# How Galaxies Grow

*Camille M. Carlisle*

**The universe's stellar metropolises rend, chew, and merge with one another. But how important are these encounters in creating the galaxies we see today?**

**Many of us have** a rough-and-tumble view of galaxy growth. In this savage landscape, the rules are simple: eat or be eaten. Spirals tear up dwarfs and munch them like Fruit Roll-Ups. Big galaxies smash together and, in their cannibalistic fervor, gnash each other beyond recognition. Cosmic history can seem like the tale of galaxies playing a grim game of king of the mountain.

In the very early universe, when protogalaxies reigned and things were more of a mishmash, a riotous picture might have had some truth to it. But in their observations of the universe's past 10 billion years astronomers have found that, when it comes to how galaxies grow, the whopping crashes of whirligigs aren't as big a deal as you might think. The cosmos isn't the Wild West; many stellar cities don't land themselves in all-out brawls.

That hasn't always been the thinking. Astronomers have flip-flopped several times on how important mergers are in galaxies' evolution, says Pieter van Dokkum (Yale). In the mid-20th century, astronomers simply weren't thinking of mergers. Then, with the development of modern cosmology in the 1980s, the idea arose that these unions were the main driver of galaxy growth. And in the late 1990s and early 2000s, astronomers discovered that the most massive galaxies already existed within the universe's first few billion years, making some wonder if mergers even had time to play a role and if the whole cosmological framework was wrong.

**MINOR SKIRMISH** Arp 273 includes a spiral galaxy (top) that has had its arms pulled askew by a second, smaller galaxy about one-fifth its mass (bottom). The smaller companion perhaps dove through the larger one on an off-center trajectory, explaining the stretched spiral. The encounter likely triggered the clusters of newly formed stars (blue). A small orange core embedded in the spiral's outer right arm might be a third galaxy.

NASA / ESA / HUBBLE HERITAGE TEAM (STSCI / AURA)

Today, we occupy some sort of middle ground. "I think everyone would agree that merging is a fundamental and important process," says Eline Tolstoy (University of Groningen, The Netherlands), "but I think we would disagree with each other about exactly how that manifests itself from one galaxy to the next."

## Sorties and Wars

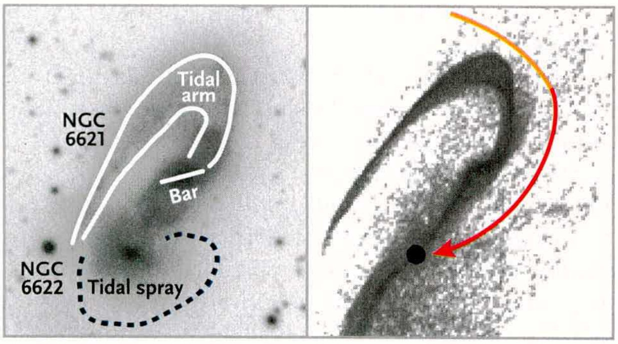
On the largest scales, cosmic structure looks like a sponge. Veins of dark matter, gas, and galaxies outline sparse voids. This spongy structure formed thanks to gravity, which exacerbated small blips in the nascent universe's density, pulling dark matter (which makes up most of cosmic particles) into a web of filaments and nodes. As this network coalesced, the first galaxies also formed, like coffee spilled on a cobbled floor, James Geach (University of Hertfordshire, UK) writes in his book *Galaxy: Mapping the Cosmos*. The sloshed coffee collects in the grooves between cobbles, much the same way the universe's pristine gas drained into gravitational valleys created by dark matter.

After that initial startup, galaxies continued to grow. For the first few billion years, they looked very little like the ones we see today — they were clumpy and turbulent, a hodgepodge of objects. Star formation ramped up, peaking across the universe about 10 billion years ago, during what astronomers call cosmic high noon. Then it dwindled, to less than one-tenth that rate today. Even so, about 95% of the stars shining now formed in the last 10 billion years, van Dokkum says.

