The Ghostliest Galaxies

Astronomers have found more than 1,000 low-surface-brightness galaxies over the past decade, significantly altering our views of how galaxies evolve and how mass is distributed in the universe

by Gregory D. Bothun

Astronomers have known for decades that galaxies exist in three basic types: elliptical, spiral and irregular. The ellipticals are spheroidal, with highest light intensity at their centers. Spirals, which include our own Milky Way, have a pronounced bulge at their center, which is much like a mini-elliptical galaxy. Surrounding this bulge is a spiral-patterned disk populated with younger, bluish stars. And irregular galaxies have relatively low mass and, as their name implies, fit none of the other categories.

With only minor refinements, this system of galactic classification has changed little since astronomer Edwin Hubble originated it some 70 years ago. Technological advances, however, have significantly improved astronomers' ability to find objects outside the Milky Way galaxy that are extraordinarily hard to detect. Over the past decade my colleagues and I have used an ingenious method of photographic contrast enhancement invented by astronomer David J. Malin of the Anglo-Australian Observatory, as well as electronic imaging systems based on improved charge-coupled devices (CCDs).

LOW-SURFACE-BRIGHTNESS GALAXY Malin 1 dwarfs a conventional spiral galaxy about the size of the Milky Way, shown for scale at the upper right in this artist's conception.

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Using these techniques, we have discovered that the universe contains, in addition to the other types, galaxies that, because of their extreme diffuseness, went essentially unnoticed until the mid- to late 1980s. These galaxies have the same general shape and even the same approximate number of stars as a conventional spiral galaxy. In comparison, though, the diffuse galaxies tend to be much larger, with far fewer stars per unit volume. In a conventional spiral galaxy, for example, the arms are hotbeds of stellar formation and are ordinarily populated with young stars emitting more bluish light. In the diffuse galaxies, the arms have much more gas and much less of a spiral structure. Apparently these low-surface-brightness galaxies, as they are known, take much longer to convert gas to stars. The result is galaxies that evolve four or five times more slowly; the universe literally is not old enough for these galaxies to have evolved fully.

Our work over the past decade demonstrates that, remarkably, these galaxies may be as numerous as all other galaxies combined. In other words, up to 50 percent of the general galaxy population of the universe has been missed.

Although low-surface-brightness galaxies are not numerous and massive enough to be cosmologists' long-sought dark matter, they may solve a different long-standing cosmological puzzle, concerning the baryonic mass in galaxies. Baryons are subatomic particles that are generally either protons or neutrons. They are the source of stellar—and therefore galactic—luminosity. But the amount of helium in the universe, as measured by spectroscopy, indicates that there should be far more baryons than exist in the known population of galaxies. The missing baryons may be in intergalactic space, or they may be in an unknown or difficult-to-detect population of galaxies—such as low-surface-brightness galaxies. More knowledge about these galaxies may not only settle this issue but may also force us to revise drastically our current conception of how galaxies form and evolve.

Low-surface-brightness galaxies have only recently begun shaking up the world of extragalactic astronomy, although the first temblors were felt 20 years ago. In 1976 astronomer Michael J. Disney, now at the University of Wales in Cardiff, realized that the catalogues of galaxies discovered by optical telescopes were potentially biased. Disney noted that astronomers had catalogued only the most conspicuous galaxies—those relatively detectable because they exhibited high contrast with respect to the background of the night sky. There was no reason to believe these galaxies were representative of the general population, Disney maintained. At that time, however, astronomers had not yet detected any very diffuse galaxies to substantiate Disney's suspicions. Thus, for a decade or so, the astronomical community dismissed his theory as applicable to, at most, an inconsequential population of extragalactic objects.

Ultimately, Disney was vindicated. In 1986 my colleagues and I serendipitously discovered an extremely large, low-surface-brightness disk galaxy that is the most massive (and luminous) disk galaxy yet observed. In extragalactic terms, it is fairly close—a mere 800 million light-years away. If this galaxy were as close as the spiral Andromeda galaxy (2.3 million light-years away), it would subtend an arc of fully 20 degrees in Earth's sky—40 times the apparent width of a full moon.

Why did an object this massive and nearby elude us for so many years? The answers require some background on galactic characteristics and the way astronomers measure them. Spiral galaxies have two main components: a central bulge and a surrounding disk with spiral arms. The disks usually emit light in a specific pattern, in which the intensity falls off exponentially with radial distance from the galaxy's center.

