Galaxy, external

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One of the large self-gravitating aggregates of stars, gas, and dust that contain a large amount of the visible baryonic matter in the universe. Typical large galaxies have symmetric and regular forms, are about 50,000 light-years (3×10^{17} mi or 5×10^{17} km) in diameter, and are roughly 3×10^{10} times more luminous than the Sun. The stars and other material within a galaxy move through it, often in regular rotation, with periods of a few hundred million years. The characteristic mass associated with a large galaxy is a few times 10^{12} solar masses. (The solar mass is 4.4×10^{30} lb or 2×10^{30} kg.) Galaxies often occur in groups or clusters containing from a few to many thousands of individual galaxies and ranging in size from a few hundred thousands to tens of millions of light-years. The nearest galaxy to the Milky Way Galaxy, the Sagittarius Dwarf Galaxy, is about 80,000 light-years (4 $\times 10^{17}$ mi or 6×10^{17} km) away; the farthest, more than 1×10^{10} light-years (6×10^{22} mi or 1×10^{23} km). Galaxies are the landmarks by which cosmologists survey the large-scale structure of the universe. *See also:* BARYON.

Composition

Galaxies consist of stars, gas, dust, planets, rocks, and some kind of mysterious stuff called *dark* matter. We can see all of these things, at least for the nearest galaxies, except the dark matter, which is detected by its gravitational influence on visible matter. Modern space telescopes and the recently-constructed giant telescopes on the ground make it possible to determine the kinds of stars in a galaxy, the amount and composition of its gas, and the optical properties of its dust. Of course, galaxies are very distant from us. The nearest spiral galaxy, M31, is about 2 million light-years from our home galaxy. For that reason, though we can detect and measure the bright blue supergiant stars and the luminous red giants for nearby galaxies, we cannot yet detect the faint stars or the planets of other galaxies. But it is possible to determine the nature of the faint material by its collective contribution to the total light of the galaxy. That is why we can say what the composition is for even very distant galaxies, off near the farthest reaches of the universe, simply be analyzing their light. *See also:* DARK MATTER; STELLAR EVOLUTION.

The stars in a galaxy include many mixes of types of stars, depending on the evolutionary history of the galaxy. In the Milky Way Galaxy there are two general types of stellar populations: One type (population I) is characterized by the presence of young stars and by ongoing star formation. It is usually associated with the presence of gas. The second type (population II) shows an absence of gas and young stars as well as other indications that star formation ceased long ago. The Sun is a population I star. *See also:* STAR; STELLAR POPULATION.

Galaxies contain gas (mostly un-ionized hydrogen) in amounts varying from essentially zero up to a considerable fraction of their total mass. Dust in galaxies, although small in mass (typically 1% of the gas mass), is often dramatic in appearance because it obscures the starlight. *See also:* INTERSTELLAR MATTER.

Most, if not all, galaxies are dominated by dark matter, a form of matter whose nature is still unclear and whose existence has been confirmed only by gravitational effects on the surrounding visible matter. Even the outermost stars in a galaxy are influenced by the dark matter that lies farther from the center. The dwarf galaxies also appear to have quantities of dark matter, especially the nearby low-surface-brightness dwarf galaxies such as those in the constellations Leo and Draco.

Form and size

Galaxies generally display strikingly regular forms. The most common form is a disk with a central bulge. The disk is typically 100,000 light-years (6×10^{17} mi or 1×10^{18} km) in diameter and only about 1000 light-years (6×10^{15} mi or 1×10^{16} km) thick. Its appearance is characterized by radially decreasing brightness with a superimposed spiral or bar pattern or both (Figs. **1** and **2**). The central bulge may vary in size from hundreds to many thousands of light-years. Such galaxies are classified as spirals (S) and subclassified a b or c (for example Sa) to distinguish increasingly open spiral structure and small bulge size. The disks of these galaxies are dominated by population I stars while their bulges contain mainly population II stars. The Milky Way Galaxy is an Sb type. *See also:* MILKY WAY GALAXY.

