ASTRONOMY

New revelations about how galaxies collide offer a preview of the Milky Way's future

By Aaron S. Evans and Lee Armus

Illustration by Ron Miller

COSMIC CRASHES

FORECASTED FUTURE: An illustration shows a possible view of the merging Milky Way–Andromeda system as seen from Pluto, which may get tossed to the galaxy's outskirts, along with the solar system.

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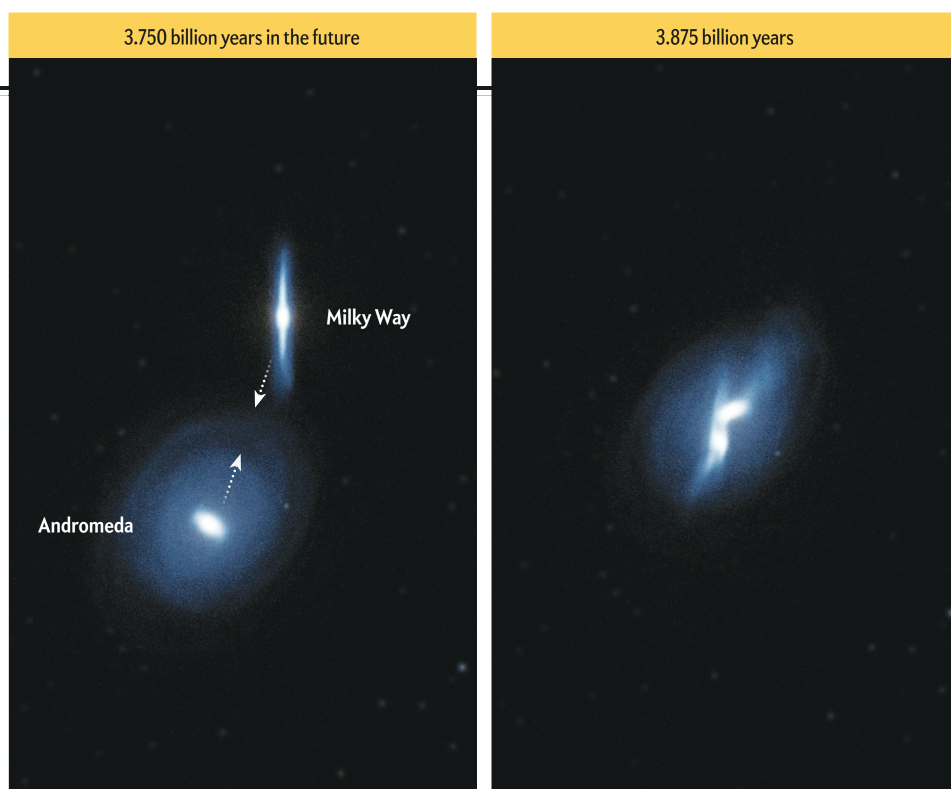
IN APPROXIMATELY FIVE BILLION YEARS, AS THE SUN EXPANDS INTO A RED GIANT STAR ROUGHLY THE diameter of Earth's orbit around it, our galaxy will collide with its nearest large neighbor, Andromeda. As gravity draws the pair toward each other for a close encounter, stars will be ripped from their orbits to make spectacular tails, and gas and dust will be squeezed toward the approaching nuclei, destroying the stately, grand spirals that have existed for almost three quarters of the age of the universe.

Eventually the centers of the galaxies will merge, and the gas pouring toward the center will ignite an explosion of star formation, producing stars more than 100 times faster than either galaxy does today. It will also feed the now quiet supermassive black holes that lurk at the centers of both galaxies. The black holes will grow while releasing a storm of energetic particles and radiation that will easily outshine the light from all the stars in both galaxies combined. After another 100 million years or so, the two supermassive black holes will spiral toward each other and merge into a single black hole in a cataclysm that will send strong gravitational waves reverberating throughout space.

Despite the fireworks, this process—which is happening around us today and was even more common in the early universe—is not really a "collision" in the strictest sense of the word. Galaxies are mostly empty space. The roughly 300 billion stars in a galaxy like the Milky Way are, on average, separated by nearly five light-years. The density of air at sea level on Earth is about 100 million billion times greater than the average density of gas in interstellar space. In other words, although a merger is transformative in the life of a galaxy and a source of immense

The Merging Sequence

Gravity will one day draw together our Milky Way with its neighboring spiral galaxy, Andromeda. This collision, which will take several billion years to unfold, will not harm most of the stars and planets inside the galaxies, which are spread too far apart to come into contact with one another. They will, however, be strewn to new locations throughout the merging bodies. This sequence from a computer simulation shows the predicted course of events. The simulation, derived from Hubble Space Telescope observations of Andromeda's motion, shows that the end result will be not a spiral but an oblong "elliptical" galaxy.



power, most stars just pass right by one another during the event.

