How we mapped

After a centuries-long mystery, scientists now understand our galaxy's spiral shape. But there's more to unravel. by Liz Kruesi

Our home galaxy's most characteristic trait is its spiral structure. While the spiral arms may seem obvious to us now, this hasn't always been the case. Because we're embedded in the Milky Way, it's much harder to know what the structure looks like. We can observe other magnificent spiral galaxies — M51 and M101, for example — but we're looking at those face-on. When you're in the maze, it's much more difficult to understand its form.

So how did astronomers disentangle the Milky Way's structure? How did they map our galaxy's spiral arms and central bar? Both astronomers' persistence and detection methods, which have utilized a large portion of the electromagnetic spectrum, were crucial to the breakthrough. By observing different types of radiation — optical, radio, and infrared — researchers could pick out different features of the arms and piece them together for the whole picture.

A rotating disk

Galactic observations began with the most familiar form of radiation: visible light. In the 1780s, William Herschel counted the number of stars in different regions of the night sky to estimate the galaxy's shape and size. In doing so, he provided the first evidence that the galaxy is a stellar system shaped like a flat disk. He noticed that there are far more stars along that

the Milky Way

The Milky Way's center glows in infrared radiation. The galaxy's dust and other absorbing material block visible light, so astronomers must observe in infrared to pierce through the dust and view the Milky Way's secrets. NASA/JPL-Caltech

starry path in the sky — the Milky Way band — than near the poles. So he saw that path as the galaxy's disk.

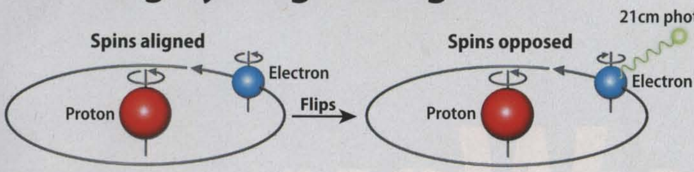
He also observed that "nebulae" (the fuzzy patches of light in the sky) aren't distributed uniformly in all directions: Their number increases as one looks away from the galaxy's plane. He didn't know it then, but the reason there appear to be more nebulae away from the disk is that the plane has more dust, stars, and gas that obscure our vision.

Another big step forward came more than a century later when astronomers began to discover that the disk rotates around a central region. The fact that the galaxy has a flattened disk suggests it's rotating. Think of pizza dough thrown in the air. What starts out bulky ends up thinning into a flattened disk because of rotation. Conversely, large orbiting star systems called globular clusters are arranged somewhat spherically, which suggests that as a whole they don't rotate with respect to the galactic center. While individual globulars have random motions, the system doesn't rotate.

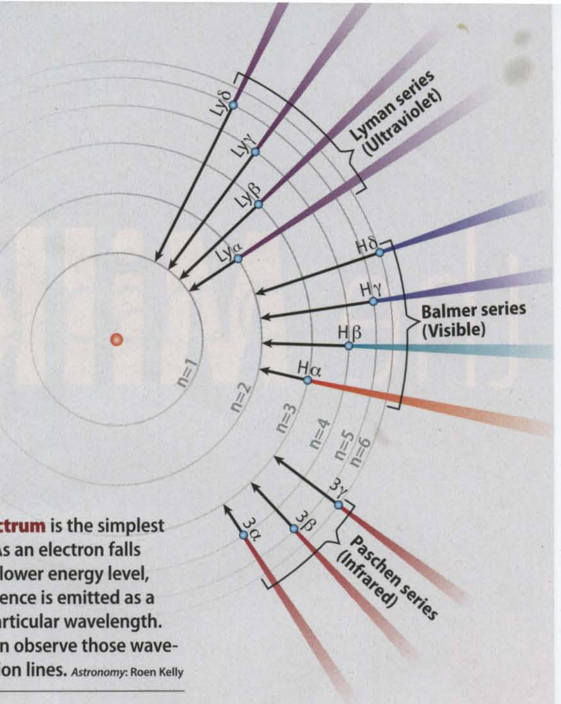
It wasn't until 1927 that astronomers found proof of the Milky Way's rotation. Dutch astronomer Jan Oort, building on Swedish astronomer Bertil Lindblad's theory, explained the relative motions of nearby stars as an effect of galactic rotation.

