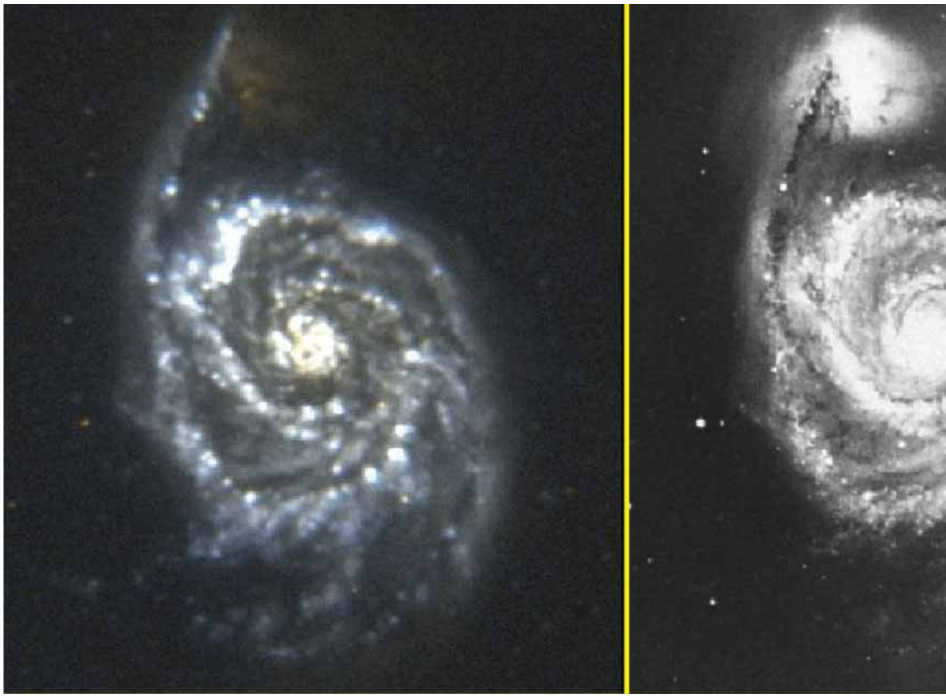


Galaxy Evolution:
The View from the Ultraviolet

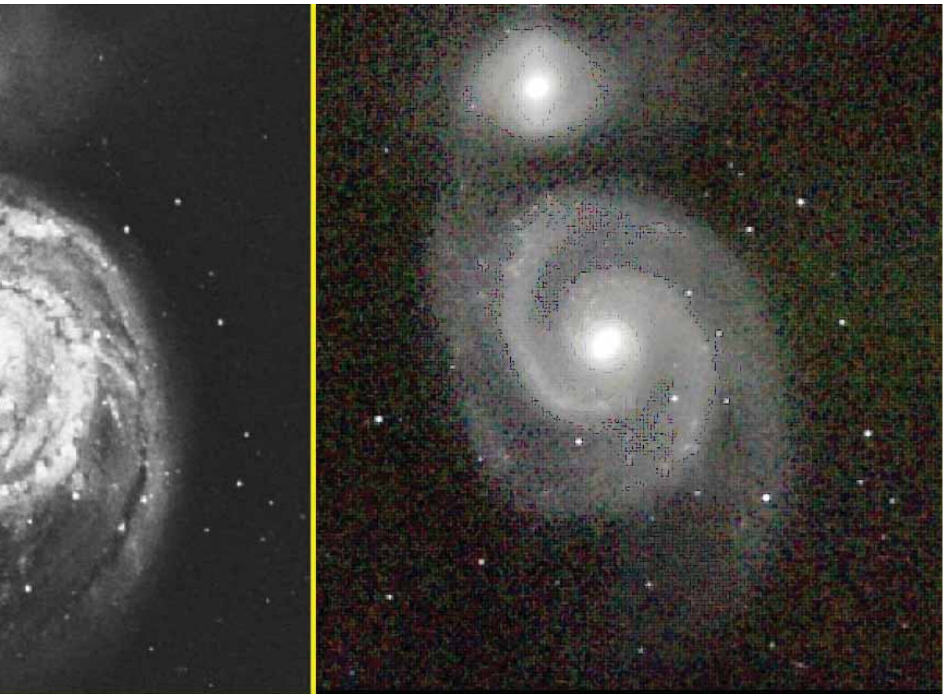
by D. Christopher Martin

Galaxies are amazing machines for forming stars. Out of a ball of gas at a density of one atom per cubic meter, a star emerges that has the density of water—about 10^{30} times denser than it started out as. How galaxies manage to form stars out of this very tenuous gas is a process that we do not yet understand, but GALEX (Galaxy Evolution Explorer) has been orbiting Earth for the past year to help us try to find out.

Most scientists believe that the universe was born 13.6 billion years ago in a cosmic explosion, the Big Bang. Quantum mechanics led to fluctuations in the energy density of the universe, which gravity caused to collapse into lumps. The lumps fell together into larger and larger lumps, finally forming very large lumps, or galaxies containing 100 million to 100 billion stars, as well as gas and dust.

