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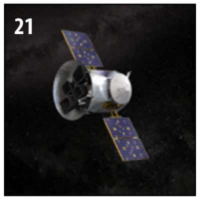

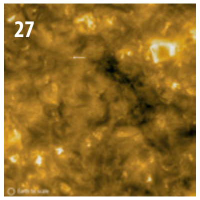

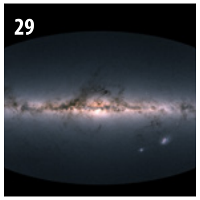

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on the cover

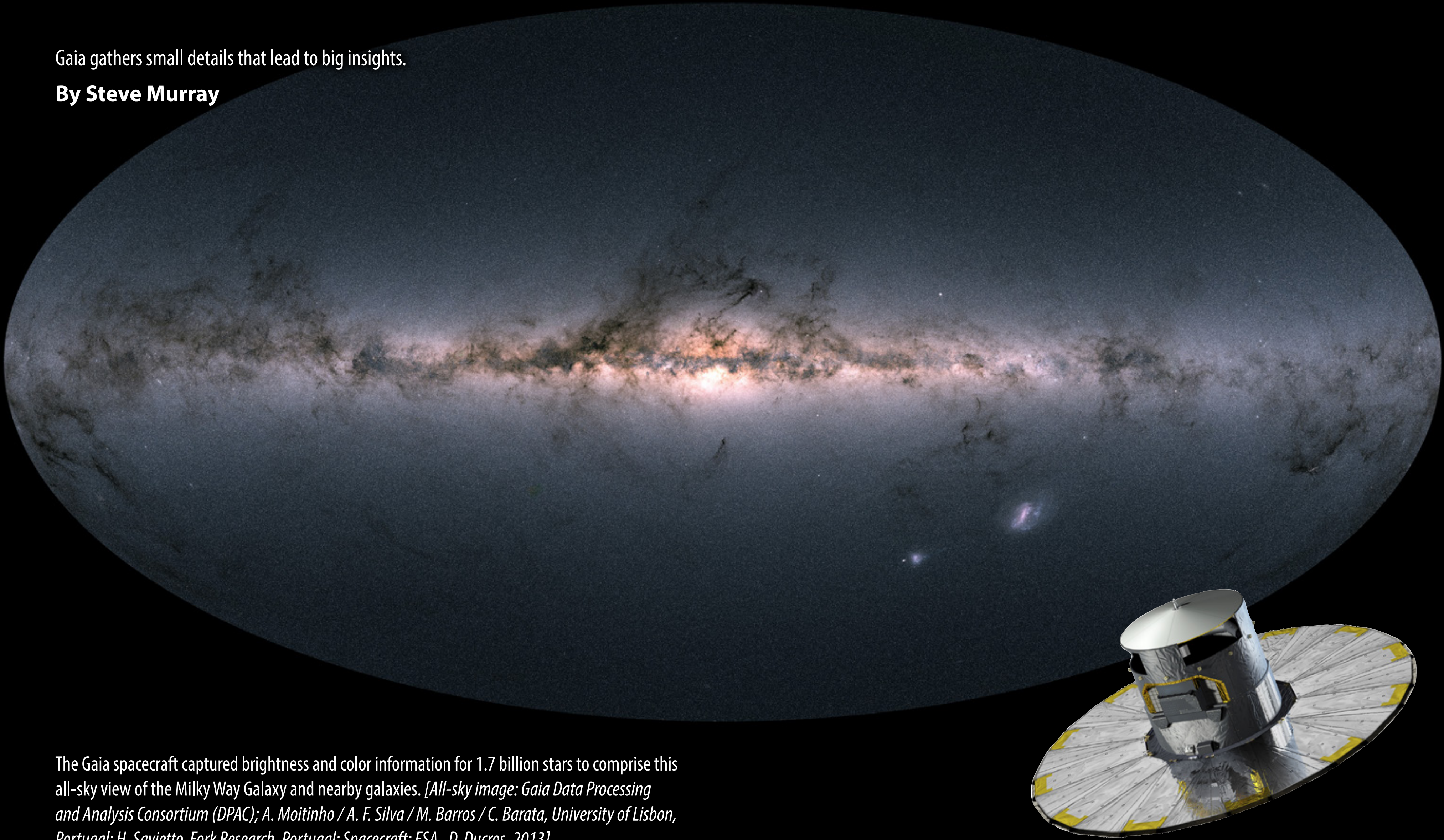
Front: Comet C/2020 F3 (NEOWISE) captivated photographers, observers, and astronomers across the Northern Hemisphere for months this summer. Here, the comet streaks above the beach at Redwood National Park in Northern California. *[© Patrick / Adobe Stock]*