## GALACTIC CRASHES

**Major and minor mergers** have different effects on the galaxies involved. NGC 6621 and 6622, also known collectively as Arp 81 *(right)*, exemplify the interaction of two evenly matched systems: the encounter has torn both galaxies apart. On the other hand, the large spiral NGC 5754 *(below)* is five times more massive than NGC 5752 *(fuzz to its right)* and survived their recent encounter relatively unscathed. *Facing page:* William Keel (University of Alabama) and Kirk Borne (now at George Mason University) endeavored to reconstruct these systems' major tidal structures (labeled images) in simulations of the interactions. In the simulation diagrams, the big dot marks the center of the contender that looped around, and orbits are orange where they passed behind the other galaxy from our perspective.

NGC 5752/4 AND NGC 6621/2: NASA / ESA / HUBBLE HERITAGE (STSCI / AURA) & ESA / HUBBLE COLLABORATION / W. KEEL (UNIV. OF ALABAMA, TUSCALOOSA); SCHEMATICS: S&T: GREGG DINDERMAN, SOURCE: W. KEEL AND K. BORNE / *ASTRONOMICAL JOURNAL* 2003

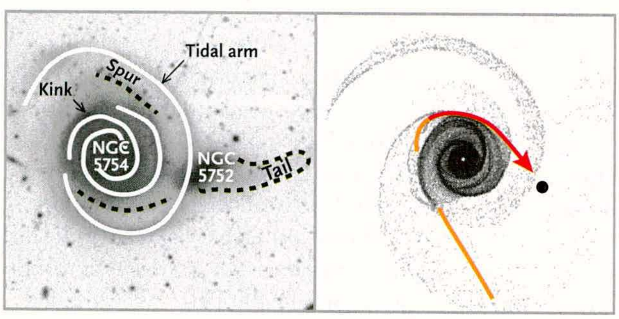



"The Milky Way wasn't really around yet, as we see it now," he says. Astronomers think that the types of systems present today — ellipticals, lenticulars ("lens-shaped"), spirals, barred spirals, and all the siblings in each of those groups — took shape between 6 and 10 billion years ago. So if we can track what's happened to stars over the last 10 billion years, we'll know how most of today's stars ended up where they are.

That's why a lot of the action — and the mystery — centers on cosmic high noon. Astronomers are fairly confident that smaller clumps of gas combined to build galaxies' early precursors. The question is what came next: how do you turn a galactic shantytown into a megalopolis?

Astronomers often tackle galaxy growth by looking at star formation, because star formation essentially *is* growth. To amass extensive stellar suburbs, galaxies need to build upon the finite resources they first incorporated. That means they need to either nab stars from elsewhere or find more gas to keep creating their own.

This sticking point is where mergers come in. When astronomers talk about mergers, they generally mean the interaction of full-grown galaxies after the universe's first couple billion years. But not all mergers are equal.




Some — including those that make for the most breathtaking Hubble images — involve two large, well-matched adversaries, such as NGC 4038 and 4039, the Antennae Galaxies in Corvus. These *major mergers* happen when one contender is at most four times more massive than the other. Major mergers spur dramatic changes, creating a maelstrom of shock waves and turbulence in the galaxies' gas clouds that subsequently triggers star formation. Toward the end of the merger, the interaction can also drive a large amount of gas into the new galaxy's center, feeding the supermassive black hole (or holes) in the core and fueling a *starburst phase*, during which hundreds to thousands of Suns form per year for a few million years.

These mergers are spectacular, but they're not terribly common. In 2009 Shardha Jogee (University of Texas at Austin) and colleagues looked back 3 to 7 billion years ago at galaxies slightly smaller than the Milky Way. The team found that approximately two-thirds of these galaxies had suffered a merger, but only 16% had clearly been in a major duel. On the other hand, at least 45% had weathered a *minor merger*, a merger with a galaxy one-fourth to one-tenth the bigger one's mass.

Minor mergers often involve a big galaxy and a dwarf galaxy. They're more common than major ones because there are a lot of small galaxies in the universe and they tend to cluster around the larger ones, leaving themselves vulnerable to cannibalism.

When the larger system is a spiral, a minor merger can warp its disk, creating pockets of star formation or puffing the pancake up and out. In some cases the merger barely leaves a mark. But the effect is hardly minor on the smaller contender: the encounter can devastate a dwarf, ripping it apart and glomming its pieces onto the rival's outskirts.

