

# Galaxies

Seen in a

# New Light

MICHAEL RICH

*By kicking the  
ultraviolet window  
wide open, GALEX  
has given astronomers new  
insights into galaxy evolution.*

ALL IMAGES COURTESY NASA / JPL-CALTECH UNLESS OTHERWISE CREDITED

**ON APRIL 28, 2003**, an L1011 jet rumbled into the early morning skies of Florida's Cape Canaveral Air Station, carrying a cruise-missile-like Pegasus rocket to an aerial launch. Although the Pegasus vehicle had experienced several prior failures, it was the only option, because its payload, the Galaxy Evolution Explorer (GALEX) satellite, was a small Explorer-class NASA mission with a hard cost cap of \$100 million — a bargain in our era of billion-dollar space telescopes. GALEX was NASA's first mission after the tragic loss of Space Shuttle *Columbia*. The successful launch, followed by spectacular ultraviolet images of objects in deep space, gave NASA a much-needed lift.

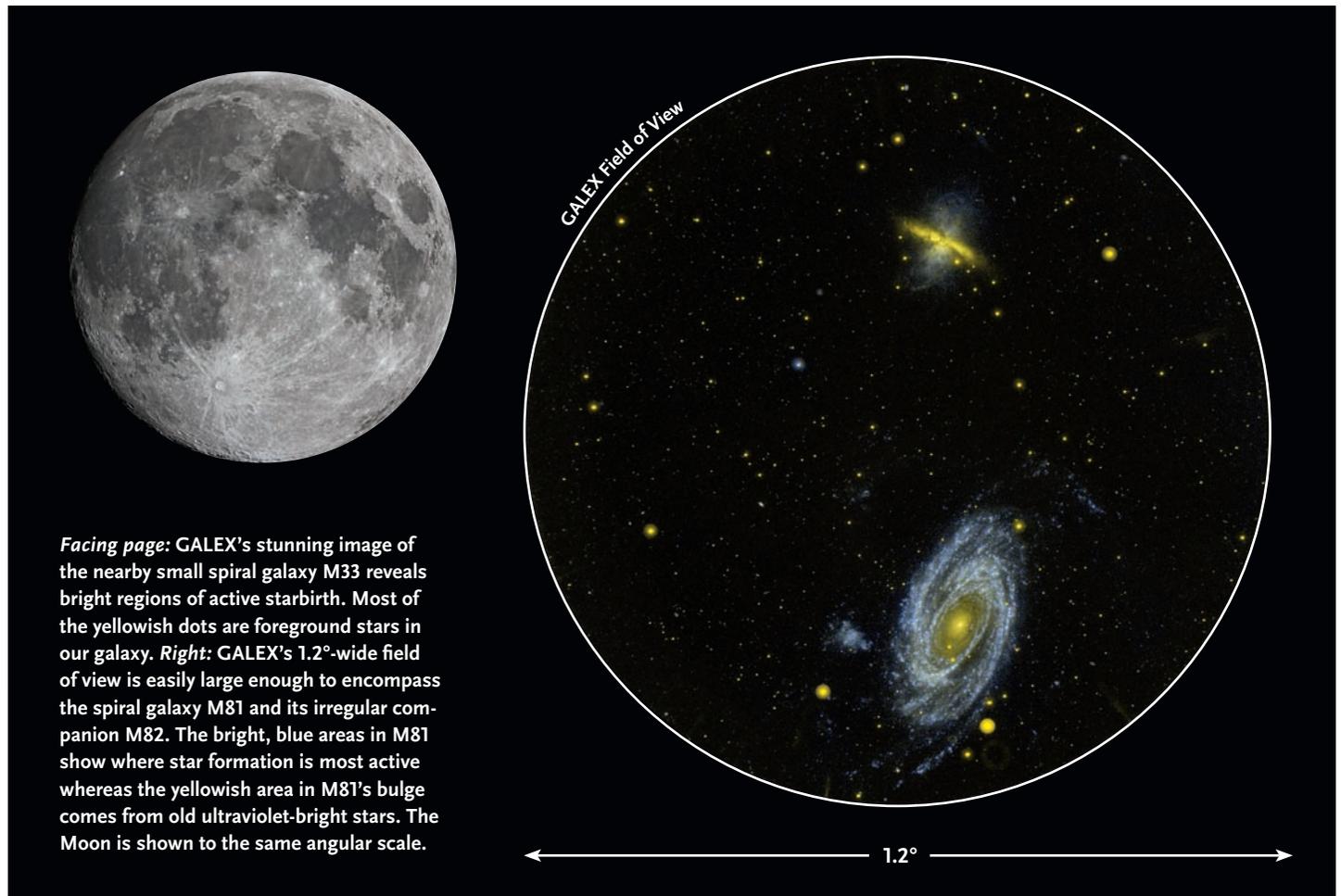
GALEX's 16-inch telescope has surveyed nearly 80% of the sky at ultraviolet wavelengths ranging from 150 to 280 nanometers — about twice the energy of the ultraviolet-B rays that cause nasty sunburns. No all-sky map of this important spectral region existed before GALEX. Although NASA's Great Observatories had surveyed and examined the sky from gamma rays (Compton) to the infrared (Spitzer), the UV window was virgin territory. GALEX's objective was to discover where stars are form-



