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GALAXY BUILDING*

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ABSTRACT

This review discusses the various processes that contribute to the building of galaxies, with emphasis on the direct observational evidence for these processes. The disks, bulges, and nuclei of galaxies are all probably built up over a significantly extended period of time by the continuing addition of matter, often in discrete amounts associated with the merging of smaller units. The information about galaxy formation available from the fossil record and from look-back observations is also reviewed, and it is concluded that the epochs of disk and spheroid formation can be identified and studied directly by observations at high redshifts, except perhaps for the earliest stage of spheroid formation which probably occurs at redshifts not yet observed.

Key words: galaxies–galaxy formation

1. Introduction

Galaxies are the basic structural units of the universe, and contain nearly all of its visible matter. They are also the astronomical ecosystems in which stars are born, evolve, and die, recycling some of their matter back to the interstellar medium and enriching it with the products of stellar nucleosynthesis. Much effort has been devoted to understanding how galaxies might have formed and acquired their observed properties, and a variety of scenarios and models have been proposed that attempt to account for some of these properties. With the amount of detailed information now becoming available, however, it seems unlikely that any single type of model will be able to account for all of the observations, and it is becoming increasingly clear that each galaxy must be viewed as an individual with its own unique history in which many complex processes have played a role. Thus, the best way to gain an understanding of how galaxies form is probably to try to identify important formation mechanisms that can be studied individually, both theoretically and observationally, and thereby to build up an increasingly detailed picture that is as much as possible empirically derived and not based on any particular theoretical model.

Of course, to make any sense of the observations, we must have some notion of the theoretically possible mechanisms that might contribute to explaining the observed properties of galaxies. In the most general terms, it is widely accepted that galaxies form by the condensation of matter that was once much more uniformly distributed in the universe, and that at least the later stages of this process are driven by self-gravity. However, this still leaves a wide range of possibilities for exactly how galaxies may be built: Structure may emerge first on either small or large scales, and galaxies may correspondingly be formed either by the bottom-up aggregation of smaller units or by a top-down fragmentation process; gas-dynamical or stellar-dynamical processes may be more important, depending in detail on just how and when the initial gas is turned into stars; and galaxy formation may be a rapid process that is completed at early times, or it may be a prolonged process that continues until the present. It is important, in particular, to understand whether galaxies are still being built by processes occurring at the present time, since if they are, we can potentially learn much about how galaxies form by identifying and studying such present-day galaxy-building processes. In this connection, it may be useful to recall the uniformitarian view that the past history of natural systems involves only processes still occurring at the present, which has been enormously influential in sciences such as geology and biology; how-

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ever, it must also be kept in mind that one can be misled by this approach if the present is not, in fact, a very good guide to the past.

How might theories of the formation and early evolution of galaxies be tested? Several types of observational tests can be made, and will be discussed in this review. First, the observed properties of present-day galaxies must be accounted for by any acceptable description of how galaxies form and evolve. Second, as noted above, one can try to identify present-day examples of galaxy-building processes and then compare the observations with theoretical models or simulations. Third, for our Galaxy and neighboring galaxies, the fossil record provided by the oldest stars and star clusters contains important information about the processes of galaxy formation; in particular, the ages of the globular clusters can provide a chronology for the formation and early evolution of our Galaxy. Finally, and uniquely in the case of astronomy, the finite travel time for light from distant objects allows us to look far back in time by observing galaxies at very large distances and redshifts; if the remote parts of the universe have made galaxies similar to the nearby ones, we can then observe directly the early evolution of galaxies just by observing systems with sufficiently large redshifts.

2. Some Relevant Properties of Galaxies

What present properties of galaxies might bear some record of how they were formed? Clearly, the most useful properties in this respect are those that are relatively permanent and unchanging, and this would exclude such probably transient features as spiral patterns and nuclear activity. The most fundamental property of galaxies is the existence of the two basic galaxy types, elliptical and spiral: The ellipticals are relatively round and are supported almost entirely by random motions, while the spirals are flat disks supported only by rotation. This division into two types immediately suggests that there may correspondingly be two kinds of formation process, a violent one that generates large amounts of random motion, and a more orderly one that produces thin rotating disks with little random motion. These two types of formation process are apparently of nearly equal importance in the universe, since disks and spheroids (elliptical galaxies and the central bulges of spirals) contain roughly the same total amount of mass (Schechter and Dressler 1987).