In a way that we don't understand, dark matter (and we don't even know what that is) somehow acts as a framework, a foundation on which galaxies are built. We think dark matter forms "halos," into which the kind of matter we're familiar with—normal gas made of hydrogen and helium—falls and forms a dense core. This core eventually becomes a galaxy. We can simulate the formation of these dark matter halos because the physics is very simple, but the collapse of gas and the evolution of a galaxy out of it has very complicated physics, too vast in scale to be simulated or even described in terms of equations.

This has led to a problem. Theorists' very simple models predict that, when we look at the sky, we'll see a mix of galaxies: old ones whose stars formed long ago, and young ones that are



Different wavelengths reveal different features of the spiral galaxy M 51. The near infrared (right; a 2MASS image) shows old stars in the companion galaxy at the top and stars of various ages in the main galaxy. More definition can be seen in the optical wavelengths (center; Digital Sky Survey—DSS), as dust appears along with younger stars in the spiral arms. In GALEX's ultraviolet view (left), the companion galaxy with its old stars has completely disappeared and all that is visible are the youngest, hottest stars forming in the spiral arms.

still forming stars. And that's what we do see, which is reassuring. But the models also predict that the old galaxies are going to be small and the galaxies that are still forming stars will be large. Unfortunately, the old galaxies that we see are large, and the star-forming ones are medium to small. So there's a fundamental failure in the model predictions.

GALEX was originally proposed to map the sky in ultraviolet wavelengths, which had never been done before. Although mapping the sky in any new part of the electromagnetic spectrum leads to a wide variety of astrophysical applications, we designed the mission around a particular scientific question: How do galaxies evolve over time in the universe? One of GALEX's major goals is to understand the mechanism that turns gas into stars. And one of the ways of doing this is to measure the average rate of galaxy building, what we call the star-formation history of galaxies over time, from the Big Bang to today. This history is also the history of element building in the universe. By elements I mean the "heavy" elements—carbon, nitrogen, oxygen—those that form planets, solar systems, and life. Heavy element formation occurs in massive stars, which burn hydrogen into helium, helium into carbon, oxygen, neon, magnesium and so on. Then they become unstable, explode in supernovae, and deposit those heavy elements in the surrounding gas and even beyond the galaxy; they can generate huge superwinds that deliver these materials out into the intergalactic medium, and this is how the universe became polluted with the heavy elements that later formed solar systems.

In a way, astronomy is similar to geology, because in both we can actually look back in time. Of course, in geology, you look back in time by going down into the ground, and as you go downward you go deeper and deeper into the geological ages of the Earth. Astronomers can do a similar thing because light travels at a finite speed. So when we look at more distant galaxies, we are seeing them at an earlier age of the universe. And astronomers have a further advantage: the fact that the universe has been expanding since the Big Bang. If you think of the universe as a balloon, with every galaxy being on the balloon's surface, then as you blow up the balloon, the galaxies that are close together will move away from one another relatively slowly, while the galaxies that are farther apart will move away from one another faster. That allows us to measure distances very easily by just measuring a galaxy's velocity, which we can do by comparing its spectrum with that of a local galaxy. The faster a galaxy is moving away from us, the more its light gets stretched, causing its spectrum to be shifted to longer, or redder, wavelengths.

For example, the light from a galaxy that is moving away from us at half the speed of light left the galaxy 5 billion years ago, so we are viewing the galaxy about 8 billion years after the Big Bang. Those that are moving away at 0.9 times the speed of light are seen only about 2 billion years after the Big Bang. We can look at different layers of cosmic time by looking at more and more distant galaxies.

The history of star formation in a galaxy can be quite complicated, with stars forming throughout the galaxy's life. Also, stars live to various ages; they can be a million, 10 million, or many billions of years old. In many bands of the electromagnetic spectrum, we can see stars with a wide range of ages, so we get a blurred picture of the galaxy's construction. Above are images of M 51 in three different wavelengths. In the near-infrared image at the right, you can see a companion galaxy, consisting of old stars, and the main galaxy with old and young stars. In optical wavelengths you start to see the dust and the younger stars in the spiral arms.

But if you look in the ultraviolet, something really interesting happens: the old stars in the companion galaxy and in the smooth spiral arms disappear almost completely. You see only the stars that formed recently in the spiral arms. When stars are born in collapsing clouds of gas, a range of masses is formed, all the way from a hundred solar masses down to maybe a few tenths of a solar mass and even less. Stars over this range of masses have very different properties. The most massive stars are very hot and incredibly bright—as much as a million times more luminous than the sun. And they live very short lives, because they're burning up so fast. So, if you start out forming a collection of stars at various masses and let that collection age, the hottest stars, which radiate at the shortest wavelengths, in the ultraviolet (the radiation's wavelength is inversely proportional to the temperature of the source), die off first. After 10 million years, the hottest stars are gone; they've blown up into supernovae and formed black holes. After 100 million years, the less hot, less massive stars (but still radiating in the ultraviolet) are gone, and so on. As the population continues to age, you lose the progressively lower and lower masses. By looking in the ultraviolet, you get a picture of what has happened in about the last 100 million years; it's like taking a short exposure shot of a scene in order to freeze the action and understand what's going on at that moment (although our moment is 100 million years long).

