GALAXIES

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Summary

Galaxies are the basic building blocks of the universe, Their visible components are baryonic, in the form of stars, gas and dust. Underlying the visible components is a

massive extended halo of dark matter which typically makes up about 95% of the mass. This dark matter is detected by its gravity but its nature is still unknown. For most of the brighter galaxies, the distribution of the stars takes one of two forms: in the more common disk galaxies, most of the stars lie in a flat disk which is supported against gravity by rotation, while in the elliptical galaxies the distribution of stars is more spheroidal and is supported mainly by the random motions of the stars. The fainter galaxies alsofall into two classes: the gas-rich dwarf irregular systems and the gas-poor dwarf ellipticals and spheroidals. Galaxies are believed to form from the early universe by hierarchical aggregation: small clumps of baryons and dark matter merge to form larger clumps and so on. Although the details are not yet well understood, there is a remarkable regularity in the outcome of the formation process. The density distributions of stars within the family of disk galaxies share some common properties and this is again true for elliptical galaxies. Galaxies are also observed to follow scaling laws. For example, the Tully-Fisher law relates the rotation speed of a disk galaxy (which is determined mainly by the gravitational field of its stars and dark matter) to its stellar luminosity. Some galaxies are isolated in space, but most are found in groups or clusters. The galaxies in these groups and clusters interact and their properties are modified by these environments. This article concludes with a brief summary of some of the outstanding problems in understanding galaxies.

1. History

Galaxies are collections of 10^4 to 10^{11} stars, plus gas, dust and invisible dark matter, held together by their gravitational field. The nearest and brightest galaxies, like the Andromeda spiral M31 and the Magellanic Clouds, are visible to the naked eye. Most of the brighter galaxies have been known for many years. In the 18th century, Charles Messier used a small telescope to make a catalog of 110 nebulae and star clusters which includes many of the brightest galaxies. The New General Catalog and the Index Catalog came late in the 19th century and include about 8000 nebulae, mostly galaxies. It remains an important source of relatively bright galaxies. At this time, the nature of the nebulae was not known: were they galactic or extragalactic? Although Slipher had measured the radial velocities of several of the nebulae in 1917 and had found that some have velocities as high as 1000 km s^{-1}, it was not until the late 1920s that cepheid variable stars were discovered in M31 and the extragalactic nature of the galaxies was firmly established.

Radial velocity measurements of galaxies by Hubble and others soon showed that the more distant galaxies were receding more rapidly, with a linear law of expansion (Hubble's law). However it took some time before the distances to galaxies were well determined. The distance scale depended primarily on the calibration of the cepheid variables, which was based partly on observations of cepheids in our Galaxy and later on cepheids in the Magellanic Clouds. The slope of the velocity–distance relation for galaxies is called the Hubble constant $H_\circ$. The first estimates were about 500 km s^{-1} Mpc^{-1}. As knowledge of the distance scale improved, the value of $H_\circ$ came down to between 50 and 100 km s^{-1} Mpc^{-1}. The current value of about 75 km s^{-1} Mpc^{-1} comes from a key project in the 1990s with the Hubble telescope to study cepheids in more distant galaxies, plus an independent estimate from the fluctuations in the cosmic microwave background. It is probably correct to within about 10%. Knowing the distances to galaxies is essential for estimating their masses and luminosities, and for understanding their stellar content and dark matter content.

Galaxies vary greatly in appearance, size and mass, but one can distinguish some basic characteristics, and separate them into basic classes. The more massive (giant) galaxies come in two kinds: the flat rapidly rotating disk galaxies (which includes the spiral systems) and the more spheroidal elliptical galaxies. The fainter (dwarf) galaxies again come in two kinds: the star-forming irregular galaxies and the more inert dwarf ellipticals and dwarf spheroidals.

We will discuss these various kinds of galaxies and then briefly describe the environments (groups and clusters) in which they are found.

2. Disk Galaxies

In this section, we discuss the disk galaxies. Dynamically, disks are very simple. Their equilibrium is primarily between gravity and rotation, so it is possible to study their gravitational potential and dark matter content with confidence. On the other hand, disks are highly dissipated structures, so much of the information about the early dynamical history of their baryons has been lost. Another complication is that most disks are still forming stars, so their evolution (dynamical, structural and chemical) continues.