Closely related to the two basic galaxy types is the Hubble classification sequence, which is essentially a sequence of types having a varying admixture of spheroidal and disk components, ranging from pure spheroid to pure disk. Many properties of galaxies vary systematically along this sequence, albeit with considerable scatter; in particular, the fractional gas content and the relative present star-formation rate increase systematically along the Hubble sequence. The higher gas contents of the later, more disk-dominated Hubble types indicate that they convert their gas into stars less rapidly than the earlier, more bulge-dominated galaxies; this difference in the rates of internal evolution can be understood as resulting from the generally lower rotation speeds of the later-type galaxies (Larson 1988*b*). If the spiral structure in galactic disks is a consequence mainly of the self-gravity of the gas, the more open spiral patterns of the later Hubble types can then be understood in terms of the higher gas contents of these systems (Carlberg and Freedman 1985; Toomre 1990). The most important physical parameter underlying the Hubble sequence may simply be the total galactic mass, as suggested by Tully, Mould, and Aaronson (1982); equivalent but more useful parameters are either the maximum rotational velocity or the virial velocity of the galactic mass distribution, both of which correlate well with Hubble type and decrease systematically along the Hubble sequence (Rubin *et al.* 1985; Lake and Carlberg 1988). Thus, whatever determines the mass of a galaxy may largely determine its other characteristics as well. A similar suggestion was previously made by Meisels and Ostriker (1984), who proposed that bulge luminosity is an important controlling parameter of the Hubble sequence.

The radial light profiles of spheroids, while readily measurable, have not so far provided a strong test of theories of galaxy formation, since several types of models can be proposed that yield equally good fits to these observations (Gott 1977). A more useful diagnostic of galaxy formation mechanisms, at least for spheroidal systems, may be provided by the metallicity gradients that are often observed in elliptical galaxies and spiral bulges (Kormendy and Djorgovski 1989). These gradients indicate that chemical enrichment is an integral part of the galaxy-formation process, and a possible explanation is that they are produced by the inflow of enriched gas toward the centers of forming galaxies (Larson 1974*a*). Whatever their origin, the process of spheroid formation must evidently not be violent enough to obliterate metallicity gradients. Abundance gradients are also seen in the disks of spiral galaxies; although these disk gradients may result partly from galaxy-formation processes (Tinsley and Larson 1978), they might also be produced by other effects, including radial gas inflows in galactic disks (Lacey and Fall 1985). Another very general chemical property of galaxies of all types is that the average metallicity of the stars in a galaxy is well correlated with galactic mass and increases systematically with mass (Faber 1973, 1977; Tully *et al.* 1982; Da Costa 1988; Skillman, Kennicutt, and Hodge 1989). Again, this indicates that chemical enrichment is somehow closely linked to galaxy-formation processes; in this case, a possible explanation is that galaxies with smaller escape velocities lose a larger fraction of their enriched gas during early stages of development (Larson 1974*b*). Franx and Illingworth (1990) have suggested that a similar explanation may also apply to metallicity gradients, since the metallicity is generally well correlated with the local escape speed in elliptical galaxies.

Many galaxies contain massive globular clusters which appear to be relics from the time of galaxy formation, and their properties also place constraints on any picture of how galaxies form. Globular clusters are found mainly in spheroidal systems, and all large elliptical galaxies and spiral bulges contain many of them (Harris 1988); in contrast, disks contain relatively few globular clusters, and nearly all of the disk clusters are smaller open clusters. Thus, the processes of star formation that occurred in spheroids must have differed in some systematic way from those that occur in disks. The larger typical size of the clusters in spheroids suggests, in particular, that young spheroids may have contained larger star-forming clumps than are now found in disks. Some massive elliptical galaxies located at the centers of large clusters of galaxies contain exceptionally large numbers of globular clusters, having more per unit luminosity than any other type of galaxy (Harris 1988); these galaxies must evidently have had unusual formation histories, presumably characterized by an extreme amount of clumpiness at early times.