Technicians at Orbital Sciences Corporation test the solar arrays on the 620-pound (281-kg) spacecraft. GALEX is one of the smallest space telescopes launched by NASA in recent years.

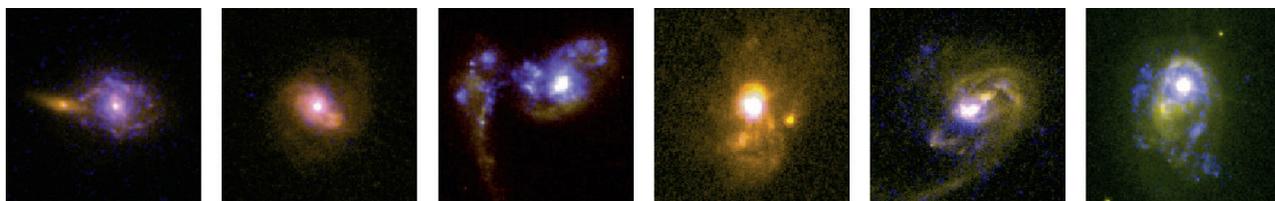
ing in the nearby universe, and to shed light on how star formation and its cessation can transform galaxies.

In contrast to the Hubble Space Telescope, whose field of view is the size of a small lunar crater, GALEX's 1.2-degree-wide field is large enough to capture the galax-



*Facing page:* GALEX's stunning image of the nearby small spiral galaxy M33 reveals bright regions of active starbirth. Most of the yellowish dots are foreground stars in our galaxy. *Right:* GALEX's 1.2°-wide field of view is easily large enough to encompass the spiral galaxy M81 and its irregular companion M82. The bright, blue areas in M81 show where star formation is most active whereas the yellowish area in M81's bulge comes from old ultraviolet-bright stars. The Moon is shown to the same angular scale.

MOON PHOTO BY S&T DENNIS DI CICCO



RODERIK OVERZIER / ESA / NASA

**LIVING DINOSAURS** GALEX enabled astronomers to identify rare ultraviolet-luminous galaxies (UVLGs) within 2 billion light-years. UVLGs, which are mere point sources in GALEX images, are compact galaxies more commonly found at much greater distances. These six follow-up Hubble Space Telescope images resolve individual starbirth regions in relatively nearby UVLGs, as well as their nuclei. Some of these nuclei appear to be emitting X-rays and forming supermassive black holes. Each frame is about 5,000 light-years across.

ies M81 and M82 in the same image. GALEX’s detectors are extremely sensitive to the ultraviolet light emitted by young stars, which are particularly bright in the UV. So despite GALEX’s small aperture, it can detect traces of star formation missed by other telescopes. GALEX can also image starburst galaxies (galaxies that are rapidly forming stars) out to redshifts of nearly 1, corresponding to a look-back time of roughly 6 billion years.

