News

As the Galaxies Turn

Spiral disk galaxies, serene icons of the universe, are hardy survivors of a battering cosmic history

Gravity conspires to produce two dominant shapes in astronomy: spheres and disks. Both are on display in spiral galaxies, home to perhaps half the stars in the universe. Spherical central bulges of old yellow suns glow serenely, girdled by a disk consisting of curved arms of hot new stars and dark bands of dust. Such grand stellar disks, long the pinups of astronomy buffs, now play a starring role in studies of how galaxies have evolved.

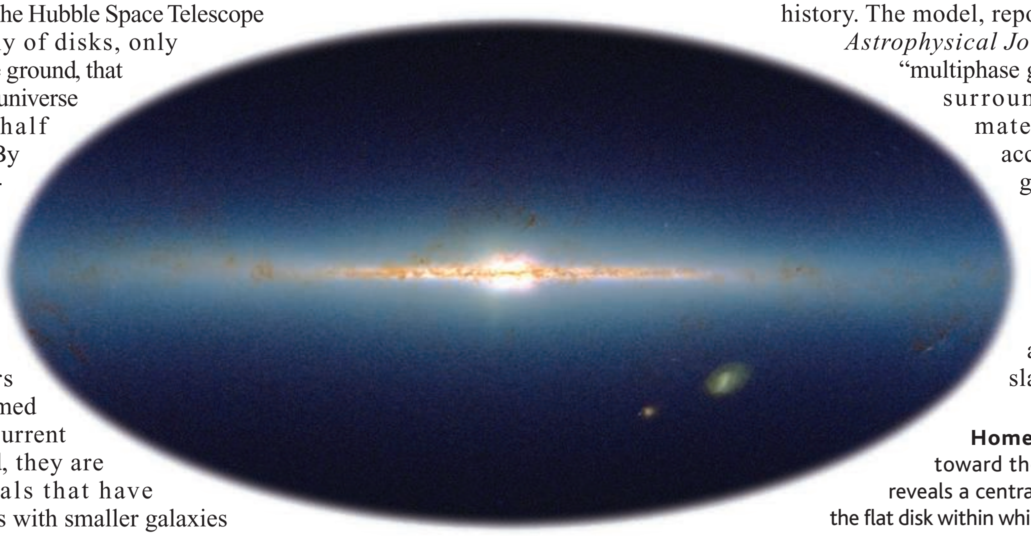
Surveys with the Hubble Space Telescope reveal a panoply of disks, only hinted at from the ground, that existed when the universe was less than half its current age. By dating and classifying this huge population, astronomers are recognizing that spiral galaxies are not delicate flowers that have blossomed slowly to their current display. Instead, they are tough perennials that have survived mergers with smaller galaxies and—on occasion—crushing collisions with big ones throughout billions of years of cosmic time.

In our edge-on view of the Milky Way's plane, we gaze upon just such a stalwart bisecting the night, one that undoubtedly consumed other galaxies. The Milky Way's disk provides clues to this history, but the sleuthing is tough because we're embedded within it. "We have an opportunity to understand it at a much deeper level than other galaxies, because we can measure the motions of individual stars," says astronomer Heidi Jo Newberg of Rensselaer Polytechnic Institute in Troy, New York. "But we're really just starting."

It's all in the gas

The disks we see today took a long time to develop. "Almost all star formation was in clumps and chaotic structures" for roughly the first 4 billion years of cosmic history, says astronomer Sidney van den Bergh of the Dominion Astrophysical Observatory in Victoria, British Columbia. But during the next 1 billion to 2 billion years, recognizable features started to form under the inexorable pull of gravity.

Astronomers believe that a typical primitive galaxy was a bloated cloud, slowly rotating and rich in warm gas that had not yet coalesced into many stars. Energy escaped from the cloud as atoms and molecules collided and radiated light. Gravity pulled the cooling gas more tightly together, forcing more frequent collisions, but it would have kept its original angular momentum. As time marched on, the fledgling galaxy flattened and spun faster and faster.



Home. An infrared view toward the Milky Way's core reveals a central bulge of stars and the flat disk within which we live.