Nevertheless, galaxy pileups are fascinating and important. By studying the mergers of other galaxies, we can see the future of our own. Studying galaxy mergers also helps us understand the history of the universe because when the cosmos was younger and denser, galactic collisions were much more common. Simulations suggest that over the past 10 billion years the Milky Way has undergone as many as five major mergers on its way to becoming the grand spiral it is today.

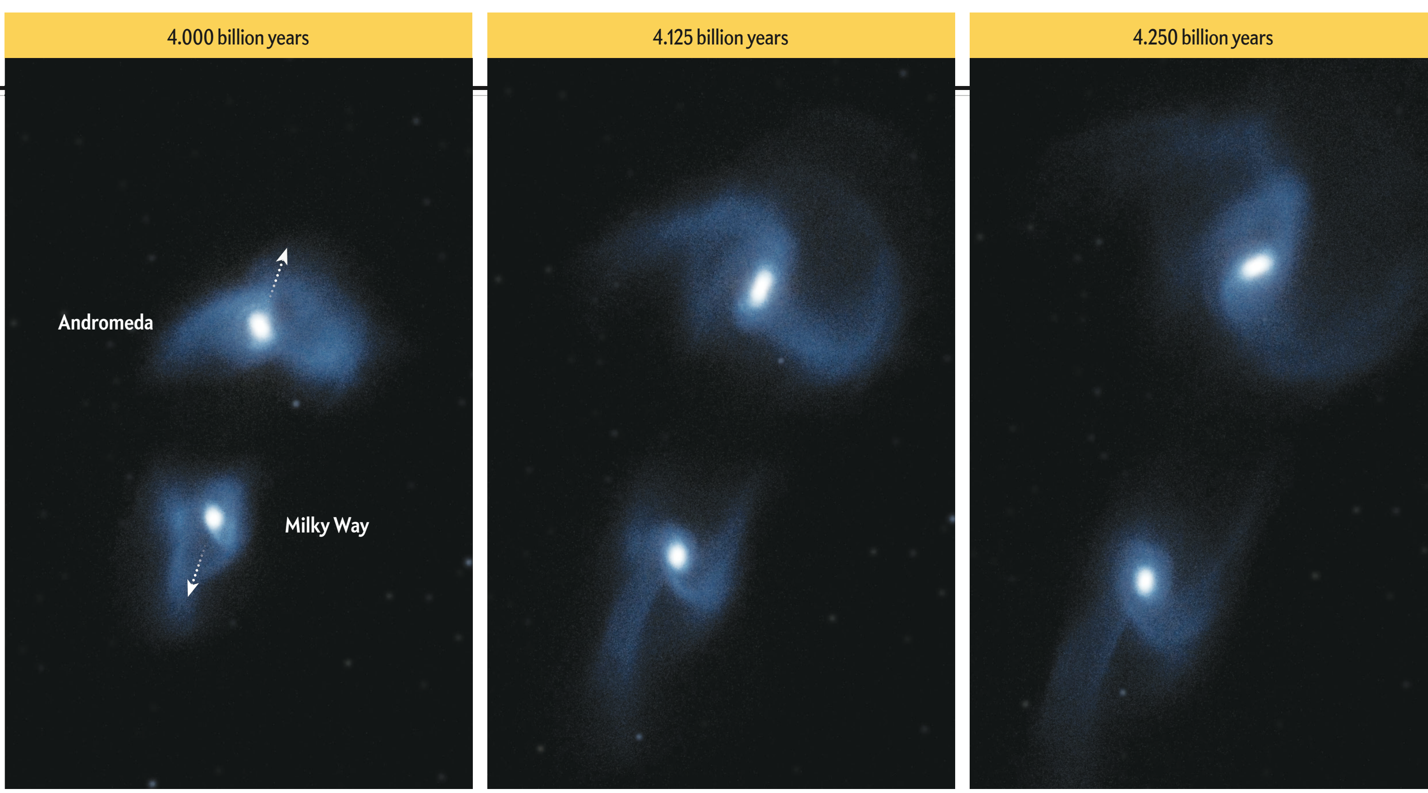
It is an exciting time to be doing this work. Until recently, astronomers lacked the tools to carefully measure and model colliding galaxies. Most of the action is obscured behind thick clouds of dust that are difficult to penetrate at visual wavelengths, even with the largest telescopes. With new instruments on current and planned telescopes, we will begin to answer some big questions about galaxy mergers, such as how stars are born during the chaos of a galactic collision and how radiation released by growing and eventually merging central black holes affects the new galaxy taking shape around them.

