Ripples *in a* Galactic Pond

Astronomers are coming to realize that the beautiful shapes of galaxies are not merely incidental. They are essential to the galaxies' growth and development

By Françoise Combes

SPIRAL GALAXIES are some of the most beautiful sights in the night sky. Most, such as galaxy NGC 1097 (*above*), have a central rectangle, or "bar," of stars. Others, such as Messier 51 (*opposite page*), do not. Both types of spiral galaxies consist of a flattened, rotating disk of stars, gas and dust. Bars and arms mark comparatively dense regions. Despite recent advances, the nature and origin of these shapes remain mysterious in many ways.

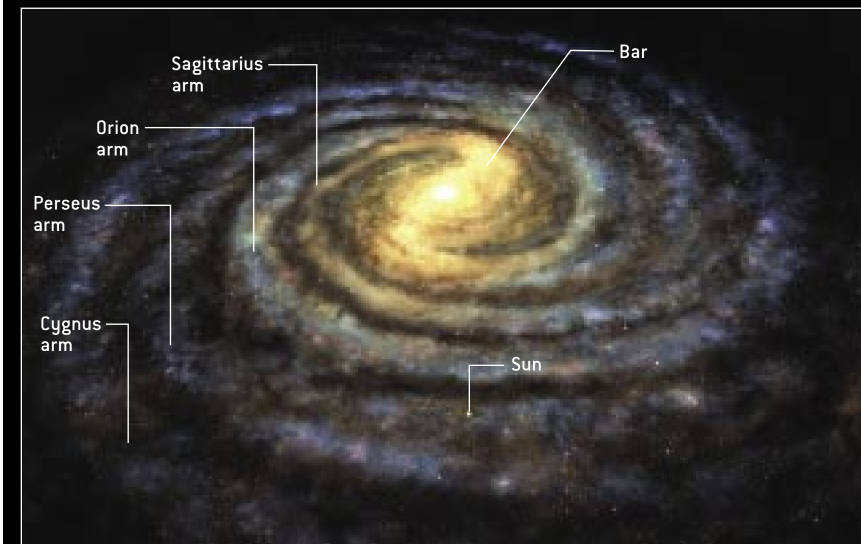
The elegant spiral shape of galaxies is one of the quintessential sights of astronomy. A classic example is the galaxy Messier 51: it resembles a giant cyclone, and one of the first names given to it was the "whirlpool." The brightest stars in this galaxy are confined like pearls on a coiled necklace. Running alongside the strands of stars are dark swaths of dust, which betray the presence of interstellar gas, from which stars are born. In Messier 51 and many other galaxies, the spiral pattern is anchored by an inner ring of stars, but in most the spiral begins in a bar—a long, luminous rectangle of stars. A barred galaxy looks like a spinning lawn sprinkler, where the water flows through a straight tube, emerges at right angles and then curves around.

Most people think of our own galaxy, the Milky Way, as a pure spiral, but astronomers now know it is actually a barred spiral. The evidence, at first indirect, began to accumulate in 1975: stars and gas tracked in the middle of the galaxy did not follow the orbits they would if the spiral pattern reached all the way in. Recent surveys of the sky in near-infrared light, which penetrates the dust clouds that block our view of the galactic core, have revealed the bar directly and dispelled the remaining doubts.

Bars and spirals may appear to be persistent bodies, like pinwheels, but in fact they are dynamic patterns—waves that sweep through the disk of stars, dust and gas, often violently redistributing the material. Observers catch them at one moment in time, as with a stroboscopic light. These waves are one aspect of a general theme of astronomy during the past decade, the realization that seemingly immutable properties of galaxies, such as their shape, change dramatically over time. The best-known shape-shifting process is galactic cannibalism: merging with a neighbor can turn an orderly spiral into a messy, beehivelike elliptical galaxy. But astronomers are coming to appreciate that internal wave processes may be even more important.

MILKY WAY BAR

Astronomers used to think that our own galaxy fell into the pure-spiral category, but today they recognize that it is actually a barred spiral. In the top image from the 2MASS survey, the Milky Way is seen edge-on, the core of the galaxy is at the center, and the colors represent the intensity of light at three near-infrared wavelengths. The galaxy is thicker than expected, and the core is wider and broader on the left than on the right. Both features are signs of the bar, as an artist's conception shows (*bottom*).



