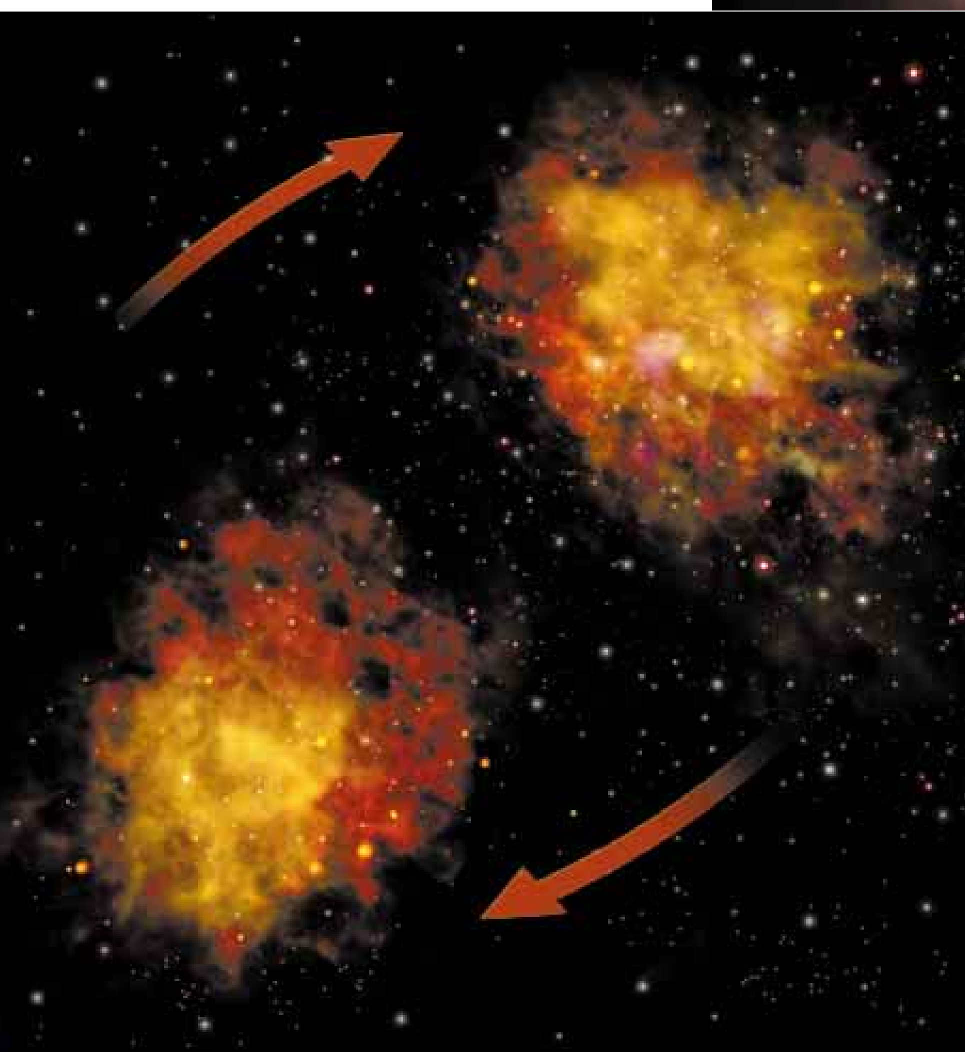
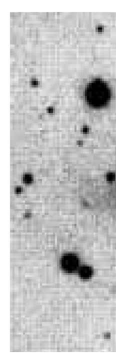
Dwarf Galaxies

Diminutive galaxies occasionally experience spectacular bursts of star formation. These starbursts are giving astronomers a glimpse of the universe's early history

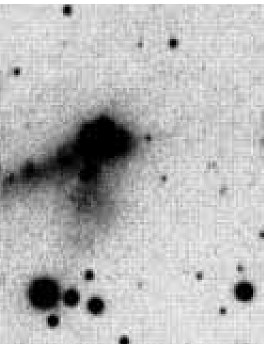
by Sara C. Beck



GALACTIC MERGER triggers star formation in this artist's conception of the evolution of dwarf starburst galaxy II Zw 40. In the first stage (*left*), two dwarf galaxies consisting of old red stars and clouds of atomic gas (*yellow*) are pulled by gravitational attraction into orbit around each other. As they spiral closer, tails of gas and stars are drawn out by tidal forces (*above*) and clumps of young blue stars begin to form. The final stage (*opposite page, top*) portrays the merged galaxy as it appears today in telescope images (*right*).