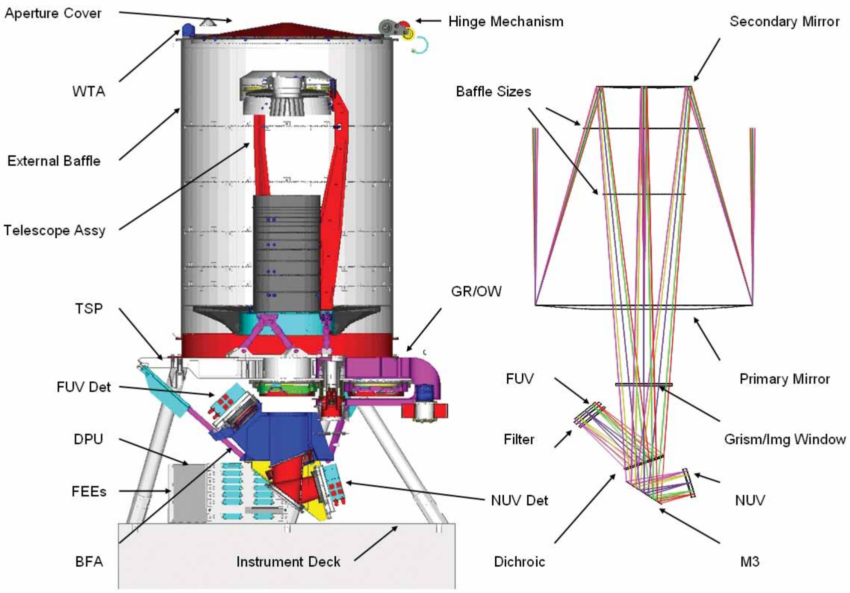
The basic idea of GALEX is to use the ultraviolet as a tool to study and understand star formation and galaxy building. We can study star formation in nearby galaxies and compare it to that in distant, younger ones. First we want to know the answer to the simple question: when did the stars form in galaxies—early on or late in their lives? Then we want to try to understand why the history was that way.

The mission is a wide-ranging partnership led by Caltech—a collaboration that includes the Jet Propulsion Laboratory, Johns Hopkins University, and UC Berkeley, as well as teams from France and South Korea. GALEX is a NASA Small Explorer, only a little more than 6 feet long and weighing 617 pounds. Its half-meter telescope observes at two bands—the far ultraviolet (the most blue) and the near ultraviolet. As you can see in the illustration at left, a typical photon hits the primary mirror and then the secondary mirror. Then it passes through either a window or a grism (a combination of a grating and a prism), which are mounted on a wheel. The wheel can rotate so that we can get either an image (through the window) or spectrum (through the grism) of every object in the field of view.

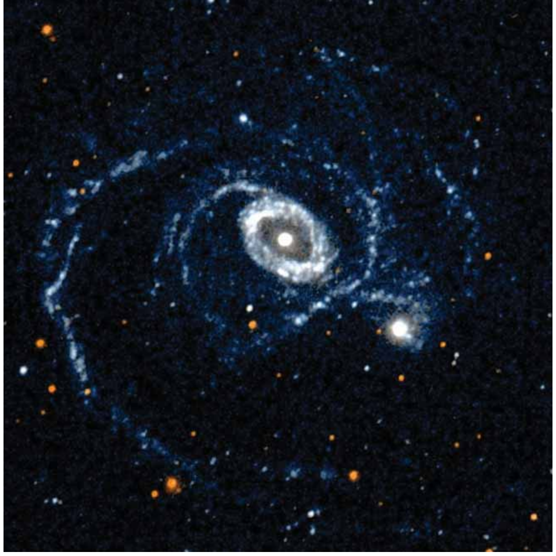
GALEX has a dichroic beam splitter, which can send the far ultraviolet signal to one detector and the near ultraviolet (which is slightly redder) to a separate detector. These detectors are not silicon or semiconductors; they're actually imaging photomultiplier tubes with millions of glass microtubes that count the individual photons. This is the largest version of this detector ever flown in space (six times larger than those on the Hubble Space Telescope), and the beamsplitter and grism are also the first of their kind. They all worked as expected, which is really amazing. *Popular Science* magazine named it one of the innovations of the year (along with the Spitzer Space Telescope).

The satellite was launched in April 2003 by a Pegasus rocket, carried aloft on an L-1011 that dropped the Pegasus at 40,000 feet, 100 miles east of the Kennedy Space Center. The launch vehicle

GALEX is a little satellite, only about the height of a man. The telescope's primary mirror is 20 inches in diameter. The solar panels, spread out here as they would be in space, provide the spacecraft's power, and although the mission is planned to last 29 months, GALEX could easily keep on observing for years—provided its electronic components, which have no backups, don't fail. Right: The satellite is tucked neatly inside the nose cone of the Pegasus rocket, which, after being hauled to 40,000 feet under an L-1011, launched it into orbit.



GALEX's innards illustrate how to pack sophisticated equipment into a very small space—elegantly. The light-path drawing on the right shows the light hitting the primary mirror, bouncing up to the secondary mirror, and then down to the optical wheel assembly (green in the left-hand drawing), where it is shunted to either the imaging window or the grism, then on to the dichroic beamsplitter, which parcels out the light to the far-ultraviolet and the near-ultraviolet detectors.