Another important, if not optically conspicuous, structural feature of most sizable elliptical galaxies and spiral bulges may be a massive central black hole; this is suggested by the fact that all of the nearby galaxies with prominent spheroids seem to show evidence for such objects (Dressler and Richstone 1988; Kormendy 1988*a*,*b*). While the inferred black-hole masses (typically $\sim 10^7$ to 10^8 $\mathfrak{M}_\odot$) are small compared with the total galactic mass, these objects can power extremely energetic nuclear activity when gas is accreted by them, especially during early stages of galactic evolution when there is still a plentiful fuel supply. Such activity might even influence the galaxy-formation process itself by ionizing or blowing away gas that has not yet condensed into stars. Thus, an adequate picture of galaxy formation must account for the formation of massive central black holes early in the history of many spheroidal systems.

3. Ways of Building Galaxies

What formation processes might account for the basic properties of galaxies mentioned above? The dominant force acting in galaxies is gravity, and most theories assume that galaxies are formed by some kind of gravitational condensation or aggregation process. The classical, and simplest, view is that galaxies form from large, nearly uniform rotating gas clouds or "protogalaxies" that collapse under their self-gravity. As such a cloud contracts, it spins up and eventually flattens to a disk; any stars that form during the early stages of its collapse might then make up the halo of the resulting galaxy, while the stars that form later make the disk. Such a picture was proposed for our Galaxy by Eggen, Lynden-Bell, and Sandage (1962) on the basis of evidence suggesting a progressive increase in metallicity from halo to disk, and in its most general qualitative aspects this picture is almost certainly correct. These authors also argued that the collapse must have been rapid, lasting no longer than 2×10^8 years; this was the only way they could account for the highly noncircular motions of the halo stars, given their tacit assumption that the initial protogalaxy contained no random motions. However, as Sandage (1990) has recognized, a realistic protogalaxy would be surrounded by a less dense envelope that would continue to fall into it for some time, plausibly extending the total collapse time to 10^9 years or more. It is also possible that such "cosmological infall" of primordial gas might continue to build up the disks of spiral galaxies over an extended period of time, perhaps even continuing up to the present (Oort 1970; Larson 1972, 1976*b*; Gunn 1982).

This simple picture of the collapse of a homogeneous rotating cloud, possibly with continuing infall, may be able to account for the formation of galactic disks, but it cannot directly account for the properties of spheroidal systems like the halo of our Galaxy, which has little rotation but very large random motions. Indeed, almost half of the stars in the Galactic halo have retrograde orbits, a fact not recognized in the picture of Eggen *et al.* (1962). This fact led Larson (1969) to consider models of clumpy and turbulent protogalaxies made up of many smaller clouds with large random motions; in these models, the dissipation of cloud motions by collisions plays an important role in allowing the system to condense. The collapse is then somewhat slower than a free-fall, and may take as long as 10^9 years or longer. Later elaborations of this type of model showed that, with appropriate assumptions, it is possible to obtain structures that reproduce many of the observed properties of elliptical galaxies (Larson 1975; Carlberg 1984*a*,*b*) and galaxies with both bulge and disk components (Larson 1976*a*; Carlberg 1985). The models of Carlberg are more realistic than the earlier models of Larson in that they allow anisotropic stellar velocity distributions, and therefore they are able to represent spheroids that are significantly flattened but have little rotation, like many real elliptical galaxies. All of these dissipative collapse models tend to predict strong radial metallicity gradients.