& Starbursts



About 12 million light-years from the earth is a large, beautiful barred spiral galaxy named M83. Pictures of this galaxy have appeared on many astronomy posters and book jackets. Looking closely at these images, one may notice, off to the side of M83, a small nebula of roughly elliptical shape. This is the dwarf galaxy NGC 5253. The casual viewer might think it is an insignificant companion to M83, but looks can be deceiving. That little galaxy is in the midst of an extreme starburst—it is forming stars at a fantastic pace. In proportion to its size, NGC 5253's star formation rate is many times higher than M83's.

In recent years, astronomers have discovered that dwarf galaxies such as NGC 5253 are far more common than previously supposed. Moreover, these galaxies are very different from their bigger cousins: they spend billions of years in a dormant state, then erupt in furious, short-lived bursts of star formation. Starbursts also occur in large galaxies, but the radiation from those

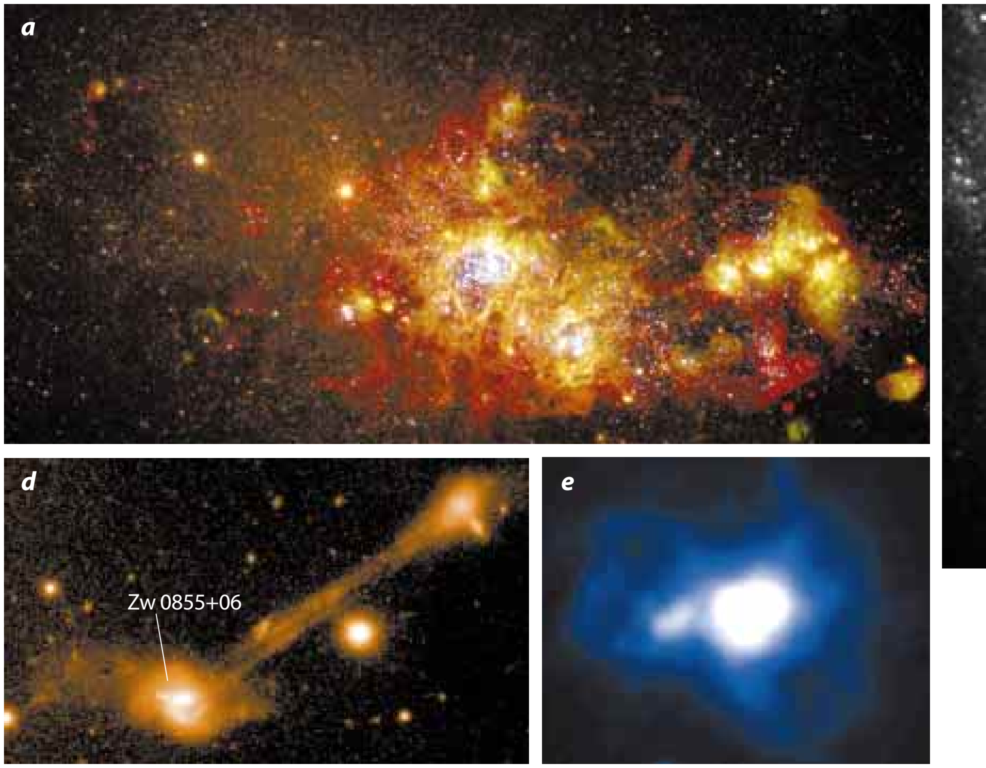
ALFRED T. KAMAJIAN; AURA/NOAO/NSF (*telescope image*) bursts is usually obscured by other galactic emissions; only in dwarf starburst galaxies can researchers get a clear look at this intriguing phenomenon. These galaxies also hold clues to the early history of the universe—they are relics of an ancient time, composed of material that has changed little since the big bang.