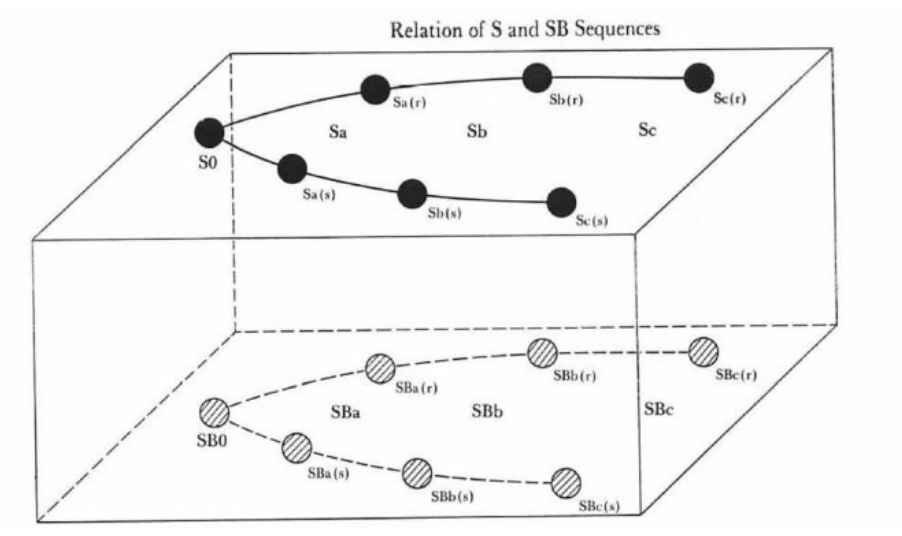

Figure 1. The Hubble sequence (from Sandage 1961.). Courtesy of the Carnegie Institution of Washington.

2.1. The Hubble Classification

Disk galaxies are classified by the appearance of their spiral structure, the amount of star formation in their disks and the relative brightness of the bulge and disk. The basic Hubble classification shown in Figure 1 proceeds from S0 (little or no star formation or spiral structure, and usually a large bulge) to Sa (tightly wound spiral structure, low level of star formation and large bulge) through to Sc (more open spiral structure, much star formation and small bulges). Galaxies at the Sa end of the classification are called *early type*, and those at the other end are called *late type*. Important extensions of the basic Hubble scheme include

- the significance of bars (SA, SAB, SB) and
- the inner and outer rings (r, R, s, rs), which are often seen, particularly in the barred spirals
- extension to type Sd and then to a class of asymmetric galaxies like the Large Magellanic Cloud, denoted Sm, and then to the irregular galaxies (Irr), many of which are disk-like though irregular in appearance and are actively star forming.

Some disk galaxies have large central bulges and others do not have bulges at all. The relative strength of the bulge and the disk is part of the Hubble classification, with the pure disk galaxies like IC 5249 (Figure 2) classified late in the Hubble sequence. We see that bulges are not an essential element of the formation of disk galaxies. The bulge-to-disk ratio affects the morphology of disk galaxies, through its effect on the shape of the rotation curve and so on the optical morphology of the star-forming disk.

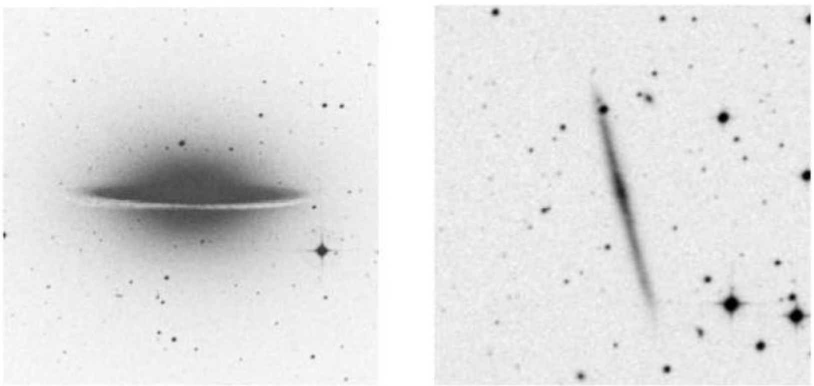

Figure 2. Examples of galaxies with a very large bulge (left: the Sombrero galaxy NGC 4594) and a very small bulge (right: IC 5249). Images from the DSS.

2.2. The Light Distribution in Disk Galaxies

Disk galaxies are relatively flat systems, and most disks have a simple exponential distribution of luminous density, of the form $I(R,z) = I_{\circ} e^{-R/h} e^{-z/h_z}$ where R and z are cylindrical polar coordinates (z is perpendicular to the disk) and h and h_z are the radial and vertical scale lengths. This distribution typically extends out to about 5 radial scale lengths, beyond which the light distribution often steepens abruptly. The scale height h_z is usually about 300 pc. The radial scale length h varies from about 1 to 7 kpc: intrinsically brighter galaxies mostly have larger scale lengths. Usually it is possible to measure only the *surface brightness* distribution $\mu(R)$ of an individual disk. This again usually has the exponential form $\mu(R) = \mu(0) e^{-R/h}$. Typical central surface brightness values range from about 18 to 24 blue mag arcsec^{-2}, although the brighter spirals are observed to cluster around a central surface brightness of about 21.5 mag arcsec $^{-2}$. These parameters are important, because their values for equilibrium disks reflect the angular momentum and mass of the stellar disk. Angular momentum transport between baryonic and dark matter during hierarchical galaxy formation affects the angular momentum of the equilibrium disks, and theories of galaxy formation need to reproduce their typical surface brightness values and sizes (which is currently a troublesome issue).