## Building Big Galaxies

Conventional wisdom — at least, of late — is that the most massive of the melon-shaped galaxies called ellipticals form via mergers. These systems contain ancient stars moving along chaotic orbits, and they're also the heftiest stellar cities, easily 10 times more massive than the Milky Way. Astronomers don't see gargantuan ellipticals at cosmic high noon, but they do see compact, bulbous galaxies, with the stars deep inside packed as tightly as they are in today's leviathans. These *compact cores* can outweigh the Milky Way, even though they're only about

### MORE THAN ONE WAY TO SKIN A GALAXY

**Mergers aren't** the only way galaxies interact. There are also encounters that aren't (or aren't exactly) mergers. These include a galaxy sucking in gas from the space around it, and *gravitational harassment* (yes, that's the technical term), when multiple high-speed passes in a crowded cluster leave a galaxy looking frazzled. In harassment and other near encounters, galaxies move past each other too quickly to grab hold and merge. But the galaxies can still end up looking not quite themselves. How common such processes are depends on how crowded a galaxy's neighborhood is, and who its neighbors are.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**DIFFERENT PEAS, SAME POD** The galactic duo Arp 116 sits in the Virgo Cluster. The giant elliptical, M60, is roughly 10 times more massive than the spiral, NGC 4647, which is on par with the Milky Way. The galaxies lie roughly 10 million light-years from each other and make a nice pair in small telescopes. M60's stars rotate coherently, which might indicate that the galaxy has had a relatively merger-free history compared with other massive ellipticals.

a tenth the size. They began as small, star-forming galaxies that burned out early, leaving behind an aging stellar population eventually dominated by reddish dwarf stars.

Some astronomers think today's massive ellipticals started as these cores, then grew by stealing stars via minor mergers and using the captured stars to expand their borders. "If you combine those two things — that they didn't form a lot of new stars, but they've changed dramatically in how they look — they must have undergone mergers," van Dokkum says. "That, I think, is almost inescapable."

In addition, we know that mergers can create ellipticals. Simulations in 2007 by Frédéric Bournaud (now at CEA Saclay, France) and colleagues suggested that, after a galaxy has grabbed more than 30% to 40% of its initial mass from other systems, it will turn into an elliptical — regardless of whether its mergers were major or minor. And in a few billion years our own Milky Way is heading for battle with its sister spiral, the Andromeda Galaxy. Computer mockups of that merger indicate they'll combine to form a big, red elliptical (*S&T:* Oct. 2014, p. 20).

But things are never straightforward in galactic astronomy. Both simulations and observations also suggest that individual major mergers don't always destroy the combatants' disks. What matters is how gassy they are. Stars can steal angular momentum from one another via gravitational interactions, leading to helter-skelter layouts nothing like the initial, orderly pancakes. But gas dilutes this effect. If there's enough of it in the two galaxies — more than half of the contents, roughly — everything will inevitably settle down and create a disk. For major mergers, this might only have happened in the universe's first few billion years, when galaxies were particularly gassy.

In addition, today's lighter-weight ellipticals might have grown without outside help. The stars in these galaxies don't fly about randomly as they do in the biggest ellipticals; they seem to move together, rotating as a unit. The ordered motion, combined with other characteristics, suggests these systems form from really massive, star-forming galaxies, without much (if any) help from mergers. Astronomers have recently detected massive galaxies shining from 10 to 11 billion years ago that look poised to churn out enough stars to grow into big spheroids all on their own (*S&T:* Aug. 2015, p. 14). So there are likely at least two galactic breeds that can grow into the ellipticals we see today.

## Spiraling into Confusion

For less massive (but still big) galaxies, including spirals like the Milky Way, the picture is even more opaque. These galaxies haven't increased in size much over the last 10 billion years, but they have increased a lot in mass — they're denser than they once were, and denser throughout, not just in certain spots. That's distinct from what astronomers see in the massive ellipticals, which are as dense in their centers today as they were 10 billion years ago.

This difference might arise because spirals and big ellipticals acquire their material differently. Thus astronomers suspect that, instead of assembling via significant mergers, spirals accrete gas steadily, with the material deposited at all radii and not just at the galaxies' edges.

"That is the most obvious explanation," van Dokkum says. "That doesn't mean it's right, but it's the most obvious one," he adds, laughing.

