Though galaxies may appear isolated and serene, they frequently swoop past one another, crash into their neighbors, and transform each other in close encounters.

by Charles Liu

We live in the Milky Way Galaxy, a vast collection of gas, dust, over 100 billion stars, and a huge halo of dark matter. If we could fly out of the Milky Way and look back from a distant vantage point, we'd see that our home is a beautiful spiral galaxy, like countless others in the cosmos. Within our galactic neighborhood, we'd also see other spiral galaxies nearby, as well as elliptical galaxies and smaller, irregularly shaped galaxies. But a select group — perhaps one in a hundred — look downright peculiar, sporting rings, loops, and long tails of stars trailing away in odd directions. These are usually the result of galaxy collisions and interactions — some of the most awesome and astonishing events in the cosmos.

Not long ago, astronomers regarded galaxy collisions as rare occurrences of little consequence. We now suspect, however, that just about every galaxy in the universe has probably experienced such a close encounter. The details of these collisions, then, reveal vital secrets of galaxy birth, life, aging, and death — and the evolution of the universe itself.

The lure of these secrets draws me to study colliding and merging galaxies. I must admit, though, that the curiosity of a rubbernecker plays a part too. After all, who can resist slowing down to take a look at the grandest traffic accidents in the cosmos?

Light Bulb Astronomy

It took most of the 20th century to reach our current understanding of colliding galaxies, which is still incomplete. By the end of the 1920s, astronomers had generally accepted the idea that the spiral nebulae, such as the Great Nebula in Andromeda (as it was called back then), were in fact galaxies like our own Milky Way. This picture of the universe came largely from the work of Heber D. Curtis and Edwin Hubble. Hubble proved that the Great Nebula in Andromeda was

The small, irregular galaxy M82 (bottom) and the larger spiral galaxy M81 (top) experienced a close encounter about 100 million years ago, which triggered a starburst in M82. Courtesy of George Jacoby/WIYN/NOAO/AURA/NSF.
Two large spiral galaxies are colliding to form the Antennae (NGC 4038/4039), 60 million light-years away in Corvus. The ground-based optical image (left) shows long tails that resemble insect antennae. Computer simulations (right) conducted in the early 1970s by Alar and Juri Toomre conclusively demonstrated that the tails are the result of tidal interactions between the two galaxies. Antennae image courtesy of Francois Schweizer. Computer simulation courtesy of Alar and Juri Toomre.

The Antennae collision induces interstellar clouds in both galaxies to collapse, leading to furious star formation and the production of star clusters that can be seen as the bright, blue clumps in a Hubble Space Telescope image (left). The nuclei of the two galaxies appear as yellowish clumps at the center left and upper right. The bright clumps in a Chandra X-ray Observatory image (right) mark the location of low- and intermediate-mass black holes. HST image courtesy of Brad Whitmore (STScI) and NASA. Chandra image courtesy of NASA/SAO/Giuseppina Fabbiano, et al.
A billion or so years ago, the elliptical galaxy Centaurus A (NGC 5128) was involved in a major galaxy collision, which left behind the dark dust lane seen in optical images (above) from the Very Large Telescope (left) and the Hubble Space Telescope (right). The Hubble image reveals dense clusters of hot, blue stars that have recently formed in the dust lane. The collision provided the fuel for the central black hole, which produces powerful jets. Below, a radio image of the jets is superimposed on an optical image. VLT image courtesy of the European Southern Observatory. HST image courtesy of Ethan J. Schreier (STScI) and NASA. Bottom image courtesy of NRAO and NOAO.

Actually the Andromeda Galaxy (M31), not a structure inside the Milky Way, but rather its own "island universe" far beyond the confines of our own galaxy.

A decade later, Hubble furthered our understanding of galaxies by classifying them by their shapes in a "tuning fork" diagram of elliptical, spiral, and barred spiral galaxies. A number of other galaxies, generally much dimmer and less massive than the Milky Way, fit in none of those categories. So Hubble labeled them "irregular" galaxies. Two examples are the Large and Small Magellanic Clouds, satellite galaxies of the Milky Way visible from the Southern Hemisphere.