Overview/*Galactic Waves*

- Since the 1960s astronomers have realized that the iconic spiral shapes of galaxies are not fixed structures but transient oscillations in the density of material. Stars and gas clouds crowd together and then separate in a self-reinforcing orbital choreography. It is almost as though someone dropped a stone into the galaxy, sending out ripples in slow motion.
- Until fairly recently, however, theorists could not explain crucial aspects of these waves, such as the relative numbers of galaxies having different shapes. It turns out that the missing ingredient in the models was interstellar gas, which exerts an effect out of all proportion to its mass.
- Waves can transport angular momentum, giving matter a chance to clump in the middle of a galaxy; the black hole at the hub may be one beneficiary. Moreover, the waves come and go in a cycle, causing the galaxy to metamorphose from one shape to another. These theoretical findings have been getting support from observations of galaxies both near and far.

PAGE 42: STEVE LEE AND DAVID MALIN *Anglo-Australian Observatory*; PAGE 43: NASA, EUROPEAN SPACE AGENCY, STEVEN BECKWITH *Space Telescope Science Institute* AND HUBBLE HERITAGE TEAM; THIS PAGE: 2MASS/J. CARPENTER, T. H. JARRETT AND R. HURT (*top*); DON DIXON (*bottom*)

Floppy Disks

ALL SPIRAL GALAXIES, barred or not, rotate; their stars orbit the center in a regular pattern. But they do not rotate rigidly. Their stars do not all go around in unison. In the Milky Way, the innermost stars have whirled around the center thousands of times over the past five billion years, whereas the sun, located about halfway out the disk, has made the trip only about 20 times. The variation in orbital rates is the reason that bars and spirals cannot be fixed structures. If they were, they would quickly coil up in the way a rope wraps around a winch.

For decades, astronomers wondered what maintained these shapes. In the 1960s the puzzle was partially solved by the theory of density waves, developed by Chia-Chiao Lin and Frank Shu, both then at the Massachusetts Institute of Technology. In this theory, bars and spiral arms are waves of excess density, where stars are crowded together temporarily in a cosmic traffic jam. Stars enter and exit the wave just as cars enter and exit a jam.

The wave involves the synchronization of stellar orbits. The orbit of a star in a galaxy does not look like the orbit of a planet around the sun or a satellite around Earth, because a galaxy is not dominated by a single central body. Although most galaxies have a central black hole, it is a small fraction of the galaxy's mass. The bulk of the mass is spread out, forcing stars to trace a Spirograph-like rosette: an ellipse that does not close on itself but gets offset each time the star completes one revolution [*see box at right*]. The sun, for example, takes about 230 million years to go around its elliptical orbit. In that time, the orbit gets offset by 105 degrees; thus, the sun's ellipse does a full rotation once every 790 million years.

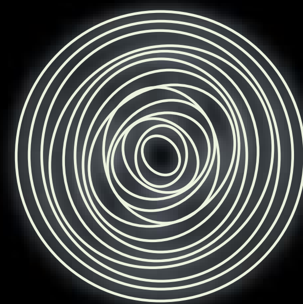
When stars' ellipses rotate at widely different speeds, the galaxy has no wave structure. Stars randomly pass close to one another, but they soon separate again, much as cars briefly bunch together even on a freely flowing highway. A wave occurs when many or all the ellipses rotate at the same rate. In a bar

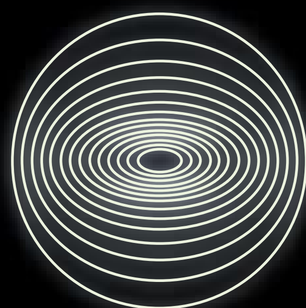
BRINGING ORDER TO ORBITS

Bar and spiral patterns are thought to represent waves passing through the galaxy. As the wave front enters a region, stars move closer to one another; as it exits, they spread out again. The wave action works not by literally pushing the stars together but by subtly choreographing their orbits.

LOOP-D-LOOP ORBITS are stars' paths through the complex gravitational field of a galaxy. A star trundles around the galaxy on an ellipse, but the ellipse itself is moving. This secondary motion is the raw material for galactic waves.

NO WAVE MOTION occurs when orbits are oriented randomly. (For simplicity, this figure shows only a sample of orbits—those that appear to be closed loops when viewed from a rotating frame of reference.)