Back: On August 25, the Hubble Space Telescope captured this view of Jupiter and its icy moon Europa. Scientists say a new storm is brewing in the Jovian clouds (the bright white stretch of swirls, about mid-northern latitude). *[NASA, ESA, STScI, A. Simon (Goddard Space Flight Center), M.H. Wong (University of California, Berkeley), and the OPAL team]*

Cataloging the Cosmos

Gaia gathers small details that lead to big insights.

By Steve Murray



The Gaia spacecraft captured brightness and color information for 1.7 billion stars to comprise this all-sky view of the Milky Way Galaxy and nearby galaxies. *[All-sky image: Gaia Data Processing and Analysis Consortium (DPAC); A. Moitinho / A. F. Silva / M. Barros / C. Barata, University of Lisbon, Portugal; H. Savietto, Fork Research, Portugal; Spacecraft: ESA–D. Ducros, 2013]*

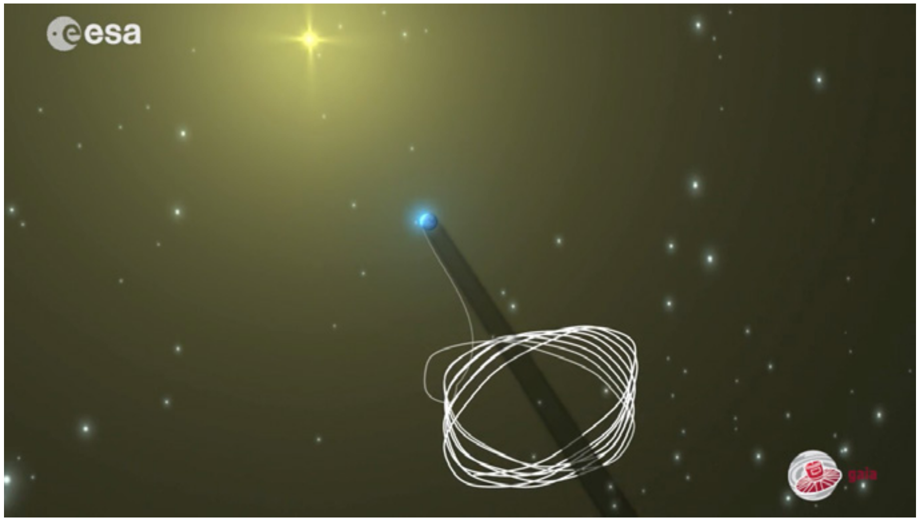
The European Space Agency (ESA) set a big task for Gaia when it launched the space telescope in 2013: measuring over one billion stars in the Milky Way with unprecedented accuracy. The spacecraft has long since passed that achievement; Gaia's next data release, its third, will contain information about the positions, velocities, luminosities, and colors of almost double that number of stars. The growing trove of data has already generated fundamental new discoveries about our galaxy and, in 2020, the pace of that productivity is accelerating.

In pursuit of precision

"Gaia" was originally an acronym for Global Astrometric Interferometer for Astrophysics and the acronym stuck, even though the interferometry approach was later dropped from the design. The Gaia telescope is the successor to Hipparcos (HIgh Precision PARallax Collecting Satellite), an ESA mission launched in 1989 and deactivated in 1993. It was the first space observatory dedicated to measuring the positions and motions of stars. During its operating life, the telescope populated a catalog of over two million stellar objects using this astrometry technique. Gaia was still a big step up, though, as its two collecting mirror telescopes gather more than 30 times the light and determine star positions and motions 200 times more accurately than Hipparcos.

