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THE ESSENTIAL GUIDE TO ASTRONOMY
APRIL 2024

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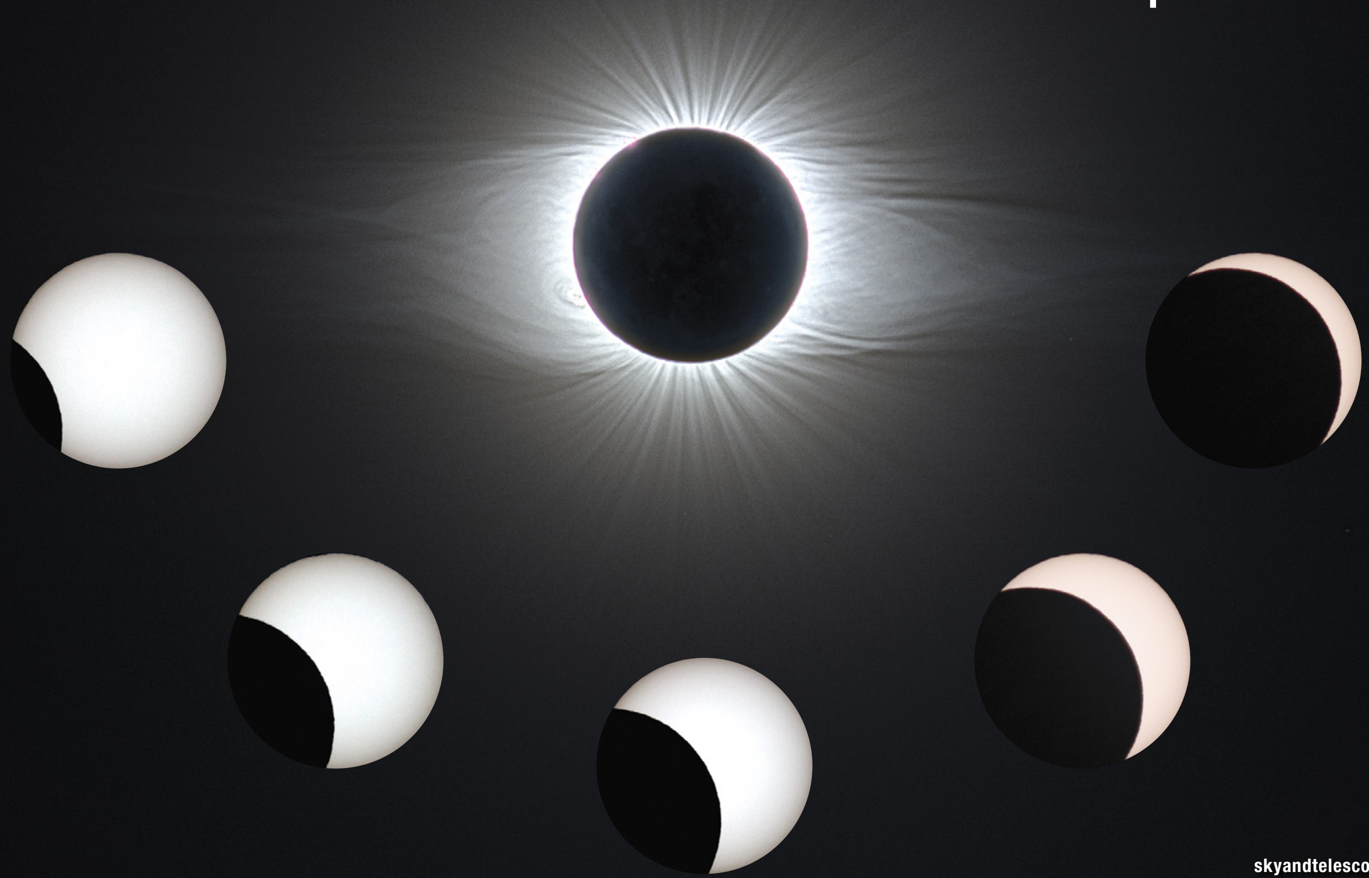