GALACTIC PILEUPS

IT HAS BEEN almost a century since Edwin Hubble first discovered that many of the glowing blobs in the sky—known at the time as "nebulae"—are not objects within the Milky Way but are instead independent "island universes." He classified these "extragalactic nebulae" into three categories: those with spherical or elliptical shapes (the elliptical galaxies), those with flattened and sometimes barred disks with a central bulge (the spiral galaxies, like our own), and misshapen oddities (the irregular galaxies).

A small fraction of the irregular galaxies were in fact highly distorted pairs or small groups of galaxies. In the years after Hubble's discovery, such pioneers as Boris Vorontsov-Velyaminov of Moscow University, Fritz Zwicky of the California Institute of Technology, and Halton Arp of the Mount Wilson and Palomar Observatories studied this class of "interconnected galaxies" in detail. Long-exposure images made from photographic plates, published in Arp's 1966 *Atlas of Peculiar Galaxies,* clearly show the distorted shapes that we now recognize as the signatures of merging galaxies. In the 1970s the brothers Juri and Alar Toomre used computers to model interactions of simple disk galaxies on bound, parabolic orbits, re-creating the shapes of several peculiar galaxies—in particular the long, sweeping tails of stars launched to great distances during the merger. These and other early simulations showed that the unusual, sometimes spectacular features highlighted by Arp and others could be explained solely by gravitational interactions. Using modern computers and state-of-the-art simulations, teams led by Joshua E. Barnes of the University of Hawaii, Lars Hernquist of Harvard University and Philip Fajardo Hopkins of Caltech have further mapped the diversity of galaxy interactions and the importance of mergers in the life cycle of galaxies.

In 1983 the Infrared Astronomical Satellite, or IRAS, was launched. This satellite produced the first far-infrared map of the entire sky—a huge boon to the study of the hidden universe and, in particular, galactic mergers. At the wavelengths it captured, the satellite was sensitive to thermal emission from warm and cool dust. Interstellar dust in galaxies almost always signals a nursery for stellar birth. In normal galaxies, stars are born in clouds of (mostly) molecular hydrogen gas and dust. As stars evolve and die, they shed heavy, dust-forming elements such as carbon and oxygen, which were produced in their interiors through nuclear fusion, thus further enriching the surrounding