The spacecraft orbits 1.5 million kilometers (just over 932 thousand miles) from Earth, around the second Sun-Earth Lagrange point (L2). At L2, the Sun's gravity and Earth's gravity pull equally, which means a craft can use less fuel to remain in a stable orbit. Here, Gaia has an uninterrupted viewing field, without the Sun or Earth in the way.

Gaia actually measures the minute movements of stars against more distant background stars to calculate distances. The spacecraft also collects stellar light spread out as a color spectrum to measure star motions toward and away from it. Scientists then compare that light to a control spectrum to calculate the star's "radial velocity." A third instrument measures red and blue color brightness, which can reveal a star's surface temperature.

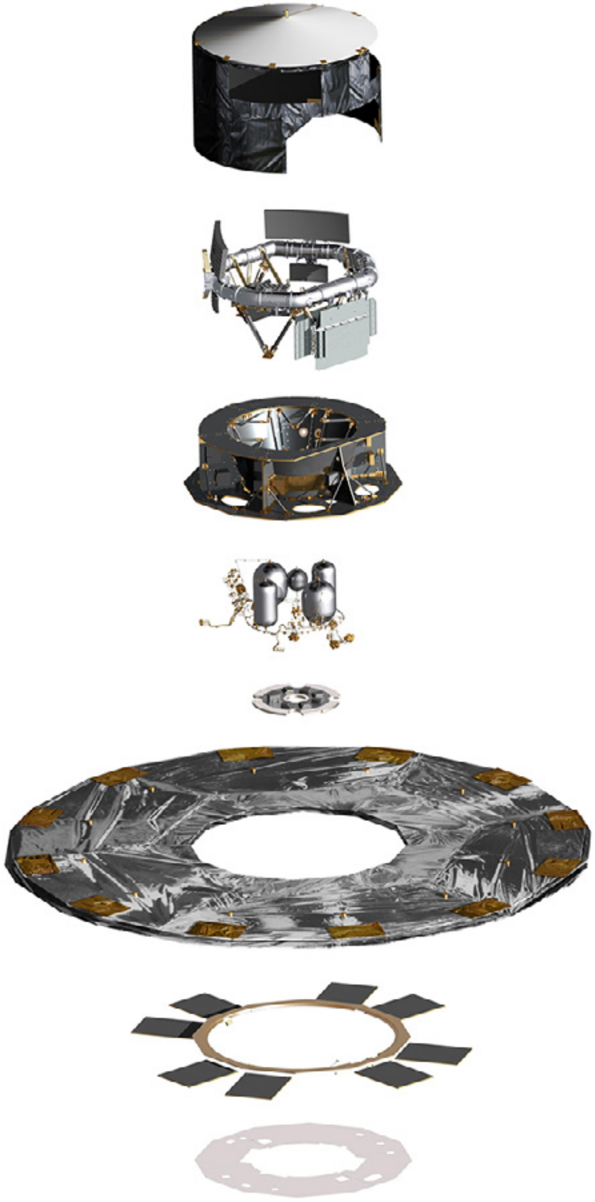


Gaia orbits a gravitationally stable point some 930,000 miles (1.5 million km) and "behind" Earth as seen from the Sun. *[ESA – C. Carreau/ATG medialab]*

The spacecraft observed its planned one billion sources about 70 times each during its initial five-year mission, and those measurements have been improved during its additional years on the job. Multiple observations like these help to document variations in stellar brightness. Gaia data offers positional accuracy as fine as 24 microarcseconds for about one billion stars, and radial velocities for the brightest 150 million of them.