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Mapping Our Galactic

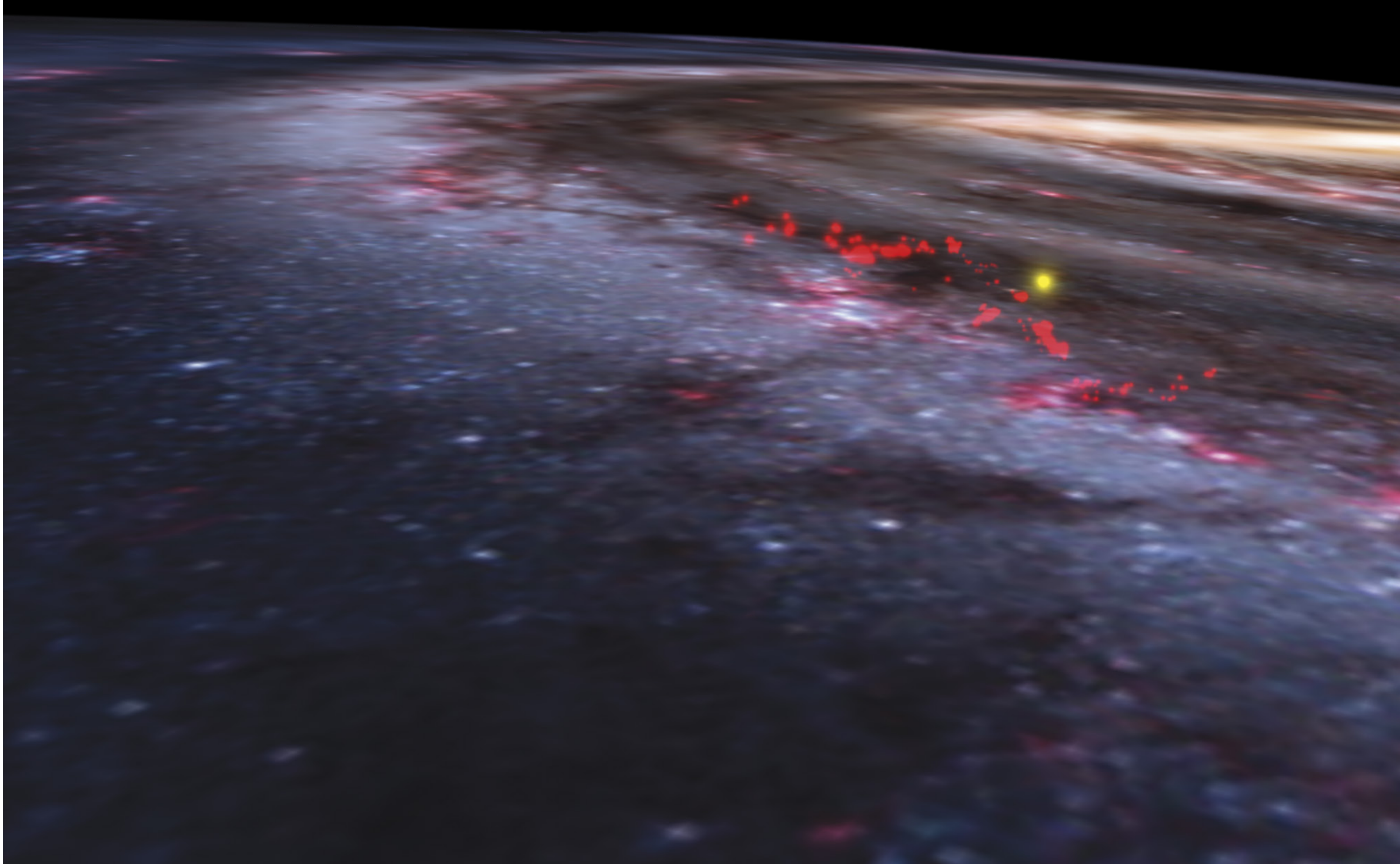
An innovative technique is revealing our suburb of the Milky Way in new and surprising detail.

Many of us have looked up on a clear, dark night and seen the hazy band of light stretching across the sky. This band of light is an edge-on view of the disk of our home galaxy, the Milky Way. The Milky Way's disk is shaped like a thin pancake with a bulge near its center. Our Sun lies about halfway out from the center of this 100,000-light-year-wide pancake, embedded deep within its disk. As a result, our view of the sky is simply a super-close-up, internal view of our galaxy's structure.

Since we are confined to our vantage point on Earth, bird's-eye views of our galaxy's structure have traditionally been artists' impressions, showing what we think our galaxy *might* look like from the outside. These artists' impressions have been painstakingly reconstructed from astronomical observations.

All astronomers agree that our galaxy has a characteristic pinwheel pattern, with several arms spiraling around the central bulge. However, while these artist's impressions appear crystal clear, the truth is that many of the details are uncertain. Astronomers even argue over how many arms make up this pattern and what their precise structure is (*S&T:* Nov. 2019, p. 16).

This uncertainty has held true even for the section of the Milky Way we should know the best: the *solar neighborhood*, where our Sun currently resides. Simply put, we



WORLDWIDE TELESCOPE / COURTESY ALYSSA GOODMAN

Backyard

know the structure of other galaxies — tens of millions of light-years away — much better than we know the structure of what lies within a few thousand light-years of the Sun.

As a galactic cartographer, I aim to change that. The goal of my research is to build more accurate maps of the Milky Way's structure. I care about the nitty-gritty details in artists' impressions because to know our galaxy's structure is to know its history, and in particular, the history of its youngest stars. In this article, I'll present work my collaborators and I have done to map stellar nurseries in the solar neighborhood. Our research reveals a hitherto-unseen, colossal gaseous structure; forces a revision to the shape of the closest spiral arm in maps of our galaxy; and sheds new light on how the baby stars in our corner of the Milky Way may have formed.

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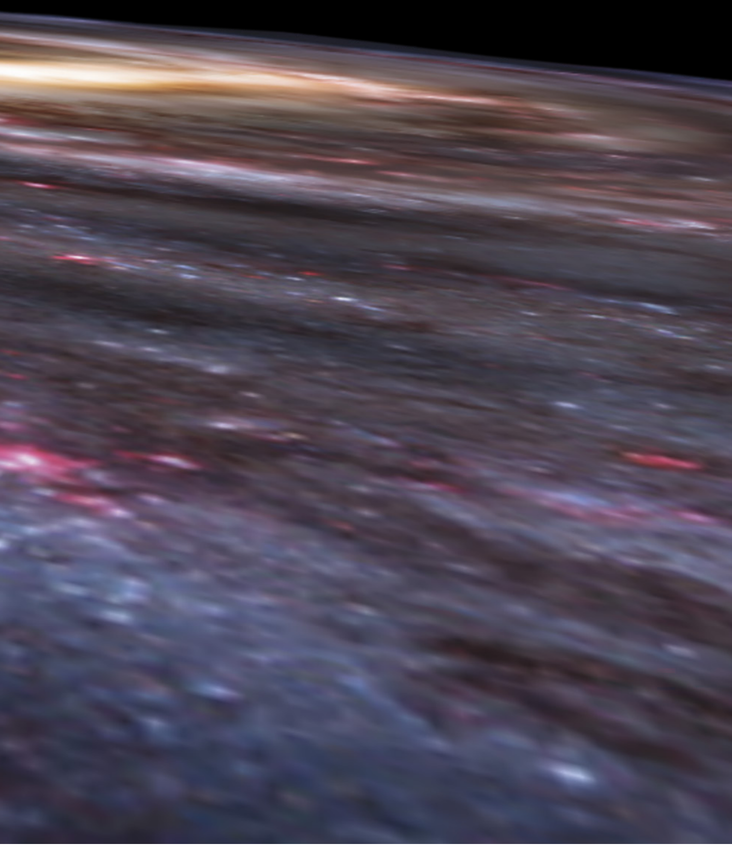
The Distance Dilemma