Many spiral and irregular galaxies have a nearly linear feature in their central regions. Called barred galaxies, these objects can otherwise fit into the general scheme of galaxy types. The letter B is added after the S in the classification of spiral galaxies that contain conspicuous barlike features (for example, M61 is an SBc galaxy). It is likely that almost all spiral galaxies have at least some stars moving in barlike orbits.

Another common type of galaxy is an ellipsoid with radially decreasing brightness. These galaxies are classified as ellipticals (E) and subclassified according to their axial ratios by a number from 0 (E0 = round; **Fig. 3**) to 7 (E7 = 3-to-1 axial ratio). Additionally, ellipticals are subclassified according to the shape of their lines of constant brightness on images, so-called isophotes. Very luminous E galaxies show isophotes with boxlike shapes (boxy E) while less luminous E galaxies show isophotes with disk-like shapes (disky E). Ellipticals may vary in size from thousands to several hundred thousand light-years. They are most commonly found in clusters of galaxies and often contain a hot gas halo and in about half of all cases appreciable amounts of dust. The brightest galaxies are usually ellipticals. They are dominated by population II stars.

Other, rarer forms of galaxies include a transition class called S0 that has a disk superimposed on an otherwise elliptical type of light distribution, and an irregular (Irr) class composed of galaxies with chaotic forms (**Fig. 4**) and generally low total luminosity.

Fig. 1 Great Spiral Galaxy in Andromeda (M31, NGC 224) and its two small elliptical companions (M32, NGC 221, closer, at left; and NGC 205, farther, at right). (*Mosaic image courtesy of R. Gendler*)

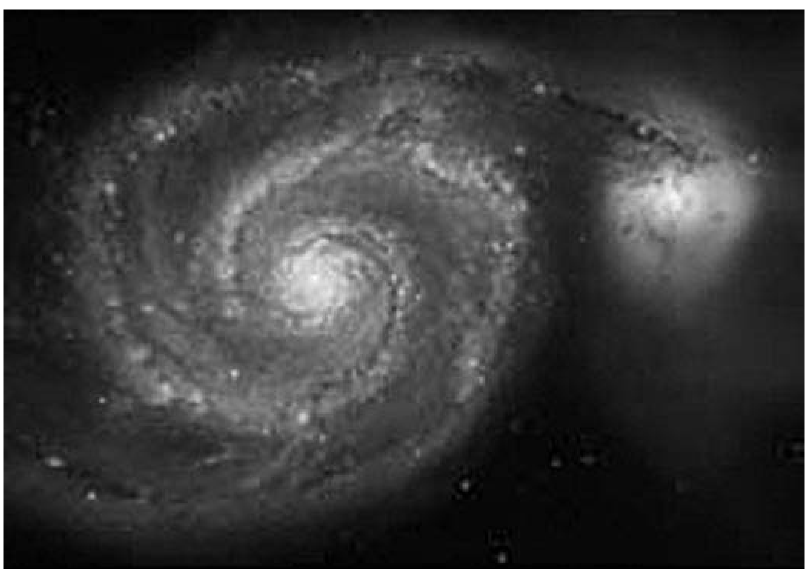

Fig. 2 "Whirlpool" Galaxy (NGC 5194), type Sc, and a companion irregular satellite (NGC 5195). [*Courtesy of NASA, ESA, S. Beckwith (Space Telescope Science Institute), The Hubble Heritage Team (Space Telescope Science Institute/AURA)*]