What causes starbursts in dwarf galaxies, and why are they so important to astronomers? To answer these questions, we must examine the mechanics of star formation. Astronomers know that stars have been forming for almost the entire duration of the universe. Our own galaxy, the unremarkable large spiral called the Milky Way, contains at least 100 billion stars. Star formation in the Milky Way is a slow, steady process involving the contraction of vast clouds of interstellar gas and dust. Every year, on average, about one solar-mass of gas and dust (that is, an amount with the mass of our sun) turns into new stars.

In contrast, a starburst is a relatively brief period—from one million to 20 million years—during which the rate of star formation is much higher than average. Astronomers have observed galaxies in which the rate is 100 times higher than the Milky Way's. We know this must be a short-lived stage because if it had been going on for more than a few hundred million years the galaxy would have run out of the gas from which stars are made.

The increased star formation rate causes a dramatic rise in the galaxy's brightness. Because starbursts are brief, they are dominated by the radiation from hot young stars of 20 solar-masses or more, which have lifetimes of only a few million years. These stars are tens of thousands of times brighter than the sun. They heat and ionize the dense clouds of gas and dust from which they form; the clouds absorb the stars' visible and ultraviolet light and then reradiate the energy as radio and infrared emissions. A strong starburst can be almost as bright as a quasar, the most luminous object in the universe. Because a starburst's luminosity is concentrated in the radio and infrared parts of the spectrum, the phenomenon has been recognized and studied only in the past 20 years as new telescopes and satellites have allowed scientists to observe these wavelengths.

Many astronomers believe that starbursts play a pivotal role in galactic evolution and in the creation of star clusters. For this reason, scientists are eager to know what triggers these sudden episodes, how they proceed and what turns them off. These questions may be easier to answer in dwarf galaxies, which hold 100 million or fewer stars, than in the large spirals such as the Milky Way and M83.