The main mystery today is the role minor mergers play in spirals' evolution. In an intriguing study last year, Sugata Kaviraj (University of Hertfordshire, UK) looked at about 6,500 local spiral galaxies from the Sloan Digital Sky Survey and checked them for signs of disturbance. Since major mergers are unlikely to preserve disks in today's universe, he assumed that any disturbances — and the starbirth they induced — were from minor mergers. Given that, Kaviraj estimates that these tussles instigate roughly 40% of all the star formation going on in spirals. Coupled with a previous study he did of elliptical and lenticular galaxies, he argues that minor mergers might trigger around half of all star formation in today's universe. Other astronomers are less optimistic, suggesting that minor mergers might only ignite about 10% of the stars in a Milky Way–type galaxy.

Kaviraj thinks dwarfs spur starbirth by stirring up gas already in the larger galaxy. These spirals are "awash in gas," he says, but that gas needs compressing before it will spawn stars. "The dwarf essentially activates this gas into forming stars," he says. "What gas the dwarf itself brings into the system is pretty much irrelevant."

**ANTENNAE GALAXIES** The iconic pair NGC 4038 and 4039 represent one of the nearest and most recent galactic interactions. The two orange orbs are the original galaxies' cores. The dust (brown), young star clusters (blue), and hydrogen gas (pink) make for a beautiful but messy picture.

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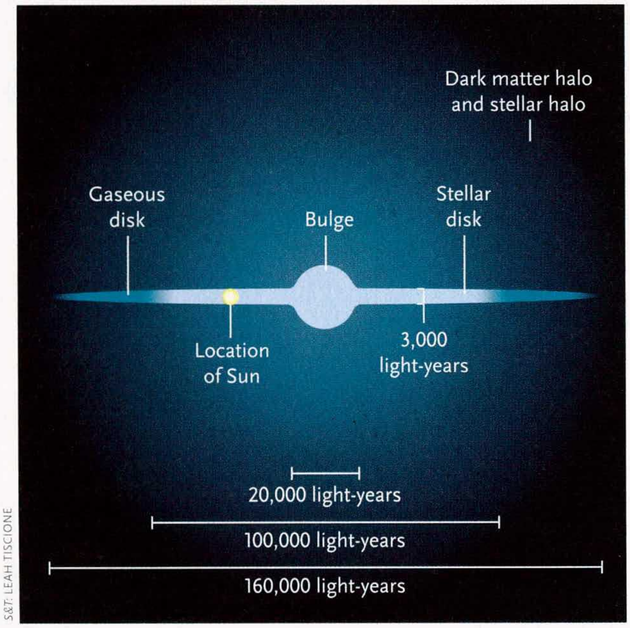



**MILKY WAY IN BRIEF** Edge-on schematic of our Milky Way Galaxy, with associated parts. Sizes are approximate.

Enrico Di Teodoro (University of Bologna, Italy) agrees that the gas in dwarf galaxies can't fuel the explosion in stars: in a study of 148 nearby spirals, he and Filippo Fraternali (also at Bologna) estimated that dwarf companions could supply at most one-fifth of the gas needed to sustain the average starbirth rate in the galaxies they observed. But he cautions that the gas in a spiral has to come from *somewhere*. Spirals generally only have enough gas to sustain a "normal" star-formation rate of one to two Suns per year for a few billion years at most. "If no fresh gas is supplied from the outside, spiral galaxies would have already exhausted their gas reservoir, and we would not observe star-forming galaxies in the local universe," he says.

Galaxies can also pull in gas directly from their surroundings, in a process called *cold-gas accretion*. Only relatively cold material can sink down deep into galaxies, cooling further until it can collapse to form stars. Astronomers think such accretion was particularly important in the early universe, when there was so much gas being channeled into galaxies that it could shove past their hot halos (which would normally stymie accretion). Simulation work by Dušan Kereš (now at University of California, San Diego) and colleagues in 2009, for example, argued that a galaxy that today has roughly 10 times the Milky Way's mass in stars built up most of that mass by accreting gas that's never been substantially heated.

Spirals' rotations, as well as how their rotation axes line up with the cosmic filaments they sit in, support the idea that these galaxies form through a more peaceful accretion of gas drawn in from their surroundings. And high-resolution simulations of the early universe also suggest that cold streams can directly connect to the edge of a galactic disk and feed the galaxy like a fuel line (see right). Because the gas is so diffuse and faint, observing such accretion is difficult in practice.

