

Watching galaxies evolve

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Astronomical observations cover more than 95% of the history of galactic evolution. The considerable activity we have seen reveals the ways in which galaxies form and evolve.

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For nearly a century, astronomers have examined galaxies. We have observed millions of them, sometimes in great detail, at wavelengths ranging from radio to x ray. Most observations have been geared toward measuring basic galactic properties or classifying galaxies based on how they appear on photographs; only recently have we begun to explore their underlying physics. Important unresolved issues include the persistence over long periods of time of structures such as spirals in the Milky Way, the nature of the nonluminous dark matter that dominates the mass of galaxies, and the reasons galaxies cluster together. Another major question relates to all those issues and more, and still awaits a complete answer: How do galaxies form and evolve? That question is the focus of this Quick Study.

The physics of galaxy formation

In the most widely accepted theory of galaxy formation, the first galaxies to form do so within dark-matter blobs—astronomers call them halos—with the first galaxies having halo masses on the order of a million times the solar mass $M_{\odot}$. Those dark-matter halos serve as the theater in which galaxy formation plays out, as gas initially in a hot state within those halos is converted to stars. (See the article by Tom Abel in *PHYSICS TODAY*, April 2011, page 51.) Although we can observe that conversion throughout most of the history of the universe, we have yet to see the very first stars form.

The universe is a violent place during the formation of the first generations of stars and galaxies. While the first galaxies are forming, their host dark-matter halos are merging with each other to form bigger and bigger halos. When galaxies are within those halos, they also merge and become more massive galaxies. Cold gas accreted from the intergalactic medium provides more feedstock for galaxy growth and star formation. The idea that galaxies form in part from such flows is becoming increasingly popular, yet the process still lacks firm observational evidence.

Even as galaxies grow due to star formation, merging, and cold gas flows, the very process of star formation and the buildup of the galaxies' central massive black holes create energy that can slow down or even halt additional star formation. The ejected energy can physically remove gas or heat it so much that it cannot cool to form stars in a reasonably short time. Stellar winds and the intense energy from exploding supernovae also contribute to the feedback mechanism that inhibits star formation. As is well known from simulations, without that feedback galaxies would build up their stellar mass at a much more rapid rate than is seen.

Direct observations of energy ejected in the course of black hole and star formation give us confidence that feed-

back operates in the early universe. Black holes at the centers of many (perhaps most) galaxies grow by accreting matter; the energy-emitting central region of the galaxy is called an active galactic nucleus. We can see that over the period of 10 billion years, a black hole at the center of a massive galaxy emits as much as 10 times the binding energy of the galaxy. We can also witness supernova events in galaxies back to roughly when the universe was half its current age. But just how the ejected energy couples with its host galaxy and its gas and how it affects later galaxy formation are complicated problems that are not fully solved.

Time slices

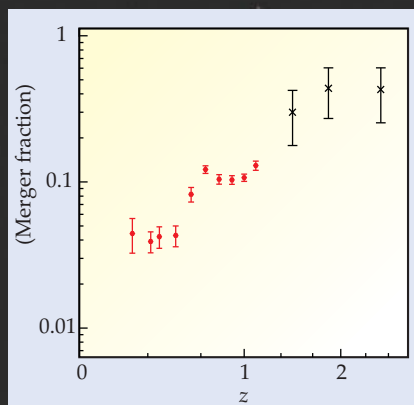
Because the speed of light is constant, astronomers see distant galaxies as they were in the past. If we connect similar galaxies at different times—for example, galaxies with similar mass—we can see how those galaxies changed over time and then attempt to piece together the physical mechanisms driving galaxy formation. Indeed, we have by now compiled considerable observational data on galaxies from as far back as when the universe was roughly 800 million years old, all the way until today when the universe is 13.7 billion years old. We have no observations of the universe during the 800-million-year period after the cosmic background radiation was imprinted a few hundred thousand years after the Big Bang. That epoch is known as the cosmic dark ages and will be the focus of major instrumentation and telescope projects in the next 20 years.