In the optical (above; DSS), NGC 1512 doesn't appear to have the spiral arms filled with young stars that emerge in the ultraviolet (left). Blue stars are those seen in the far ultraviolet, and red, the near ultraviolet.

drops for 5 seconds—a very long 5 seconds—then the booster is lit, and it flies aerodynamically for a few tens of seconds and then flies ballistically. The satellite orbits 700 kilometers above the Earth, completing one orbit every 98 minutes. We spend two-thirds of each orbit (about an hour) in the day with the solar panels pointed toward the sun, and then we slew over to the target of interest for that particular orbit and spend about half an hour on the night side, observing. Then we slew the solar panels back to the sun on the day side. We can't observe during the day because the ultraviolet background from Earth's tenuous outer atmosphere is so large.

We have now been observing galaxies for more than a year. Above are images of galaxy NGC 1512. In the optical image you can see that most of the light is in the center, but in the ultraviolet you see a lot of star formation going on in the spiral arms, swirling way outside the inner body of the galaxy. Blue represents the far ultraviolet and the red, the near ultraviolet. These spiral waves are probably caused by a companion galaxy, which you can see at the lower right. The companion is orbiting around the main galaxy, generating density waves, which are one way to trigger star formation. If you've ever driven on Los Angeles freeways (especially the 405), you've encountered density waves—patterns that persist long after the trigger for the pattern is gone. For example, a traffic accident can jam up the freeway for hours after the cars have been towed away. This is exactly what's happening in spiral arms. Different radii of the galaxy rotate at different rates, causing the beautiful spiral pattern. And because most of the star-forming clouds wind up in the spiral arms, the clouds collide with one another and become denser still. Ultimately the most dense bits will collapse into stars.

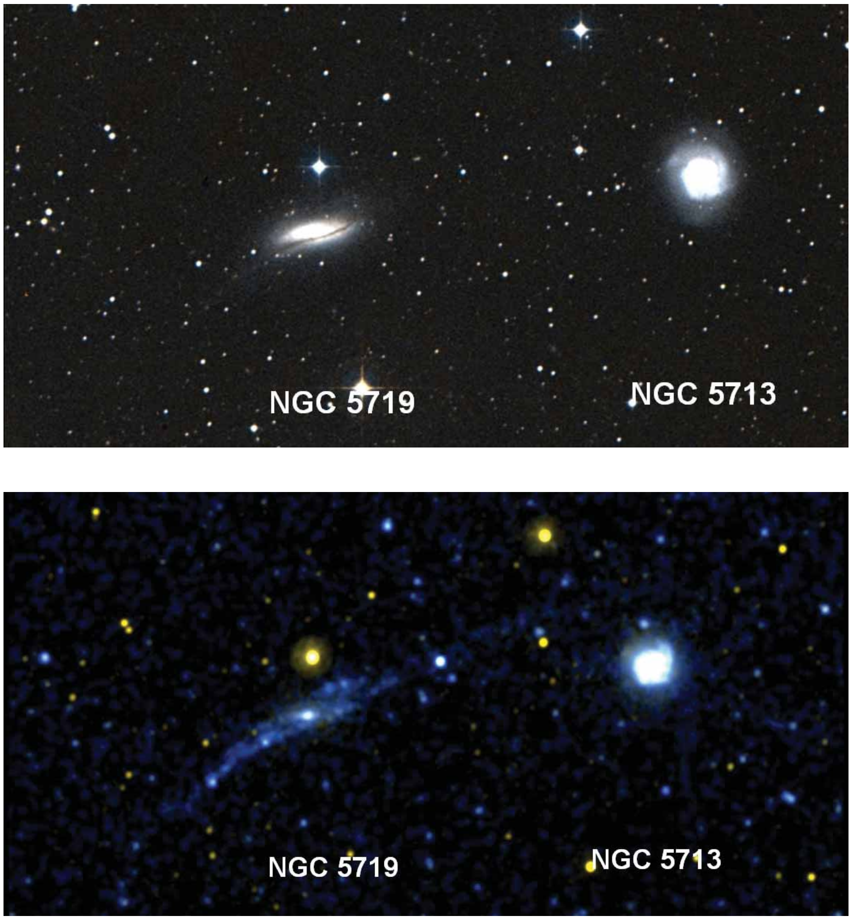
Some galaxies, such as M 33 at right, don't have prominent spiral density waves, and we see only a kind of random, raggedy spiral pattern. This is

The messy spiral of M 33 (below) is the result of turbulence.

GALEX is not a JPL spacecraft; it's a *Caltech* spacecraft, the Institute's first space mission. Chris Martin, professor of physics and the project's principal investigator, is responsible directly to NASA, and not through the usual prime contract under which Caltech operates JPL for NASA. Still, it made a lot of sense to call on the Jet Propulsion Lab for its expertise in managing space missions and developing science instruments. Jim Fanson (MS '82, PhD '87), a JPL employee, was appointed project manager. He brought a small team down the hill from the Lab, and they set up the project office on the fourth floor of Downs, where Martin's team also resides. The combined group included Frank Surber, project engineer; Amit Sen, instrument manager; Peter Friedman, project scientist; David Schiminovich, science operations and data analysis manager; and Kerry Erickson, mission manager. Work began in December 1997, and the satellite was launched in April 2003.