A few percent of galaxies, however, could only be described as downright peculiar. Unlike irregular galaxies, which generally appear as amorphous blobs of stars and gas, these "peculiar" galaxies exhibited clear structures — they just weren't spiral arms or elliptical bulges. Rather, these oddballs appeared to have loops, whorls, and long, thin tails. Furthermore, they seemed to show up more often in clusters of galaxies than among isolated field galaxies. This observation led some astronomers to suspect that gravitational interactions between nearby galaxies might cause distortions in their normally regular shapes — and that collisions could cause peculiarities of galactic magnitude.
Astronomers of the early 1900s were intrigued by the collision hypothesis, but they lacked the tools to test its correctness. Galaxies are not single, solid objects, but rather agglomerations of billions of particles all bound together by gravity. Each star or gas cloud in a galaxy moves according to the combined gravitational pull of all the other stars and gas clouds nearby. In a single, symmetrical galaxy, the motions of its component parts can often be approximated by single equations. But when galaxies collide, those symmetries are broken — so the equations of motion for each piece must be computed individually. Scientists and mathematicians of the 1930s had no way to make the millions upon millions of necessary calculations quickly and correctly.

In 1941, Swedish astronomer Erik Holmberg found an ingenious partial solution to this problem. Gravity follows an inverse-square law: If you double the distance between two objects, the gravitational force between them drops by a factor of four (that is, two squared). Coincidentally, the flux of light from a bright object follows the same inverse-square law. Holmberg arranged 74 light bulbs into two spirals of 37 bulbs each, and placed these spirals next to each other on a large tabletop. With a sensitive light meter, he then measured the total light flux that each light bulb intercepted from all the other bulbs on the table. In other words, Holmberg used light to trace the action of gravity on each bulb. With his light bulb "gravity computer," Holmberg showed that galaxies in close proximity could indeed change shape and, over many millions of years, develop decidedly peculiar structures. His experiment was still incomplete, however; there was still no way to watch two galaxies engage in a full-scale collision.

Debate continued on the origin of peculiar galaxies for decades. Carnegie Institution astronomer Halton "Chip" Arp suggested that galaxies might occasionally disintegrate or explode, creating massive disruptions of their shapes from within. To get a handle on his ideas, Arp assembled a sample of more than 300 peculiar galaxy systems, organizing the various kinds of strange-shaped galaxies according to the kinds of distortions they showed. Published in 1967, Arp's Atlas of Peculiar Galaxies remains the most commonly used catalog of colliding galaxy systems — an irony, because Arp himself remains unconvinced to this day that all peculiar galaxies stem from collisions or interactions.

The advent of electronic computing technology finally laid the origin of peculiar galaxies to rest. In 1972, brothers Alar and Juri Toomre of MIT published a landmark study of gravitational interactions between galaxies. Using a computer, they traced the evolution of colliding galaxies over hundreds of millions of years, and discovered that they could reproduce, with uncanny accuracy, the
Using spectroscopy, astronomers have measured the motion of the Andromeda Galaxy (M31), our nearest large galaxy neighbor, about 2.2 million light-years away from the Milky Way. The result is somewhat surprising: Andromeda is coming toward us at 300 kilometers per second — a slow crawl by cosmic standards, but a breakneck pace in terrestrial terms. A light-year is about 10 trillion kilometers; so a back-of-the-envelope calculation shows that at this rate, Andromeda will be right on top of us in just two or three billion years.

What might happen if these two galaxies collide? John Dubinski of the Canadian Institute for Theoretical Astrophysics recently produced a computer simulation of this event. The engine he used to power his calculations was Blue Horizon, a massive bank of 1,152 interlinked CPUs at the San Diego Supercomputing Center in California, working together to make a trillion mathematical operations per second! His results appear to be completely consistent with all our observations of spiral galaxy collisions: Over the course of a billion years, the Milky Way and Andromeda will merge and form a single elliptical galaxy. Because both galaxies harbor millions of solar masses of free-floating gas, we can expect cosmic fireworks too — powerful starburst activity, and possibly the ignition of an active nucleus or quasar.