BAR WAVE arises when orbits align. Gravity causes the ellipses to move in unison, maintaining their alignment. The wave front is the area of greatest star density, which occurs along the major axis of the ellipses.

SPIRAL WAVE arises when the ellipses move in unison but are not perfectly aligned; each ellipse is slightly skewed compared with its neighbors. The density of stars is highest where the ellipses crowd together.

BARRED SPIRAL pattern arises when orbits near the center of the galaxy are aligned but those farther out are skewed.

ALISON KENDALL

wave, these ellipses are aligned, producing a region of enhanced density along their major axis. In a spiral wave, the orbits are progressively misaligned, so that the region of enhanced density is a curved line.

In short, stellar orbits can move in unison even if the stars themselves do not. What causes the ellipses to move in lockstep? It is a spontaneous gravitational instability. Because gravity in these systems is not a fixed external force but a product of the stars themselves, waves can be self-reinforcing. The process starts when stellar orbits become aligned by chance. Amplified by proximity, the gravity of the stars modifies the rotation speed of the ellipses. Faster ones slow down and slower ones speed up, so they bring themselves into sync. When a star enters the wave, gravity locks it in, but only temporarily; after a while, it becomes unlocked and exits. Stars coming in the other side of the wave ensure that the structure persists.

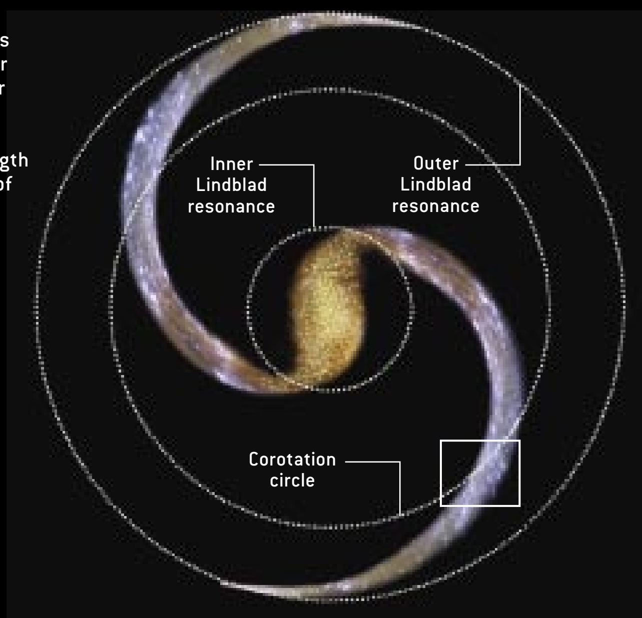
Breaking the Waves

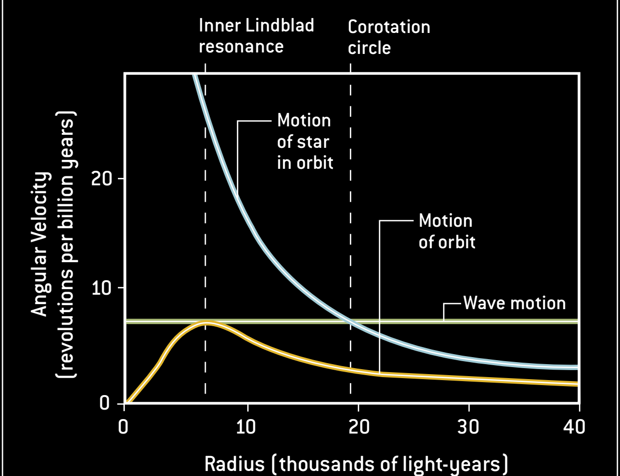
IN THE INNER PARTS of a galaxy, stars move faster than the wave, so they catch up with it; in the outer parts, they move slower, so the wave hits them from behind. In between is a corotation circle where the wave accompanies the stars at the same velocity. Besides the corotation circle, there are two other special locations in the disk—one inside the circle, the other outside—known as Lindblad resonances, after their discoverer, Swedish astronomer Bertil Lindblad. Stars orbiting at these positions have a certain synchrony with the wave: each time they hit (or are hit by) the wave, they have reached a particular point in their orbits. This consistency allows the gen-

ANATOMY OF A WAVE

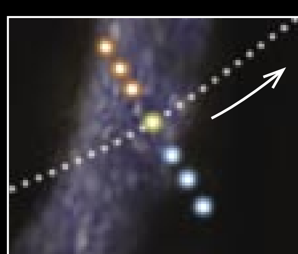
In some ways, bars and spiral arms are like the wave sweeping around a sports stadium. As the wave front passes by, individuals act in a coordinated way: spectators in a stadium stand up and down together; orbits in a galaxy arrange themselves to bring stars closer together. Galactic waves have the added complication that the stars themselves are moving.