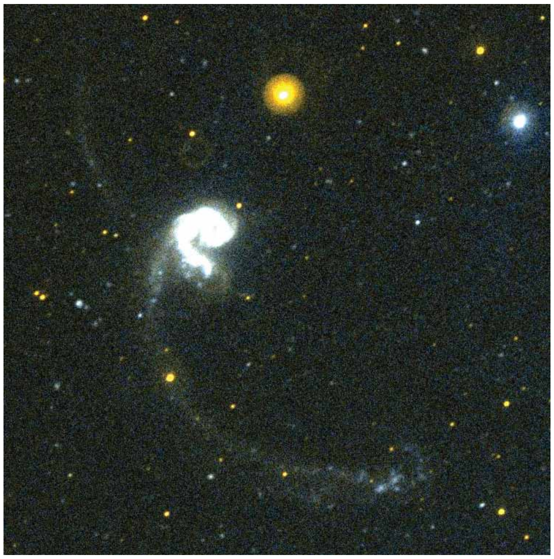
The project is a NASA Small Explorer mission, which means not only small in size, but also small in cost. GALEX cost less than $100 million (and $24 million of that was for the Pegasus rocket). Being able to do work at the campus or JPL, whichever was best suited to the particular task, gave the team added flexibility to keep costs low. Most of the major procurements, including the spacecraft bus made by Orbital Sciences Corporation in Virginia, were made from Caltech. Most of the telescope, on the other hand, was built at JPL.

Besides Caltech and JPL, GALEX involved an international team of investigators, which gave the project crew a whole education in export-control requirements. French scientists at the Laboratoire d'Astronomie Spatiale in Marseilles were in charge of the optical design, and they also produced the grism, a critical optical component for which they had unique technology in France. Korean investigators from Yonsei University in Seoul performed software development for mission planning and science operations. In the United States, investigators at Johns Hopkins University, which houses the archive for the Sloan Digital Sky Survey, have responsibility for the GALEX catalog, whose sources will be matched with Sloan sources. At UC Berkeley, Ossie Siegmund and Pat Jelinsky built the UV detectors, the largest of their kind ever flown in space. *—Ed.*



Left: Two galaxies that look independent in the optical (top) are exposed in the ultraviolet (bottom) as having a relationship, as the blue band of new stars in NGC 5719 reaches out toward NGC 5713.

Below: The two Antennae galaxies are colliding and forming stars at a rapid rate, making them extremely bright in the ultraviolet. Tails full of new stars have also resulted from this interaction, and at the end of the lower tail, a new galaxy can be seen evolving.

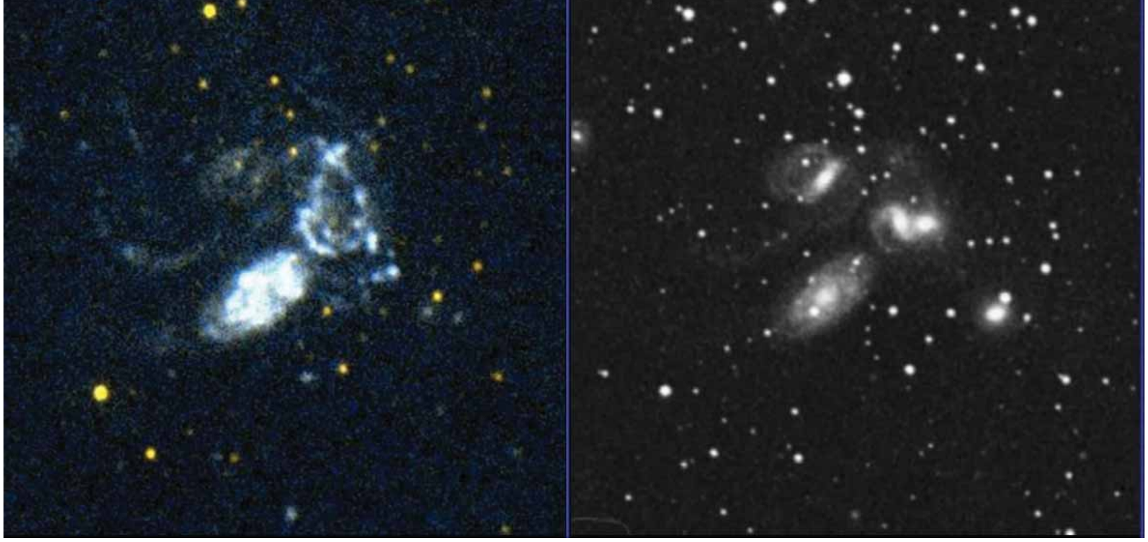


mainly due to the fact that the differential rotation is shearing the star formation regions around. This kind of patchy distribution is actually consistent with turbulence—it's essentially noise that has many different size scales. Energy is being dumped into the gas at various scales, and that energy ultimately results in the collapse of the gas and formation of stars.

At left are a couple of galaxies that in the optical do not appear to be interacting. But seen in the ultraviolet, one galaxy (NGC 5719) is elongated and stretched out—almost bridging the other galaxy (NGC 5713). And in fact, if you look at where the gas is, clearly the interaction between these two galaxies has pulled the gas out of 5719. As the gas is pulled out, it becomes unstable and collapses into new stars. It may even be forming a new galaxy—the little clump at the far left end.