A radically different way to form elliptical galaxies was suggested by Toomre (1977), who proposed that some, and possibly all, elliptical galaxies are the products of mergers of two or more smaller galaxies, typically pairs of spirals. In this view the dynamical friction acting on two galaxies during a close tidal encounter (see Binney and Tremaine 1987) causes them to sink together and coalesce into a single centrally condensed system. The violence of the encounter disrupts any preexisting disks and largely randomizes the stellar motions, although significant anisotropy of the velocity distribution may remain after the merger. The most realistic simulations of these effects treat galaxies with not only disks but also bulges and dark halos, and they produce systems that closely resemble elliptical galaxies in both structure and kinematics (Barnes 1988, 1990). In these simulations the dark matter plays an important role by absorbing both energy and angular momentum from the visible matter, allowing the visible stars to settle into a condensed and slowly rotating system similar to observed elliptical galaxies.

Toomre (1977, p. 420) also went farther to suggest that there occurred "a great deal of merging of sizeable bits and pieces (including quite a few lesser galaxies) early in the career of every major galaxy, no matter what it now looks like. The process would obviously have yielded halos from the stars already born, whereas any leftover gas would have settled quickly into new disks embedded within such piles of stars". That is, even large spiral galaxies might be built up by the mergers of smaller gas-rich galaxies. If large galaxies form by the merging of many small ones, this could occur in a hierarchical fashion, with smaller galaxies merging into progressively larger ones. Scenarios for galaxy formation by hierarchical mergers were elaborated by White and Rees (1978), Silk (1978), and Tinsley and Larson (1979), and these authors discussed how various properties of galaxies and clusters of galaxies might be accounted for in such a framework. For example, the increase of metallicity with mass can be understood if successive mergers are accompanied by bursts of star formation that convert progressively more of the residual gas into stars (Tinsley and Larson 1979; Struck-Marcell 1981). In these hierarchical merger schemes, the residual gas is assumed to continue to dissipate energy and settle into a more compact configuration after each merger, until collision velocities finally become so large that the gas is heated to very high temperatures and can no longer cool within the Hubble time; this occurs when the galactic mass reaches about 10^{12} solar masses. After this point gaseous dissipation, star formation, and chemical enrichment all cease to occur, and further merging may produce only relatively diffuse systems. The importance of gas cooling had originally been emphasized by Rees and Ostriker (1977) in the context of a collapse picture, and they proposed that this effect leads to characteristic radii and masses for large galaxies that are of the order of 75 kpc and 10^{12} solar masses, respectively.

A specific picture of galaxy building by hierarchical mergers that has received much attention is that implied by the "cold dark matter" theory of structure formation in the universe. In this theory the spectrum of initial density fluctuations has the largest amplitudes on the smallest scales, so that small structures develop first and then merge hierarchically into progressively larger ones. The visible matter should, at least initially, follow closely along with the dominant dark matter and so should tend to build up visible galaxies by successive mergers. Simulations of the growth of structure in a cold dark-matter universe and their implications for galaxy formation by mergers have been discussed by Frenk *et al.* (1985, 1988), Carlberg and Couchman (1989), and White (1989, 1990). An important prediction of this theory is that much of the galaxy-building activity occurs at fairly late times, i.e., at redshifts of order 2 or less; this prediction is subject to direct test by observations at high redshifts (see Section 8).

4. Spheroid Formation: The Direct Evidence

As we have seen, there is a wide range of possible ways in which spheroidal systems might form, ranging from the collapse of clumpy protogalaxies to the merging of fully formed spiral galaxies. What direct evidence exists regarding these mechanisms? Because mergers can occur at the present time, and because observations of possibly merging systems can be compared in detail with numerical simulations, there has been much interest in testing observationally the merger hypothesis. As a result, it is now well established that mergers occur and play a role in building up at least some elliptical galaxies, although there is also some evidence constraining merger pictures of spheroid formation.

The possibility of forming elliptical galaxies by merging spirals was first suggested by Toomre and Toomre (1972), who showed that many peculiar galaxies can be modeled as tidally interacting disks, and argued that such interactions should often lead to mergers. Such interactions and mergers have recently been simulated in detail with realistic models, not only for pairs of spirals (Barnes 1988) but also for interacting groups of galaxies (Barnes 1989), and there is no doubt that some of the observed systems that have been modeled in this way are in the process of merging. Detailed observational studies of apparently merging or recently merged systems (Schweizer 1982, 1983, 1986, 1990) have added strong support to the merger hypothesis and have shown that the putative merged systems have structural properties similar to those of elliptical galaxies, in agreement with the simulations. Thus, there can be little question that when all of the violence of a merger of two similar spiral galaxies has subsided, the result will be an elliptical galaxy, or at least a strongly bulge-dominated early-type galaxy.