The growing compendium of Gaia information addresses a lot questions in astronomy. A star's current position combined with its velocity lets astronomers trace its path backward to identify the location and time of its birth, while star color and luminosity can place it on the Hertzsprung-Russell (HR) diagram. A star's location on the HR diagram can say a lot about its age and evolution. Combinations of stars with similar features can be used to better characterize specific regions of the Milky Way Galaxy, like the central bulge and halo. "Gaia helps us to better understand the three-dimensional structure of the galaxy," says Alyssa Goodman, the Robert Wheeler Willson Professor of Applied Astronomy at Harvard University. "Most astronomers are trying to do that by studying the motions of the stars, using them as point particle tracers. If you could determine the motion of every point in the galaxy," she notes, "you could measure anything you wanted."

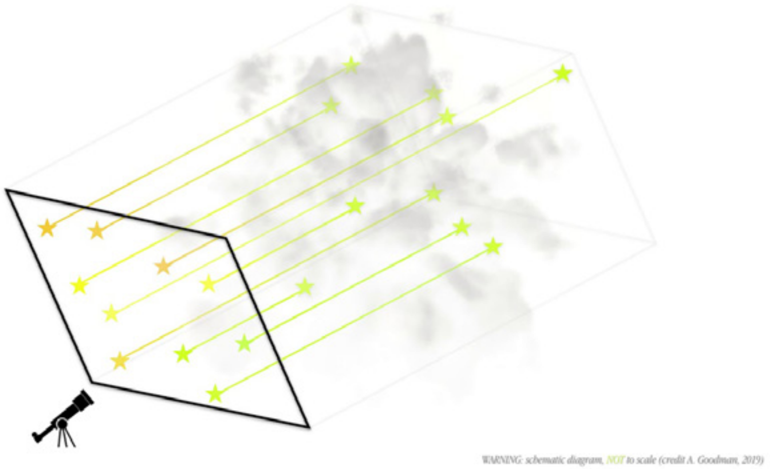
Accurate data about a star's motion can also be used to find other things around it — like exoplanets. Project scientists expect Gaia to find every Jupiter-sized planet within 150 light years of the Sun, and also between 10,000 and 50,000 planets beyond our solar system, by measuring the "wobble" of stars as their planets gravitationally tug them. Closer to home, the telescope should eventually detect hundreds of thousands of minor planets, from Near Earth Objects (NEOs) to Kuiper Belt bodies.



Gaia's scientific instruments sit around the circular payload module, shown second from the top in this exploded-view diagram. *[ESA/ATG-medialab]*

From numbers to knowledge

Measuring a billion stars — one percent of all the stellar objects in the Milky Way — creates a lot of data. According to ESA sources, Gaia observes an average of 70 million objects and generates up to 40 gigabytes of information each day. All that information is checked for quality and organized by specialized groups of astronomers that make up the Gaia Data Processing and Analysis Consortium (DPAC). So far, DPAC has published two vetted data sets, in 2016 and 2018. Successive releases contain more stars, with better position and velocity resolution, and with better data on characteristics such as color and light curves. The third data release will come in two parts: one portion later this year and a full set in 2021.



Clouds of intervening dust redden star colors, as shown in this diagram. By measuring precise distances to those stars using a different method (like Gaia does), astronomers can then map out the distribution of those dust clouds. *[Alyssa Goodman]*

Exploring enormous volumes of data requires the right mathematical tools. "Looking at the data set as a whole, and trying to really find subtle patterns, is where you need a huge knowledge of modern statistics," says Goodman. "The real angle on Gaia," she adds, "is the people who can do the best statistics will get the best information." Goodman is involved in a number of Gaia-related studies with her colleagues. "There's a generation of people between, say, 20 and 35 years old, who've grown up with statistics and who help us all cash in on the amazing riches of Gaia."