So the galactic disk is rotating, but where is its center? When observing the plane in visible light, the

Reading hydrogen's signature



At neutral hydrogen's lowest energy level — n=1 in the diagram to the right — the electron and proton both have a spin. This spin is analogous to Earth and the Sun spinning separately as Earth rotates around the Sun. The electron's spin can either align with the proton's spin (left) or oppose it (right). As the electron's spin flips from the higher energy state to the lower, it emits a 21-centimeter wavelength photon. *Astronomy*: Roen Kelly



Hydrogen's spectrum is the simplest of all elements. As an electron falls from a higher to lower energy level, the energy difference is emitted as a photon with a particular wavelength. Astronomers then observe those wavelengths as emission lines. *Astronomy*: Roen Kelly

part that's toward Sagittarius is brighter than other parts. This implies that the center is in Sagittarius' direction. Additional evidence came by way of American astronomer Harlow Shapley in 1918. He determined the locations and distances to 69 globular clusters. Assuming they're arranged in a roughly spherical distribution, he found their average center of motion is just south of the Milky Way's plane. And because the richest concentration lies in the direction of Sagittarius, he assumed (correctly) that the center lies there. Many studies throughout the following decades proved this finding and also added to it: Our Sun is about 26,000 light-years from the center.

Tracing the arms

Prior to the advent of stellar mapping techniques, astronomers suspected the Milky Way is a spiral because of two main facts: The galactic system is flat, and they knew that hot young blue stars exist. From observations of other spiral galaxies, they saw blue stars within star-forming regions speckling the arms.

Astronomers believe arms form because of spiral compression waves, or "density waves," moving through the disk. These waves move at a different speed compared with the material in the plane. So stars, gas, and dust compress as they enter a region of higher density (the entrance to the arm), in the same way there's a traffic jam on the expressway. As this compression happens, it initiates star formation. After the material gets past the entrance point, the density falls.

In the late 1940s, German-born American astronomer Walter Baade and American astronomer Nicholas Mayall studied M31's spiral structure and found that young blue stars and their surrounding gas clouds, or "emission nebulae," trace the arms. So astronomers began looking for such objects.

Ultraviolet radiation from hot young blue stars within hydrogen gas clouds ionizes the hydrogen. Ionized hydrogen (HII) emits characteristic colors, or wavelengths. Astronomers then look for these wavelengths to map the HII.

In 1951, astronomers gained direct evidence of the galaxy's spiral arms. American astronomers William W. Morgan, Stewart Sharpless, and Donald Osterbrock observed two parallel strips of HII regions, which correspond to spiral arms.

Observing emission nebulae and blue stars in visible light worked well for the galaxy's nearby structure. But as astronomers found out, the galactic plane has gas and dust that obstructs light. They would have to find another tool to observe more distant portions of the galaxy.

Something's out there

In 1930, Swiss-born American astronomer Robert Trumpler proved that dust and gas affect starlight. He observed some 100 "galactic clusters" of young stars and calculated their distances two ways. First, he assumed the clusters had the same diameter, and that would mean that the smaller a cluster appeared, the farther away it was. Second, he compared the observed luminosities of certain stars with their intrinsic luminosities (estimated from their spectral types). The dimmer the observed brightness, he concluded, the farther away the cluster was. The data from both methods should have matched if the galaxy didn't contain any absorbing material. But they didn't line up, which meant gas and dust were obstructing light in the plane.