A more common event is likely to be the capture of a small galaxy by a larger one, leading to some growth in mass of the larger galaxy. Much recent observational and theoretical work has demonstrated that captures of small galaxies occur fairly often and that they contribute to the building up of many elliptical galaxies. Numerical simulations show that the stars in a captured small galaxy are dispersed into a spray with a sharp outer edge that appears as a shell-like feature in the halo of the larger galaxy, where the stellar orbits reach their maximum distance from the center and turn around; subsequent orbit crossings may create many such concentric shells (Quinn 1984; Dupraz and Combes 1986; Hernquist and Quinn 1988, 1989). Such faint shell-like features have been observed in almost half of all elliptical galaxies (Malin and Carter 1980, 1983; Schweizer and Ford 1985), and even in some early-type spirals (Schweizer and Seitzer 1988). Since the shells remain visible for only a fraction of the age of the galaxy, it is clear that whether or not elliptical galaxies are initially formed by mergers, most of them must subsequently grow by capturing smaller galaxies. Captures of gas-rich smaller galaxies appear also to be responsible for causing radio jet activity in elliptical galaxies by feeding gas to the central black hole, and indeed the best studied radio galaxies, such as Fornax A (NGC 1316) and Centaurus A (NGC 5128), all show evidence for recent mergers in the form of tails, loops, shells, and dust features (Schweizer 1980; Malin, Quinn, and Graham 1983; Heckman *et al.* 1986).

Could all elliptical galaxies have been formed by mergers? Toomre (1977) estimated from the observed numbers and expected lifetimes of apparently merging systems that a fraction of the order of 10% of bright galaxies have undergone a major merging event, and noted that this is not very different from the fraction of such galaxies that are ellipticals. Toomre therefore suggested that all, or a large fraction, of the (giant) elliptical galaxies could be merger products. However, it does not seem likely that the majority of ellipticals were formed by the merging of spiral galaxies like those typically seen today. Several difficulties have been raised with this hypothesis, the most serious of which (van den Bergh 1990) is that ellipticals contain about ten times as many globular clusters per unit luminosity as spirals. These clusters cannot plausibly have been formed as a result of galactic mergers, since they are more metal poor than the bulk of the stars, whereas the residual gas should be more metal rich. However, there are a few giant elliptical galaxies that do contain anomalously small numbers of globular clusters and so could indeed have been formed by the merging of spirals; an example is NGC 3557, which also has other characteristics such as rapid rotation suggesting that it may be a merger product (Morbey and McClure 1985).

A special but particularly interesting possibility is that the brightest members of large clusters of galaxies, or their extended envelopes, may have been built up by the merging or cannibalism of smaller galaxies (Ostriker 1977; Tremaine 1990). Much effort has gone into testing this hypothesis, both by modeling the dynamical friction effects involved (Binney and Tremaine 1987) and by searching for direct observational evidence (Lauer 1990), and the current consensus is that cannibalism can account for part but not all of the luminosity of these systems. However, the possibility is not excluded that the brightest galaxies in large clusters were formed by the merging of subgroups early in the evolution of the cluster. Also, if two clusters should merge, their brightest galaxies would almost certainly merge too, and this might account for the "dumbbell" galaxies seen at the centers of some clusters (Tremaine 1990). The relatively shallow surface brightness profiles of the brightest cluster galaxies (Schombert 1987) are consistent with a merger origin, since simulations of hierarchical mergers show that they tend to generate progressively shallower density profiles (Farouki, Shapiro, and Duncan 1983).