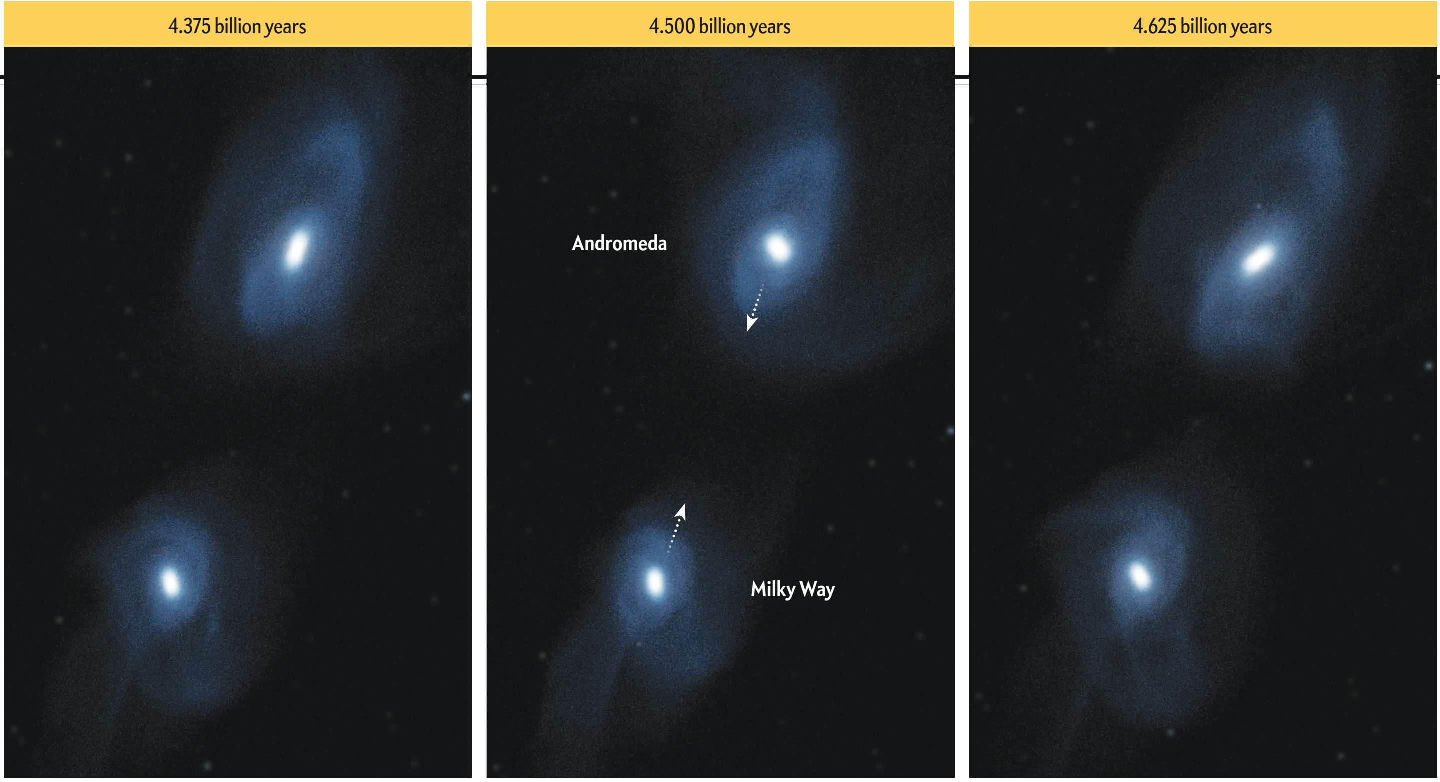
NASA, ESA, Frank Summers and Space Telescope Science Institute *(visualization)*; NASA, ESA, Gurtina Besla, Columbia University, Roeland van der Marel and Space Telescope Science Institute *(simulation)* clouds with dust. (The dust already in the clouds was formed in prior episodes of star formation.) In colliding galaxies, this process is in overdrive—the merger concentrates gas and dust into compact regions, igniting waves of star formation called starbursts that in turn produce more heavy elements and more dust. Therefore, although young and massive stars release most of their energy at short ultraviolet wavelengths, very little of this light actually makes it to Earth. The surrounding dust grains absorb the ultraviolet light and reemit it in the infrared. Telescopes equipped with sensitive infrared detectors can measure this light, allowing us to peer through the veil of dust and study the earliest stages of stellar birth and the growth of supermassive black holes.

IRAS detected many such stellar nurseries in the Milky Way and in thousands of other galaxies, greatly improving our understanding of galaxy mergers in two important ways. First, IRAS provided accurate measures of the energy generated within these objects and showed that merging galaxies are among the most intrinsically luminous objects in the universe. Second, IRAS detected colliding galaxies, solely on the basis of their infrared emission, over vast distances, giving us our first accurate census of galaxy mergers over cosmic time. Some of these collisions were so far from Earth that the light we see was emitted when the universe was just one fifth of its current age. In some merging galaxies, more than 90 percent of the total power output occurs at far-infrared wavelengths—their true natures are completely hidden from optical telescopes.

But IRAS showed us that a large infrared "excess" is an excellent way to find interacting and merging galaxies. In particular, it discovered a class of galaxies called luminous infrared galaxies, or LIRGs for short. These objects, with far-infrared luminosities above 100 billion times the brightness of the sun (about three times more than the total energetic output of all the stars in the Milky Way), are often merging galaxies. Even rarer and more spectacular are ultraluminous infrared galaxies, or ULIRGs. These galaxies, which have a far-infrared luminosity of more than a trillion times the sun's brightness, are almost always violent galactic collisions.