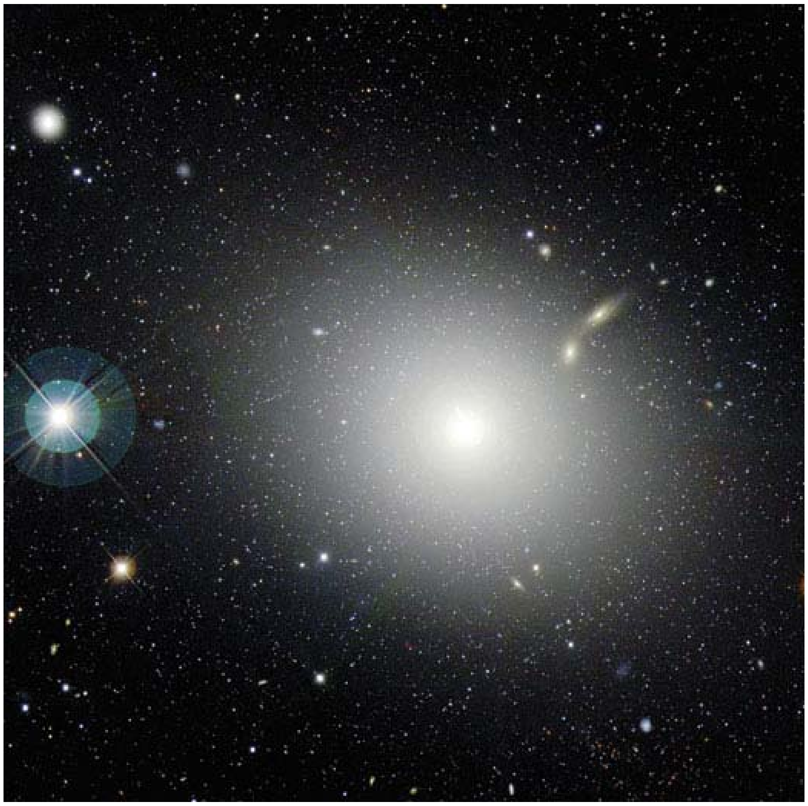

Fig. 3 E0 galaxy M87 (NGC 4486) in the Virgo cluster, which is in the constellation of Virgo. This galaxy is a source of radio emission, and it has an active nucleus. (*Courtesy of Canada-France-Hawaii Telescope*)

Fig. 4 The irregular galaxy NGC1569, a starburst galaxy, with very active star-formation. Gas and dust streams surround it. [*Courtesy of NASA, ESA, The Hubble Heritage Team (Space Telescope Science Institute/AURA)*]

Exotic galaxy types

Some galaxies lie outside the normal range of morphologies. Most of these galaxies have suffered some disturbing event, such as a gravitational encounter, a merger, or violent nuclear activity. Other such galaxies seem to have started out with anomalous characteristics, such as the low-surface-brightness galaxies. Those with activity in their nuclei are described below.

Starbursters. One of the more spectacular examples of exotic galaxies is the starbursters, galaxies that are presently manufacturing stars at an unusually vigorous rate. It is now known that some gravitational impulse has triggered the unusual star formation activity in at least most cases. The burst is a temporary condition and the galaxies now bursting must have spent most of their lives in a more quiet condition. *See also:* STARBURST GALAXY.

Low-surface-brightness galaxies. Another type of exotic galaxy is the low-surface-brightness galaxies, star systems that have such a low spatial density of stars that they are almost invisible. The Sculptor dwarfs have many characteristics similar to the globular star clusters (very old stars, cluster-type variable stars, and smooth stellar distribution) but are millions of times less dense, and are dominated by dark matter. Other low-surface-brightness galaxies have a composite population of stars. For example, at least two star-forming events occurred in the Carina dwarf, one about 13×10^9 years ago and one about 7×10^9 years ago. *See also:* STAR CLUSTERS.

Another type of low-surface-brightness galaxy includes extreme irregular and spiral galaxies, which have some of the structural properties of the normal examples of these types but are so faint that it is difficult to detect them against the sky's brightness. A significant fraction of the mass of the universe may be in the form of these nearly invisible galaxies.

Internal motions

The stars and interstellar matter in a galaxy revolve around the center of mass of the galaxy, which is often a bright nucleus. In a spiral galaxy such as the Milky Way, there are generally two types of stellar orbits. The stars in the flat plane tend to have nearly circular orbits, while the stars in the bulge and halo have more highly elliptical orbits. All of the motions are the result of the stars responding to the gravitational field of the galaxy. The galaxies are supported against gravitational collapse by these motions in the same sense in which the planets of the solar system are kept from falling into the Sun by their orbital motions. Usually, the inner regions in the plane of a spiral galaxy undergo nearly solid-body rotation (velocity proportional to radius), while the outer regions rotate differentially (velocity constant). The spread in velocity of the material within galaxies varies from one to several hundred miles per second. Typical orbital periods for stars are several hundred million years.