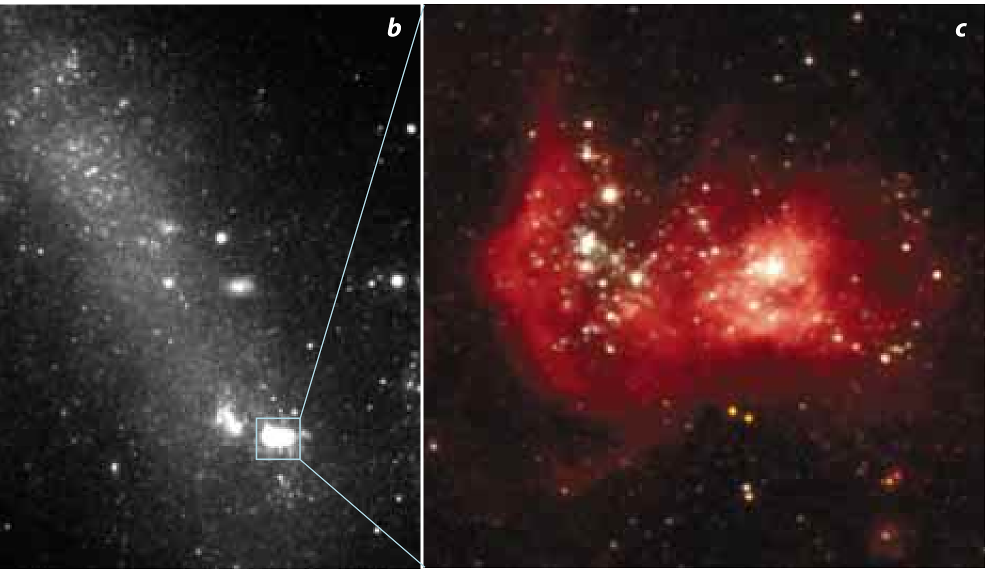
A Deluge of Dwarfs

Researchers have given serious attention to dwarf galaxies only in recent years simply because most of them are so faint. The two best-known dwarfs are the Large and Small Magellanic Clouds, which seem bright because they are relatively close to our galaxy (less than 300,000 light-years away). No other dwarf galaxies are visible to the naked eye. But powerful telescopes, modern detectors and large-scale surveys have found that dwarfs actually outnumber large galaxies by a wide margin. The Local Group, the cluster of galaxies that includes our own, contains (at last count) just two large spirals—the Milky Way and Andromeda—and about 40 dwarfs. This ratio is probably typical of most of the nearby universe.

Some dwarf galaxies are called dwarf ellipticals because of their shape, and the smallest and faintest of these are called dwarf spheroidal galaxies. But most dwarfs have no simple structure or shape and are thus called irregulars. Observers have often referred to them as "blobs," "little fuzzies" or "fried eggs," which gives an idea of their typical appearance, but in print the name "irregular" is preferred.

Dwarf galaxies are not scaled-down versions of large galaxies. Their evolution is driven by different mechanisms. Spiral galaxies have giant clouds of molecular hydrogen, helium and dust that can readily form stars. The spiral-arm pattern is maintained by density waves, which trigger star formation by compressing the molecular clouds that they pass through. As a result, spiral galaxies are never completely quiescent; they always have some newly born stars.

In contrast, dwarf galaxies have little molecular hydrogen. They do have a lot of atomic hydrogen—that is, hydrogen atoms floating freely rather than bound into two-atom molecules. In a typical dwarf galaxy the mass contained in clouds of atomic hydrogen is 10 times greater than the mass in stars. Because these clouds are not nearly as dense as clouds of molecular hydrogen, they are less likely to collapse gravitationally and produce stars. Furthermore, dwarf galaxies do not have density waves or other organized gas motions that can cause a cloud to collapse. So dwarfs spend the great majority of their time in a quiescent state: during this stage, all their stars are faint, red and old. Only the starburst dwarfs have the hot, bright blue stars that indicate recent star formation.



DWARF STARBURST GALAXIES such as NGC 4214 (*a*) contain clumps of young blue stars surrounded by clouds of glowing gas. Starburst clumps are also visible in dwarf galaxy NGC 2366 (*b*); a close-up image taken by the Hubble Space Telescope shows a dense cluster of massive stars embedded in a gas cloud (*c*). The starburst in dwarf galaxy Zw 0855+06 (*d*) was apparently caused by a close encounter with another dwarf galaxy, which also created the bridge of stars between them. Dwarf starburst Henize 2-10 (*e*) has a tidal tail of gas, leading astronomers to believe it swallowed a smaller galaxy. Henize 2-10 also has shells of gas expelled by massive young stars.

NASA/SPACE TELESCOPE SCIENCE INSTITUTE (*NGC 4214 and NGC 2366 close-up*); CFHT (*NGC 2366*); DAVID I. MÉNDEZ AND CÉSAR ESTEBAN *Instituto de Astrofísica de Canarias (Zw 0855+06 and Henize 2-10)*

Evidence for long periods of quiescence in dwarf galaxies can be found in their chemical content. Star formation changes a galaxy's composition: when massive stars reach the end of their lives, they explode in violent supernovae, which enrich the surrounding galactic gas with the heavy elements formed by the star's thermonuclear reactions. If no stars are born, however, the galaxy will remain chemically unevolved. The history of a galaxy can be roughly judged by its abundance of metals, as astronomers call all elements besides hydrogen and helium (to the disgust of chemists). The lower the metal abundance, the less evolved the galaxy.