Scientists took a step toward explaining what happens at the cores of merged galaxies in the late 1980s, when they made a connection between mergers and another class of celestial bodies called quasars, which are powered by active supermassive black holes. These are the most energetic objects in the universe, with a brightness more than a trillion times that of the sun. David Sanders, who was then a postdoctoral fellow at Caltech working with Tom Soifer and the late Gerry Neugebauer, postulated that ULIRGs are an early, dust-enshrouded phase between galaxy mergers and quasars. This evolutionary link between ULIRGs and quasars built on previous studies by Alan Stockton of the University of Hawaii, John MacKenty of the Space Telescope Science Institute in Baltimore and Timothy Heckman of Johns Hopkins University, who showed that galaxies hosting active central black holes often looked distorted, consistent with their being galaxy mergers.

The proposed connection between powerful infrared galaxies and quasars, two types of celestial objects that are seemingly very different, provided a testable model that spurred research on the relation between these apparently disparate classes. By providing a framework to connect luminous infrared galaxies, powerful starbursts, and active galaxies and quasars, it helped renew interest in how galactic mergers influence galaxy evolution over cosmic time. Because more than half the light ever generated by stars in the history of the universe gets reprocessed into infrared light by dust, the role of mergers may be critical.



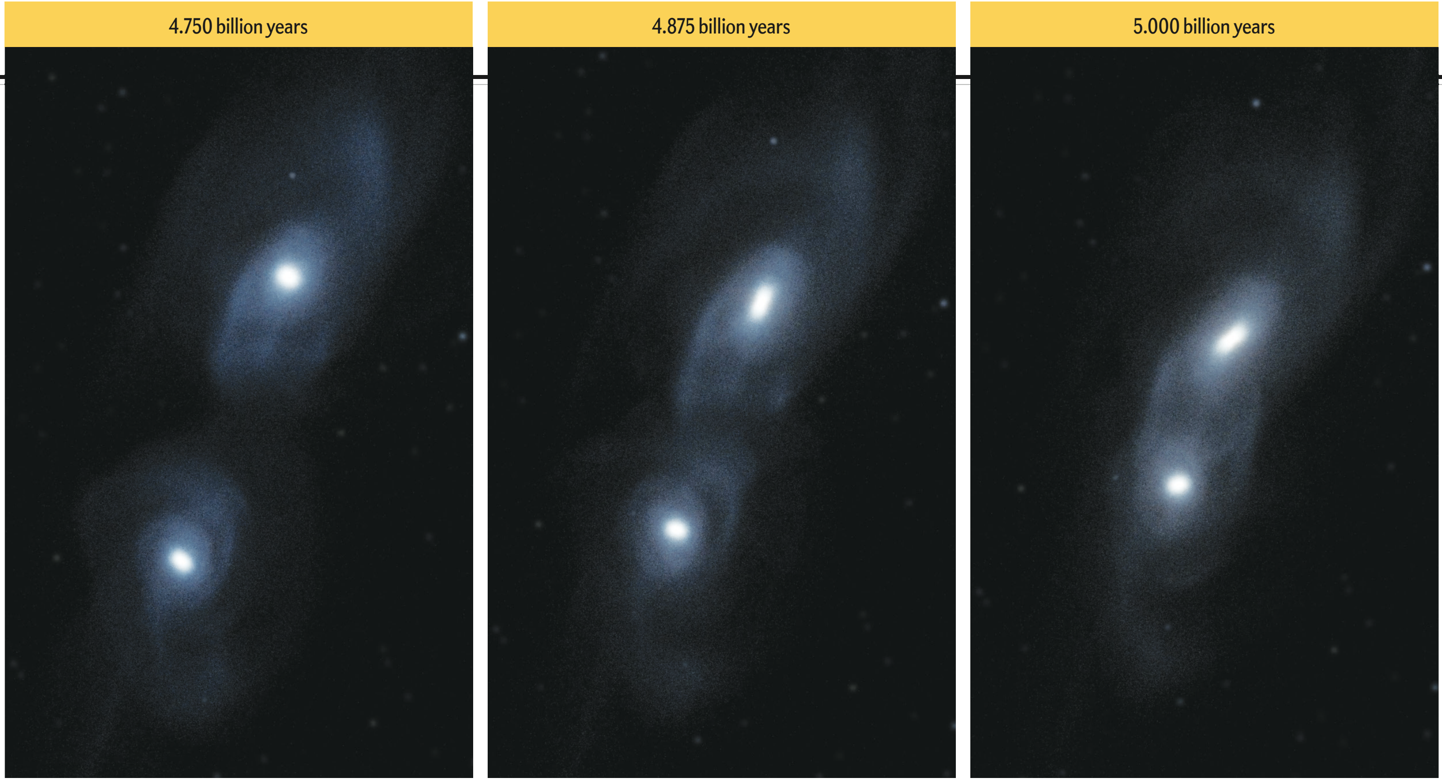
AMBITIOUS GOALS

IN 2004 the two of us and our collaborators initiated the Great Observatories All-Sky LIRG Survey (GOALS) to collect images and spectroscopy of colliding galaxies using three of NASA's Great Observatories: the Spitzer Space Telescope, the Hubble Space Telescope and the Chandra X-ray Observatory. These instruments provide a multiwavelength view of the merger life cycle. The GOALS sample consists of all the brightest infrared luminous galaxies in the local universe. This collection of more than 200 objects, all within 1.3 billion light-years, enabled the most detailed studies of infrared luminous galaxies to date.

Our team also uses ground-based telescopes such as the Very Large Array (VLA) in New Mexico, the Hale 200-inch telescope at Mount Palomar in California, the twin Keck 10-meter telescopes in Hawaii, and the Atacama Large Millimeter/submillimeter Array (ALMA) in Chile. The team has also collected data with Europe's far-infrared Herschel Space Telescope and NASA's NuSTAR x-ray telescope; the latter studies very high-energy hard x-rays.