SPIRAL ARMS seen by astronomers are a wave caught at one moment in time. In this example, the wave is propagating clockwise. Individual stars also move clockwise, but at a different speed (**insets**). Those in the inner region move faster than the wave. They catch up with it, join the wave for a certain period and then zoom out of it. Stars in the outer region of the galaxy get hit from behind, enter the wave and are left in its wake. The corotation circle defines the boundary between the two regions. The length of the spiral arms is defined by two other circles, marking the positions of so-called Lindblad resonances, where wave and stars move in phase.

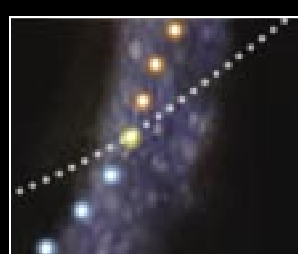




ANGULAR VELOCITY of the wave is constant throughout the galaxy, whereas stars' orbital velocity drops off with distance from the center. The two velocities are equal at the corotation circle. The stars' orbits are not fixed in space; they, too, rotate. Where their rotation rate equals the wave velocity, a Lindblad resonance occurs. (For clarity, the graph shows only one resonance.)



The wave moves clockwise (*right to left across this box*). So do the stars.



Interior stars move faster than the wave; exterior ones, slower.

DON DIXON (*illustrations*); ALISON KENDALL (*graph*) tle tug exerted by the wave on the star to build up. The Lindblad and other resonances play a distinct role in shaping the orbits and delimiting the density waves. Similar processes define planetary rings [see "Bejeweled Worlds," by Joseph A. Burns, Douglas P. Hamilton and Mark R. Showalter; SCIENTIFIC AMERICAN, February 2002].

The theory of density waves explains how the bar and spiral structure can persist, but not long after Lin and Shu proposed it, it ran into problems of its own. Alar Toomre of M.I.T. observed that waves lose their energy by setting up shock waves in the interstellar gas. Something has to reinvigorate them. One idea was more complex wave motions. Instead of a single wave swooping around the galaxy, multiple waves can travel inward and outward. The corotation circle acts as an interface that can either reflect or transmit these waves, allowing them to gain energy at the expense of the global rotational kinetic energy of the galaxy. Waves can bounce back and forth across the central region, becoming successively amplified—a cosmic echo chamber.

This complex mechanism of wave amplification and reflection was a plausible hypothesis, but the equations were too complex to solve exactly except with severe approximations. So astronomers had to undertake numerical computer simulations—not an easy task in the days of punch-card computing. Early efforts indicated that the extra wave complexity, far from saving the spiral structure, actually accelerated its destruction. A spiral developed at first but rapidly faded away, leaving a bar. Theorists could not find a way to avoid bar formation—and thereby explain the galaxies that lack such a structure—without contradicting other observations.

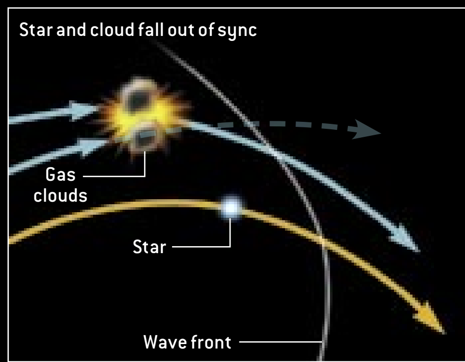
This unsatisfying state of affairs changed completely in the 1980s and 1990s when my colleagues and I included another ingredient in the simulations: gas. Because gas constitutes only a few percent of the mass of spiral galaxies, modelers had neglected it to make the simulations more tractable. But gas has a disproportionate, dynamical role. Interstellar gas clouds frequently collide and convert their kinetic energy into shock waves and radiation. Thus becalmed, the clouds are more susceptible to wave instabilities. Stars, in contrast, seldom collide, so they maintain a wider range of relative velocities and put up more resistance to passing waves.