GALEX’s main surveys are nearing completion, but the telescope has also notched some unexpected discov-

eries. These include the discovery of gigantic star-forming disks three times larger than our Milky Way, “living dinosaur” galaxies resembling those from the early universe, a black hole caught in the act of devouring a star, supposedly “dead” galaxies with signs of star formation, and a spectacular comet-like tail associated with the bright variable star Mira.

### Living Dinosaurs

GALEX was 10 years in the making, the dream of principal investigator Chris Martin (Caltech). The science team, which includes astronomers from the U.S., France, and South Korea, knew GALEX could be a discovery engine like its visible-light predecessor, the Palomar Sky Survey.

The universe’s brightest sources of UV radiation are the youngest stars (10–100 million years old), some of the oldest stars (such as white dwarfs and hot post-red giants), and gas swirling around interacting binary stars and black holes. GALEX is so sensitive that it can also detect UV radiation in unexpected places, such as elliptical galaxies whose light is dominated by red giants, the tidal tails of interacting galaxies, and the outermost disks of spiral galaxies.

One of GALEX’s first achievements was to isolate the nearby counterparts of galaxies ordinarily seen in the distant universe: rare ultraviolet-luminous galaxies (UVLGs). These extreme galaxies pack 10 billion Suns of ultraviolet luminosity into a volume only 10% the size of our Milky Way. In 1996 Charles Steidel (Caltech) discovered the faraway versions of UVLGs at redshifts of 3 or greater, corresponding to at least 11.5 billion years of look-back time. GALEX’s relatively nearby UVLGs, within 1 to 2 billion light-years, are literally the astronomical equivalent of finding a living dinosaur in the present time.

The UVLGs detected by GALEX are close enough for Hubble follow-up studies. Images taken by Roderik Overzier (European Southern Observatory) reveal spectacular



**FAR-OUT STARS** This GALEX image clearly shows patches of UV light — the hallmark of star formation — well beyond spiral galaxy M83’s visible disk (the bright inner region). This result startled astronomers by informing them that stars can somehow manage to form in gas-poor environments.



**ANDROMEDA PORTRAIT** GALEX's ultraviolet image of the Andromeda Galaxy (M31) is one of the observatory's iconic images. Nearly concentric rings of bright star-forming regions surround the center. The nucleus's surprising brightness in ultraviolet light is probably due to ancient stars that are fusing helium in their cores as they near the end of their lives.

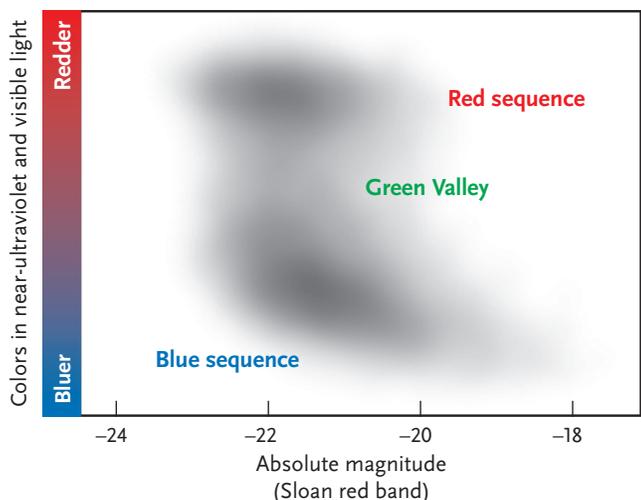
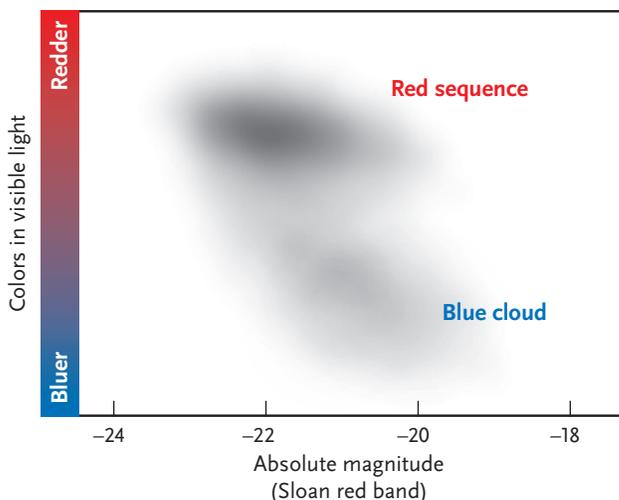
giant star clusters and the occasional galactic nucleus star cluster as the bright sources of UV emission. Intriguingly, some of these galaxies appear to have nuclei that might be on the way to producing a supermassive black hole — but as yet still do not exhibit all of the hallmarks of black-hole formation. These nuclei might contain precursors of the supermassive black holes found in many galactic centers, making them objects of keen interest. Eventually, these galaxies might evolve into giant ellipticals such as M84, M86, and M87 in the Virgo Cluster.