Galaxies with central surface brightness $\mu(0) > 23$ mag arcsec $^{-2}$ are usually called low surface brightness galaxies. Most of these LSB galaxies are dwarfs, with absolute blue magnitudes fainter than -18. (For comparison, this is approximately the absolute magnitude of the Large Magellanic Cloud). The possible existence of giant galaxies with low surface brightness as a major component of the galaxy population has been an issue for many years. Although a few such galaxies are known, it seems that such galaxies are relatively rare.

2.3. The Rotation of Disk Galaxies

Disk galaxies are rotating systems. Most of the stars and gas are moving around the galaxy in circular motion. The larger galaxies rotate more rapidly: the rotational velocity for a large galaxy like the Milky Way is about 220 km s $^{-1}$. The acceleration required for this circular motion is provided by the gravitational field of the galaxy. The rotational velocity $V(R)$ may be roughly constant with radius R or may increase with R, depending on the shape of the gravitational field of the galaxy. The circular motion makes it relatively easy to measure how the gravitational field changes with radius. In the plane of the galaxy, if $g(R)$ is the gravitational acceleration at radius R, then

$$g(R) = -V^2 / R.$$

Most disk galaxies, except those of very early Hubble type, have a layer of neutral hydrogen in their plane which often extends in radius far beyond the stellar disk. In most galaxies, the hydrogen is moving in near-circular orbits. Its rotation curve $V(R)$ can be measured using the 21 cm line of neutral hydrogen. The rotational velocity $V(R)$ for larger disk galaxies usually has the form shown in Figure 3, rising from the disk center to an approximately constant rotational velocity at larger radii. This galaxy NGC 3198 is somewhat less luminous than the Milky Way and has a rotational speed of about 150 km s $^{-1}$. The radially constant rotational (flat) rotation curve is not consistent with the gravitational field calculated from the stars and gas alone: we would expect the rotational velocity to decrease rapidly in the outer disk. To provide the acceleration required to explain the observed rotation curve, it is necessary to invoke the presence of a massive dark component, with a rotation curve contribution as shown in Figure 3. Out to the end of the observed rotation curve, the mass of this dark halo is about 4 times the mass of the luminous components. This kind of rotation curve is seen in almost all large galaxies for which neutral hydrogen rotation curves have been measured. In the Milky Way and a few other galaxies, it is possible to use other tracers of the gravitational field to show that the dark halo extends far beyond the stars and the neutral hydrogen, and its mass is typically about 20 times larger than the mass of the stars and gas. In the Milky

Way, the stellar mass is about 6×10^{10} $M_\odot$, and the mass of the dark halo is in excess of 10^{12} $M_\odot$. The dark halo extends out to a radius of at least 150 kpc.

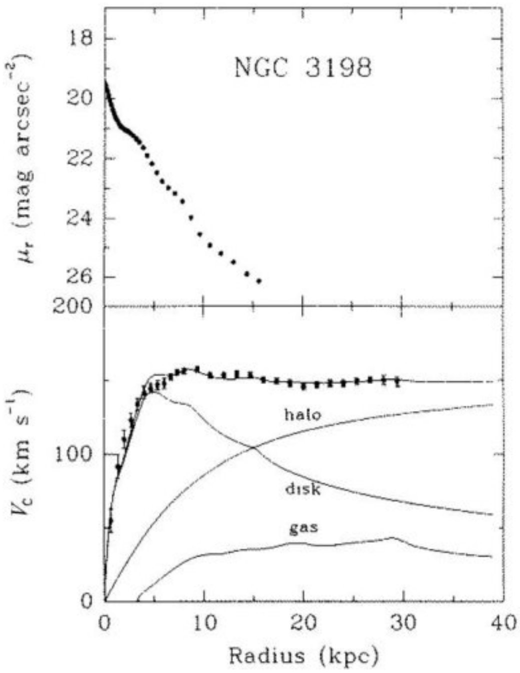

Figure 3. *Upper panel*: Surface brightness distribution of the disk galaxy NGC 3198. *Lower panel*: 21 cm rotation curve of NGC 3198. The rotation curve in the outer parts of the galaxy is much higher than the curve expected from the stars and gas alone. A massive dark halo is needed (adapted from Begeman, 1989).

Early evidence for a dark halo in the Milky Way and M31 came from a study in 1959 of the motion of M31 relative to the Galaxy. These two galaxies are now approaching each other with a velocity of about 118 km s^{-1}. Their total mass must be large enough ($>2\times10^{12}$ $M_\odot$) to have turned around the local expansion of the universe within the age of the universe (about 13.7 Gyr). Evidence for a dark halo from rotation curve data began to accumulate from 1970. The evidence for the dark halo is fairly simple and direct, and by about 1980 most astronomers were convinced of its existence.