The metal abundances of dwarf galaxies generally range from 2 to 30 percent of that in the sun's neighborhood, with the peak of the distribution around 10 percent. Only a few very active starburst dwarfs have metal abundances comparable to a spiral galaxy's. The unevolved state of dwarf galaxies has raised the possibility of finding one that is truly primordial—unchanged since the big bang. The galaxies with the lowest metal abundances detected so far—two dwarfs called I Zw 18 and SBS 0335-052—do not appear to be primordial: they seem to have already gone through a few generations of star formation. Nevertheless, the search continues. In the meantime, cosmologists can study these galaxies for clues to how the first generations of stars were born.

Bursting with Stars

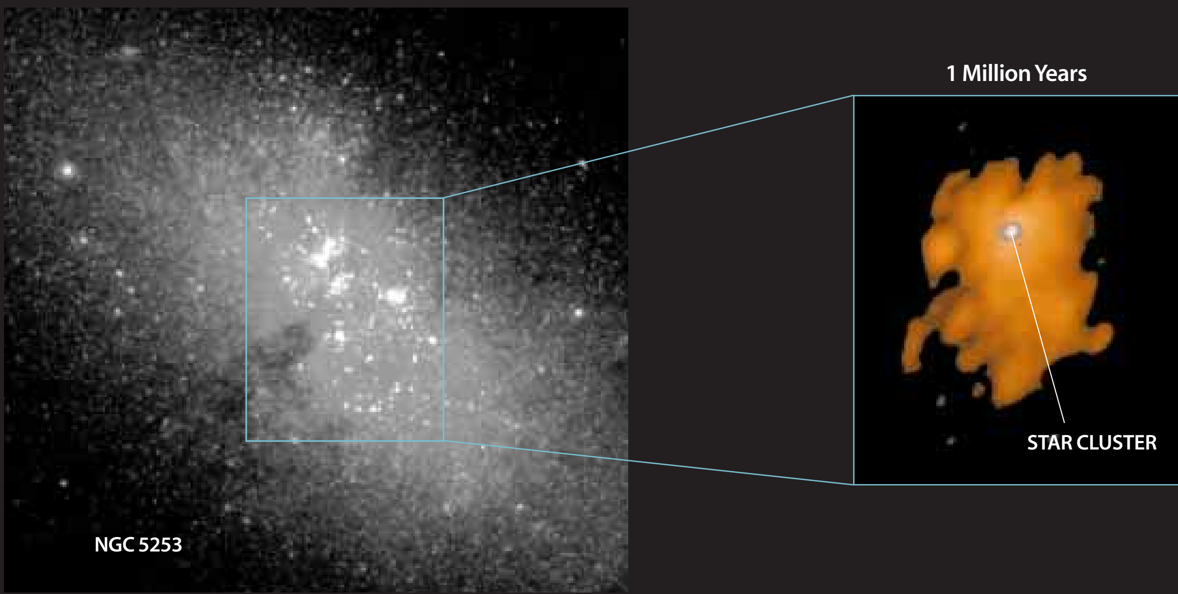
Dwarf galaxies undergoing a starburst episode have a unique appearance. They contain patches or clumps of hot, young blue stars within a larger, fainter envelope of cool, older red stars. The starburst dwarfs are remarkable for their brightness. During the starburst, a dwarf can be as bright as a large spiral, whereas a quiescent dwarf of the same size would be only 1 percent as luminous or even fainter. All this activity comes from a small area: the diameters of the starburst clumps usually range from a few hundred to 1,000 light-years. (The galaxies themselves are typically less than 6,000 light-years in diameter.) Each clump contains hundreds to tens of thousands of bright O- and B-type stars. A starburst dwarf may contain several clumps, and they are usually not in the center of the galaxy.