At about the same time, GALEX imaged the nearby spiral galaxy M83 and found star formation way beyond its visible disk, where only hydrogen gas had been detected. This result tells us that it takes far less hydrogen to form stars than we thought; many spirals consequently have much bigger disks of stars than we previously realized.

### The Green Valley

GALEX's most fundamental contribution is an improved diagram for galaxies analogous to the Hertzsprung-Russell diagram for stars. When astronomers plot the luminosities of stars against their temperatures in an H-R diagram, they see distinct groups: stable hydrogen-burning stars (the main sequence), red giants, and white dwarfs (*S&T*: December 2010, page 30). A similar diagram for galaxies plots their intrinsic brightness (luminosity, or absolute magnitude) against their "color" — red to blue.

When we do this in optical colors using, for example, the Sloan Digital Sky Survey's huge database, the brightest galaxies, such as Virgo's giant ellipticals, tend to be red. In fact, these galaxies define a "red sequence" of galaxies that have similar populations of older stars. In very dense galaxy clusters such as the Coma Cluster, nearly all



**THE GALAXY H-R DIAGRAM** Astronomers have produced a galaxy version of the famous Hertzsprung-Russell diagram for stars. *Left:* This plot from Sloan Digital Sky Survey data classifies galaxies according to their colors in visible light. Almost all galaxies are members of either the red sequence (old stars) or the blue cloud (young stars). *Right:* This diagram incorporates GALEX ultraviolet data in the color index. Blue galaxies form a more clearly defined sequence rather than an amorphous cloud. In addition, a third region known as the green valley emerges. Galaxies in this class appear to be in transition from the blue sequence to the red sequence.



the galaxies fall on the red sequence. But most galaxies don't reside in very dense clusters; some dwell in small groups and others live in relative isolation, and many of these tend to have young stars and disks. These galaxies are fainter and bluer than the red galaxies, falling in a region of the galaxy H-R diagram called the "blue cloud."

Star-forming galaxies such as M33 and the Magellanic Clouds live in the blue cloud. Surprisingly, even though the Milky Way and Andromeda galaxies are still forming stars, they fall on the red sequence because the old stellar populations of their inner disks and bulges outshine the younger, bluer stars in the spiral arms. If we plot this graph using visible light only, the red galaxies show some sense of a sequence, whereas the blue galaxies fall in the amorphous "blue cloud."

