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GALAXY EVOLUTION

Milky Way Researchers' Home Away From Home

Right next door and easy to study, Andromeda provides an excellent model of how our own galaxy probably evolved

If you were stuck forever inside your house, you could still learn a lot about houses by studying the one across the street. For astronomers trapped inside the Milky Way, the Andromeda galaxy is that neighboring house. And unlike the Milky Way, it can be imaged and studied in its entirety. At a distance of 2.5 million light-years, it is our closest galactic neighbor comparable to the Milky Way: far enough to offer a global view and close enough for telescopes to take a good look at individual stars inside it.

As such, Andromeda has come to be regarded as one of the best models available for understanding the evolution of galaxies, including our own. That's why it has acquired a dedicated fan club of astronomers who have been studying the galaxy in ever-increasing detail over the past 15 years. These studies have helped astronomers define Andromeda's structure with unprecedented clarity, showing that the galaxy's disk and halo extend far beyond the boundaries that had been assumed before. The details of the picture are providing clues about how Andromeda came to be the galaxy it is today.

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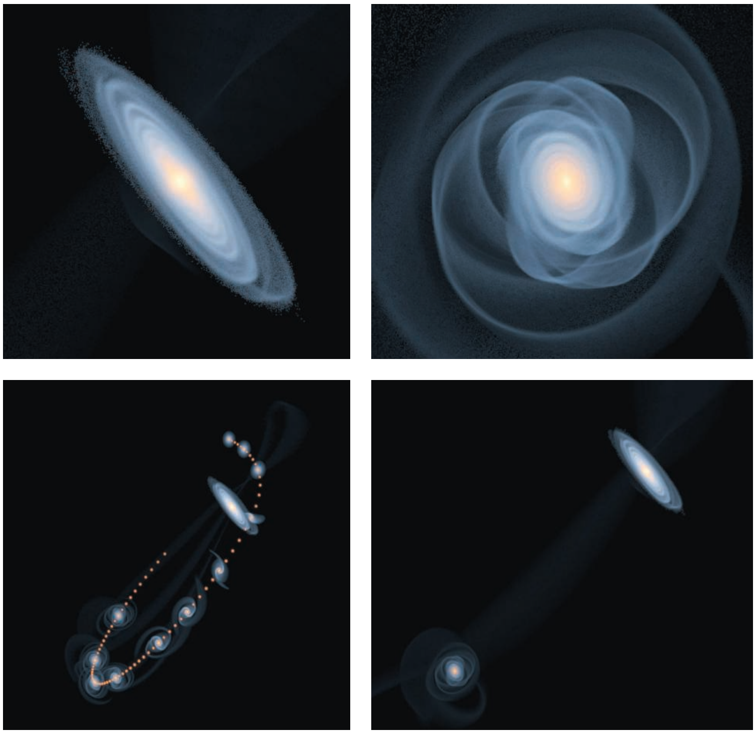
Over the years, astronomers have discovered a dozen stellar streams falling into the outer regions of the galaxy that have been shown to be the remnants of smaller, satellite galaxies. The presence of these so-called tidal streams indicates that Andromeda has swallowed up numerous smaller galaxies in the past, incorporating their stars, gas, and other matter into its structure over billions of years. By studying the velocities and chemical compositions of stars within these streams and elsewhere in the galaxy, astronomers are beginning to piece together a detailed evolutionary history of Andromeda.

The results confirm the long-held idea that large galaxies like our own have formed through the hierarchical assembly of smaller galaxies. The picture is what astronomers expected to see based on current theories of dark matter, the invisible stuff that makes up 80% of the universe. "The fact that Andromeda seems to be surrounded by all of these streams is a smoking gun that hierarchical structure formation is happening," says James Bullock, a theoretical cosmologist at the University of California (UC), Irvine. "So indirectly, these numerous streams provide compelling evidence that we are not so far off base in our understanding of dark matter."



Steady loss. A simulation showing how the Triangulum galaxy is beginning to lose stars and gas to Andromeda as it orbits the larger galaxy.

Mistaken identity

Andromeda can be seen in the night sky with the naked eye. Like the Milky Way and other spiral galaxies, it consists of a flat, rotating disk of stars with a central bulge, nested inside a more-tenuous spherical halo of stars. Understanding the precise characteristics of its structure has gone hand in hand with efforts to understand its evolution.