"The final state of a runaway collapse is a thin disk where all particles go in exactly circular orbits," says astrophysicist Julio Navarro of the University of Victoria, British Columbia. But a galaxy isn't an idealized whorl of gas, he notes: "When the gas collects into tiny little packets of stars, you get a collection of bullets that never collide." Without energy-robbing collisions, a star-filled disk cannot settle down if it gets perturbed by another young galaxy plunging into it—a common event in the cosmic past. Instead, stars tend to scatter into spherical swarms, like a disturbed hive of bees.

This is exactly what happened when astronomers constructed computer simulations of evolving galaxies dominated by stars. "Disks are very fragile, dynamical entities. Mergers mess them up," Navarro says. But if mergers and collisions were so common in the early universe, why don't we see the sky full of formless elliptical galaxies?

The influence of gas is the key, Navarro and others now agree. Effervescent gas would have damped out the otherwise shattering effects of major mergers. Adolescent galaxies could have kept gas stirred up in plenty of ways: intense ultraviolet light from massive newborn stars, shock waves from supernova explosions, or outpourings of energy from vigorous cores.

Recent simulations have shown this damping effect of gas in action. For instance, a team led by graduate student Brant Robertson of Harvard University in Cambridge, Massachusetts, produced one of the first realistic disk galaxies in a simulation that spans cosmic history. The model, reported in the 1 May *Astrophysical Journal*, relies on a "multiphase gas" of cold clouds surrounded by hotter material, which more accurately captures a galaxy's interstellar environment. This hybrid recipe preserves gas during mergers and stabilizes the disk against external onslaughts, Robertson says. The approach works, but it's only a start: Just 1 of 20 simulated galaxies ended up with a flat pinwheel of stars and gas, compared with about half in the real universe. Improved models may need to churn up the gas even more with early bouts of star formation, other researchers believe.

And in new work submitted to *Astrophysical Journal Letters*, two of Robertson's co-authors demonstrate that a classic spiral galaxy can emerge even from the wreckage of a violent collision. Astrophysicists Volker Springel of the Max Planck Institute for Astrophysics in Garching, Germany, and Lars Hernquist of Harvard plowed two simulated gas-rich disks into each other. The concussive impact sparked a blaze of star birth, but enough gas remained to settle the merged object into a flat superdisk with clear spiral arms. "If disks can 'survive' even major mergers, they are probably less fragile than previously thought," the researchers write.

Forty thousand personalities

Simulations are an alluring way to peer back to galactic youth, but nothing beats the real thing.

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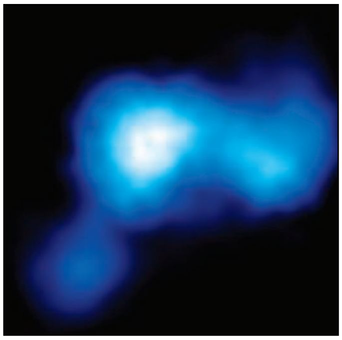
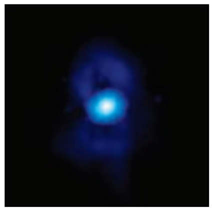
Enter GEMS—Galaxy Evolution From Morphology and Spectral Energy Distributions—an ambitious program to deduce how overall populations of galaxies have evolved. GEMS studies about 40,000 galaxies in the Hubble Space Telescope's largest contiguous color image of the sky: 150 times as broad as its "deep field" image taken in 1994. Astronomers have good distance estimates to some 10,000 of those galaxies, from spectra obtained at the European Southern Observatory's 2.2-meter telescope at La Silla, Chile.

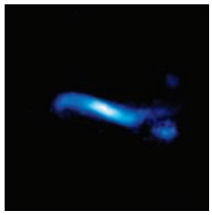
For astronomers, GEMS has been as transforming as seeing a photo album of hundreds of ancestors rather than just a few faded snapshots. "From the ground, these galaxies are dots. But from Hubble, each one gets a personality," says lead scientist Hans-Walter Rix of the Max Planck Institute for Astronomy in Heidelberg, Germany.