This characteristic provides astronomers with a convenient means of measuring the size of a galaxy. The scale length of a spiral galaxy (the size indicator preferred by astronomers) is a measure of the distance from the center of the galaxy to the point in the disk where the surface brightness falls to the reciprocal of *e*, the base of natural logarithms.

The other key parameter astronomers use to characterize galaxies is the central surface light intensity, which is a measure of bluish light in the center of the galaxy, an indicator of stellar density. The word "surface" in this expression refers to the fact that galaxies, which are three-dimensional, are viewed on the two-dimensional plane of the sky; thus, their brightness is projected onto this two-dimensional "surface."

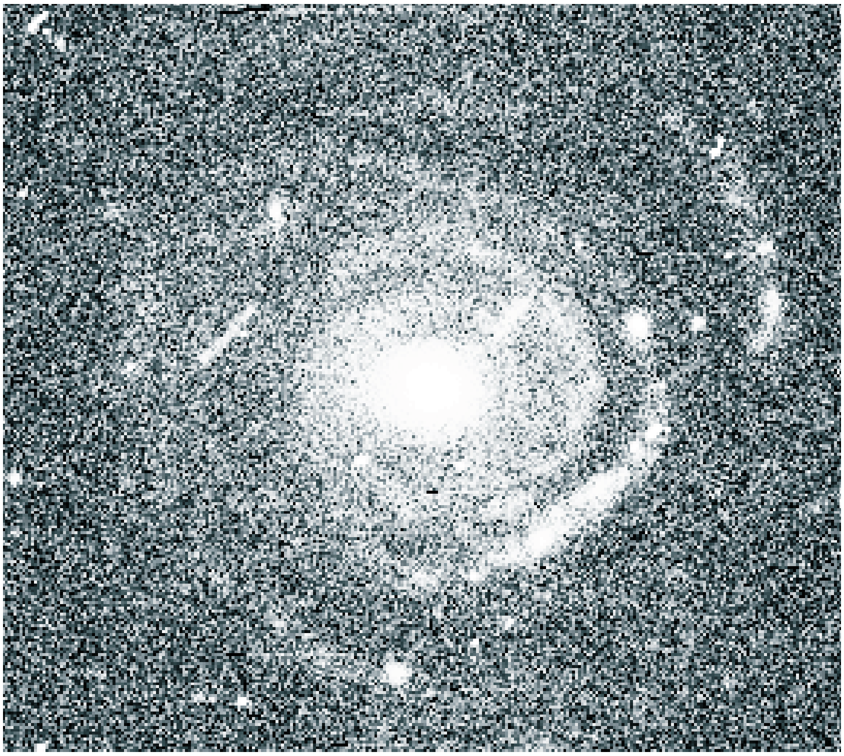
A typical spiral galaxy might have a central surface light intensity (in the blue part of the spectrum) of about 21.5 magnitudes per square arc second. For the purposes of this article, we might define a low-surface-brightness galaxy as one whose central surface light intensity has a value of at least 23 magnitudes per square arc second. (Remember, the higher the magnitude value, the less luminous the object.) To put this value into perspective, it is about equal to the brightness of the background night sky, as measured in the bluish spectrum between 400 and 500 nanometers, on a dark, moonless night at a good astronomical observing site.

Together, by simple integration, the scale length and the central surface light intensity can give us a galaxy's total mass and luminosity. Astronomers' standard catalogues of galaxies generally list them according to diameter or luminosity, as derived from scale length and central surface light intensity. As the discovery of low-surface-brightness galaxies attests, however, the complete range of galactic types is still being determined. Thus, the full range of scale lengths and central surface light intensities is not yet known. The range of these parameters is controlled by the process of galaxy formation, which remains a mystery.

Discovery and Verification

In 1984 astronomer Allan R. Sandage of the Carnegie Institution of Washington released a survey of the Virgo Cluster, which sparked our group's initial quest to locate very diffuse galaxies. In his survey, Sandage had found some very diffuse galaxies that were most likely low-mass dwarf galaxies. Pondering those images lead my colleague Chris D. Impey of the University of Arizona and me to consider whether more diffuse galaxies existed below the detection threshold of the Sandage survey. To test this hypothesis, we enlisted the aid of Malin, who provided us with contrast-enhanced prints of several regions in the Virgo Cluster. These high-contrast prints had many apparent "smudges" on them that were candidates for very diffuse galaxies.