As soon as we included gas, the simulations produced a rich variety of galactic morphologies. The torque exerted by the stellar bar acted as a giant stirrer, continuously driving a spiral structure in the gas. The spiral did not fade away as it had in earlier simulations. Moreover, the gas-rich waves solved a number of other long-standing problems in galactic astronomy. To begin with, they explain the presence of dust lanes on the leading edge of spiral arms. Because of collisions, the gas (mixed with dust) is not in phase with the stars: it loses orbital energy, falls toward the center, and runs ahead of the stars in the spiral arms [*see box above*].

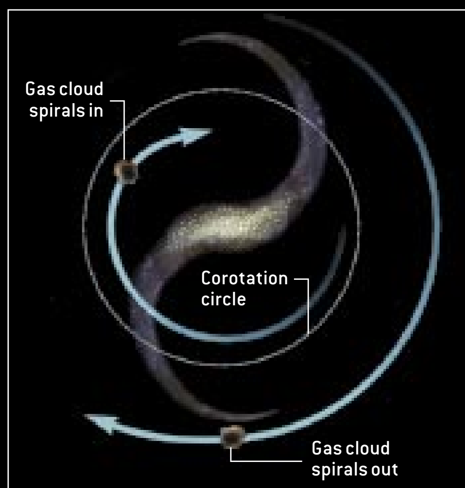
Energy dissipation pulls gas all the

GAS VS. STARS

Galactic waves turn out to be an essential process for redistributing interstellar gas within a galaxy and thereby triggering star formation. The key to this process is that although stars and gas clouds participate in the wave, they respond differently.



IF A STAR AND CLOUD begin on similar orbits, the star holds to its path, but the cloud—by virtue of its enormous size—cannot avoid hitting others of its kind, losing energy and dropping into a lower orbit. Consequently, a galactic wave cannot bring stars and gas clouds into perfect synchrony.



IMBALANCE OF FORCES, arising because the clouds and stars are out of sync, produces a torque on the clouds. A cloud inside the corotation circle outpaces the stars in the bar, so their gravity holds it back—taking away its orbital energy and angular momentum, dragging it down. A cloud outside the circle is pulled forward in its orbit—adding to its orbital energy and angular momentum, hauling it to a higher orbit.

DON DIXON

THE AUTHOR

FRANÇOISE COMBES, an astronomer at the Paris Observatory, is a leading expert on galaxy dynamics. In an age of increasing specialization, she maintains a broad range of interests, from interstellar gas to quasars to dark matter, spanning both observation and theory. Last year Combes was elected to the French Academy of Sciences—the first female astronomer so honored—and currently serves as president of the French National Committee on Astronomy. In her spare time, she does Impressionist-style oil painting.

way to the center within a few rotations of the bar, typically about one billion years. There the gas forms new stars. Thus, the waves explain the persistently high rate of star formation in galactic centers. They could also solve the mystery of what refuels central black holes. Pouring matter into a black hole is not as easy as one might think. Although the tendency of a galaxy is to minimize its gravitational potential energy and therefore to concentrate mass at its center, rotation and the corresponding centrifugal forces counterbalance gravity [see "A Universe of Disks," by Omer Blaes; SCIENTIFIC AMERICAN, October 2004]. For material to fall inward, the angular momentum must be transferred away by galactic-scale torques. Bars and spirals can do just that.

Astronomers have observed that gas falls into black holes in large puffs. Waves could perform the fueling in two steps. First, as the gas descends it reaches a resonance where it is in phase with the bar and hence immune to its torque. The gas piles up in a ring and gives birth to stars. Second, gas and stars inside the ring form their own small bar wave. This mini bar dumps gas into the black hole. In our galaxy, such a bar has been suspected from near-infrared surveys. These waves are therefore more than a beautiful decoration. They allow our galaxy to grow.

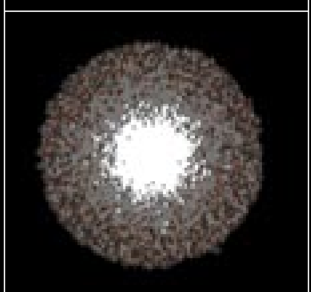
Disbarred

NOT ONLY DOES the bar pull material laterally across the disk, it can elevate it vertically out of the disk. A star can come into a resonance in which its vertical oscillations and its encounters with the bar occur at the same rate (or a multiple thereof). Then the bar can pump up the oscillations like a parent pushing a child on a swing. We found this phenomenon almost serendipitously during three-dimensional computer simula-

A GALAXY REINVENTS ITSELF

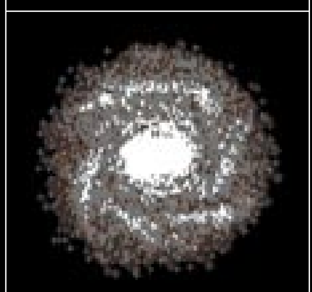
Astronomers used to regard bars and spirals as permanent features of a galaxy but now think that they come and go. The gravitational processes that make a bar ultimately destroy it and then create it anew, as this simulation shows.