After more than a year, the GEMS team can make firm statements about the life and times of disks since the universe was about 5 billion years old. For example, the team charted the hottest starlight from newborn suns. "For the last 8 billion years, by far the largest majority of stars have formed in disk galaxies that start to resemble our Milky Way," Rix says. In contrast, elliptical galaxies had their heyday of spawning stars billions of years earlier.

At the outer reaches of its survey, the team sees what Rix calls "a sufficient number of galaxies with a bulge in the middle and small disks around them." These objects, he says, are most likely the ancestors of large disk galaxies such as the Milky Way and nearby Andromeda. Moreover, such galaxies grew their disks from the inside out, a maturation that the team traces by comparing the sizes of disks to their distances from us. Today's biggest disks clearly avoided catastrophic disruption from large mergers within the last 8 billion years, Rix says.







Flattened. In 12 billion years of simulated evolution, a galaxy morphs from chaotic blob (above) to flat disk (bottom right).

The right neighborhood was important. Galaxies evolved more quickly if lots of others were close by, presumably driven by the stronger gravitational influences. "In dense knots, we find some disk galaxies at early times that appear like the Milky Way today, but they are premature," Rix says. "They are likely to run out of gas and star formation, merge, and become ellipticals. That is their fate."

Step up to the bar

Not all is symmetrical in the realm of spiral galaxies. About two-thirds of all disks sport "bars"—elongated concentrations of stars embracing the galactic cores. Our Milky Way has one: a stubby bar first suspected in the 1980s and recently mapped by laborious census of a distinctive class of stars within the disk.

Looking back. A journey far above the Milky Way's disk might reveal this view of its spiral arms and central bar.

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Bars can alter disk galaxies by redistributing mass and angular momentum. "Any kind of perturbation in a cold disk tends to form bars or spiral arms," says astronomer Shardha Jogee of the University of Texas, Austin. Once formed, a bar tugs gravitationally on gas and pulls it toward the center of the galaxy, triggering the birth of new stars. In theory, this may sow the seeds of a bar's destruction. Some early simulations showed that a central buildup of mass propels passing stars farther out onto great looping paths, dissolving the bar and its narrowly confined stellar orbits.

But more recently, astronomers have wondered how quickly these transitions might happen. "The evolution from barred to unbarred and back again can go on in the lifetime of a galaxy, but there has always been a lot of question about how fast this process is," says astronomer Mousumi Das of the University of Maryland, College Park. GEMS points to a slower transformation than expected. The team, led by Jogee, found a constant ratio of strongly barred to unbarred galaxies at all epochs. The structures survive at least 2 billion years, if not much longer, the authors concluded in the 10 November *Astrophysical Journal Letters.*

Another valuable tracer of a galaxy's history is its so-called thick disk, a smattering of older stars that wander above and below the main disk. Astronomers aren't yet sure how stars in the Milky Way's thick disk got there. In one popular scenario, a galaxy merger harassed the stars out of their cozy orbits in the thin disk, perhaps 10 billion years ago. Because there are no stars younger than that in the thick disk, that event probably was the galaxy's last noteworthy consolidation, says astronomer Rosemary Wyse of Johns Hopkins University in Baltimore, Maryland.

However, Julio Navarro and his colleagues think they see imprints of a more fascinating tale. Scrutiny of the motions and chemical compositions of stars in the thick disk reveal a few odd groupings that have properties dissimilar to those of the rest of the galaxy. The team proposes, provocatively, that the thick disk is not a puffed-up set of the Milky Way's own stars but is shot through with aliens. Arcturus, a bright star not far from the sun, could be one such immigrant from a long-ago devoured galaxy.

The next step for astronomers involved in this galactic archaeology will be a thorough charting of the motions of millions of Milky Way stars all around us. One such effort, the Radial Velocity Experiment, is under way at the 1.2-meter U.K. Schmidt Telescope in Siding Spring, Australia. And a proposed extension of the U.S.-led Sloan Digital Sky Survey would examine stars in the galaxy's crowded plane, a region the survey has largely avoided.

Starting in 2011, the European Space Agency's Gaia satellite will scrutinize a billion stars, fully 1% of the galaxy's population. We may then learn how our familiar disk has kept itself together in a universe full of disorderly influences.

–ROBERT IRION

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