But it remains unclear whether the collision will actually happen. Andromeda is streaking in our direction, but it might not be coming head-on. Even a small approach angle would mean that eons from now, it would pass by the Milky Way harmlessly, hundreds of thousands of light-years to the side. The technology to measure the angle of approach won’t be available for at least a decade or two. In any case, there’s no need to worry — two billion years is a long time! — CHARLES LIU

The Andromeda Galaxy is approaching the Milky Way. If the two galaxies collide, computer simulations suggest they will merge into an elliptical galaxy. Top image courtesy of Bill Schoening, Vanessa Harvey/REU program/AURA/NOAO/NSF. Bottom images courtesy of John Dubinski (CITA).
A small galaxy plowed through the Cartwheel Galaxy about 200 million years ago, leaving behind a disrupted spiral galaxy. Courtesy of Kirk Borne (Hughes STX Corporation), et al., and NASA.

long tails of stars observed in peculiar systems like the “Antennae” galaxies (NGC 4038/4039; the name Antennae comes from the tails’ striking resemblance to insect antennae). The Toomres showed that these tails are produced by tidal interactions, generated as one galaxy entered the gravitational field of another.

The Toomres’s computer was state of the art in 1972. But today, even a typical home computer is many times more powerful than their machine. Computational astrophysicists now use machines that can crunch hundreds of billions of mathematical calculations per second. Combined with sophisticated software algorithms, these “virtual experiments” continue to produce ever more detailed and complex simulations of colliding galaxies. Whereas Holmberg had dozens of particles and the Toomres had hundreds, Christopher Mihos at Case Western Reserve University (who co-authored “Cosmos on a Computer,” page 23) and John Dubinski at the Canadian Institute for Theoretical Astrophysics routinely use millions of particles in their calculations.

Galaxies for Dinner

Just as an experienced forensic investigator can reconstruct a traffic accident by studying the smashed cars and broken parts at the scene, an astronomer can deduce how galaxies collided by observing the remnants of the interaction. The distances and scales of a galaxy interaction, however, complicate matters. Although the galaxies involved often race toward each other at a million or more kilometers per hour, galaxies are many quadrillions of kilometers across, so each collision takes eons to unfold. A fast, glancing blow usually ends within a couple hundred million years (about the length of the Age of Dinosaurs here on Earth). A slower interaction, on the other hand, often locks the participants into a mutual gravitational embrace — and over the course of a billion years or more, the two galaxies merge into one.

Throughout the process, the tidal forces generated by the swirling streams of stars and gas produce the cosmic wreckage seen in colliding galaxy systems. On Earth, tides are weak but clearly evident: The Moon's gravity pulls on Earth's near side harder than it does on the far side, so the oceans bulge outward along the Earth-Moon axis. For galaxies, the combined effects of large sizes and long timescales produce far more visible tidal effects. Small galaxies can be pulled apart like pasta, or stretched into huge “polar rings” (forming rare polar ring galaxies such as NGC 4650A). Larger galaxies can produce tails and streamers hundreds of thousands of light-years long. New clusters of stars may form along these tails. We see evidence, for example, of embryonic globular clusters in the tails of the Antennae.

Hubble Space Telescope images (left) show that many quasars are found inside interacting galaxies, strongly suggesting that such interactions play a major role in supplying fuel to the supermassive black holes that power quasars. An image taken with Europe’s Very Large Telescope (right) shows a quasar inside a galaxy with a long tidal tail — the hallmark of a galaxy interaction. HST images courtesy of John Bahcall (Institute for Advanced Study), Mike Disney (University of Wales), and NASA. VLT image courtesy of the European Southern Observatory.
Many of these systems have colorful nicknames to describe their twisted morphologies. A small galaxy crashing into a larger one typically results in less damage. For example, a passing small galaxy has disrupted the Cartwheel Galaxy’s spiral pattern, but its disk remains mostly intact. Collisions of two large galaxies, on the other hand, produce utter chaos, as in the cases of The Antennae, The Wasp (Arp 195), The Mice (NGC 4676), and Atoms for Peace (NGC 7252, named for the Atoms for Peace symbol of the 1950s).