But there's the problem of semantics: when is an interaction a minor merger, and when is it cold-gas accretion? It's hard to tell when a clump of gas qualifies as a dwarf galaxy. Some astronomers draw the line based on whether the cloud sits in its own dark matter halo, as both dwarf and large galaxies do. But confirming such a halo poses its own challenges: astronomers are still debating whether a recent high-speed visitor to the Milky Way, the Smith Cloud, survived because of a magnetic sheath or because it has its own dark matter holding it together — and that gaseous object is a mere 40,000 light-years away, right in our backyard.

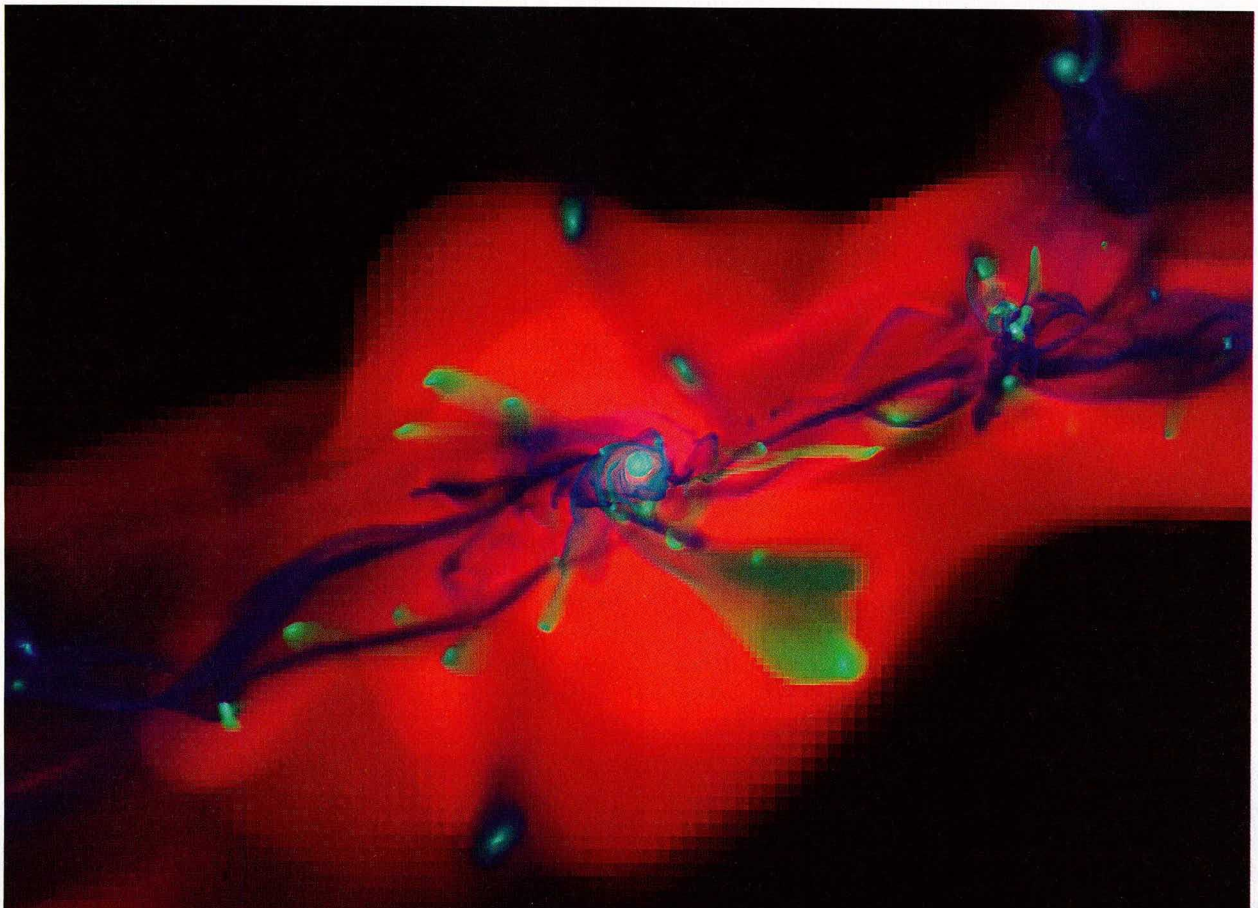
## Going It Alone

Astronomers have other reasons to doubt mergers' role. The 2009 study by Jogee's team revealed that only a third (at most) of the stars being born 3 to 7 billion years ago were in visibly merging galaxies; instead, most new stars were lighting up in galaxies that weren't interacting. Other observations support this picture: many of the stars born in the last several billion years — and thus much of the growth that's happening — arise in quiet galaxies.