Unlike the Milky Way and other large galaxies, starburst dwarfs do not have a distribution of stars of all ages; they typically contain only the clumps of very young stars and the surrounding envelope of stars that are a few billion years older. Astronomers estimate the ages of stars in these galaxies by looking for specific stages of stellar evolution. Perhaps the most important age diagnostic for young stars is the Wolf-Rayet stage, which very massive stars (more than 25 solar-masses) achieve when they are between two million and 10 million years old. During this stage, stars expel most of their initial mass at speeds of a few thousand kilometers per second. The emission lines of ions in the rapidly moving material are broadened by the Doppler effect; instead of appearing as narrow stripes on the spectrum, they spread toward the red and blue ends. When astronomers see this broadening in the spectrum of a starburst clump, they know it contains a significant number of Wolf-Rayet stars and cannot be more than 10 million years old.

In large galaxies a starburst clump is often superimposed on the bright galactic nucleus or on one of the galaxy's spiral arms, making observations more difficult. What is more, the radiation caused by the continual star formation in the galaxy can be confused with the emissions from the starburst clump. This problem is particularly bad in the radio part of the spectrum. As noted earlier, the massive young stars in starburst clumps ionize the surrounding gas clouds. These clouds produce radio emissions with a thermal spectrum—the intensity of the emissions varies by frequency in a distinctive way. But when the massive stars go supernova, the remnants from the explosion emit radio waves in a nonthermal spectrum. The radio spectrum of a large galaxy is a combination of the thermal radiation from the current generation of massive stars and the nonthermal radiation from past generations. The nonthermal radiation, though, can be much stronger and last longer than the thermal radiation. Therefore, in a large galaxy the distinctive emissions from a starburst are often swamped by other emissions.

Dwarf galaxies, however, have no history of continual star formation, so the starburst clumps are much easier to observe in isolation. In the dwarf starburst galaxies NGC 5253 and II Zw 40, for example, only the thermal emissions from young stars are seen, because the radio contributions from earlier bursts of star formation have faded away. The absence of nonthermal emissions can be used as an age diagnostic: it means that none of the stars in the starburst clump have gone supernova yet, so the starburst's age must be less than the age at

EVOLUTION OF A STARBURST



YOUNG STARBURST at the center of dwarf galaxy NGC 5253 (*above left*) was apparently triggered when the galaxy absorbed an intergalactic gas cloud. The youngest part of the starburst, which is probably less than one million years old, is visible only in radio and infrared images (*above right*) because its stars are still enshrouded by the nebula from which they formed. Astronomers believe that after 10 million years stellar winds will blow away the surrounding gas, as shown in the artist's rendering (*opposite page, left*), and that after several billion years the starburst clump will evolve into a globular cluster, perhaps resembling NGC 6093 in our own galaxy (*opposite page, right*).

which these massive stars explode (a few million years). This estimate agrees with other observations indicating that the starbursts in NGC 5253 and II Zw 40 are the youngest detected so far.

The youngest part of the starburst in NGC 5253 cannot be viewed optically, because it is still enshrouded by the cloud of gas and dust from which it formed. But a detailed study has shown that its radio and infrared emissions are concentrated in a very small source, which is believed to be a clump of 100,000 extremely young stars in a region only about three to six light-years in diameter. The stellar content and size of this source are highly similar to those of globular clusters, the dense, spherical clumps of stars seen in the Milky Way and other large galaxies.