Some of those riches came in January, when Harvard astronomers reported the discovery of the Radcliffe Wave, an undulating string of star-forming regions in the disk of the Milky Way. Named after Harvard's Radcliffe Institute for Advanced Study, where Goodman is Codirector for Science, the finding demonstrated how Gaia data precision can lead to new breakthroughs. It also showed how one insight can build on another, as a Harvard team had earlier used Gaia data to pioneer 3D dust mapping, a method to better determine the distribution of dust clouds. "The way that it was done prior to Gaia," says Goodman, "was to infer the 3D distribution of stars and dust based on the colors of stars and the brightening effects of dust. What Gaia lets you do is constrain the distances to stars used as probes." Equipped with precise positions from Gaia for the stars they used, Goodman and her colleagues measured the amount their color reddened to chart out the locations of intervening dust clouds.

Mock Data for Testing Real Models

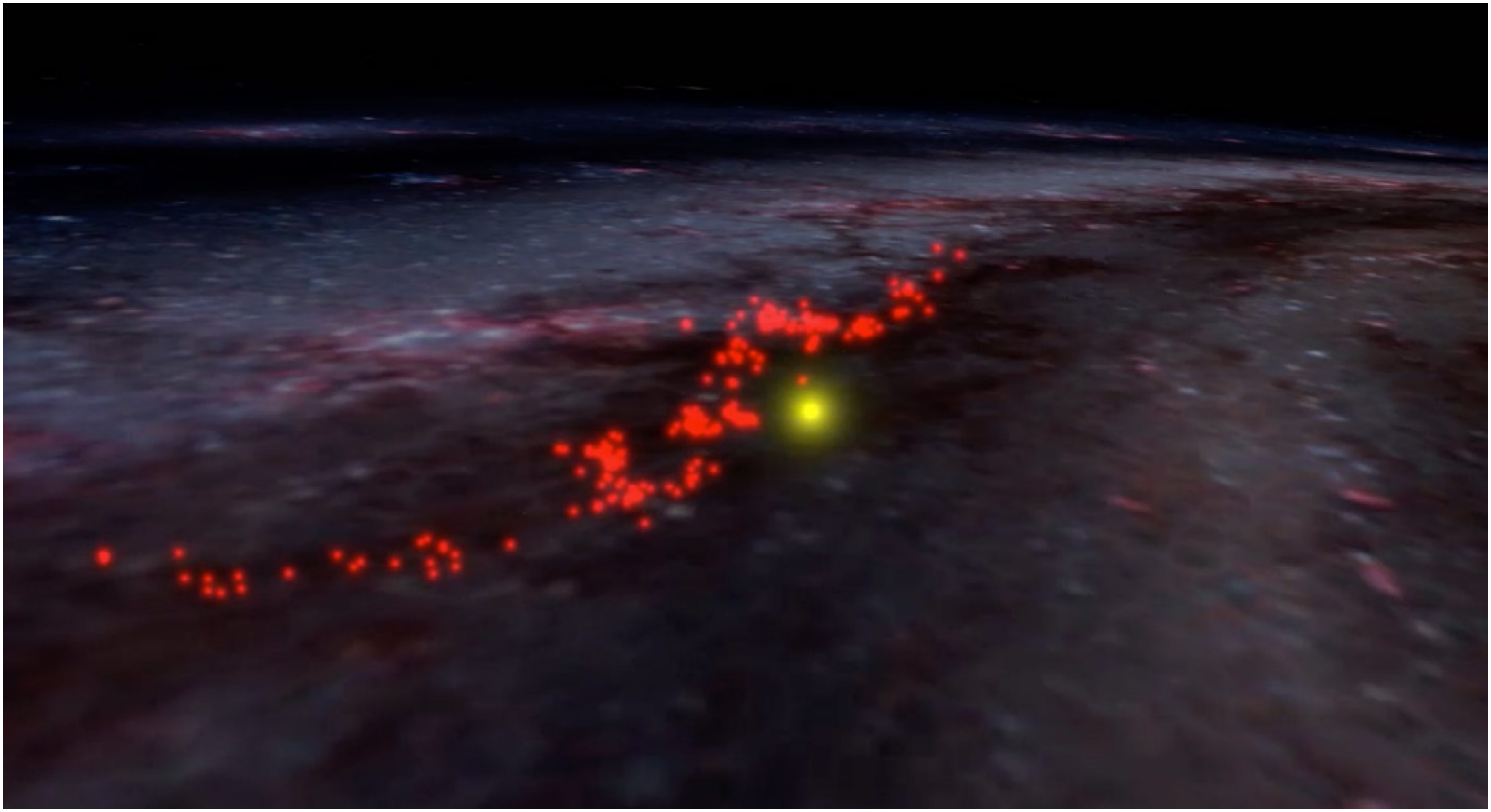
"Gaia does not provide distances," says Jan Rybizki, an astrophysicist with the Gaia group at the Max Planck Institute for Astronomy (MPIA) in Heidelberg, Germany. "It provides parallaxes of the stars, and from those one derives distances. We did that using the first mock catalog." Gaia DPAC teams convert Gaia's raw information into distances and other variables, which they enter into mock catalogs — a subset of processed data used for testing galaxy models and analysis techniques.