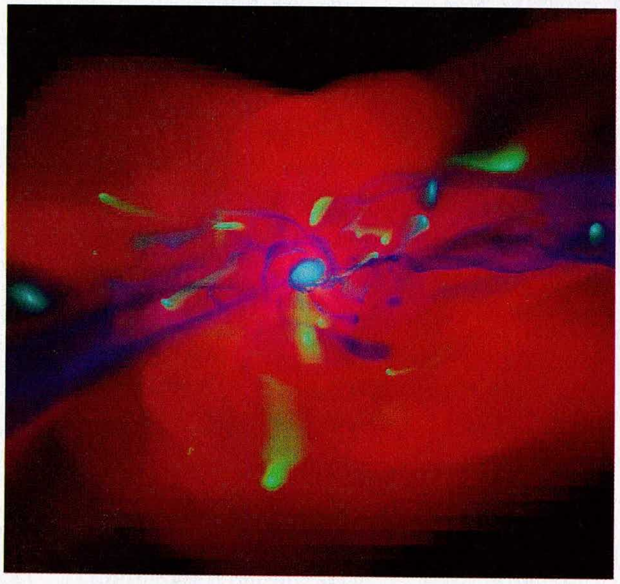
Another cause of suspicion is stellar halos. These gigantic clouds of old stars surround galaxies like the Milky Way, extending far beyond the spiral disk. Some astronomers predict that most of the halo stars come from dwarf galaxies the spiral has ripped up and eaten over time. Observers do see hints of stellar streams in the Milky Way's halo, including shreds of the dwarf Sagittarius, supporting this idea. And the Andromeda Galaxy is "a big mess," Tolstoy says, with a halo rich with substructures and clear evidence of a major accretion event. The merger debris could be from one of Andromeda's dwarf companions or another unidentified galaxy.

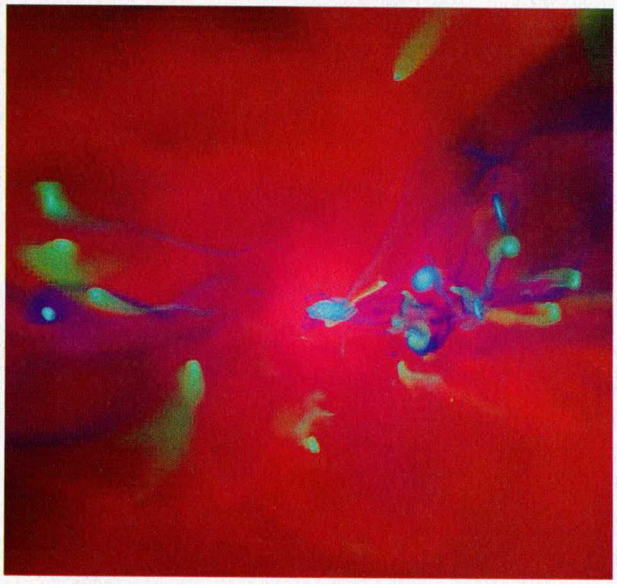
But a merger-made halo is hard to reconcile with the Milky Way's chemistry, Tolstoy warns. The halo stars astronomers have studied in detail have fairly pristine hydrogen-and-helium compositions, with low levels of heavy elements. The latter build up as stars die and seed the gas around them with things like carbon. The chemistry suggests that any consumed dwarfs had to have stopped forming stars after only a billion years, then merged with the Milky Way. "That becomes quite contrived," she says.

One unexpected turn comes from van Dokkum's team. The astronomers took a hard look at the nearby spiral M101, the Pinwheel Galaxy in Ursa Major. Using a compound instrument called the Dragonfly Telephoto Array, which combined eight Canon EF 400-mm f/2.8 telephoto lenses on a common mount, the team studied M101 down to a magnitude per square arcsecond of 32,



**COLD-GAS SIMULATION** In the universe's first couple billion years *(top)*, many protogalaxies grow by accreting cold gas along cosmic filaments (blue streams, forming galaxy in center). But as the gas falls into the gravitational well a galaxy sits in, the gas is shocked and heats up (red). At early times, the cold gas could push past the hot to accrete directly onto disks. But over time, the gas heats up and filaments become more diffuse, breaking up into smaller clouds that mix with the halo *(bottom left, 10 billion years ago, and bottom right, 7 billion years ago)*. Astronomers observe cold accretion onto the Milky Way today in the form of high-velocity clouds, potentially condensations from the galaxy's gaseous halo. One estimate puts this accretion rate just shy of one solar mass per year. To fuel the current starbirth rate, the Milky Way uses several times that amount of gas.