To turn 2D images of the night sky into a 3D model of the Milky Way, we first need to know how far away things are. Yet distances have been a challenge in astronomy for as long as the field has existed. My favorite example of the need for accurate distances is the Great Debate, which took place in 1920 between the astronomers Harlow Shapley and Heber Curtis. They were debating whether celestial objects known as "spiral nebulae" were small and nearby or big and far away — because confusion about distance leads to confusion about size.

Curtis argued that the Sun sat near the center of a small Milky Way and that spiral nebulae were external galaxies. In contrast, Shapley argued that spiral nebulae were nearby gas clouds, and that the universe contained only one very large galaxy, with the Sun situated far from its center.

Over the next decade, new observations largely resolved the debate — and proved the two astronomers both right and wrong. In the mid-1920s, Edwin Hubble observed and analyzed Cepheid variable stars in Andromeda, the closest spiral nebula. He deduced that the nebula was much farther than even Shapley's proposed extent of the Milky Way. Andromeda had to be an external galaxy separate from our own, as Curtis had argued. But history ultimately proved Shapley the winner regarding both the Milky Way's large size and the location of our Sun closer to its outskirts.



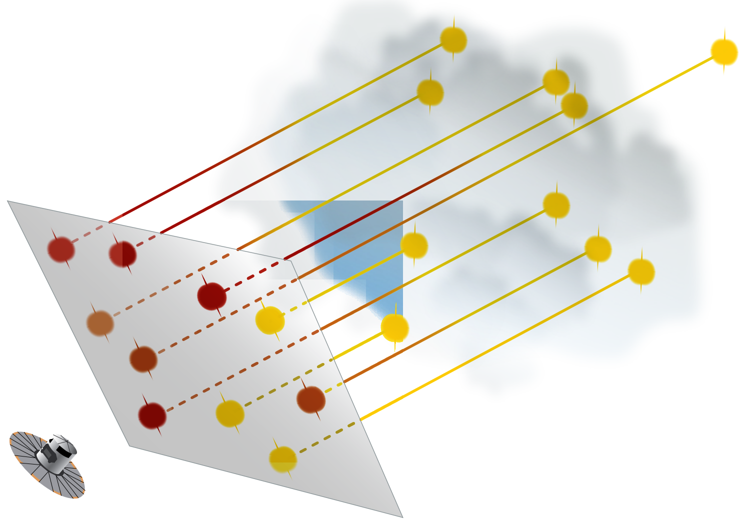
◀ **THE RADCLIFFE WAVE** A new technique is showing the Milky Way in 3D, revealing previously unseen structures like the Radcliffe Wave, a sinusoidal alignment of stellar nurseries.

The Nearest Stellar Nurseries

A century later, many themes surrounding the Great Debate persist, with entire subfields devoted to finding distances to a variety of celestial objects. Some objects, such as Hubble's Cepheid variables, are much easier to measure distances to than others.

In 2018, as a third-year PhD student at Harvard University, I set out to find distances to a class of celestial objects that presented a particular challenge: interstellar gas clouds. These are enormous clouds of gas occupying the space between the stars within our Milky Way.

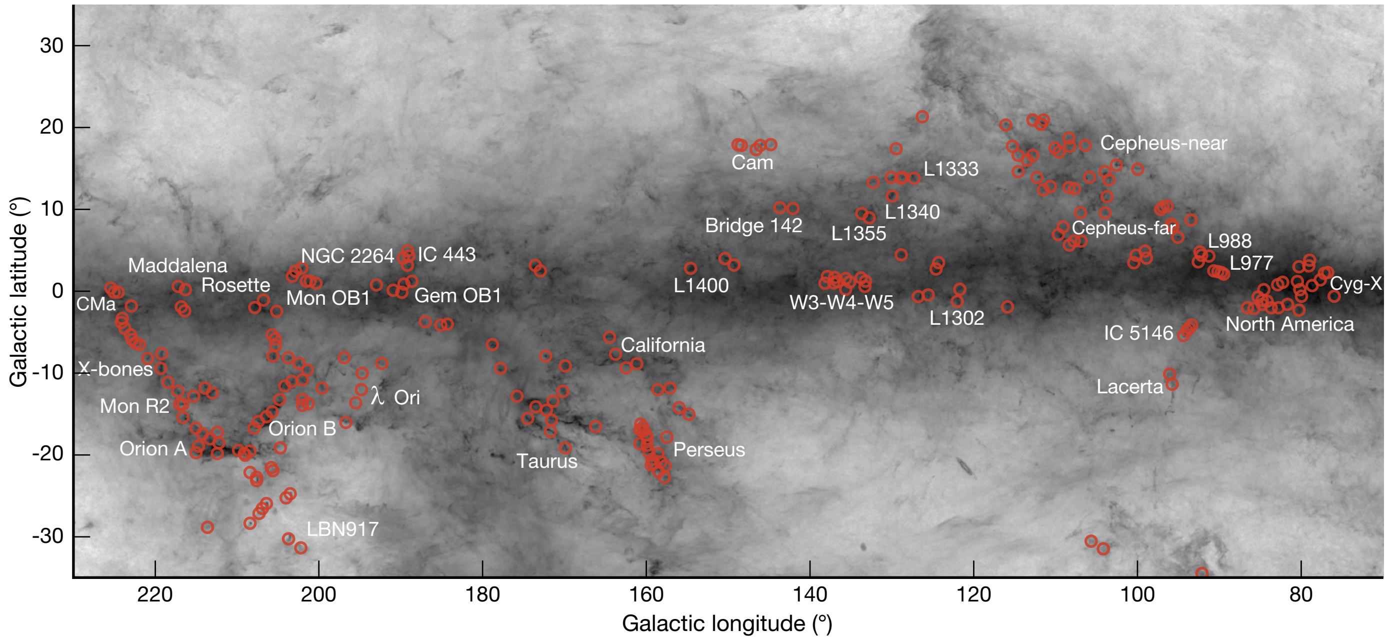
Our targets were specifically interstellar gas clouds in the solar neighborhood. These nearby clouds are of interest because they are the closest sites of star formation: They contain pockets dense enough to collapse under their own gravity and give birth to new stars. Given their proximity, these interstellar clouds have informed much of our knowledge about the intricacies of the star- and planet-formation process. Stellar nurseries are also one of the best tracers of the Milky Way's pinwheel structure, because those spiral arms constitute traffic jams of material where denser gas builds up (*S&T:* Mar. 2023, p. 14).