GOALS has already significantly increased our knowledge of colliding galaxies. A long-standing question, for instance, has been whether young stars or active black holes contribute more to the light coming from merging galaxies. One way we can separate out their respective contributions at different times in the merger life cycle is by looking at the different energy profiles (the amount of energy released as a function of wavelength) of the two types of objects. Stars are simple thermal sources of radiation—they emit most of their energy at a peak wavelength that depends on their temperature, and their energy output declines very rapidly at shorter and longer wavelengths. In contrast, the accretion disk around a feeding black hole is viscous and hot, and its temperature increases from its exterior toward the event horizon of the black hole. An accretion disk has a much broader energy profile and produces a much larger fraction of high-energy radiation than a star, and it can heat and ionize (strip electrons from) a wide range of elements in the surrounding gas. Finding strong emission from highly ionized elements in a galaxy's spectrum is a dead giveaway that an accreting supermassive black hole lies at its center.

GOALS found that over the entire population of LIRGs, starbursts appear to be more important energy sources than black holes. About one fifth of all the luminous infrared galaxies in GOALS seem to host active supermassive black holes, but even in these galaxies stars contribute a significant amount of energy. But we may be missing active black holes that are so buried by dust that even infrared diagnostics cannot identify them—a phenomenon that is currently being studied in detail by two members of the GOALS team, George Privon of the National Radio Astronomy Observatory and Claudio Ricci of the Diego Portales University in Chile, and by a team at Chalmers University of Technology in Sweden led by Susanne Aalto. Also, we tend to identify active black holes during the latter stages of a merger life cycle, which suggests that much of the supermassive black hole growth may lag behind star formation, giving starbursts more time to contribute to the total energy. Alternatively, some black holes may also grow early, as has been suggested by observations of some LIRGs at the highest resolution in the infrared by GOALS team member Anne Medling of the University of Toledo. The precise timescales over which the stars and the central supermassive black holes grow inside galaxies is the subject of a great deal of current research attempting to understand one of the deepest mysteries of the past two decades: why the mass of the central black hole and the stars in the bulges of present-day spiral and elliptical galaxies have a nearly constant mass ratio of roughly one to 1,000 in galaxies today.