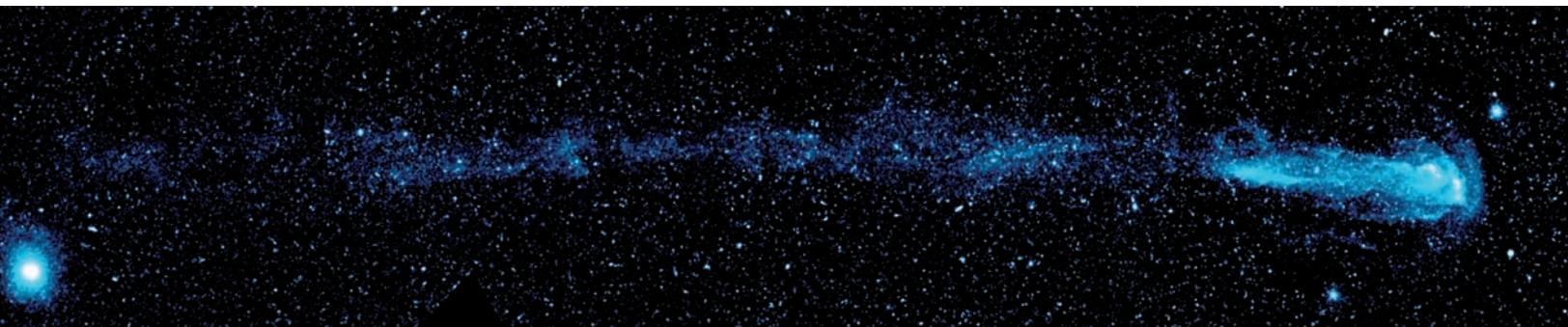
But when astronomers measure galaxy brightnesses in GALEX's near-UV filter, and plot their intrinsic optical magnitudes against an optical-UV color index, the plot becomes more interesting: there's a red sequence of old galaxies and a separate blue sequence of galaxies that are actively forming stars. Falling between the red and blue sequences is a gap christened the "green valley" because it's a region with relatively few galaxies (a "valley") whose members are a kind of hybrid between the red and blue sequences. By applying GALEX's UV data to this plot, astronomers could classify the galaxies in the blue sequence as mostly star forming, those in the red

#### ULTRAVIOLET LIGHT

Ultraviolet light is a form of radiation sandwiched between the X-ray and visible-light portions of the spectrum. UV wavelengths range from 100 to 400 nanometers, shorter than visible light but longer than X rays. Most UV photons are absorbed by Earth's atmosphere, which is a good thing for us because excessive exposure to this high-energy radiation causes sunburn and skin cancer. But it also means that astronomers must loft telescopes into space to detect cosmic UV sources. Normal CCDs don't work in the UV, so GALEX uses a combination of old and new technology to detect UV photons while rejecting 100% of visible-light photons.

sequence as lacking young stars, and those in the green valley as possibly being in transit to the red sequence.

We're interested in the green valley because that's where we can find galaxies on the move, so to speak, thanks to the processes that cause galaxy evolution. Some galaxies in the green valley may have just experienced a "wet merger," in which two gas-rich galaxies merged and converted nearly all their gas into stars, with no gas left to form new stars. Some green-valley residents appear to have been forming stars until an active galactic nucleus turned on, producing radiation and gas outflows that may have quenched their star formation. Other green-valley members appear to be red-sequence galaxies (our "red-and-dead" seniors) that are taking a fling with youth,



NASA / JPL-CALTECH / C. MARTIN / M. SEIBERT

## Mira's Extended Tail

GALEX has made stunning discoveries in our own galaxy. The red-giant star Mira would, it seems, surely be no candidate for an ultraviolet study. Its fame derives from its 900-day period of variability from naked-eye visibility to invisibility. Mira is a huge, cool star that was expected to be invisible in the UV. While inspecting a portion of the All-sky Imaging Survey, GALEX team scientist Karl Forster

**NOT A COMET** Astronomers were stunned when GALEX revealed a 13-light-year-long tail extending from the variable-star Mira (far right). As Mira moves through space, collisions with interstellar material blows off some of the gas in the star's outer atmosphere at a rate of about one Earth mass per decade. In this follow-up GALEX image, the left end of the tail consists of material shed by Mira 30,000 years ago, when our home planet was still caught in the grip of the last Ice Age.

(Caltech) noted a strange smudge, like a comet. Much to his surprise, the smudge coincided with Mira's coordinates in the constellation Cetus. GALEX principal investigator Chris Martin (Caltech) obtained deeper exposures that revealed a bow shock and a comet-like

tail 13 light-years long that results from the erosion of Mira's extended atmosphere as it plows through interstellar gas. Much to everyone's surprise, the tail glowed most brightly in the far-UV, most likely the radiation of excited hydrogen ( $H_2$ ) molecules.

forming stars from some newly acquired hydrogen gas. We think those galaxies will be back on the red sequence in less than a billion years. Alternatively, they could instead be galaxies that once had massive disks like our Milky Way, and are fading onto the red sequence. We're not completely sure, and that is why the green valley offers a trove of interesting case studies to explore in great depth.