▲ **IN BETWEEN** Dust reddens stars' colors, much as our atmosphere reddens the sunset. Since astronomers infer what stars' colors should be (all shown here as yellow) as well as their distance, we can deduce how much dust lies between us and them, and how far away that dust is.

▲ **DUST MAP** Determining the distances to dusty, star-forming clouds enables astronomers to map out their distribution across our local neighborhood, as shown in this data visualization. (See additional visualizations at **https://bit.ly/dustmaps**.)

DUST-MAPPING DIAGRAM: BEATRIZ INGLESSIS / *S&T*; SOURCE: ALYSSA GOODMAN; ARTIST'S CONCEPT OF ACTUAL DUST MAP: GREGORY GREEN / CC BY-SA 4.0 DEED



▲ **HIDDEN IN PLANE SIGHT** Viewed in the plane of the sky, facing away from our galaxy's center, the Radcliffe Wave is invisible. It's only when astronomers create a 3D map of the nearby stellar nurseries (red circles) that the wave reveals its shape. (Not all of the nurseries shown are in the Wave.)

Without precise distances, it is difficult to pinpoint even the most basic properties of these interstellar gas clouds, such as their size or mass — let alone their distribution in the galaxy. With the goal of helping astronomers better understand how stars form, I set out to chart the distances to the closest clouds with more accuracy than ever before.

But these clouds are simply dense blobs in a continuous distribution of mostly hydrogen and helium gas known as the *interstellar medium*. How does one find distances to structures with no finite boundaries or sharp edges? To do so, I needed help from a space mission called Gaia.

A 3D Dust-Mapping Revolution

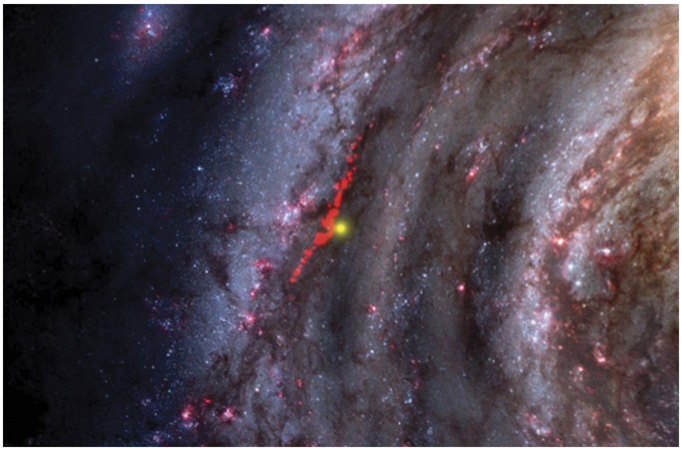
One of the leading goals of the Gaia mission, launched in 2013, is to reveal the 3D structure of our Milky Way by providing accurate distances to more than 1 billion stars, about 1% of the total number of stars in our galaxy. While an early-1990s mission, Hipparcos, provided distances to more than 100,000 stars out to a few hundred light-years from the Sun, Gaia now measures distances to stars 200 times more accurately and over a much larger volume of our galaxy (*S&T:* Feb. 2023, p. 34).

Gaia provides distances to *stars*, though, and I wanted to find distances to the stuff *between* the stars. Key to solving that puzzle is the composition of the interstellar medium. About 99% of the mass of the interstellar medium is hydrogen and helium gas, but about 1% is dust: tiny, sooty particles composed of heavier elements like silicon and carbon. Dust has an outsize influence on how we view our night sky due to an effect called *reddening*, in which dust absorbs and scatters blue light more than red light. The effect makes stars appear redder than they would if no dust lay between us and them. (A similar effect causes sunsets to appear red.) How reddened a star becomes depends on how much dust its light passes through before reaching our telescopes.

Historically, astronomers considered dust a nuisance, an obnoxious smoke-like substance that obscures our view of the cosmos. For me, though, dust was not a nuisance but a boon, because encoded in the color of every reddened star is information on how much dust the light has passed through on its way to Earth. And now thanks to Gaia, we know many stars' distances. Each of these stars thus helps reveal the distance of the dusty clouds, since the dust must lie closer than the star does for us to observe this reddening effect. The idea that the colors and distances of stars can tell us the distances of interstellar clouds underpins a technique known as *3D dust-mapping*.