Until the early 2000s, astronomers thought Andromeda's halo was metal-rich: that is, made up of stars containing heavier elements in addition to hydrogen and helium. Because heavy elements formed relatively late in the universe's history, their presence is a marker of youth. Researchers studying the halo in 2002 estimated that a third of the stars were between 6 billion and 8 billion years old—nearly 4 billion years younger than most of their counterparts in the halo of the Milky Way. One possible explanation for the difference was that Andromeda began to form much later than the Milky Way did.

But that age estimate turned out to be a case of mistaken identity: The stars that researchers had identified as belonging to Andromeda's halo were in fact from the outer reaches of the galaxy's bulge, where stars had been recently forming. Using the Keck telescopes atop Mauna Kea in Hawaii, a collaboration led by Puragra Guhathakurta of the University of California, Santa Cruz (UCSC), spotted faint stars far out from the bulge—up to five times farther out than where stars had been sighted before. In 2005, Guhathakurta's collaboration—which goes by the name SPLASH (Spectroscopic and Photometric Landscape of Andromeda's Stellar Halo)—reported that these newly discovered stars were part of Andromeda's true halo and were as ancient as stars in the halo of the Milky Way.

Star man. Guhathakurta helped locate Andromeda's true halo.

The finding meant that Andromeda and the Milky Way were likely to have evolved through similar processes: interactions with other, ancient galaxies. Because the newly discovered stars could not possibly have been born so far from the central star-forming regions in Andromeda's disk, astronomers concluded that they probably came from other galaxies that were sucked into Andromeda.

Death plunge

Astronomers had already glimpsed one clear incident of cannibalism by Andromeda. In 2001, peering through the Isaac Newton Telescope on the Canary Islands, Rodrigo Ibata of the Strasbourg Observatory in France and his colleagues discovered a dense line of stars poking through Andromeda's southern halo and pointed toward its disk. They realized that it was a giant stream of stars moving in unison. "It was plunging radially toward the center of the galaxy," says Scott Chapman, an astronomer at the University of Cambridge in the U.K. and a co-author of a *Nature* paper reporting the discovery.

In 1994, Ibata had discovered a similar stream flowing into the Milky Way, which researchers determined to be a flow of stars from the Sagittarius dwarf elliptical galaxy, a satellite galaxy being shredded by the Milky Way. In Andromeda's case, the Giant Southern Stream—as the structure came to be called—was speculatively linked to two of Andromeda's satellites, M32 and M110, although there was no firm evidence for the connection.

The stream quickly became the subject of detailed studies aimed at nailing its progenitor and figuring out exactly how the cataclysmic shredding had proceeded over time. Mark Fardal, now a postdoc at the University of Massachusetts, Amherst, was at the forefront of these efforts. Using data

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on the velocities and chemical abundances of stars within the stream, which revealed bifurcations and narrower currents inside it, Fardal came up with simulations of the event. He concluded that the stream had not come from M32 or M110 after all. It was likely some other local satellite that had been completely cannibalized by Andromeda, leaving no trace outside Andromeda's halo.

Fardal suspects that the vanished satellite may have begun its plunge into Andromeda 700 million years ago. By that time, Andromeda's gravitational pull had gradually stripped the satellite of dark matter and outer stars over hundreds of millions of years. "It's the same phenomenon as tides on Earth, only much more extreme," Fardal says. "You get a stretching of the satellite that results in stars being unbound from it." In Fardal's estimate, the satellite behind the Giant Southern Stream may have been as massive as 3 billion suns, less than 1% of the mass of the Milky Way. Its shredding not only brought new material into Andromeda but also likely sent shock waves rippling through the galaxy, which might have induced the formation of new stars in other regions and shaped the overall structure of the galaxy in unknown ways.

After the discovery of the Giant Southern Stream, astronomers stepped up efforts to look for other streams within Andromeda. Looking through the 8-meter Subaru telescope in Hawaii, SPLASH collaborators Mikito Tanaka and Masashi Chiba of Tohoku University in Japan discovered two dense lines of stars in the northwest region of the galaxy. An analysis of the stars' spectra yielded their velocities, from which researchers at UCSC confirmed that the lines were indeed streams. The stars were moving coherently "as a group that 'remembers' the orbital speed of the progenitor dwarf galaxy to which the stars once belonged," Guhathakurta says.