Thus, there is evidence that mergers occur and play a role in the formation of at least some large elliptical galaxies and bulges, but there is also evidence suggesting that mergers of spiral galaxies like those typically seen today are not the dominant process responsible for the formation of most spheroids. None of this evidence excludes the more conventional view that most elliptical galaxies and spiral bulges were formed at early times by the dissipative collapse of clumpy protogalaxies. Indeed, some properties of spheroidal systems, such as their metallicity gradients and their highly condensed and metal-rich cores, suggest that the settling of enriched gas toward their centers has played an important role in the formation process. In reality, as Kormendy (1989, 1990) has emphasized, galaxy formation almost certainly involves elements of both the merger and the dissipative collapse scenarios, and the relative importance of these two types of process depends on the size of the galaxy. Small elliptical galaxies and spiral bulges are so compact that they cannot have been formed by the mergers of any plausible progenitor objects; moreover, they are rotationally flattened (Davies *et al.* 1983; Davies 1987), much as predicted by the dissipative collapse models. By contrast, the most luminous elliptical galaxies have structures and dynamical properties that are more in accord with the results of merger simulations. The fact that metallicity gradients are usually present in large ellipticals but are weaker than predicted by the dissipative collapse models (Thomsen and Baum 1989) could be accounted for if gas flows tend to establish gradients, perhaps in smaller progenitor systems, but these gradients are weakened by the violent mixing associated with mergers or with interactions between large subclumps in protogalaxies (see Section 7).

Violent gravitational interactions among subsystems also provide the most economical way to explain the typical radial structure of elliptical galaxies, since similar radial structures are obtained quite generally in numerical simulations, not only of mergers of spirals but also of mergers of elliptical galaxies (White 1978; Villumsen 1982, 1983) and even of the collapse of inhomogeneous or asymmetric systems of stars (van Albada 1982; Villumsen 1984). This tendency of different detailed dynamical histories to lead to similar structures is reminiscent of the "violent relaxation" concept proposed by Lynden-Bell (1967), but it seems likely that the basic effect involved is simply the tendency for the stars to be scattered roughly uniformly over a wide logarithmic interval in radius, rather than any true relaxation toward a most probable state.

5. Observations of Disk Formation

Disk formation must be a more orderly and less violent process than spheroid formation, since the raw materials can only be diffuse gas and this gas must settle into a thin layer with small random motions, a process that requires the continuing action of dissipation. Collapse models and also the fossil record provided by the ages and metallicities of old stars both indicate that the disk of a spiral galaxy like our own forms after the halo. Again, however, this leaves a range of possibilities for just how and when disks may form: A disk may form rapidly by the near free-fall collapse of a rotating protogalactic cloud, as envisoned by Eggen *et al.* (1962) and studied further by Fall and Efstathiou (1980), or there may be a more prolonged period of dissipative settling of gas which builds up the disk from the inside out, as in the models of Larson (1976*a*); disks may even continue to be built up gradually over the lifteime of a galaxy by the steady infall of primordial gas (Gunn 1982). Disks may also be formed or built-up by the occasional accretion of gas from another galaxy, possibly as the result of a merger or capture event.

There is good evidence that disks have recently formed, or are still forming, in some peculiar elliptical galaxies from gas originally belonging to recently captured smaller gas-rich systems. The best studied example is the nearby giant radio galaxy Cen A (NGC 5128), which shows evidence, including shell structure, for a recent merger or capture event (Malin *et al.* 1983). Its most conspicuous feature is a broad, chaotic, strongly warped disk or ring of dusty gas that appears as a dark band across the luminous stellar spheroid. Dynamical models constructed by Tubbs (1980) and Simonson (1982) show that this dark band can be understood as a newly acquired disk undergoing differential precession as it settles into a symmetry plane of the spheroid. Detailed observational studies of this disk by Graham (1979) and by Bland, Taylor, and Atherton (1987) show that it is vigorously forming stars and is rotating much like the disk of a typical bright spiral galaxy, although it is dynamically unrelated to the stellar spheroid which has almost no rotation. Similar dusty disks are seen in some other radio galaxies as well (Kotanyi and Ekers 1979), and both the radio activity and the dust bands are probably the results of mergers with smaller gas-rich galaxies (e.g., Heckman *et al.* 1986).