Whereas skeptics suggested these smudges were probably artifacts (dust, water spots and so on) of Malin's photographic contrast-enhancement process, we remained uncertain. In February 1986 our first CCD ran to see if the "smudge" galaxies could be detected and verified. All of Malin's candidates turned out to be detectable in our CCD data. This finding indicated, of course, that these were real galaxies. To understand these galaxies, we had to measure their distances. Yet, because they are so faint, obtaining their optical spectra was nearly impossible. Our only hope was that these diffuse galaxies had sufficient amounts of atomic hydrogen to detect with the



MALINIZATION TECHNIQUE enables the imaging of low-surface-brightness galaxies. This one is known, appropriately enough, as Malin 2; it was discovered in 1990 and was the second such galaxy to be found. It is about 450 million light-years away and, with a scale length of 15 kiloparsecs, is about five times the size of the Milky Way.

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Arecibo radio telescope in Puerto Rico. During the course of these radio observations in October 1986, we made a discovery.

Atomic hydrogen makes up roughly 10 percent of the baryonic mass of many galaxies and usually concentrates in the spiral arms. It was perfectly possible that some of our smudge galaxies appeared so diffuse because they were composed mostly of gas. Thus, emissions from atomic hydrogen in the smudge galaxies would corroborate their existence. One object turned out to be unique, displaying a redshift 25 times greater than that of Virgo. This was the discovery of Malin 1, an absolutely immense and extraordinarily diffuse disk galaxy. Malin 1 has a central surface light intensity only 1 percent as bright as a typical, conventional spiral. This was the first direct verification of the existence of low-surface-brightness galaxies.

Finding More Galaxies

Based on these results, Impey and I initiated three new surveys, hoping to characterize the extent and nature of this apparent population of previously undetected galaxies. The first survey relied heavily on the goodwill of James M. Schombert, at that time a postdoctoral researcher at the California Institute of Technology. Schombert was associated with the new Palomar Sky Survey and had access to the survey's plates, which he let us inspect for diffuse galaxies with sizes larger than one arc minute.

A second survey using the malinization technique was initiated in the Fornax cluster. In this survey, we could detect galaxies with central surface light intensities as low as 27 magnitudes per square arc second—a mere 2 percent brighter than the background night sky. The final survey was initiated with Michael J. Irwin of the Royal Greenwich Observatory in Cambridge, England; it was able to make use of automatic techniques to scan photographic plates.

As a result of these surveys, we detected a total of approximately 1,000 objects that we believe to be low-surface-brightness galaxies. The group includes both very small, gas-poor dwarfs and about a dozen extremely large, gas-rich objects like Malin 1. (A decade after its discovery Malin 1 remains the largest known galaxy.) In general, these galaxies span the same range of physical size, rotational velocity and mass as normal spiral galaxies. But a small percentage of the low-surface-brightness population is relatively gigantic, with scale lengths that exceed 15 kiloparsecs.

We found that in clusters of galaxies—and perhaps in the universe at large—low-surface-brightness galaxies seem to be much more numerous than conventional ones. Furthermore, if the ratio of mass to luminosity increases with decreasing surface brightness (that is, if there is more mass in less visible galaxies), then these diffuse galaxies harbor a great deal—perhaps most—of the baryonic mass in the universe.

The most startling result of these surveys has come from a recent analysis by Stacy S. McGaugh, now at the Carnegie Institution. McGaugh found that if the space density of galaxies is plotted as a function of their central surface brightness intensity, the plot is flat out to the limits of the data. In other words, there seem to be just as many very diffuse galaxies with a central surface light intensity of 27 magnitudes per square arc second as there are conventional galaxies for which this value is 21—or 23.5 or 22 or 20 and so on. This fact means that up to 50 percent of all galaxies are spirals with a central surface light intensity fainter than 22 magnitudes per square arc second.

Interestingly, low-surface-brightness galaxies are similar in several ways to the enormous number of faint, blue galaxies detected in CCD surveys of very, very distant galaxies. The two galactic types share such attributes as color, luminosity, mean surface brightness and extent of clustering. It may well be that these faint, blue galaxies are low-surface-brightness galaxies in their initial phase of star formation. At closer distances, where the objects are seen as they were in the less distant past, these objects have faded to surface brightness levels that are not intense enough for us to detect. If these faint, blue galaxies are indeed young low-surface-brightness galaxies, then there must be a still larger space density of these low-surface-brightness galaxies than is accepted at present.