The gas and dust, called the interstellar medium (ISM), absorbs and scatters — and therefore dims and reddens — starlight. How does this happen? Visible light's wavelength is similar in scale to dust particles and gas molecules. So the ISM scatters visible light. Longer wavelengths (such as radio and

William Herschel counted all stars visible in select regions to create his map of our galaxy. He placed the Sun (shown as the larger "star") near the center because astronomers at the time didn't know of the dust and other material in the Milky Way's plane. Linda Hall Library of Science, Engineering, and Technology

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Dust in the galaxy's disk severely hampers our view. It wasn't until 1930 that astronomers realized gas and dust affect starlight. Tunç Tezel

infrared), on the other hand, can make it through the ISM unimpeded. Naturally, the next step was to move away from visible mapping techniques.

The radio revolution

In 1944, Dutch astronomer Hendrik van de Hulst predicted that neutral hydrogen atoms in galactic gas clouds emit radiation at a characteristic wavelength. This sharp emission lies at a wavelength of 8.3 inches (21 centimeters). So astronomers looked for this "21cm line" to chart the location of hydrogen in the disk, assuming the hydrogen would map out the spiral arms.

To map in radio emission, scientists must decide on a general section of the sky to observe (say with dimensions of 20° by 20°). They then pick a few specific locations and measure (in that wavelength) along that line of sight — gathering information about everything that the line intersects.

Remember that the galactic disk is rotating, so every hydrogen cloud they observe is moving, and therefore its emission lines shift along the electromagnetic spectrum. For a patch moving toward the observer, the detected wavelength will be smaller because the wavelengths are condensed. If it's moving away from the observer, the wavelengths will stretch and therefore be longer. This is called the Doppler effect. You likely have encountered this as the sound of a train moving away from or toward you. As the train moves toward you, the pitch you hear is higher (shorter wavelength) than what you hear when it moves away from you (longer wavelength).

By comparing the measured emission line with the standard 21cm line, astronomers can determine at what velocities the hydrogen clouds are moving. The 21cm line doesn't provide an actual distance. That must be calculated using the detected velocity. In our galaxy, just like any rotating, flat object, an object's speed depends on its distance from the center.

Astronomers measure the speeds of stars in other galaxies and compare those versus the stars' distances to create "rotation curves." They also create such a plot for the Milky Way, except it's more difficult when you're within the galaxy.

In addition to knowing how velocity varies with distance from the galactic center, astronomers must know how far the Sun is from the center. Remember, it's about 26,000 light-years distant.

So each cloud along the line-of-sight measurement will be at a different distance from the center and therefore traveling at a different speed. The scientists see multiple sharp emission lines near 21cm, but slightly Doppler-shifted.

They have the clouds' velocities, and by comparing the velocities to the rotation curve, the astronomers can determine the clouds' distances from the center. Now the astronomers can plot the clouds' locations. And it turns out the clouds trace spiral arms. In 1953, Oort and van de Hulst were the first to publish results from a 21cm radio survey.

Like any galaxy mapping survey, astronomers have to take 21cm observations with a grain of salt. Some galactic sections

M51: Bob and Janice Fera; M101: John Smith

Compared to the Milky Way, M51 (top) is a more compact grand design spiral and M101 (bottom) is a looser spiral. Astronomers have used many mapping techniques to determine our galaxy's structure.

Astronomers obtained the first image of our galaxy's central bulge in infrared in 1990. The Diffuse Infrared Background Experiment (DIRBE) mapped stellar emission along the Milky Way's plane in three different infrared wavelengths to create this composite. The COBE Project/DIRBE/NASA

deviate from circular motions; some move randomly. By combining different methods, astronomers can piece together a more accurate structure map.

By the late 1950s, astronomers knew that the Milky Way has several arms that are trailing as the galaxy rotates. They also knew that our galaxy is probably not a compact grand design like M51, but it's more compact than M101 (see galaxy images on page 31).