The process of building a galaxy by acquiring others can create giant “central dominant” or “cD” galaxies like M87 in the Virgo Cluster. Some of these bloated behemoths can be hundreds of times more massive than our own galaxy. These “cD” galaxies appear at the hearts of rich clusters of galaxies, and often have several bright nuclei — the remains of cannibalized galaxies not yet fully digested.

But mounting evidence from observations of young, faraway galaxies suggests that even ordinary citizens of the galaxy community have grown to adulthood through a series of accreting collisions. Even now, our Milky Way is consuming the Sagittarius Dwarf Galaxy, which was only discovered in 1994. As it draws ever closer, the Sagittarius Dwarf is unraveling into spaghetti-like strands, pulled apart by the Milky Way’s powerful gravity. Our galaxy may have reached its present size by devouring dozens or even hundreds of nearby dwarfs over the past 10 billion years.

Theoretical studies using supercomputers as virtual time machines, simulating the universe as it was billions of years ago, support this picture. Observations with the Hubble Space Telescope, such as those made by Sam Pascarelle and Rogier Windhorst at Arizona State University several years ago, provide evidence as well. They found dozens of young, immature galaxies — often described as “subgalactic clumps” — that appear to be falling toward a common center. Over several billion years, they seem destined to coalesce into a single large body about the size of the Milky Way Galaxy.

NGC 4650A is one of only about 100 known polar ring galaxies, which almost certainly formed from galactic mergers. In this Hubble Space Telescope image, the larger of the two original galaxies now appears as a horizontal disk composed mostly of old, reddish stars. The smaller galaxy was tidally shredded, and the remnant shows up as a polar ring of younger stars and gas that orbits almost perpendicular to the horizontal disk. Courtesy of the Hubble Heritage Team (AURA/STScI/NASA).

Giant elliptical galaxies such as M87, known as cD (central dominant) galaxies, probably form as the result of galactic mergers. Copyright Anglo-Australian Observatory/Photograph by David Malin.
Starbursts and Quasars

Galaxy collisions create new, bigger galaxies — and they also make new stars. But galaxy collisions almost never produce stellar collisions. Individual stars are tiny compared to the typical distances between them. If the Sun were the size of a tangerine, for example, its closest stellar neighbor would be some 2,000 kilometers away! So the hundreds of billions of stars in two large colliding galaxies almost always pass by one another without touching.

But vast interstellar clouds of gas and dust many trillions of kilometers across lie amongst the stars, and these stellar nurseries do crash together. The resulting friction and turbulence cause pockets of gas to collapse, heat up, and ignite new stars at dozens or hundreds of times the usual rate. Such “star bursts” can completely transform a staid galaxy into a seething cauldron, ablaze with dazzling young stars and titanic supernova explosions. The Antennae provides a dramatic example of this violent activity.

Even if galaxies approach each other but don’t actually collide, gravitational disturbances cause interstellar clouds to collapse, forming new stars at a furious rate. The small irregular galaxy M82 is experiencing a starburst episode as a result of a recent close encounter with its larger neighbor, M81. The most massive stars formed during this starburst are already long gone. Not surprisingly, high-resolution radio observations show that M82 has been wracked by supernovae over the past million years.