Imagine we want to use 3D dust-mapping to find the distance to the Orion Nebula — one of the most famous nearby regions of massive star formation. Stars are scattered throughout the dusty cloud in 3D, but as seen in a 2D image of the nebula, everything is projected onto the flat plane of the sky. Yet stars behind the cloud (at greater distances) will on average have more reddened colors than stars in front of the cloud (at lesser distances). If we combine the colors of stars with their distances from Gaia in this patch of the sky, we will find a distance where a jump in reddening occurs. That jump must be the distance of the cloud.

In reality, the situation is more complicated, because not every star is the same intrinsic color in the absence of dust. However, thanks to the precision of large photometric surveys (which provide constraints on stellar colors sampled at dif-



▲ **BIRD'S-EYE VIEW** A top-down view of the Radcliffe Wave in the Milky Way shows its linear shape from that angle. The Sun is the yellow star (not to scale) next to the Wave.

ferent wavelengths), data-science techniques, and a lot of computing hours, it is possible to account for these effects.

While 3D dust-mapping existed prior to Gaia, astronomers used solely stellar colors. Those maps had low resolution because there's only so much information about distance and dust that you can squeeze out of stellar colors. Gaia's distance measurements aren't based on stars' colors, and adding its results provided a huge resolution boost, improving our accuracy by a factor of five essentially overnight. With the deluge of stellar distances available in Gaia's second data release in April 2018, we had all the necessary data to finely chart the distances to nearby stellar nurseries for the first time.

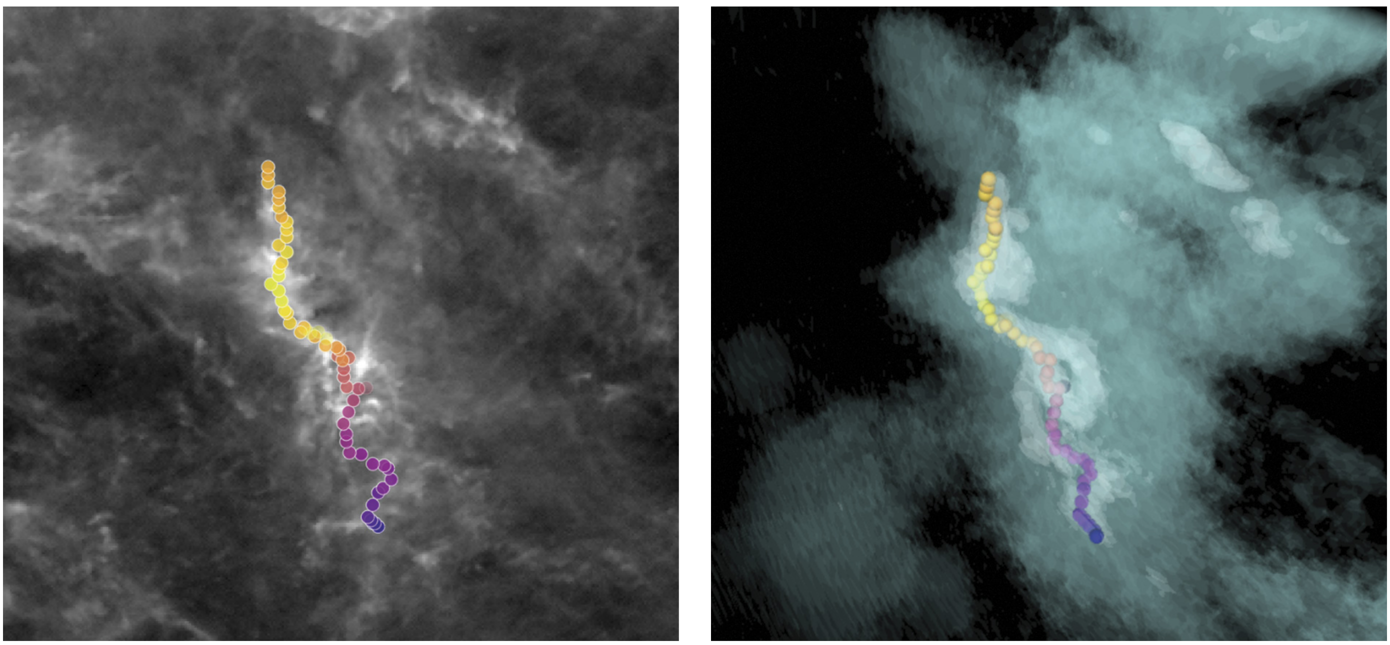
Rise of the Radcliffe Wave

In collaboration with fellow PhD student Josh Speagle and under the auspices of Doug Finkbeiner's 3D dust-mapping group, I spent that summer developing our new Gaia-informed 3D dust-mapping pipeline and applying it to nearby stellar nurseries. However, it was not until later that fall, when we started collaborating with João Alves (University of Vienna), that we started to see a pattern.

João, who was spending his sabbatical year working on Gaia data as a fellow at Harvard's Radcliffe Institute, came to me with a kernel of an idea. He had been staring at previous 3D dust maps (the ones built on stellar colors alone) and thought he saw the barest hint of a physical connection between the Orion Nebula and a second stellar nursery, called Canis Major OB1.

By transforming the new distances into an updated 3D map of the gas in this region, we found the two nurseries are indeed connected, forming a 3,000-light-year-long filamentary arc that starts from the midpoint of our galaxy's pancake-like disk (near CMa OB1) and dips all the way down to Orion, 500 light-years below the disk.