This view is supported by studies of the color of low-surface-brightness galaxies, which are generally quite blue. This blueness, typically a sign of star formation, is difficult to understand. It generally indicates a galaxy that has not progressed past an early formative stage, a fact consistent with the low densities of these structures. Thus, it appears that most low-surface-brightness galaxies collapsed quite late and that their first stars formed rather late as well.

Several other findings had intriguing implications for our views about how galaxies evolve. For example, the amounts of neutral hydrogen in low-surface-brightness and convention-

SURFACE BRIGHTNESS of a spiral galaxy declines more or less exponentially with radial distance away from the galaxy's center. Past the central bulge, however, the decline in brightness is almost linear. If this linear region is extended leftward to the vertical axis, it intersects the axis at a value known as the central surface light intensity, an indicator of stellar density.

al galaxies tend to be similar, except that the low-surface-brightness galaxies have much lower densities of the gas. This and other data support the idea that a rotating gas disk must reach a minimum, or threshold, surface gas density before widespread star formation can occur. Furthermore, low-surface-brightness spirals are comparatively deficient in molecular gas.

Taken together, these observations suggest that the density of neutral hydrogen gas on the surface of the diffuse galaxies is insufficient to transform the gas into the giant molecular clouds that, in conventional galaxies, subsequently fragment to form massive stars. It seems that low-surface-brightness spiral galaxies are on a parallel evolutionary track, one in which only small stars form within lower-density clouds of neutral hydrogen gas. Because they lack massive stars, low-surface-brightness galaxies produce the heavier elements (those with atomic numbers greater than 12) at quite low rates. Ordinarily, the more massive a galaxy is, the more heavy elements it tends to contain. The fact that low-surface-brightness galaxies, regardless of their mass, are so deficient in heavy elements suggests that these diffuse galaxies are among the most unevolved objects in the universe and have changed little over the course of billions of years.

Startling Conclusions

Only during the past decade have we come to realize that up to half of all galaxies have been ignored, simply because we could not detect them through the immense noise of the night sky. Now we know that these diffuse galaxies may harbor much baryonic matter. The fact that low-surface-brightness galaxies show properties so different from normal spiral galaxies indicates that many galactic features may exist that we simply cannot detect.

Yet, given the dominance of dark matter in all galaxies, differences in their optical properties may not matter so much. Compelling new evidence now suggests that low-surface-brightness galaxies also reveal differences in the nature of their dark matter, compared with spiral galaxies.

In 1997 our team measured nearly a dozen rotation curves of low-surface-brightness disk galaxies—which differ substantially from those of high-surface-brightness rotating galaxies. In general, a galaxy's rotation speed stems from its total mass at a given radius. If most of a galaxy's mass falls near its center, then the rate at which it rotates will drop as its radius grows, much the same way that the speed of a planet's orbit falls as its distance from its host star rises.

For about 30 years, astronomers have known that most disk galaxies show a constant rotational velocity as their radii extend, indicating that the galaxy's mass grows with its radius. This observation tells us these galaxies must have dark-matter halos, containing roughly 90 percent of their total mass.

Our data have led us to two startling conclusions about low-surface-brightness galaxies. One is that their dark-matter halos extend farther and are less dense than those of spiral galaxies. Second, they contain a much smaller fraction of baryonic matter than spirals galaxies do.

Low-surface-brightness galaxies may well have fundamentally different dark-matter distributions than normal spiral galaxies do. They appear to be physically distinct from normal spirals, even though they share global properties. More important, the data also indicate that these galaxies have less baryonic matter than normal galaxies do. They are close to a hypothetical class of "dark galaxies" in which no baryons collapsed to form stars. Indeed, these galaxies may represent the tip of the iceberg of a large population of dark objects that could account for some of the universe's "missing" mass.

In just over a decade, a whole new population of galaxies has presented a unique window onto the evolution of galaxies and the distribution of matter in the universe. Over the next few years we will search for these galaxies more rigorously, with CCD surveys of wide fields of the sky at the darkest sites. In these new surveys, we should be able to find galaxies with central surface light intensities of 27 magnitudes per square arc second. SA

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