Mergers everywhere

More recently, several more tidal streams have been discovered by the Pan-Andromeda Archaeological Survey (PAndAS), a collaboration led by Alan McConnachie at the Herzberg Institute of Astrophysics in Victoria, Canada. Observing with the Canada-France-Hawaii Telescope, the researchers surveyed the entire outskirts of Andromeda, identifying 17 dwarf satellites that had not been known before.

"Some of the satellites are in a stage of significant disruption; others don't appear to be getting disrupted at all," McConnachie says. "We also see a bunch of streams that don't seem to have a satellite connected to them, which means the satellite has exerted completely consumed."

The survey also showed just how powerful an influence Andromeda has exerted on its neighborhood. McConnachie says he and his colleagues were surprised to discover that Andromeda was starting to nibble stars away from the Triangulum galaxy, a neighbor that is half the size of the Milky Way and several times larger than any dwarf. The researchers expected Triangulum's significant size and heft to protect it from Andromeda's gravitational tug.

But on the edge of Triangulum, they saw "a vast, extended, distorted distribution of stars, which is exactly what you would expect of stars pulled off of Triangulum," McConnachie says. His group has done simulations showing that "about 3 billion years ago, the Triangulum galaxy passed relatively close to Andromeda, and Andromeda's gravity caused several of Triangulum's stars to unravel," McConnachie says. At some point in the future, Triangulum could end up as a line streaking through Andromeda's halo into its center.

"We've gone from not really knowing that galaxy cannibalism occurs to having a few examples of the process to knowing that this is an extremely common process."

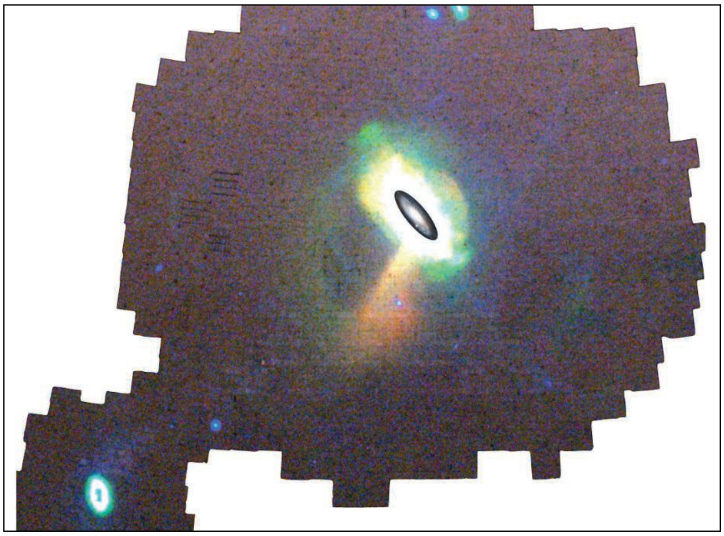
—ALAN MCCONNACHIE, HERZBERG INSTITUTE OF ASTROPHYSICS

The discovery of the various tidal streams has convinced astronomers that the chewing up of small galaxies by bigger ones—and more generally galaxy mergers—are a frequent occurrence in the universe. "We've gone from not really knowing that galaxy cannibalism occurs to having a few examples of the process to knowing that this is an extremely common process," McConnachie says.

Guhathakurta says the number of streams suggests Andromeda may have had "a more troubled past than the Milky Way." Researchers are now digging deeper into the streams to get a better handle on questions such as the durations of encounters with different satellites, the orbits of the progenitor galaxies, and the structural and chemical characteristics of the satellites before they were swallowed.

The study of Andromeda has provided theorists with a rich trove of data to test ideas of galaxy evolution, says Bullock. "We can actually predict fairly accurately how many little dwarf galaxies should have been accreted and destroyed," he says. "The first of these predictions were in place before PAndAS and SPLASH made their discoveries, and things look pretty good in comparison." He says continued investigations of Andromeda will be critical for gaining key insights about the universe at large. "For example, how small do the dark matter clumps have to be before they stop making galaxies?" he says. "Andromeda provides a perfect place to explore these questions."

–YUDHIJIT BHATTACHARJEE



Assimilated. Reddish streak of stars high in heavy elements shows remains of a dwarf galaxy on Andromeda's outskirts.

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