At the present time, the nature of the dark matter is not known. It seems likely that it is in the form of a weakly interacting massive particle. Much work is in progress to make a direct detection of the dark matter in the laboratory. Astronomers are also exploring the possibility that Newton's inverse square law of gravity is not correct at the very low accelerations associated with galactic rotation. For example, a change from an R^{-2} law of gravity at higher accelerations to an R^{-1} law at lower accelerations could produce the flat rotation curves like that in Figure 3. The weight of evidence is currently not in favor of this possibility, although it has been difficult to disprove.

Dark matter is now an integral part of the formation picture for galaxies. From the Cosmic Microwave Background data, combined with data on the expansion rate of the universe from type Ia supernovae, it appears that baryon matter (matter made of protons and neutrons) provides about 16 % of the matter of the universe: the rest is in the form of dark matter. (Matter makes up about 27 % of the universe: the rest is in the form of dark energy, which we will not discuss here.)

In the Cold Dark Matter scenario, galaxies form from coalescing clumps of baryons and dark matter. The dark matter is presumably not dissipative and forms an extended dark halo. The baryonic gas is able to dissipate its energy by radiation and contracts to a rotating disk and forms stars. At the end of this process, the galaxies have about 5 % of their mass in baryons, so a large fraction of their initial baryon content was lost, presumably ejected into the intergalactic medium by winds driven by supernova explosions.

In simulations of the growth of density fluctuations in the expanding universe, pre-galactic blobs of matter acquire angular momentum from each other by tidal torques. The dimensionless parameter $\lambda = J\,|E|^{\frac{1}{2}}\,G^{-1}M^{-\frac{5}{2}}$ is a measure of the ratio (rotational velocity)/(virial velocity) for a blob. (Here J, E and M are the angular momentum, binding energy and mass of the system). For disks in centrifugal equilibrium, $\lambda \simeq 0.45$. Simulations of hierarchical galaxy formation show that the typical value of λ is 0.05 ± 0.03. In the absence of significant transport of angular momentum from the disk to the dark halo as the galaxy is forming, λ is a useful measure of the collapse factor for the baryons, and hence for the surface brightness of the ensuing disk. Simple arguments, assuming that the specific angular momentum of the dark matter and baryons are similar, show that the collapse factor for the baryons is $r_{\rm t}/h = \sqrt{2}/\lambda \simeq 30$ where $r_{\rm t}$ is the truncation radius of the halo. For our Galaxy, $h \simeq 4$ kpc so the truncation radius of the dark halo should be about 120 kpc. This is consistent with the observed extent of the galactic dark halo. If the baryons and dark matter maintain the same specific angular momentum throughout the collapse of the disk, disks with higher λ-values are initially closer to centrifugal equilibrium, have a smaller collapse factor and lead to disks of lower surface density.

The Cold Dark Matter framework for galaxy formation is not yet fully satisfactory. Simulations of galaxy formation generate dark halos with strongly cusped central regions: the dark matter density ρ increases with decreasing radius r like $\rho(r) \propto r^{-1}$ or even faster. On the other hand, observations indicate that the density distribution in the inner parts of dark halos is much more nearly constant. Another apparent problem is the large amount of substructure predicted for dark halos from the simulations.

A large halo like that of the Milky Way should have about 500 subhalos substantial enough to house dwarf satellite galaxies. However the actual number of known satellites is an order of magnitude smaller (see Section 3).

Currently it is very difficult to generate galaxies like the Milky Way in CDM simulations: most of the simulations of large galaxies have much larger bulges (see Section 2.9), because of the high level of continuing merger activity in CDM.

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Biographical Sketch

Kenneth Freeman was born in Perth, Western Australia. He studied at Scotch College and then at the University of Western Australia, graduating with first class honors in applied mathematics in 1962. He then did postgraduate work in the Department of Applied Mathematics and Theoretical Physics at the University of Cambridge (Trinity College) in theoretical astrophysics, and graduated PhD in 1965.
He was a Fellow of Trinity College 1965-1969, a Postdoctoral Fellow at the University of Texas in 1966, and then a Queen Elizabeth II Fellow at Mount Stromlo Observatory at the Australian National University. He was a senior visiting scientist at the Kapteyn Institute of the University of Groningen, Distinguished Visiting Scientist at the Space Telescope Science Institute, and Professor at Large at the University of Western Australia, and is now Duffield Professor at the Research School of Astronomy & Astrophysics of the Australian National University in Canberra. He has written about 770 research papers and reviews and two popular level books; the most recent is Shrouds of the Night (New York, New York:

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