Testing models involves trying out different initial boundary conditions or parameters.

"There are many variables," Rybizki explains. "One can play around with the parameters and then compare the mock data results to small observations of real data and get a likelihood that one is represented by the other." As astronomers revise their input assumptions to better match a model to actual observations, they improve their underlying theories.

While it's not yet an official DPAC product, Rybizki and his team are currently developing a mock catalog of data from the third release. And, because some research studies require data from several survey telescopes, DPAC astronomers also try to cross-match their catalogs with those of other instruments. — *S.M.*

Data from the dust mapping work helped researchers find the Radcliffe Wave, an entirely new structural pattern in the galaxy. "We had these incredibly accurate distances to basically every known molecular cloud within a few kiloparsecs of the Sun" says Goodman. "Instead of using stars as probes, we could then use the clouds directly." Those clouds, each a stellar nursery, are the building blocks of an undulating string 9,000 light years long and 400 light years wide. Its crest and trough reach 500 light years above and below the galactic plane. And it can't be detected with only a 2D view of the sky. "It's one of those moments where you go 'what is that?'" she adds.



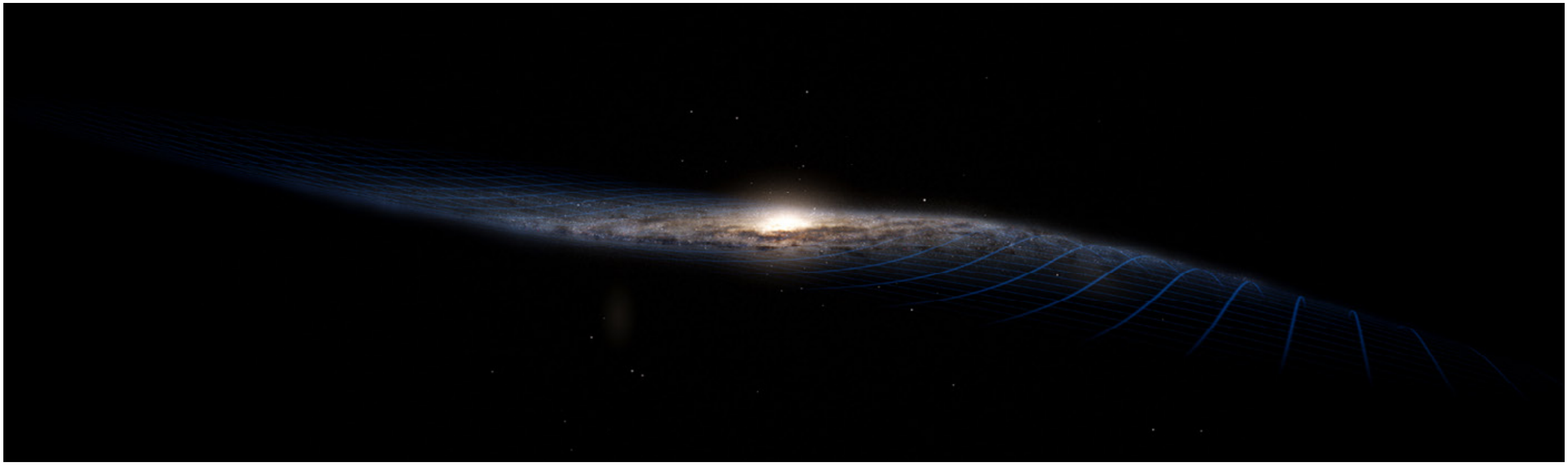
The newly discovered "Radcliffe Wave" is shown in red points in this illustration. (The yellow point is our Sun.) *[Harvard/WorldWide Telescope]*