Roughly half the hydrogen in the ISM is not atomic (single atoms of hydrogen), but molecular H_2 (meaning that it's made up of two hydrogen atoms). H_2 emits weak radio wavelengths. However, carbon monoxide (CO) emits strongly in radio and shows up in the same locations as H_2. These molecules also appear in a relatively consistent ratio. So astronomers can chart H_2 by tracking CO's emission lines.

In the 1970s, scientists began mapping CO, and therefore H_2, regions. They used different radio techniques to piece together a map of the galaxy's spiral structure.

However, even with those methods they struggled to understand the structure within the galaxy's inner regions. In the late 1950s, astronomers observed curious motions of the arms close to the core. They noticed that the gas didn't simply rotate around the center (like the rest of the galaxy) — it also moved away from core. They called it the "3 kiloparsec expanding arm." But what created this arm?

Some suggested our galaxy might harbor a central bar extending some 10,000 light-years (3 kpc) from the center on each side. At the bar's ends could be a ring structure or spiral arms. Determining the structure of our galaxy's center would have to wait until the 1990s when infrared satellites were lofted into space.

Filling out the picture

Researchers continued their multiwavelength assault of the Milky Way. They soon turned to infrared — higher energy (shorter wavelength) than radio but lower energy (longer wavelength) than visible light. Because infrared passes unimpeded through galactic dust, astronomers could observe the galactic core through the dusty haze. Although astronomers observed the Milky Way in infrared as early as the 1950s, they found little success because Earth's atmosphere blocks most of the infrared spectrum.

NASA's Cosmic Background Explorer (COBE) fixed this problem by carrying into space the infrared detector Diffuse Infrared Background Experiment (DIRBE). In 1990, DIRBE took the first near-infrared image of our galaxy's central bulge. The view was impressive — and the edge-on image looked just like other spiral galaxies' profiles.

Additional infrared surveys have created sharper images of our galactic plane and the bulge. But probably more importantly, astronomers now can see through the dust and study the motions of the stars near the core.

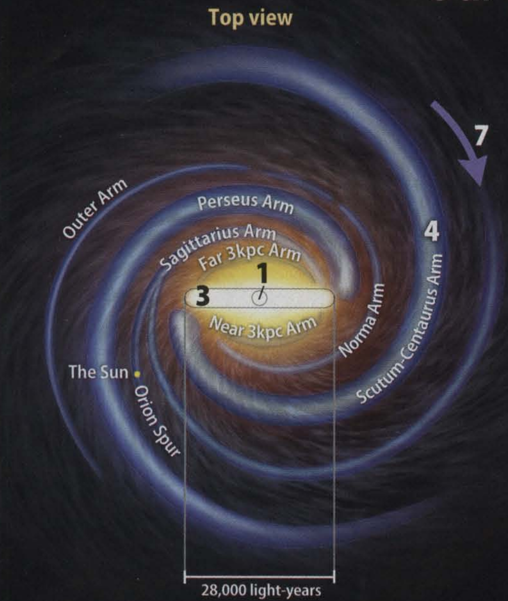
Finding the unseeable

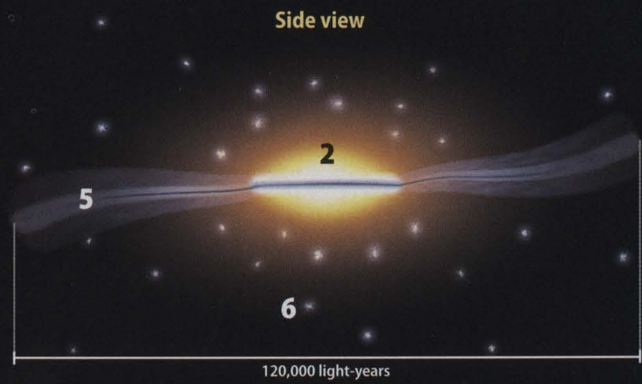
In the 1970s, while astronomers were mapping the galaxy's spiral structure, they happened upon a mystery. Imagine the surprise when the stars in the outer parts of the Milky Way didn't do what scientists predicted. They expected the velocities to reach a maximum and then decrease farther from the center. But instead the stars' speeds reach a maximum and then plateau. With velocities of this magnitude at the outer edge of galaxies, the stars should fling out of their orbits. But they don't. So some sort of mass that we can't see must hold these outer stars in their paths.