An example of a much later phase in such an encounter is the Antennae galaxies (below, left), in which two disks are colliding. It's very bright in the center, where the disks are colliding, which shows that star formation is occurring at at least a factor of 10 more efficiently than it does in a normal spiral galaxy. We believe this is happening because the two disks are bringing their gas reservoirs together, increasing the density very rapidly. The tails are the remnants of this interaction, which has been going on for about 300 million years. In this ultraviolet image you can see the star formation going on in these tails. Out at the end of the tail at lower right, you can see a lump that may be a new galaxy being born before our eyes. In this lump, or dwarf galaxy, we can use the ultraviolet color as a clock to date the age of the star formation; we know that it is much younger than the interaction, proving that the action of pulling the gas out actually forms new stars.

In the nearby galaxy group known as Stephan's Quintet, you can see four galaxies and an interloper that's not really part of the system. Even



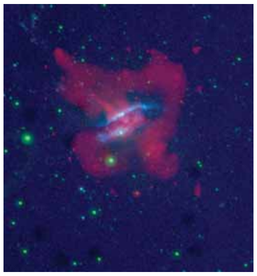
The misnamed Stephan's Quintet looks more like a quartet plus a soloist at visible wavelengths (right; DSS), but in the ultraviolet (left), where all the interaction can be seen, the four galaxies seem to be merging into one.

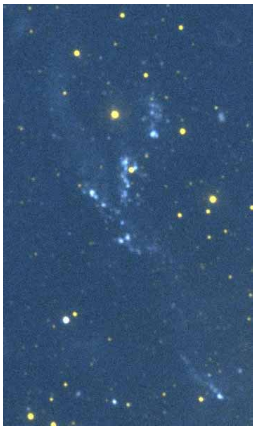
though there's lots of interaction going on and it's a very close group, in the optical version you can see that these are four distinct objects. But when you look at it in the ultraviolet, it looks completely different. That's because you're not looking at four galaxies anymore; you're looking at a picture of what the interaction has done to form stars in the last 100 million years. This has nothing to do with the original galaxies. It has to do with how the gas has been pulled out of them and made unstable, forming new stars in the process. Stephan's Quintet is not only an interesting object in *today's* universe; the process of galaxies merging together and forming new, larger galaxies was probably happening in the very early universe also, so this is a way of studying the early universe in our local environment, where the observations are much easier.

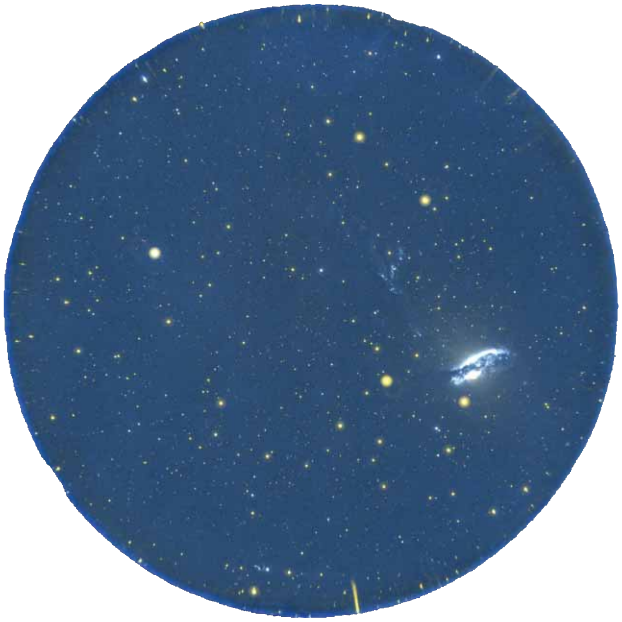
There are still other ways to trigger star formation. The galaxy at right, Centaurus A, has a massive black hole in the center that produces a very energetic jet, traced by red X-ray contours in the picture. When the jet comes out and strikes the cloud of gas (which you can't see here), it causes dense gas to form, which ultimately collapses into new star-formation regions. And if you blow that up (far right), you see all sorts of star formation going on due to this interaction. This is unusual in our local universe, but in the distant universe, it may perhaps be a much more common mechanism. Many galaxies in the early universe were forming stars at a prodigious rate. These so-called starburst galaxies produced massive winds of energetic plasma, which they ejected. Because most of the gas in their environs had not yet been converted into stars, there would be a lot of it, and getting struck by the plasma winds would trigger an explosion of star formation.

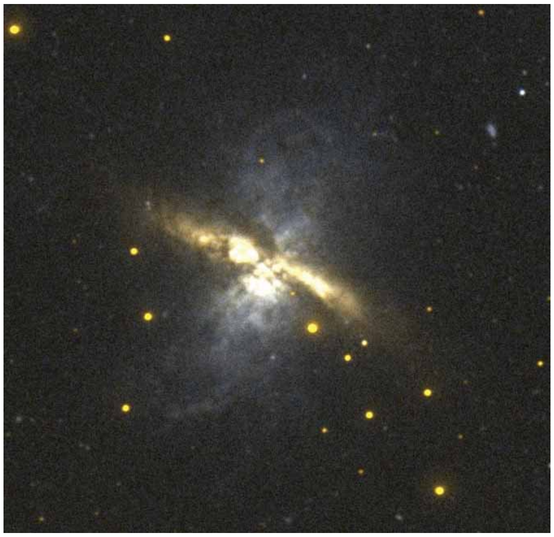
One problem we have in measuring galaxies in the ultraviolet is that dust absorbs the light from some of the stars, and in some dusty regions GALEX can't see anything at those wavelengths.