"We found that the entire local arm of the Milky Way *is* this thing that's very straight from the top, but this weird sinusoidal shape from the side." The structure appears to be the product of an ancient stellar collision, although the team is exploring a range of explanations.

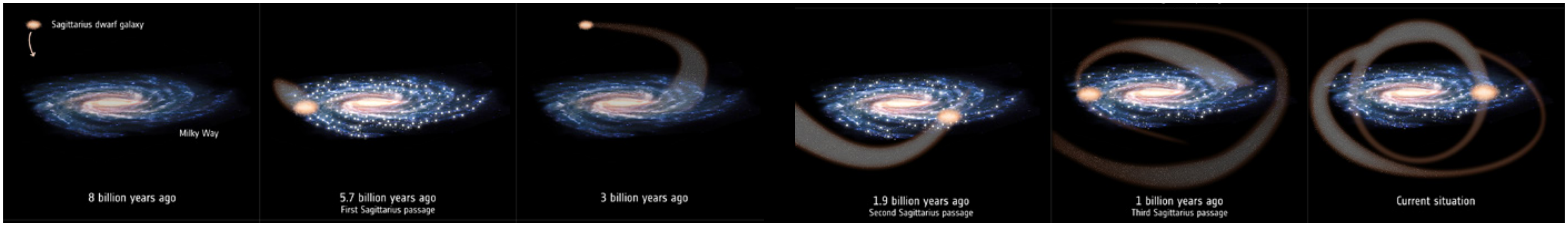
Teaming telescopes

Although Gaia helps to open new perspectives on the galaxy, many questions are still better answered with data from several telescopes working in different parts of the electromagnetic spectrum. "Gaia is a whole sky search," says Jan Rybizki, an astrophysicist with the Gaia group at the Max Planck Institute for Astronomy (MPIA) in Heidelberg, Germany, "and that's a really cool data set. The problem is that it's only in the optical. Some researchers are interested in dust properties, either for extinction of stars in the dust or in dust before stars are created. For that, one needs infrared data." The 3D dust mapping work, for example, used near-infrared data from the PanSTARRS telescope and the Two Micron All-Sky Survey (2MASS) to supplement Gaia parallax measurements.