But we did not stop there. Over the following months, in collaboration with Alyssa Goodman (also at Harvard), we mapped more and more of the filament until ultimately its full shape was revealed: a 9,000-light-year-long wave, undulating in and out of the disk, along which tens of thousands of new stars are forming. Named the Radcliffe Wave in honor of João's time as a Radcliffe Fellow, the structure contains a majority of the stellar nurseries in the solar neighborhood (*S&T:* Jan. 2023, p. 26), connecting gas clouds over such a



▲ **BONES** Star-forming clouds, once thought to be roughly spherical in shape, are anything but. These dusty, gaseous regions are arranged in elongated filaments. Using 3D dust mapping, the author and colleagues mapped the Perseus molecular cloud, visualizing the region in 2D *(left)* and in 3D *(right)*. The cloud is densest along its "spine," whose points are colored by distance from near (blue-purple) to far (yellow-orange). View an interactive version of this figure at **https://bit.ly/perseusskeleton**.

RADCLIFFE WAVE, TOP-DOWN: WORLDWIDE TELESCOPE / ALYSSA GOODMAN; FILAMENTARY "BONES": C. ZUCKER ET AL. / *ASTROPHYSICAL JOURNAL* 2021 large range in distances that astronomers never predicted they could be related. Containing around 3 million times our Sun's mass, the wave also represents the largest coherent gaseous structure known in our galaxy.

The Sun lies roughly 400 light-years away from the closest point of this colossus — the wave has been right in front of our galactic noses. While many regions in the wave are visible in the sky with a backyard telescope (*S&T:* Jan. 2023, p. 26), we only discovered it now thanks to the huge boost in 3D dust-mapping's distance resolution that Gaia enabled. With accurate distances, we could finally turn the 2D view of our sky into a 3D view of star formation throughout the solar neighborhood.

So, given that stellar nurseries are excellent tracers of the Milky Way's pinwheel pattern, what's the relationship between this wave-like structure and the nearby spiral arms seen in artists' impressions of our Milky Way? It turns out that — at least as far out as our 3D dust maps can see — the Radcliffe Wave is the gaseous reservoir of the nearest spiral arm to our Sun, dubbed the Local Arm.

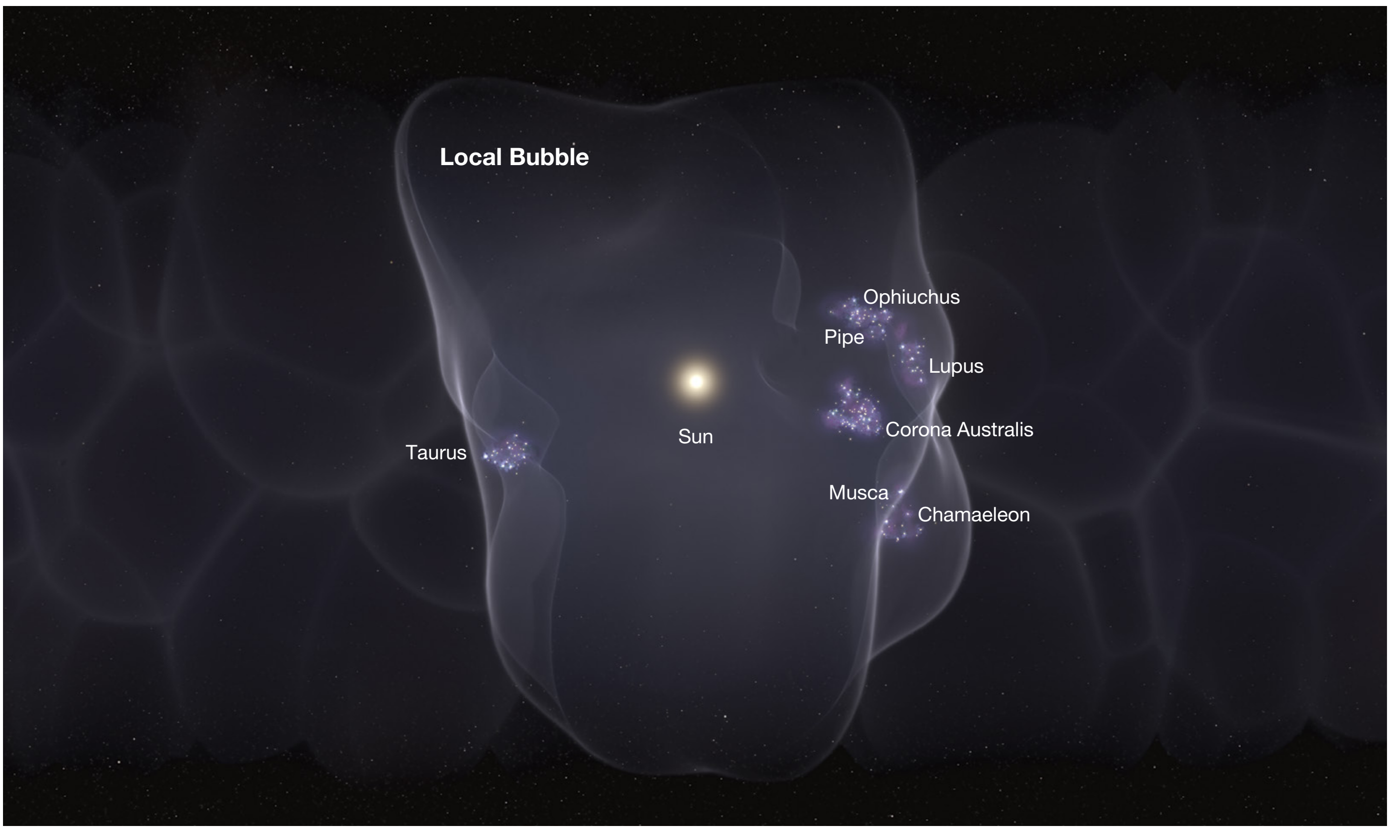
Previous pictures, which relied on the stellar nurseries sparsely scattered throughout the galaxy, had suggested that the Local Arm lies nestled within the Milky Way's pancake-disk when seen edge-on. Artist's impressions show it as having an arc shape when seen from above the disk, kind of like a chocolate swirl in the batter.