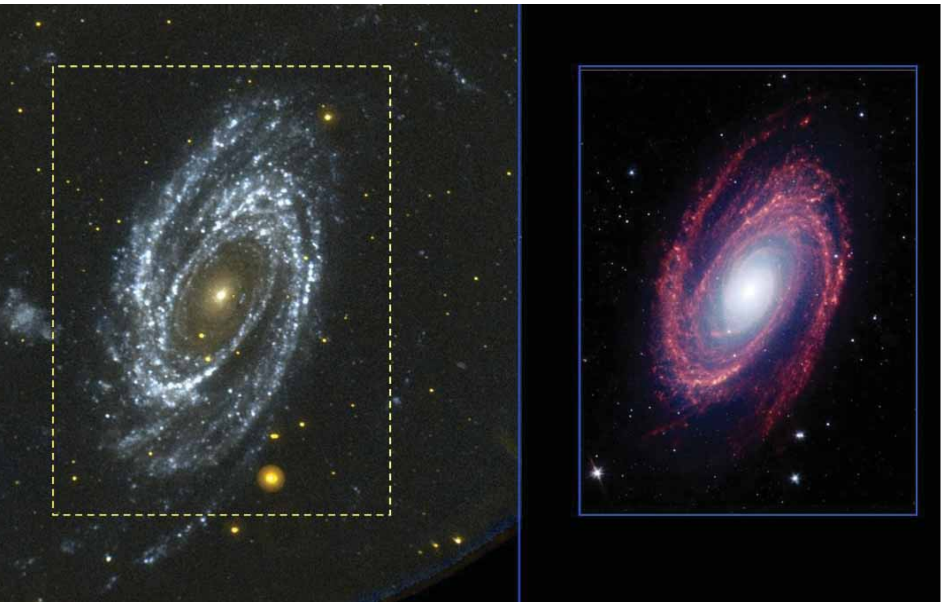
Below: The active galaxy Centaurus A is seen in GALEX's field of view (bottom). And, in a close-up (below, right) of the region to the upper left of the galaxy, new stars are forming. X-ray emission (below, left) of the jet of energetic particles from the galaxy center is traced by NASA's Chandra observatory (red is X-rays, blue is far ultraviolet, and green is near ultraviolet).











Right: Supernova explosions from young stars are causing the starburst galaxy M 82 to eject great, glowing gusts of dust, which are so bright in the ultraviolet because they're reflecting light from the violent activity in the center. Below: Comparing the GALEX image of M 81 (left) with the mid-infrared image from the Spitzer Space Telescope shows up stellar nurseries, where the ultraviolet is being absorbed and reradiated in the infrared.

I like to make an analogy between that and reprocessing perfectly good, healthy grapes (purple, or ultraviolet) into unhealthy wine (red, or infrared). Dust absorbs the ultraviolet radiation from the massive stars and reradiates it in the infrared. We're trying to understand this effect, because it's a way of tracing metals in galaxies. Dust is formed from heavy elements, and we want to trace the evolution of this dust over cosmic time as more and more heavy elements are being formed.

Of the two famous galaxies Messier 81 and 82 (see cover), M 81 is a classic, grand-design spiral galaxy, and M 82 is a starburst galaxy, with exploding winds of gas coming out the two axes of the disk. There's an interaction going on between these two galaxies. When we first observed M 82 in the ultraviolet, we were astonished to see how bright these two cones of ejected material are. Based on our analysis, we believe now that what we're seeing is dust that is being ejected out of the starburst galaxy by these winds. The dust is scattering the starburst light in the center. So in this case, dust isn't absorbing light but reflecting it, just as clouds on Earth can both absorb and reflect light. Stars are being formed, a process possibly promoted by the interaction between these two galaxies.

We have an extensive plan to do joint observations of M 81 with the Spitzer Space Telescope, which is observing in the mid and far infrared [*E&S*, 2003, No. 4]. The mid-infrared image of M 81 traces a molecular material which we believe is associated with dust. It's interesting to compare it with the image obtained in the far ultraviolet. You can see that there's a sort of global correlation, but there are regions where you see only infrared, which are probably very new molecular regions, where the ultraviolet is being absorbed and reradiated entirely in the infrared. And then there are regions where you see only ultraviolet, in which the molecules have been disrupted by the action of the massive stars. The massive stars have winds and produce supernova explosions, which are very important mechanisms for adjusting the local rate of star formation. If you form too many stars, they will blow the gas out of the galaxy and stop the star formation. It's a form of negative feedback.

Stars are simple. You can label them with a number for their mass and pretty much predict what they're going to do. But galaxies are complicated with a lot of bells and whistles. In order to try to understand them in a controlled experiment, you need a million galaxies, out of which you can find two sets of maybe a hundred each that are exactly the same except for one variable. Then you can make a controlled comparison between those two. So we're performing an all-sky survey to collect millions of galaxies in the local universe as well as deep surveys of representative pieces of the distant universe, totaling 100 degrees square, also with millions of galaxies. We'll end up with a huge sample of these distant galaxies to compare with younger, closer galaxies.