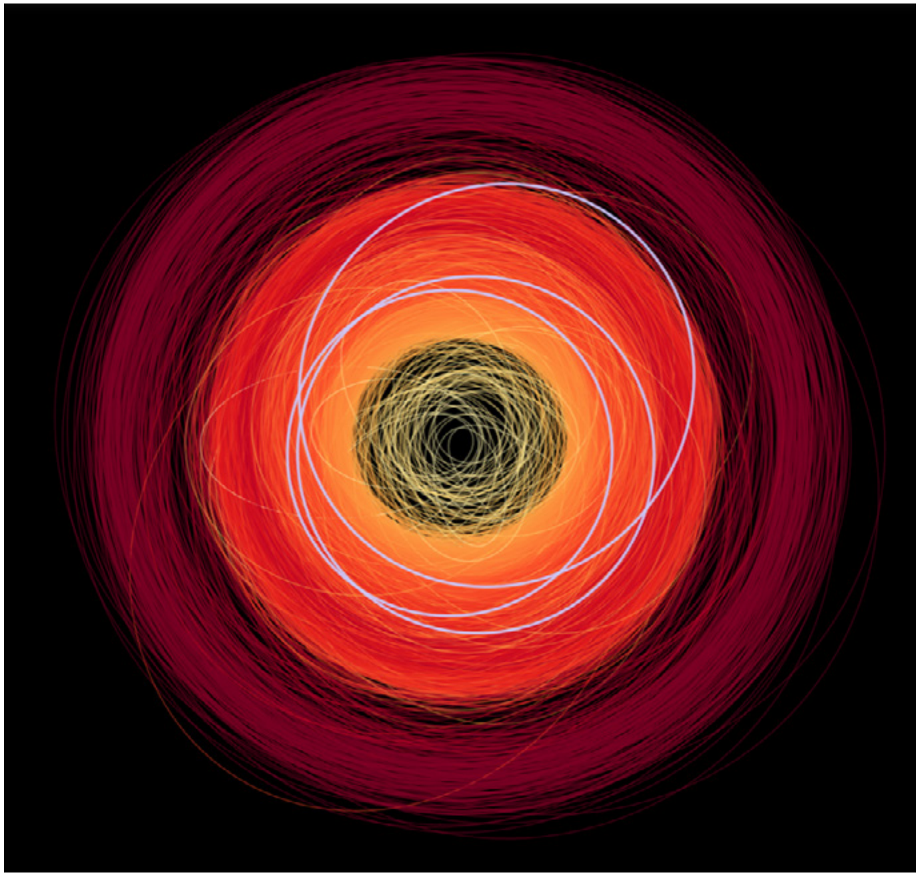
In July 2020, several other teams of scientists reported discoveries using Gaia data in combination with other data sets. Astronomers used Gaia velocity measures of stars escaping from the Hyades Cluster — the closest star cluster to Earth — to determine that it's gradually thinning away and, in several million years, will probably no longer exist. Another team reported on an effort to detect the distributions of invisible "dark matter" with Gaia by looking for tiny apparent motions in the positions of millions of stars as dark matter clumps pass in front of them. A student-led group of astronomers submitted a paper that used data from both Gaia and a ground-based sky survey (the Sloan Digital Sky Survey) to measure radial velocities of over 3,000 stellar remnant white dwarfs. This work better describes how and why white dwarf stars shrink in size as they add mass. And another study used data from Gaia and the H3 Stellar



Astronomers used Gaia data to discover the Milky Way's disk is warped. *[Stefan Payne-Wardenaar; Magellanic Clouds: Robert Gendler/ESO]*



Collisions with the Sagittarius dwarf galaxy (the smaller peach-color galaxy) may have generated star formation in the Milky Way (the larger galaxy) as it passed through multiple times. *[ESA]*



Scientists have observed more than 14,000 asteroids in Gaia data. Those asteroids' orbits are illustrated here. *[ESA/Gaia/DPAC]*

Spectroscopic Survey on over 800 stars in the Sagittarius dwarf galaxy to tease out a component that was stripped away from its earlier ancestor galaxy.

Gaia's mission was originally scheduled to end in late 2018, but ESA has already extended its operating life considerably. "It was formerly five years," says Rybizki, "but it's now getting probably 10 years — as long as the propulsion works on the spacecraft." Eventually, of course, there will be a final Gaia operation date and a final catalog release containing data for the entire mission. ESA, however, is already evaluating a new Gaia-style concept, Voyage 2050, which would perform surveys in both visible and near-infrared (NIR) wavelengths and collect astrometry data on up to eight billion new stars, including many in the heart of our galaxy's bulge.

Meanwhile, Gaia has much more to disclose about the galaxy. Goodman and her colleagues continue to examine its data with better analytical tools, and their efforts continue to pay off. "Our extended group is currently working on six new papers," she said. "If you thought the Radcliffe Wave was fun, wait till you see the rest of this!" ★

STEVE MURRAY is a freelance science writer & NASA Solar System Ambassador. A former research engineer, he follows developments in astronomy, space science, & aviation.