The distribution of kinetic energy into randomly oriented and circular rotational motions varies with the galaxy type. The disk of a spiral galaxy may have only about 1% of its total kinetic energy in random motions, while boxy E galaxies in contrast to disky E galaxies may have most of their kinetic energy in their random component.

Luminosities

The number of galaxies with total luminosities L is roughly proportional to L^{-y}, where y is between 1 and 1.5 for luminosities less than about 3×10^{10} solar luminosities. The number is exponentially cut off for higher luminosities. The brightest observed galaxies are fainter than 2×10^{11} solar luminosities; the faintest, brighter than about 1×10^{6}. The Milky Way Galaxy's total luminosity is roughly 1×10^{10} times greater than the Sun's.

The distribution of luminosities is such that while there are very many faint galaxies, they do not contribute a large fraction of the total light given off by galaxies. Only the brighter galaxies, visible for great distances through space, can be observed easily and in great numbers. It is generally found that the masses of galaxies are roughly proportional to their luminosities.

At each luminosity the fraction of different galaxy types strongly varies with luminosity. The most luminous galaxies are mainly ellipticals and the less luminous mainly spirals. Additionally the number of elliptical galaxies at all luminosities increases in environments where the density of galaxies is high.

Clustering

Although galaxies are scattered through space in all directions for as far as they can be observed, their distribution is not uniform or random. Most galaxies are found in associations (**Fig. 5**) containing from two to hundreds of individual bright galaxies and at least 10 times as many fainter dwarf galaxies. The E and S0 galaxies tend to be concentrated in large clusters more strongly than spirals. The Milky Way Galaxy and the Andromeda Nebula (Fig. 1) are members of a cluster called the Local Group. *See also:* ANDROMEDA GALAXY; LOCAL GROUP.

Like the stars within a galaxy, the galaxies within a cluster move about under the influence of their mutual gravitational attraction. The motions are generally randomly oriented and the cluster shows little evidence of rotation. Typical velocities range from about a hundred up to a thousand miles per second or more.

On scales larger than individual small groups and rich clusters, the distribution of galaxies through space is still not random. This very large scale structure in the galaxy distribution is usually referred to as superclustering to indicate that it involves the higher-order clustering of the individual first-order associations of galaxies. The largest structures generally do not have the shape of spherical clusters, but rather the concentrations of galaxies tend to be filamentary in nature. Between filaments there are often large-scale voids, in which few galaxies are found.

This very large scale structure is generally attributed to the hierarchical clustering that resulted from the gravitational instability from primordial fluctuations immediately following the big bang. These would have systematically formed small galaxies first, followed by larger and larger concentrations of more massive galaxies. Evidence for the existence of the density fluctuations that are inferred to have seeded structure formation has come from the discovery and mapping of the relic temperature fluctuations in the cosmic microwave background. Indeed, computer simulations of conditions in the early universe indicate that the observed