The Milky Way Galaxy that astronomers were so familiar with (which included a disk, core, and spherical halo) represented only part of the structure. Another huge halo of invisible matter, called dark matter, surrounds our familiar galaxy. That halo is some 5 times wider than the luminous part of our galaxy and about 10 times more massive. Today's surveys still haven't given astronomers much new information about this odd invisible matter. — *L. K.*

The Milky Way Galaxy is embedded in a dark matter halo. This simulation shows the dark matter density, where brighter areas correlate to higher density. Diemand et al.

Our galaxy — a primer





1. The **galactic center** lies about 26,000 light-years from Earth.
2. The **galactic bulge** is a spherical population of stars orbiting the center.
3. The **galactic bar** is some 28,000 light-years long. Stars orbit in narrow elliptical paths.
4. **Spiral arms** are regions of higher density and compression of gas. This compression triggers star formation.
5. The **galactic disk** contains most of the galaxy's stars. It's some 120,000 light-years wide.
6. **Globular clusters** orbit the center within the spherical halo.
7. **Rotation of material** helps maintain the galaxy's disk shape.

After centuries of research, astronomers have a pretty good idea of what our galaxy's structure looks like. They know it has a central bar and four spiral arms, where two appear more prominent than the others. (The Outer arm is a portion of the Norma arm.) The disk also seems to have a slight warp as one looks toward the edges. *Astronomy*: Roen Kelly

Remember that in the 1950s some astronomers noticed that the gas didn't move as expected within a radius of about 10,000 light-years (3 kpc). Infrared studies have the ability to explain what caused those motions.

In the 1990s, scientists were analyzing infrared studies of the galactic center from balloons and DIRBE. They observed the bulge as elongated and slightly "thicker" on one side — thus implying a bar that is angled to us (as it rotates around the center).

A more recent study nailed down the bar's existence. In 2005, the Galactic Legacy Infrared Mid-Plane Survey Extraordinaire (GLIMPSE) survey observed further into the mid-infrared wavelengths and catalogued some 30 million sources to accurately map the galactic center. GLIMPSE astronomers observed a greater star count on one side, which implied a bar. They also determined that the bar has a length of about 28,000 light-years. Compare that to the Sun's distance from the galactic center (26,000 light-years).

So what is a central bar? It's a large grouping of stars moving in elongated elliptical orbits around the center. Two spiral arms — the Scutum-Centaurus and Perseus — attach to the ends of the bar. Two other arms likely start from the long sides of the bar.

And here's the kicker. For decades, astronomers believed our galaxy has four major arms — Perseus, Sagittarius, Scutum-Centaurus, and Norma — along with a few spurs (such as the Orion Spur, where we live). But in 2008, the GLIMPSE survey made another big discovery: Our galaxy may have two major arms and two minor arms. Scutum-Centaurus and Perseus appear rich in gas, young stars, and old stars. But Sagittarius and Norma seem to be mostly gas sparsely sprinkled with stars.


ESO

M83 is a barred spiral galaxy, like the Milky Way. Astronomers think that if we could view our home galaxy from above, it might look something like M83.

Astronomers have used radio, infrared, and visible light to come up with a fairly detailed map of the galaxy. The disk is about 120,000 light-years wide, with a central bar 28,000 light-years long. We are 26,000 light-years out from the core and move at 140 miles per second (220 km/s). But there are still a lot of mysteries — the composition of dark matter and how many arms are there, just to name a couple. Astronomers won't lack research topics anytime soon.

A+ Our galaxy is one of many; how and when did astronomers determine this? Visit www.Astronomy.com/toc to find out.