What we find is that typical distant galaxies were smaller, less massive, and formed stars at a greater rate than typical galaxies in today's universe. They were also more irregular in appearance than galaxies are now. Thus observations clearly establish that galaxies have evolved, but how they have evolved is a different issue.

One way to address that question is to compare observed galaxy properties with models and large computer simulations that can effectively follow the evolution of galaxies with different masses. Those simulations, however, are very complicated and include a number of variables that parameterize everything from how dark matter is distributed to how energy ejecta regulate star formation. The inherent complexity of simulations makes it desirable to have a more direct, empirical handle on the processes—for example, mergers, gas accretion, and feedback—that drive galaxy assembly.

Several observational methods have enabled astronomers to trace the cosmic star formation history. For the most part, those methods involve measuring the energy output from massive stars, which are short-lived and bright and

Galaxy mergers were more common in the early universe than they are now. The plot shows the fraction of galaxies with stellar masses greater than 10^{10} solar masses that are in the process of merging, as a function of redshift z , a measure of cosmic time. The present day corresponds to a redshift of 0; the halfway point of cosmic history corresponds to a redshift of about 1. Data are from the *Hubble Space Telescope* COSMOS field (red) and Ultra Deep Field (black) surveys. The background image (courtesy of NASA) shows the aftermath of a collision of a large, spiral galaxy with a smaller galaxy to the lower right, nearly out of the field of view. The blue-white area is a region of star formation triggered by the collision.



which emit most of their energy in the blue and UV parts of the spectrum. Astronomers also observe emission from dust heated by those energetic photons to quantify the amount of star formation in distant galaxies.

The various approaches paint a consistent, if rough, picture. Summed over all galaxies, the star formation rate increases from the earliest time we can see galaxies and peaks when the universe was a few billion years old. The star formation rate then declines again and is currently as low as has ever been observed. About half the stars in the universe today had already formed by the time the universe was half its current age, and the bulk of all stars that will ever form have likely already done so.

Through examining the form and structure of galaxies with stellar masses greater than $10^{10} M_{\odot}$, we also know that in the course of the past 12 billion years, those massive systems have undergone a handful of major mergers with other galaxies of similar mass. Each merger roughly doubles the amount of mass in a galaxy. As the figure shows, most of the mergers occur early in the history of the universe; indeed, on average, a massive galaxy has participated in just a single major merger during the second half of cosmic history. How mergers fit into the formation of lower-mass galaxies is not yet known with any certainty, although theory predicts that minor mergers may be of major importance.

Although merging builds up the masses of galaxies in a blunt way, as described earlier, another important process may be the accretion of gas from the intergalactic medium. The accreted gas is in a cold state and can quickly form stars once it is within the galaxy. It is, however, relatively difficult to observe those accretion processes, which would require an unambiguous signature—such as an absorption line—that signals gas falling into a galaxy as opposed to gas being ejected from a galaxy.

Wider and deeper

In the future, observations with large telescopes—such as the *James Webb Space Telescope* and ground-based 30-m-class optical-near-IR telescopes being developed—will enable us to directly study the most distant galaxies in detail. We should even be able to peer into the currently inaccessible dark ages. On another front, large surveys with space telescopes such as the European Space Agency's *Euclid* and NASA's *Wide-Field Infrared Survey Telescope* and ground-based telescopes such as the Large Synoptic Survey Telescope and Pan-STARRS (Panoramic Survey Telescope and Rapid Response System) will map a large number of systems, spanning most of the history of the universe, and will allow us to examine statistical properties of galaxies. New telescopes such as the Atacama Large Millimeter Array and the Square Kilometer Array will observe the gas content of galaxies in radio frequencies and will provide a new and unexplored way to examine how galaxies change over time. With those new observational methods and tools, astronomers should be able to see how galaxies assemble over all of cosmic history and address one of the fundamental questions of modern astrophysics.

Additional resources

- J. Binney, M. Merrifield, *Galactic Astronomy*, Princeton U. Press, Princeton, NJ (1998).
- L. Sparke, J. S. Gallagher III, *Galaxies in the Universe: An Introduction*, 2nd ed., Cambridge U. Press, New York (2007).
- M. S. Longair, *Galaxy Formation*, 2nd ed., Springer, New York (2008).