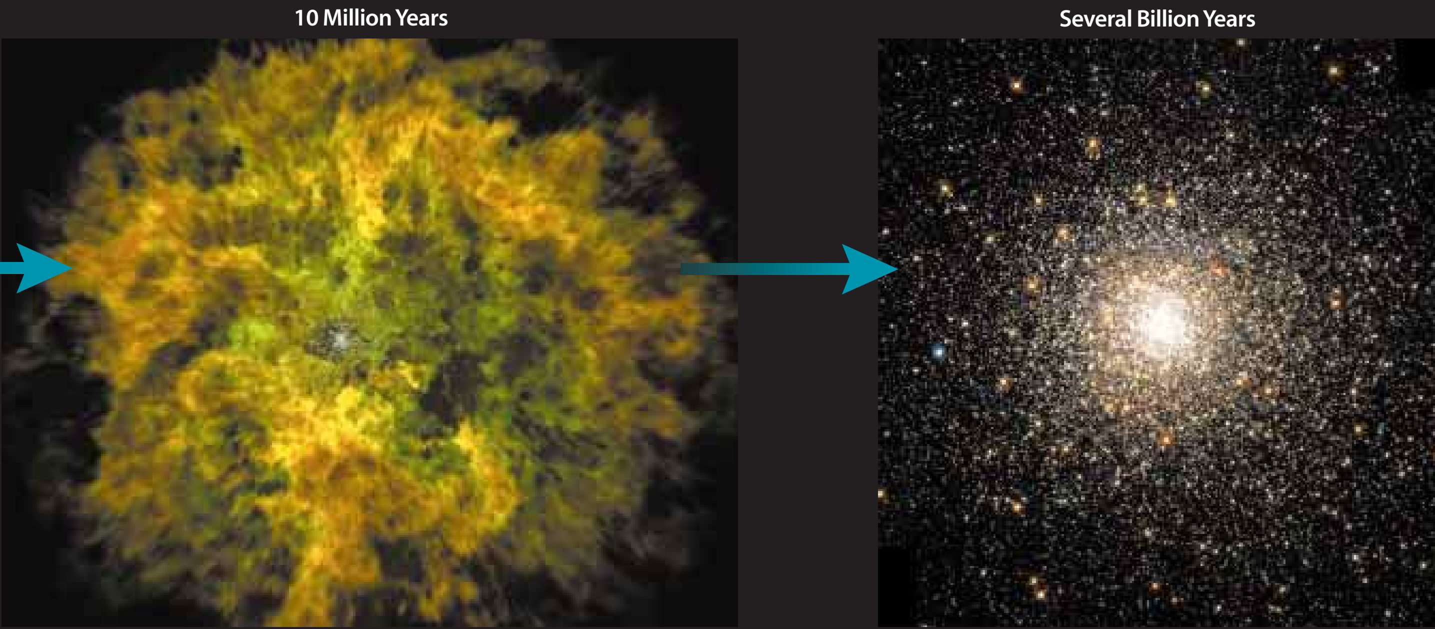
The Milky Way's globular clusters, however, are at least several billion years old—they contain the oldest stars in the galaxy. The logical conclusion is that our galaxy has not formed globular clusters for many billions of years or that all newly formed clusters have been pulled apart and destroyed by gravitational stresses as they orbited through the galaxy's disk. The starbursts in NGC 5253 and other dwarf galaxies may well be globular clusters in formation. If so, they may reveal hidden aspects of our own galaxy's history.

We must remember, though, that what is true for dwarf galaxies may not always be true for large galaxies. One important difference is in star propagation—how the birth of stars in one part of the galaxy can lead to the formation of stars in another part. The apparently random distribution of starburst clumps in dwarfs raises the question of how star formation can spread through a galaxy that has no spiral arms or other organized gas motions. The currently favored model is called Self-Propagating Stochastic Star Formation. In this model a starburst clump in one part of the galaxy triggers secondary starbursts in other parts. The massive young stars in the first center of activity disturb the gas in an adjacent region with stellar winds, ionization and other energetic activities. The gas then collapses and begins its own starburst. The process continues until there is not enough gas in position to be affected by the young stars. This model seems to suit the progress of star formation in dwarfs but is probably not applicable to spirals. And it leaves open the question of what caused the initial starburst.

How starbursts are triggered is an important question for large galaxies as well as dwarfs, and there are undoubtedly different answers for different galaxies. But the best-studied starburst dwarfs seem to be interacting with, merging into or absorbing other astronomical objects. For example, II Zw 40 is known as the "X marks the spot" galaxy because it appears to consist of two dwarf galaxies that are merging [*see illustration on pages 66 and 67*]. Or consider Henize 2-10, a relatively large dwarf galaxy with a relatively mature starburst (about 10 million years old). Astronomers believe that it probably gobbled up a much smaller galaxy perhaps 100 million years ago. The smaller galaxy has been well absorbed; only a tidal tail of gas stretching out of Henize 2-10 can still be seen [*see illustration on page 68*]. The starburst dwarf Zw 0855 +06 is interacting with another dwarf (with no starburst) that is close enough to cause tidal disturbances in the galaxy. And there are many other examples.