OSCAR AGERTZ (3)

similar to studies of the Milky Way's galactic family, the Local Group. To their surprise, the astronomers found *no* stellar halo.

If more spirals turn out to look like the Milky Way and M101, then galaxies might experience fewer mergers than astronomers think. But with only three big spirals studied at this depth, it's hard to say. "I have a completely open mind on this particular question," van Dokkum says.

## Making Sense of Mergers

Astronomers are investigating the true role of mergers in several ways. One is the work Kaviraj and others are doing, trying to determine observationally the impact minor mergers have across cosmic time. For that work, astronomers are looking to deep, large-scale projects, such as the Dark Energy Survey and the upcoming Euclid mission and Large Synoptic Survey Telescope.

There are also chemical and dynamical clues closer to home. Stars born together should have similar chemical makeups, revealing their common ancestry. A 5-year survey at Siding Spring Observatory in Australia, called GALAH (Galactic Archaeology with HERMES), is looking for these "chemical tags" in the Milky Way's halo stars, in order to identify debris from disrupted stellar clusters and dwarf galaxies. Similarly, ESA's Gaia spacecraft (*S&T:* Apr. 2014, p. 10) is hard at work compiling a detailed map of the Milky Way's stars and how they move. Preliminary Gaia data have turned up stars in the halo that do look like they've been snatched from elsewhere. But the data also suggest that our galaxy hasn't merged with anything larger than one-tenth its mass since its disk formed about 9 billion years ago. That would mean that between then and now, the Milky Way hasn't scuffled with anything bigger than the Large Magellanic Cloud.

Learning more about how the Milky Way grew will shed light on how relatively isolated galaxies evolve. And because most stars today are in Milky Way–type galaxies, understanding our galaxy and those like it will help us understand how important mergers have been in the universe overall. ✦

S&T *Science Editor* ***Camille M. Carlisle*** *might trump the universe's galaxies in snacking frequency.*

**SPIRALS DANCE** The two galaxies of Arp 238 in Ursa Major hold each other at arm's length. The arms are tidal tails of gas and stars torn from the galaxies' outer edges by the encounter.

NASA / ESA / HUBBLE HERITAGE (STSCI / AURA) & ESA / HUBBLE COLLABORATION / A. EVANS (UNIV. OF VIRGINIA, CHARLOTTESVILLE / NRAO / STONY BROOK UNIV.)

## How Astronomers Watch Galaxies Age

**It's hard to track** galaxies across cosmic time. As astronomers study the universe at higher and higher redshifts, pushing farther back in cosmic time, they essentially take snapshots of what galaxies looked like at a particular moment. But these snapshots show an assortment of galaxies at different look-back times; they don't track the same set of stellar metropolises through their evolution across 10 billion years. Instead, astronomers have to connect the dots between epochs based on what they see.

"It's like having the fossil record: you see all these different animals at different times, but then you have to say, 'Okay, this dinosaur turned into this chicken,'" quips Pieter van Dokkum. In biology, scientists have genetic tools to help them understand the record. "We haven't quite found the DNA of galaxies yet."

Sans galactic DNA, astronomers often turn to mass as a proxy: they assume that the first, second, third, and so forth most massive galaxies today were also one of the first, second, third, and so forth most massive galaxies 5 billion or 10 billion years ago — in other words, they rank them by mass, and then use that rank as a sort of roll call to pick out the progenitors of today's galaxies across cosmic time. So long as galaxies don't on average hopscotch over one another in the mass pecking order, this trick works. Rank order is how astronomers determine that, compared with their appearance now, the progenitors of today's disk galaxies were fluffier but about the same size several billion years ago. In fact, disk galaxies' precursors seem to have a range of appearances about 8 billion years ago, from smooth or unstable disks to interacting systems.