START



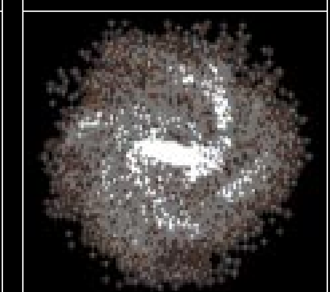
The galaxy is born as an amorphous disk of stars, gas and dust.

2 BILLION YEARS



Bar and spiral waves develop. Gas trickles in from intergalactic space and will double the disk mass in 6.5 billion years.

5 BILLION YEARS

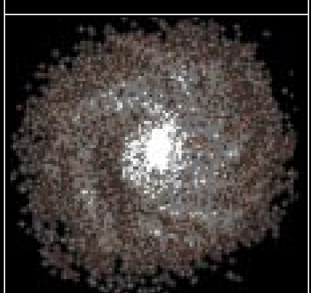


The waves strengthen. The bar sweeps up gas near the core but holds intergalactic gas at bay.

8 BILLION YEARS

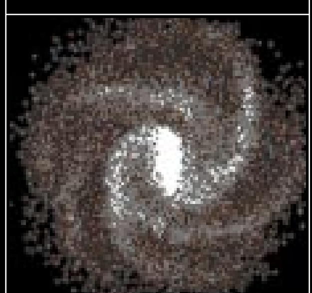
Gas accumulating in the core begins to tear apart the bar.

11 BILLION YEARS



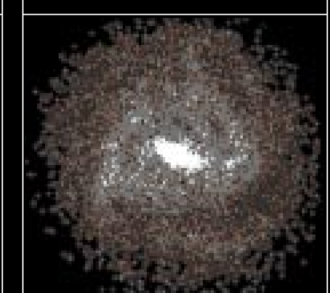
The bar is history. No longer held back by its torques, the intergalactic gas that had been lingering in the galactic outskirts pours in.

14 BILLION YEARS



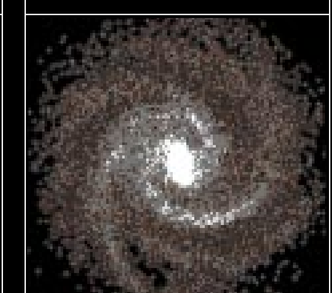
The bar reemerges. Gas infall is crucial: in simulations without it, the bar, once gone, never comes back.

17 BILLION YEARS



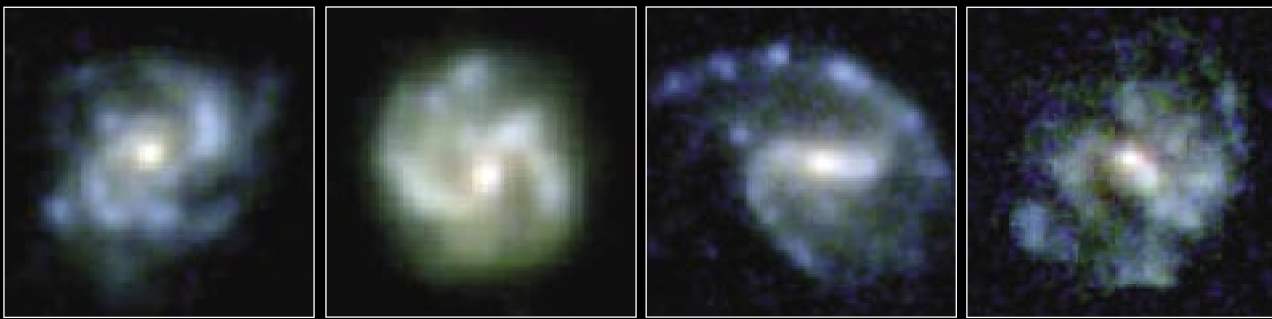
As before, the bar starts to peter out.