Perhaps even more remarkable is the probable link between galaxy collisions and quasars, the extraordinarily powerful cores of interacting galaxies leave a bewildering variety of systems (clockwise from the far left): NGC 4676 (The Mice), NGC 2623, NGC 7252 (Atoms for Peace), Arp 240, NGC 1409/1410, NGC 5090/5091, ESO 510-13, NGC 6872/IC 4970, NGC 6745. NGC 4676 and NGC 2623 images courtesy of NOAO. NGC 7252 image courtesy of John Hibbard, Puragra Guhathakurta, et al. Arp 240 image courtesy of the Sloan Digital Sky Survey Collaboration. NGC 1409/1410 image courtesy of NASA, William C. Keel. NGC 5090, ESO 510-13, NGC 6872 Images courtesy of the European Southern Observatory. NGC 6745 image courtesy of NASA and The Hubble Heritage Team. 

distant galaxies powered by supermassive black holes. Think about what would happen if you dropped a brick onto your living room floor. The energy the brick releases at the end of its fall is substantial, capable of doing significant damage to the floorboards (or your foot, if it got in the way). Now imagine dropping a trillion trillion bricks onto a supermassive black hole every second. That’s about how fast mass falls into a quasar. The power of such a gravitational engine can be tremendous. In fact, a quasar can release more energy in one second than our Sun produces in 10 million years; and the size of this prodigious engine barely exceeds our solar system.

Some quasars reside at the centers of perfectly normal-looking galaxies. But images from ground-based and space-based telescopes show that many, if not most, of relatively nearby quasars appear in colliding galaxy systems. Theory suggests that a galaxy collision could funnel millions of Suns’ worth of gas into the center of a galaxy, where the monster black hole resides. Could newly infalling matter directed by a galaxy collision cause a quiet black hole to blossom into a full-fledged quasar?

The giant elliptical galaxy Centaurus A (NGC 5128), just 10 million light-years away, might be a relatively nearby example of just such a system. About a billion years ago, Centaurus A was involved in a major galaxy collision, leaving behind the famous dark dust lane that bisects the elliptical galaxy in optical images. This merger undoubtedly fed huge quantities of gas into Centaurus A’s central black hole. Powerful magnetic fields near the black hole redirect some of this gas into two enormous particle jets shooting thousands of light-years outward from the galaxy’s nucleus. While Centaurus A might not be energetic enough to be considered a quasar, its active nucleus strongly suggests that galactic cannibalism can provide the necessary fuel to ignite quasars.

The Calm After the Storm
Eventually, the furious activity caused by a galaxy collision finally subsides, leaving a new generation of stars to carry on in the transformed, post-collisional galaxy. What happens in that last evolutionary stage from starburst to quiescence, however, remains rather
uncertain. How long will the galaxy continue to feel the effects of collision-induced frenzy, and what will be the galaxy's final configuration? A long-held theory, supported by computational models, states that a galaxy collision of two large galaxies ultimately winds up, billions of years later, as perfectly ordinary-looking elliptical galaxies like M84 and M86 in the Virgo Cluster.

Details of the transition are sketchy, in part because observational examples of final-stage colliding galaxy systems are rare. One particular galaxy with the cryptic nomenclature "G515" provides at least one answer. My observations and analyses of G515 over the past several years show that the visible light from this galaxy, about a billion light-years from Earth, comes almost purely from stars between 900 million and 1.1 billion years of age — a sure giveaway that a titanic starburst occurred then. Furthermore, this post-starburst galaxy shows all the hallmarks of a mature, fully formed elliptical galaxy. But faint, residual tidal tails and structures point to a violent collision exactly coeval with the fossilized starburst. G515 is a smoking gun — clear evidence that a merger can, after triggering massive starburst activity, create an elliptical galaxy. Studies by other researchers, such as those by Tzu-Ching Chang and Jacqueline van Gorkom at Columbia University, and Ann Zabludoff at the University of Arizona, have yielded similar results.

As we solve the many riddles of galaxy collisions, fresh mysteries continue to surface. Recent studies have hinted that the galaxy collision rate was much higher billions of years ago than it is today. If so, why do large spiral galaxies still far outnumber large ellipticals? Closer to home, some have speculated that our Sun may have been born during a starburst episode in the Milky Way nearly 5 billion years ago. Did a galaxy collision lead to humanity's emergence? Looking ahead, the Milky Way seems to be heading toward the Andromeda Galaxy at more than a million kilometers per hour. Are we destined to get up close and personal with our neighbor, billions of years from now? To me, questions like these make the study of colliding galaxies interesting and challenging — and fun.

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