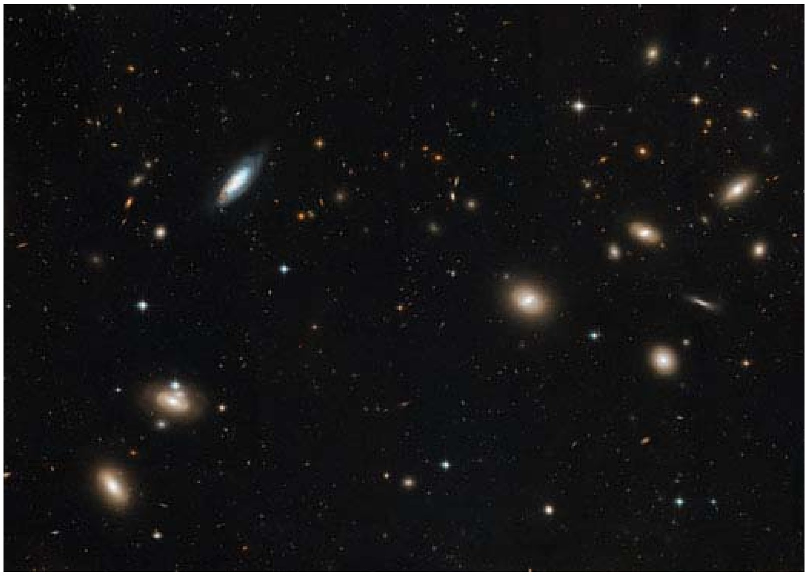

Fig. 5 Clustering characteristics of galaxies. This association of galaxies in the constellation of Coma is made up primarily of E and S0 type galaxies. [*Courtesy of NASA, ESA, The Hubble Heritage Team (Space Telescope Science Institute/AURA)*]

large-scale distribution of galaxies and galaxy clusters is a natural result of the evolution of the universe after the big bang, when the earliest structures began to form in what was then a much denser universe. *See also:* COSMIC BACKGROUND RADIATION; COSMOLOGY; UNIVERSE.

Active nuclei

In the very central regions (sizes at least as small as a light-year, 6×10^{12} mi or 1×10^{13} km) of galaxies, violent behavior is often observed. This activity is manifested in many ways, including the high-velocity outflow of gas, strong nonthermal radio emission (implying relativistic particles and magnetic fields), intense and often polarized and highly variable radiation at infrared, optical, ultraviolet, and x-ray wavelengths, and ejection of jets of relativistic material. In the most extreme cases the energy in the nuclear activity surpasses that in the rest of the galaxy combined. These phenomena are generically referred to as nuclear activity, and the objects that exhibit them are called active galactic nuclei.

One of the most prominent characteristic features of active galactic nuclei is the ejection of large masses of high-temperature gas at great velocities. Characteristic temperatures and velocities are in the range of tens to hundreds of thousands of kelvins and thousands to over 10,000 mi/s (16,000 km/s). Total gas masses exceeding 1×10^6 times that of the Sun may be involved. These powerful gas flows reveal themselves as bright and broad spectral lines.

A second characteristic feature of active galactic nuclei is the emission of radiation over a wide range of different wavelength bands, from the radio band to gamma rays. An object such as an ordinary star, which emits radiation because it is hot, does so in a characteristic wavelength band. Such radiation is called thermal, and the characteristic wavelength is determined by the object's temperature. The typical active galactic nucleus emits a quite different sort of radiation, called nonthermal radiation, implying that it is produced by a quite different mechanism. *See also:* HEAT RADIATION.

Another indication that the radiation is of an unusual, nonthermal origin is the dramatic brightness changes of active galactic nuclei over relatively (by astronomical standards) short periods of time. Most active galactic nuclei show moderate changes over time scales of months to years, and some show dramatic variations (by factors of 2 to 10 or more) over times ranging down to a few hours. Since sources of radiation cannot generally change their brightnesses in times much shorter than that required for light to travel across them, these variations imply that the radiation from an active galactic nucleus arises in a very small region, in extreme cases no larger than the solar system. This is a fantastically small volume, considering that the total radiative power output can rival or exceed that of an entire galaxy many tens of thousands of light-years across.

Another important and peculiar phenomenon exhibited by active galactic nuclei is the emission of highly directional jets of relativistic plasmas and magnetic fields. These jets contain elementary particles, particularly electrons, moving at velocities near the speed of light, and often extend far outside the nucleus and even beyond the whole body of the galaxy. *See also:* PLASMA (PHYSICS).

There is a variety of classes of active galactic nuclei. The Seyfert galaxies display the broad emission lines produced by the rapid outflow of hot gas but frequently do not exhibit much radio-wavelength emission. Another complementary class shows strong radio emission but weak or absent emission lines. Yet another class (BL Lac objects, often referred to as blazars) also shows only weak emission lines but is often extremely variable. When active galactic nuclei achieve such great luminosities that they dominate that of the rest of the galaxy, they are sometimes referred to as AGNs. Quasars are the most extreme sort of active galactic nuclei, with emission so intense that the ordinary galaxy in which they exist is entirely lost in the glare of the nuclear emission. It appears that active galactic nuclei in general, and certainly quasars, were much more common during the early history of the universe than they are at present. If so, most or all large galaxies may contain the burned-out remnant of an active nucleus in their centers, although only about 1% still show detectable activity. *See also:* QUASAR.