## Unexpected Discoveries and the Future

GALEX has made many other discoveries. In March 2004, the satellite serendipitously caught a burst of UV emission from the nucleus of a distant galaxy. Suvi Gezari (Johns Hopkins University) discovered this on a series of GALEX images while she was working at Caltech. The fading of the burst matched nearly exactly the predictions for what we would see if a star was tidally shredded as it fell into a 100-million-solar-mass black hole.

GALEX has even been used to isolate nearby stars that are good candidates to be young enough to host planets still visible by their own radiation. UCLA astronomers David Rodriguez and Ben Zuckerman used the UV properties of nearby stars to winnow through thousands of objects to find just the right candidates that might have young Jupiter-mass planets shining in infrared light from their heat of formation, making them bright enough to be seen with adaptive-optics imaging.

Despite GALEX exploring the ultraviolet sky for nine years, some problems in UV astronomy remain unsolved. Among the enduring mysteries is the exact cause of UV radiation seen in very old red galaxies and bulges. This mysterious light was one of the first important discoveries made by any space satellite (in this case, the Orbiting Astronomical Observatory-2 in the late 1960s). We know that the rising UV flux comes from a population of very old stars that burn helium as their energy source. But the exact stellar population remains a mystery. The Hubble Space Telescope might reveal the individual stars responsible in Andromeda's bulge. But the mystery might persist until an 8-meter UV-optical space telescope can be lofted into orbit.

About two years ago, GALEX's far-UV detector failed, leaving the satellite to undertake its mission with only its near-UV detector. But the near-UV eye is so sensitive that the 16-inch mirror can still image, in only about an hour of integration time, galaxies out to 10 billion years of look-back time, and quasars to even greater distances.



**HELIX NEBULA** GALEX turned its eye on the Helix Nebula (NGC 7293), a nearby planetary nebula. The hot central white dwarf is faint in visible light, but is very bright in the UV. GALEX also reveals gas well outside the area of optical emission.

GALEX had been slated to continue surveying the area of the Sloan Digital Sky Survey to a depth of 23rd magnitude in the near-UV band, and it would have provided critical complementary data to a new generation of surveys, including the 8-meter Large Synoptic Survey Telescope (LSST). Unfortunately, NASA must stop its funding of the GALEX surveys in early 2012, and unless private or international funds can be found to continue the mission, GALEX will be shuttered, detecting its last UV photon.

But in what may be its final few months, GALEX has undertaken one of its most exciting missions: mapping the plane of the Milky Way, the bulge, and the Magellanic Clouds — regions once considered too dangerous to point at for fear of damaging sensitive detectors. After GALEX's mission ends, the satellite will continue orbiting but not operating. A deeper survey of the ultraviolet sky will remain a dream for future generations of astronomers.

Even after GALEX ceases operation, team scientist Mark Seibert (Carnegie Observatories) will produce a final catalog from the mission. GALEX data is being combined with those of NASA's Wide-Field Infrared Space Explorer (WISE) mission. The combination of the vast GALEX trove with all of these new data sets has resulted in yet more discoveries and will doubtless spur research for decades to come. Despite its small size and low cost, GALEX has beautifully complemented the missions of the Great Observatories (Compton, Hubble, Chandra, and Spitzer), fueling astronomical discoveries just as effectively as its visible-light cousin, the 48-inch Palomar Schmidt telescope, did a half-century ago. ♦

---

*GALEX science team member Michael Rich is an astronomer at the University of California, Los Angeles.*



### Listen to a BONUS AUDIO INTERVIEW



To see more beautiful GALEX images of galaxies and other objects, and to listen to an interview with author Michael Rich, visit [skypub.com/galex](http://skypub.com/galex).