But our new view, using the galaxy's ubiquitous dust to trace where gas lies, suggests a different, much more dynamic picture. Rather than being flat when seen edge-on, the Radcliffe Wave dips above and below the midpoint of the disk's central plane, with an amplitude of about 500 light-years. This amplitude is about three times larger than the thickness that astronomers have traditionally assumed for the Milky Way's dense gaseous disk, out of which stars form, based on approaches that average over the entire galaxy. And rather than curving when seen bird's-eye, the wave is straight, stretching about 25 times as long as it is wide.

In fact, on large scales, all spiral arms may be made up of a series of such linear sections. It's only when stuck together that they make a curved shape, like a long train of boxcars rounding a bend in the tracks (*S&T:* Mar. 2023, p. 14). Needless to say, we now need a new artist's impression of our galactic backyard.

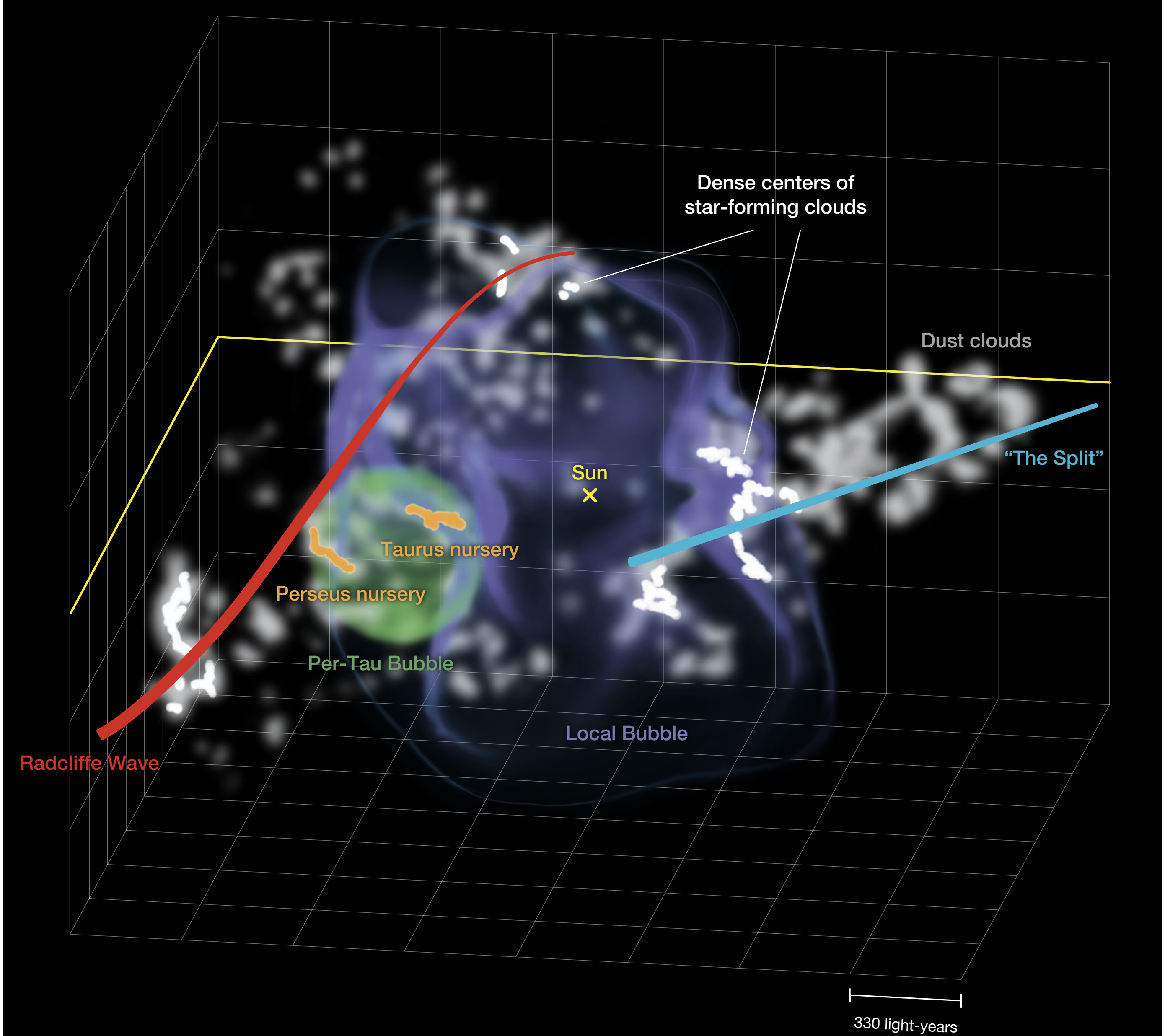
Origin of an Undulation

The wave's peculiar shape also has profound implications for how the youngest stars in our local Milky Way may have formed. To understand the formation of these youngest stars, though, we need to understand the formation of the wave. One culprit could be an external source of disturbance — a clump of dark matter or an infalling cloud of gas hitting the disk of the Milky Way would have shaken the disk up, like a



CENTER FOR ASTROPHYSICS, HARVARD & SMITHSONIAN / LEAH HUSTAK (STSCI)

▲ **NEW LIFE** As the Local Bubble expands outward, it sweeps up gas like a snowplow, compressing it until stars begin to form. 3D dust-mapping has revealed that stellar nurseries line the edges of the Local Bubble.