Using these two surveys, we now have our first measurement of the star-formation history of the universe. We can compare it to previous measurements, which are all over the place, partly because these earlier measurements use diverse techniques. We've used a consistent technique (measuring the ultraviolet to get the star-formation rate) to go all the way from the local universe out to the distant universe to measure the star-formation history. Our early results seem to be telling us that star formation was much more vigorous in the past— in other words, that galaxies formed most of their stars early in their lives, chiefly in the first third. This means that something has changed very radically about star formation since that time, making it much less prevalent today. It could be something as simple as the gas running out. Or it could be something subtle: that all the gas that could fall to the center of galaxies and form stars has been used up, but the spinning gas, which can't fall easily because of angular momentum, is still forming stars, although much more slowly. The interesting thing is that the history we have measured completely disagrees with some of the most recent models. These first results are based on only 1,000 galaxies, so we are looking forward to using 100 times as many to measure not only the average star-formation history, but also to ask how the star-formation history depends on other properties of a galaxy, such as its mass, its morphological type, and its neighborhood. One of the most interesting questions is how star formation depends on the number of galaxies in a region of space.

Whenever you do a survey in a new part of the spectrum, you find all sorts of new and interesting things. We are finding them, and we're not even looking, since our small science team is focusing on one topic: galaxy evolution and star formation. But we have discovered remnants from the explosion of a peculiar binary system with a white dwarf star that may have occurred 2,000 years ago. This is the first direct evidence connecting this kind of system with explosions called novae. We have also discovered evidence that exploding stars produce shock waves in the gas in the interstellar medium, suggested by remarkable cirrus-cloud-like structures never before seen in the ultraviolet. And we have seen flare stars that change brightness by factors of more than a thousand during a single observation. We have found many other interesting things, and we have only just begun to survey the sky. As our own team and other astronomers explore the data, we look forward to many discoveries in the future. □

Chris Martin has been professor of physics since 1993. He earned a BA in physics from Oberlin College in 1978 and a PhD in physics from UC Berkeley in 1986. After leaving for the East Coast to be assistant, then associate, professor at Columbia University from 1987 to 1993, he returned to the West Coast to join the Caltech faculty. This article is adapted from his Seminar Day talk in May.

Think building a small, relatively cheap spacecraft is a snap? Read on before you decide to try it. Every mission involves a few unexpected problems, but Project Manager Jim Fanson believes GALEX had more than its share of bolts from the blue. He has a few favorites:

When the new type of gyroscope to orient and point the spacecraft turned up as the subject of a patent-infringement suit against the manufacturer, a mad scramble ensued to find a replacement. First the team switched to a gyro that had just been launched on another satellite, FUSE (Far-Ultraviolet Spectroscopic Explorer). Then that one began failing in orbit. Up against the wall, Fanson's group launched a dragnet to find existing gyros to beg, borrow, or cannibalize, and found one (of the type used on Cassini) sitting on a shelf at the Goddard Space Flight Center. Its solid-state resonators, however, had been contaminated by helium gas, and a new set of resonators had to be built. With a heroic effort, they were ready in time.

Then there was the radio, necessary to receive data from the spacecraft. Just before the radio was completed by the low bidder (a company in England), Fanson received a phone call that they were going out of business and being liquidated. "If we wanted any of our hardware," recalls Fanson, "we nearly had to show up in a back alley in the dead of night." The radio was duly collected and flown back to the U.S., where the team tried to figure out how to finish the critical tuning of its radio frequency circuits. The experts at JPL said this had to be done by the engineer who designed it. "And this is when we entered something of a logic-free zone," says Fanson, in trying to get the design engineer involved. The State Department lumps spacecraft in the same category as munitions, and licenses are required before spacecraft hardware can be shipped to a foreign company. The project had *had* a license, but because the company had gone bankrupt, it was no longer valid. "So even though the radio was originally built by this guy, we couldn't send it back to him to work on," Fanson explained.

Another dragnet, this time for an existing radio. They found one in a finished spacecraft, sitting in cold storage because of payload problems. "We joked about going in late one night, opening it up, and making off with the radio," says Fanson. Ultimately, they did get permission to take it, but because the donor spacecraft was an earth-science mission and GALEX is a space-science mission (which are assigned to different sections of the electromagnetic spectrum), bureaucratic somersaults had to be turned to get permission to operate "out of band." Then they had to build all new ground receiving equipment to accommodate the different frequency and data rate.

And then there's the grism—large, fragile, and difficult to make, etched out of a single calcium fluoride crystal. A firm outside Paris was doing the etching using machines bolted to the basement foundation for stability. The firm's address was "rue du Canal." (You know what's coming, don't you?) Yes, the storm of the century roared through Europe in December 1999, dumping vast amounts of rain on Paris; the "canal" overflowed its banks, of course, flooding the adjacent basement, and the grism was a goner. At least it was the spare. The GALEX crew coped by babying the one they had left and sparing it any unnecessary handling and testing.

But there's always a silver lining. Fanson figures he got "two or three projects' worth of experience out of this mission. Just about everything that could go wrong did go wrong. It had great training value." —*Ed.*

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