Dwarf Encounters

Close encounters also cause starbursts in large galaxies. Collisions and mergers of galaxies do not affect the existing stars—the stars in one galaxy almost never collide with the stars in another because there is so much space between stars in even the densest parts of galaxies. But the interactions can dramatically affect the galaxies' gas clouds, which experience shocks, compression and gravitational stresses that make them fragment, collapse and form stars. These processes



should work just as well in dwarf galaxies as they do in larger systems.

Many of the dwarf starbursts, however, are not encountering other dwarf galaxies but systems smaller and fainter than themselves. If dwarf galaxies are the little fish in the celestial pond, what littler fish do they eat? Some astronomers believe that these small systems are clouds of atomic gas (mostly hydrogen) with masses ranging from one million to 10 million solar-masses. For example, NGC 5253 may have accreted a small gas cloud (roughly one million solar-masses) from intergalactic space. Researchers have conducted sensitive radio searches for intergalactic gas clouds with the characteristic emissions of atomic hydrogen. They have found that starburst dwarf galaxies are much more likely to have such gas clouds as companions than nonstarburst dwarfs are.

The hypothesis that starbursts in dwarf galaxies can be triggered by interactions with other dwarfs or intergalactic gas clouds may explain why bursts occur sporadically and at long intervals. But what turns the starburst off? The answer may be found in a striking feature of starburst dwarfs: many of them are surrounded by or contain large-scale structures of ionized gas, shaped like shells, bubbles, halos, forks or chimneys. These structures reflect the vigorous life of massive young stars, which generate strong outflows of gas. If they are massive enough, they may pass through the Wolf-Rayet phase and then die as supernovae. The shells and bubbles seen in starburst dwarfs are most likely the remnants of massed Wolf-Rayet winds and supernova explosions.

Violent mass loss typifies all massive young stars, not just those in dwarf galaxies, and ionized bubbles, plumes and filaments are seen in large starburst galaxies as well. But those structures in dwarf galaxies extend much farther from the galaxy than those in large systems do. The explanation is simply that the smaller mass and weaker gravity of a dwarf galaxy make it possible for the expelled gas to move farther from the galaxy and in many cases to escape it completely. Starbursts are apparently self-braking—the energetic stellar activity disrupts the interstellar gas on which star formation depends and brings the process to a halt. The less massive stars formed in the starburst, which do not become supernovae, blend in with the dwarf galaxy's underlying envelope of faint red stars. And the galaxy returns to its quiescent state: no longer a dwarf starburst but now an ordinary irregular dwarf, waiting for its next encounter.

Dwarf starburst galaxies are attracting more and more research interest as observational capabilities improve. Large optical and infrared telescopes in space and on the earth, radio and millimeter-wave arrays, and satellites that detect high-energy radiation have already made it possible for us to observe star formation in dwarf galaxies in unprecedented detail. By focusing on these dynamic systems, astronomers can study phenomena that cannot be seen anywhere else in the universe. Dwarf starbursts are clearly one of the best examples of good things found in small packages. SA

The Author

SARA C. BECK is a senior lecturer at the Tel Aviv University School of Physics and Astronomy. She received her Ph.D. in physics in 1981 from the University of California, Berkeley. Her primary research interest is star formation in our galaxy and others, and she uses infrared, radio and millimeter-wave spectra and images in her work. She is also a visiting fellow at JILA at the University of Colorado at Boulder, which is where her ideas on dwarf galaxies began to crystallize.

Further Information

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NASA/STScI *(galaxy and globular cluster images)*; J. L. TURNER *(radio/infrared image)*; ZAREH GORJIAN AND VAROUJAN GORJIAN NASA/Jet Propulsion Laboratory *(artist's rendering)*