OUR NEIGHBORHOOD The 3D dust-mapping technique has revealed a map of our Sun's surroundings. Dusty gas clouds appear gray, and denser star-forming regions are white. The Sun, marked with a yellow X at center, is traveling through the Local Bubble (purple), a supernovae-carved cavity. The nearby Radcliffe Wave (red line) extends along the red line from the stellar nursery CMa OB1, through Orion, Perseus, and Taurus nurseries, and on to Cepheus. The Perseus and Taurus nurseries (orange) are about halfway up the wave. These nurseries sit on the edge of the Per-Tau shell (green), another bubble-like cavity. Several stellar nurseries are also found along the roughly 5,000-light-year-long spur nicknamed "The Split," which follows the blue line. (See this visualization in 3D at https://bit.ly/3DLocalMap.)

C. ZUCKER ET AL. / *NATURE* 2022

pebble making waves in a pond's surface. However, origins closer to home are also possible: A series of supernova explosions might have pushed the disk's gas hundreds of light-years beyond the midplane of the disk.

Thanks to Gaia's third data release in 2022, we are closer to discriminating between such ideas. Unlike Gaia's second data release, which mainly provided information on the 3D positions of stars, the third release also includes constraints on the 3D *motions* for millions of stars, including many that are still forming within the wave. These young stars inherit the motion of their natal clouds and act as proxies for the gas's motion, which is much more difficult to measure.

Using the 3D motions of the wave's baby stars, new work by Harvard PhD student Ralf Konietzka shows that the Radcliffe Wave doesn't just *look* like a wave, but it also *moves* like a wave. In other words, it is oscillating.

The oscillation is consistent with being what physicists call a *traveling wave*: Like waves propagating over the open ocean, the crests and troughs of the Radcliffe Wave shift position with time, so the gas disk in this section is never completely level. The baby stars forming in the wave act similar to buoys, bobbing up and down and revealing the rippling motions of the gaseous disk. Comparing the specifics of this oscillation with predictions from computer simulations should ultimately shed light on exactly how the wave formed.

One thing, however, that the wave has already taught us is that star formation is much more dynamic than previously thought. Nearby stars do not form in static blobs of gas that evolve gently in isolation. As our Milky Way's disk is bombarded by external disturbances from outside and by supernova explosions from within, its gas is repeatedly shaken and stirred; as a result, star-forming clouds likely disperse quickly.

Our Sun passed by the Radcliffe Wave roughly 13 million years ago and now lies (by chance) at the Local Bubble's center. The dynamic nature of star formation means that the part of the galaxy we are leaving behind may appear unrecognizable 13 million years in the future. The artists' impressions of today are not the artists' impressions of tomorrow.

From Distances to Shapes

The 3D dust-mapping revolution has accelerated even faster than I could have predicted. Thanks to advances in data-science techniques led by Torsten Enßlin's group at the Max Planck Institute for Astrophysics, the field has shifted from being able to determine distances to clouds to being able to outline their shapes. We can now figure out not just where clouds are, but what they look like.

Analyzing the shapes of dense clouds in and beyond the Radcliffe Wave in 3D for the first time, we recently found that they are not spherical (as traditionally assumed) but rather shaped like filaments. We've found that these stretched-out clouds in turn appear to be intimately related to cavities of tenuous gas carved out by supernovae.

When we matched up the orientation of these filaments with the walls of cavities around supernovae, we found that the closest clouds are draped over these cavities' boundaries. Like a snowplow that sweeps up and compacts snow on the edge of its blade, these supernovae sweep up the ambient gas, evacuating the cavities and leading to a pile-up of denser gas along their surfaces.

Our Sun happens to be traveling through the center of one of these supernova-swept cavities, called the Local Bubble. We've found that this bubble is actually still expanding, sweeping up and compacting the gas in the closest region of the Radcliffe Wave.

In fact, such bubbles are everywhere — in the wave and around it, with a huge range of sizes. Those inside the wave carve out its gas, while those outside push it this way and that. The entire wave looks like holey string cheese (made of Swiss instead of the traditional mozzarella).

This means that nearby star-forming clouds do not just lie *in* the Radcliffe Wave, but they also lie *on* the surfaces of bubbles. Stellar death therefore likely plays a role in shaping stellar birth — regardless of whether supernovae are ultimately responsible for the wave's overall undulation.

The Hidden Milky Way

Despite these exciting discoveries made close to home, the solar neighborhood ultimately represents a small suburb within the sprawling metropolis that is the Milky Way. About 90% of our galaxy is yet to be fully resolved with 3D dust-mapping, including the entire half of the Milky Way located on the other side of our galaxy's center. Such vast distances are largely beyond the reach of current visible-light observatories, even those as powerful as Gaia.

To unlock the hidden Milky Way, we must turn to the next generation of observatories, including the Nancy Grace Roman Space Telescope, set to launch between late 2026 and early 2027. With a field of view about 100 times larger than that of the Hubble Space Telescope and equipped with an infrared camera to peer through the heart of our Milky Way's dusty disk, Roman will open new doors for understanding the structure and dynamics of our galaxy. I and many other galactic astronomers are advocating for a survey of the disk with Roman. Such a survey will constrain the colors of tens of billions of stars, a subset of which would also have accurate distances — the two key ingredients necessary for building reliable 3D dust maps over the remaining 90% of our Milky Way.

The Copernican principle tells us we are not privileged observers of the universe, so we cannot happen to lie right beside the only example of a bubbly, sinusoidal wave of stellar nurseries in our galaxy. There must be more out there, waiting to be discovered. With next-generation space telescopes like Roman, we will be on the hunt to find them.

CATHERINE ZUCKER is an astronomer based in Cambridge, Massachusetts. She spends her days combining data science, data visualization, and gigantic ground- and space-based surveys to better understand the galaxy we call home.