NEW INSIGHTS

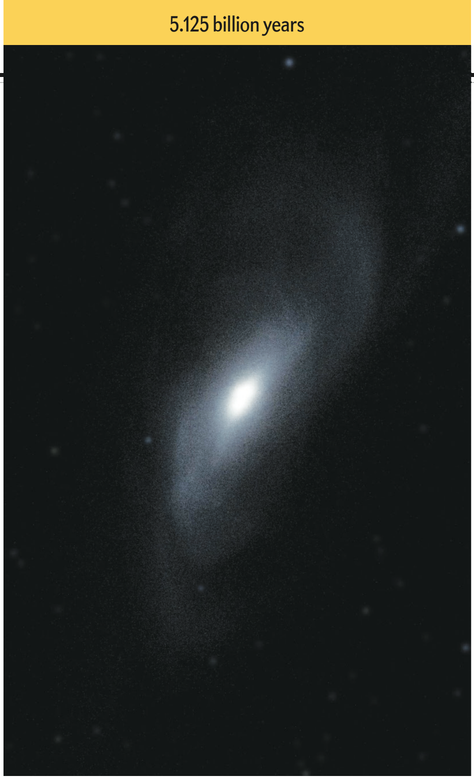
OTHER RECENT PROJECTS have revealed new clues about LIRGs and how stars form in colliding galaxies. For instance, by mapping the gas heated by the most massive stars inside these objects, researchers, including GOALS members Kirsten Larson of the Space Telescope Science Institute, Tanio Díaz-Santos of the Foundation for Research and Technology–Hellas in Crete, and Loreto Barcos-Muñoz and Yiqing Song of the University of Virginia, have found that most of the star formation in LIRGs happens in extremely compact and energetic starburst regions. These areas have star-formation rates and gas densities a factor of 10 or more higher than we find in normal galaxies. Early in the merger process, the most active star-forming regions tend to reside in areas outside the nuclei of LIRGs. As the merger evolves, however, the primary starbursts are compact clumps in and around the merging nuclei, as gas originally in the spiral arms falls toward the center.

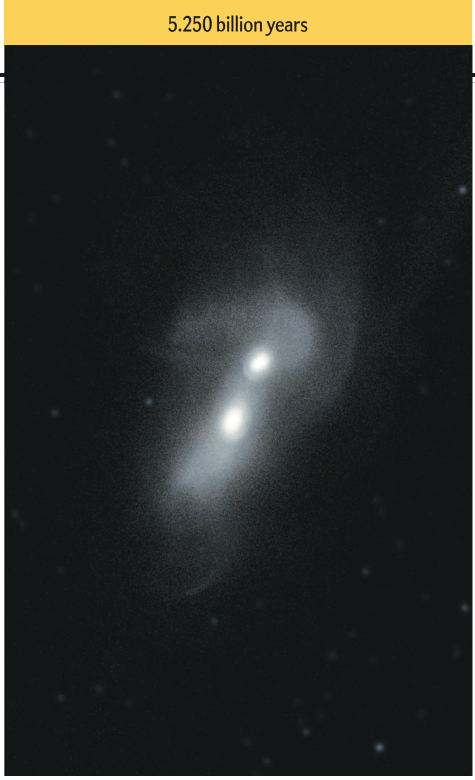
Interestingly, the densities of the central concentrations of molecular gas in the most energetic late-stage mergers are so high that they begin to resemble giant molecular clouds. A prime example of this phenomenon is the nearest ultraluminous infrared galaxy, Arp 220, which is located 250 million light-years away. Kazushi Sakamoto of Taiwan's Academia Sinica and Nick Scoville of Caltech have mapped the molecular gas at the center of this object in exquisite detail with the ALMA array, showing it contains several Milky Way's worth of molecular gas concentrated in a region not larger than 3,000 light-years across—a factor of 20 smaller than the extent of the Milky Way's gaseous disk.

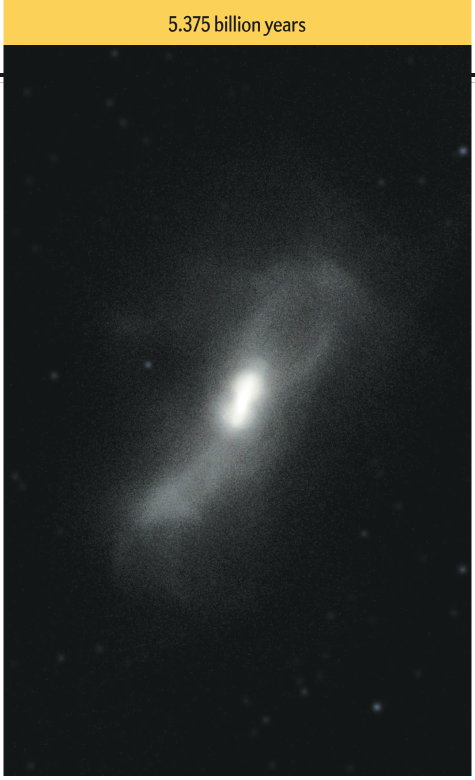
Although mergers are powerful stellar factories, star clusters formed in the collision may actually live surprisingly short lives. Using data from the Hubble Space Telescope, Angela Adamo of Stockholm University and GOALS member Sean Linden of the University of Massachusetts Amherst have seen a dramatic drop-off in the number of clusters as a function of cluster age, suggesting that significant numbers of star clusters are destroyed in merging galaxies shortly after they are born. The collision triggers enhanced star formation, but gravitational tidal forces and winds from supernovae within the clusters may easily tear them apart.

