stars in the galactic center and dusty spiral arms. By revisiting stars from the Gaia catalog, the new mission would also vastly improve on proper motion measurements. The development of a Gaia-like drift scan detector for infrared wavelengths is still a technological challenge, says Brown, but once that's been solved, GaiaNIR could launch in the 2040s.

For now, astronomers are just wallowing in the wealth of ultra-precise data from Europe's indefatigable star mapper. As Frédéric Arenou (Paris Observatory) says: "Gaia is an all-in-one instrument. There are no fancy images, but Gaia is providing material for an important fraction of the astrophysical field for several years, if not decades. The most profound revolutions are sometimes quiet."

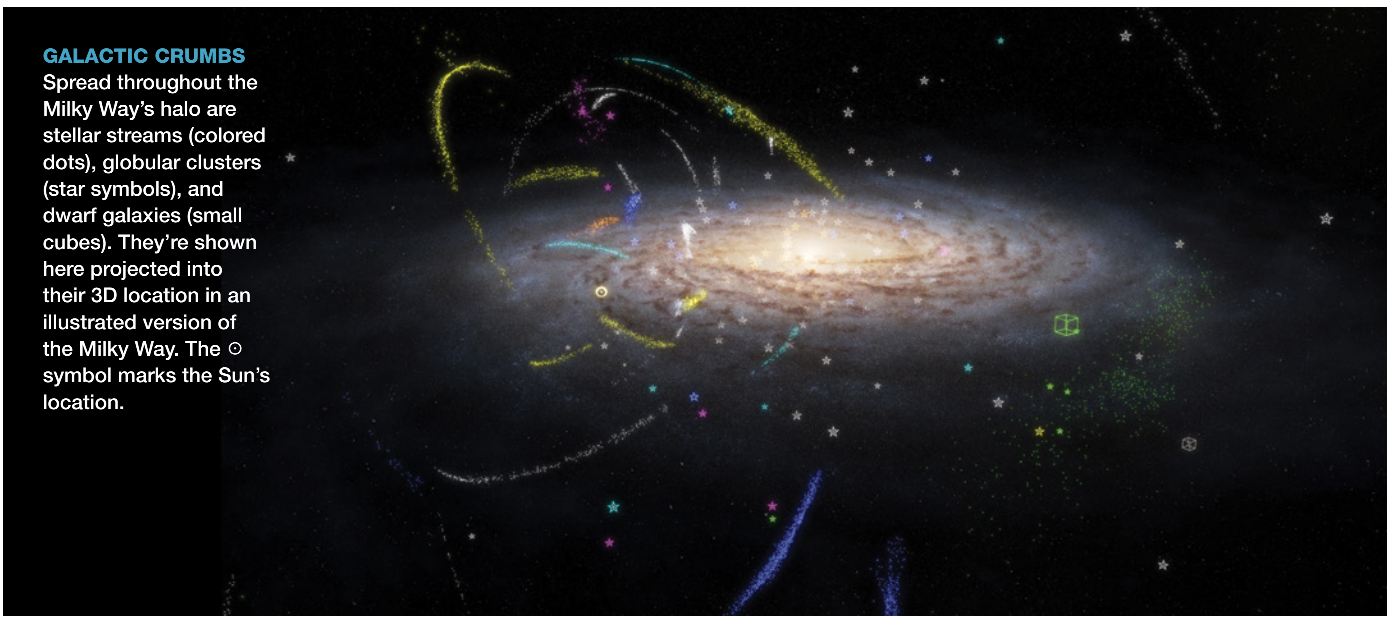
■ Contributing Editor **GOVERT SCHILLING**'s coordinates put him in the Netherlands, and his proper motion is restricted to the surface of a rocky planet orbiting a *G*2V star.

MINE THE ARCHIVE

The 1,548 charts of the 1997 *Millennium Star Atlas* (produced by *Sky & Telescope* in close collaboration with the European Space Agency) were based on data from ESA's Hipparcos mission. There are currently no plans to turn the Gaia measurements into a hardcopy atlas, given that there would be no notable differences in the positions of stars bright enough for observers' use. "But all data are freely available, so everyone can do it," says Anthony Brown, the chair of Gaia's Data Processing and Analysis Consortium (DPAC).

For individual stars and other objects, you can access the latest information through the Gaia Archive (**https://gea.esac.esa.int/archive**) or through the SIMBAD astronomical database (**https://simbad.u-strasbg.fr/simbad**). Moreover, Gaia scientists produced an open-source software package, *Gaia Sky*, advertised as a "3D universe simulator with support for more than a billion objects." You can download Gaia Sky from **https://zah.uni-heidelberg.de/gaia/outreach/gaiasky**.

▲ **MSA** The three-volume *Millennium Star Atlas* used Hipparcos data as well as nebula outlines hand-traced from sky images. It's now a collector's item.



GALACTIC CRUMBS Spread throughout the Milky Way's halo are stellar streams (colored dots), globular clusters (star symbols), and dwarf galaxies (small cubes). They're shown here projected into their 3D location in an illustrated version of the Milky Way. The ⊙ symbol marks the Sun's location.

MSA: S&T; STELLAR STREAMS IN THE HALO: S. PAYNE-WARDENAAR / K. MALHAN, MPIA