Perhaps the most intriguing question concerning active galactic nuclei is that of the nature of the energy source that drives all of their diverse phenomena. While there is no certain answer to this question, there is a widely accepted model that appears consistent with all that is known about active galactic nuclei. The basic idea of this model is that active galactic nuclei are powered by the energy released when matter falls into a massive black hole occupying the center of a galaxy. These black holes are found to have masses in the rough range of 10^6–10^9 solar masses and to have formed because of the high density of material expected to accumulate at the center of a galaxy due to its gravitational field. Such a black hole will continue to accrete any gas that finds its way into the vicinity. As such gas falls toward the black hole, its angular momentum will cause it to take up a nearly circular orbit in a disk of material surrounding the black hole. This disk (called an accretion disk) will slowly inject gas into the black hole. As the gas approaches the black hole, the latter's enormous gravitational field will compress and heat the gas to very high temperatures, causing it to radiate. Intense jet radio emission, powered by energy released during infall onto the central black hole, is ejected along the minor axis of the accretion disk. Depending on the viewing angle of the observer, the resulting morphology can account for a wide variety of active galactic nuclei, radio galaxies, and quasars. A given mass of gas can release 10 or more times as much energy in this way as it could if it were used as nuclear fuel in a star or a reactor. A gas infall rate onto the central engine of several solar masses of gas per year suffices to power the most luminous active galactic nuclei in the universe. There is ample gas available in the interstellar medium to act as a fuel supply. Gas may be driven into the central regions of the galaxy, perhaps following a merger, where it can supply and activate the nucleus. The mechanisms that convert the thermal radiation generated in this way into the nonthermal radiation and relativistic plasmas observed in active galactic nuclei are not well known. *See also:* ASTROPHYSICS, HIGH-ENERGY; BLACK HOLE.

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Correlations

A remarkable number of well-established correlations exist between structural properties of elliptical and spiral galaxies that are indicative of their origin. As mentioned above, spiral galaxies rotate like a solid body in their inner parts and differentially in their outer parts. A maximum in the rotation velocity usually occurs at the transition point between these two regimes. This maximum rotation velocity is strongly correlated to the luminosity of the spiral galaxy in such a way that it increases with luminosity. A similar correlation has been found for elliptical galaxies between the amount of random motion (the so-called velocity dispersion) of their stars and their luminosity. More luminous ellipticals show larger random motion of their stars.

Additionally the global percentage of heavy elements in a galaxy of any type increases with its luminosity. This is explained by the larger gravitational potential generated by the larger amount of mass in more luminous galaxies. This potential is very effective in keeping the heavy elements produced during the life cycles of stars that subsequently are ejected into the interstellar medium by supernovae. The heavy elements are subsequently incorporated in the next generation of new stars and cause them to be redder. This and an old generation of stars are responsible for the observed correlation that more luminous galaxies are redder.

Elliptical galaxies over a wide range of luminosities are compared according to their central surface brightness μ_0, central velocity dispersion σ_0, and effective radius R_0, which is the radius from within which half the light of the galaxy is emitted. The comparison shows that they do not occur in all possible combinations but occupy a two-dimensional plane, called the fundamental plane, in this three-dimensional parameter space. Thus, only certain combinations of these three parameters are realized by nature. This correlation is usually attributed to the condition that the galaxies are in an energetically relaxed state.

It is widely believed that bulges of both spirals and elliptical galaxies harbor supermassive black holes with masses up to several times 10^9 solar masses at their centers. A striking correlation between the central velocity dispersion of ellipticals and bulges of spirals with the central black hole mass has been established, which hints toward a connection in the formation of bulges and supermassive black holes. Spheroids with larger velocity dispersion have more massive black holes.

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Keywords

galaxies; extragalactic nebulae; dark matter; stellar populations; spiral structure; active galactic nuclei; black holes

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