20 BILLION YEARS



The bar is all but gone. In simulations under different conditions, bars form and vanish more quickly.

ALISON KENDALL



DISTANT GALAXIES, representing an earlier epoch of cosmic history, appear to have the same basic bar and spiral shapes as closer ones—supporting the idea that these shapes have been generated by internal wave processes. These galaxies are so far away that their detailed structure is hard to see, so researchers have debated the relative abundance of different shapes.

ROBERTO G. ABRAHAM *University of Toronto* AND SIDNEY VAN DEN BERGH *Herzberg Institute of Astrophysics*

tions. The disk of stars thickened considerably in the region of resonance, giving the inner regions of the galaxy a boxy or a peanut shape. These findings explained the odd shapes that telescope observers had been seeing for a decade or longer.

Ironically, by pulling matter into the core of a galaxy, a bar can destroy itself. The accumulated mass scatters stars and prevents them from orbiting regularly, as a bar requires. The bars that seemed too robust when only the stellar component was taken into account are quite fragile when the gas is included. But if so, what accounts for the large number of barred galaxies that astronomers see? In visible images, two thirds of galaxies have bars, and near-infrared surveys in 2002 raised the estimate to three quarters. The logical conclusion is that bars form, fall apart, and form once again in a continuous cycle.

Explaining the reformation of bars is a challenge. The galaxy has to evolve considerably from the conditions that initially destroyed the bar. In particular, the orbits have to settle back down again into a regular pattern with low relative velocities. One way to do that is for the galaxy to accrete a large amount of intergalactic gas. As the gas clouds fall in, they collide, lose energy and regularize their orbits. Their high initial angular momentum slows their descent and gives the bar a chance to regroup. The amount of gas required is truly huge: to reform bars at the right frequency, a typical galaxy has to double its mass over 10 billion years. Astronomers now know that intergalactic space contains reservoirs equal to the task [see "Our Growing, Breathing Galaxy," by Bart P. Wakker and Philipp Richter; SCIENTIFIC AMERICAN, January 2004].

One way to check this model is to look back in time. The Hubble Space Telescope is powerful enough to discern the shape of earlier generations of galaxies. The first attempt to do so, conducted by Sidney van den Bergh of Herzberg Institute of Astrophysics in Victoria, British Columbia, and his collaborators between 1998 and 2002, concluded that bars were once much less frequent than they are today. This result was very surprising; it cast doubt not just on the gas-infall model but on the entire theory of bar waves. Early galaxies were more gaseous and less centrally concentrated, so if anything bars should have been more frequent. But Shardha Jogee of the University of Texas at Austin and her colleagues recently explained van den Bergh's preliminary results as observational bias. Bars are hard to recognize in distant galaxies. Correcting for this effect reveals that they were as prevalent in the past as they are now, suggesting that they are destroyed and rebuilt in a steady state.

In short, it appears that galaxies are not born with a given shape, barred or unbarred. They metamorphose. If three quarters of galaxies are barred, a typical galaxy must spend three quarters of its life barred. During this time, the bar prevents fresh gas from entering the central part of the galaxy. The gas accumulates in the outer region and, after the bar self-destructs, pours in and rejuvenates the galaxy.

The other, better-known way to assemble mass in galaxies is cannibalism, or successive galactic mergers. This process, though also very important, is destructive. A major merger wipes out the disk and leaves an elliptical galaxy in its place. Only a minority of galaxies have been transformed so thoroughly. Gentle gas accretion from intergalactic space allows galaxies to grow while maintaining their shape. Waves distribute the fresh material and save the galaxies from slowly winding down. They keep the universe a vibrant place. SA

MORE TO EXPLORE

Galactic Rings. Ron Buta and Françoise Combes in *Fundamentals of Cosmic Physics,* Vol. 17, pages 95–281; 1996. Available at **http://nedwww.ipac.caltech.edu/level5/Rings/frames.html**

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Redesigning the Milky Way. William H. Waller in *Sky and Telescope,* Vol. 108, No. 3, pages 50–56; September 2004.

Secular Evolution versus Hierarchical Merging. Françoise Combes in *Penetrating Bars through Masks of Cosmic Dust.* Edited by D. L. Block, I. Puerari, K. C. Freeman, R. Groess, E. K. Block. Springer, 2004. **astro-ph/0406306**