Just as the gas in clusters can be swept clear as stars evolve, so, too, can the merger fall victim to feedback from supernovae and the central black holes, with profound effects on further galactic evolution. Large flows of ionized gas streaming away from mergers were first studied in the early 1990s by Heckman and his collaborators, who found evidence for powerful winds—dubbed superwinds—in some low-redshift LIRGs and ULIRGs. Subsequent studies targeting this hot atomic gas have found not only that winds are common in LIRGs and ULIRGs but that the fastest of these can break free from the galaxy and eject gas into intergalactic space, as has been shown by David Rupke of Rhodes College and others. On the finest scales, jets and bubbles of hot, shocked gas mark the regions where the nuclei pour energy into the galaxy and drive the outflows, as has been mapped by GOALS team members Medling and Vivian U of the University of California, Irvine, using the twin Keck telescopes.

Galactic superwinds are multiphase, meaning they can contain hot and cold atomic and molecular gas. A number of astronomers, including Sakamoto, Barcos-Muñoz, Miguel Pereira-Santaella of Spain's Center of Astrobiology and Eduardo González Alfonso of the University of Alcalá in Spain, have studied the dense, molecular gas in superwinds, often finding large amounts of cold gas flowing outward from merging galaxies. These outflows can easily cover 10,000 light-years and sometimes carry more gas than is being made into stars in the nuclei, effectively robbing the gal-







axy of fuel for ongoing star formation. Just as important, these winds can send heavy elements (metals) and dust into intergalactic space. In nearly all cases, the outflows seem to originate near the nucleus of the merger, driven by the combined effects of supernovae, radiation pressure and jets (fast columns of gas) from the central black hole. These outflows may be important in the life cycle of galaxies, as detailed simulations by Chris Hayward of the Flatiron Institute suggest that stellar feedback can simultaneously regulate star formation and drive outflows.

THE BIGGEST EYES ON THE SKY

THE SOON-TO-LAUNCH James Webb Space Telescope is poised to greatly expand our understanding of galaxy mergers across cosmic time. This 6.5-meter-diameter infrared telescope is due to lift off at the end of 2021. Webb is the scientific successor to IRAS, the Infrared Space Observatory (which flew in the 1990s) and Spitzer (which was decommissioned in 2020), but Webb will be at least 50 times more sensitive and have nearly 10 times the spatial resolution of Spitzer, delivering sharp images of galaxies in the near- and mid-infrared part of the spectrum. It will also carry imaging spectrometers that can generate hundreds of spectra in a single pointing. This capability will allow it to map star-forming regions and the regions around actively accreting supermassive black holes in nearby mergers in exquisite detail.

The GOALS collaboration will observe four nearby luminous infrared galaxies as part of a Webb Director's Discretionary Early Release Science program. Other researchers will use the observatory to target nearby, bright active galaxies, distant quasars and deep, blank fields in search of the earliest galaxies. The GOALS early-release targets include galaxies with powerful starbursts and active central black holes. They are all caught in the throes of a galactic merger and are all experiencing galactic outflows. These galaxies will be valuable local laboratories for understanding how these processes unfold in the early universe. Beyond the early-release programs, several projects have been selected in the first General Observer Cycle for Webb, which will examine feedback from young clusters and active black holes, the fraction of star formation hidden from us at optical wavelengths and the nature of obscured nuclei in LIRGs.

The next-generation Very Large Array is the planned replacement for the 27-dish Very Large Array. This 263-dish radio- and millimeter-wave interferometer will observe star-forming regions, active black holes and light associated with exploding stars with 10 times the sensitivity and resolution of the VLA.

Overall, these new telescopes will unveil the astrophysics occurring in nearby and early-universe galaxy mergers. High-resolution simulations, coupled with these detailed new observations, will be the key to understanding how physical feedback processes help to regulate star formation and black hole growth in merging galaxies. Future planned and proposed observatories will be able to detect the gravitational-wave signatures of colliding supermassive black holes and the dusty cores of forming galaxies over the vast majority of cosmic time. As we discover more exotic objects at the farthest reaches of the universe, we will continue to use these new tools to better understand how galaxies are born and live out their lives.

FROM OUR ARCHIVES

Colliding Galaxies. Rudolph Minkowski; September 1956.

scientificamerican.com/magazine/sa