Some more normal elliptical galaxies that are not radio galaxies also show evidence for recently acquired gas that has settled into a disk or ring that is often dynamically unrelated to the stellar spheroid (Bertola 1987; Schweizer 1987; Knapp 1987). Moreover, examples have also been found of rapidly rotating nuclear disks in elliptical galaxies, which are sometimes counter-rotating with respect to the outer part of the galaxy (Franx and Illingworth 1988; Jedrzejewski and Schechter 1988; Bender 1988); such disks could only have been formed by late infall or capture events unrelated to the bulk of the galaxy-formation process. Some early-type spiral and S0 galaxies, of which the best-known example is NGC 2685, have "polar rings" of gas and young stars that have apparently been formed by the accretion of gas from, or the complete capture of, gas-rich companion galaxies with nearly polar orbits (Schweizer, Whitmore, and Rubin 1983; van Gorkom, Schechter, and Kristian 1987). All of these examples of recent disk formation are somewhat special cases in which, due to favorable dynamical or observational circumstances, the evidence for a recent infall or capture event is still clearly apparent; thus, such events cannot be particularly rare.

Presumably, spiral galaxies also experience accretion events that occasionally add fresh gas to their disks; possibly this is less apparent because such galaxies already contain large amounts of gas and dust, so that newly acquired gas and dust would be a less conspicuous addition to them. One might, nevertheless, expect observable disturbances to be produced in the disks of galaxies that accrete new material; in fact, warps and asymmetries are quite common in the outer disks of spiral galaxies, and they might sometimes be the result of accretion events (Larson 1976*c;* Binney 1990). A major disturbance may in the future be produced in the outer disk of our Galaxy by the infall of the Magellanic Clouds and the Magellanic Stream, which are apparently in the process of being disrupted and captured by our Galaxy.

Is there any significant continuing infall of primordial gas into galactic disks? While it has become customary to assume such infall in models of galactic chemical evolution (Tinsley 1980; Matteucci 1990), direct evidence for it remains elusive. Studies of high-velocity clouds around our Galaxy provide some evidence for a net inflow of gas (van Woerden, Schwarz, and Hulsbosch 1985; Mirabel 1989), although the rate is small (between 0.2 and 0.5 solar mass per year, according to Mirabel), and at least some of this gas is already enriched in heavy elements, indicating that it is not primordial; much of it could in fact be debris from the Magellanic Stream. A few other large spiral galaxies, notably M 101, also show evidence for high-velocity gas and for disk disturbances possibly caused by infalling clouds (van der Hulst and Sancisi 1988; Sancisi *et al.* 1990). There is also evidence for infall of gas into the nuclei of some radio galaxies (van Gorkom *et al.* 1989; van Gordom 1990). Nevertheless, galaxies showing signs of gas infall are relatively rare, and intergalactic gas clouds that might fuel such infall are also rare (Lo and Sargent 1979; Haynes and Roberts 1979; Schneider *et al.* 1989*b*). Thus, it would appear that the supply of primordial gas available for making disks has largely been used up by now, or possibly made unavailable by heating to very high temperatures. With current data, models for the evolution of galactic disks do not require large amounts of gas infall at recent times (Larson 1990*c*), although it remains likely that infall played an important role in the earlier evolution of galactic disks.

In summary, it appears that disk formation, like spheroid formation, is a process that has largely been completed by the present time, although disks may still occasionally form or be built up by the acquisition of new gas. The accretion of gas by disks does not produce such distinctive signatures as the loops and shells that are the telltale signs of mergers of stellar systems, but some of the warps seen in the outer parts of spiral disks could be caused by the recent addition of new gas. Also, as noted by Binney (1990), the thickening of the older parts of galactic disks could be a result of the cumulative effect of past warps, that is, of a somewhat chaotic history of disk building.

6. Formation of Dense Cores and Nuclei

Large elliptical galaxies and spiral bulges typically have small and very dense cores, and these cores sometimes contain even smaller distinct nuclei (Kormendy and Djorgovski 1989). Although the cores contain only a small fraction of the galactic mass, they are prominent structural features and often harbor massive central black holes, whose existence must also be accounted for. The formation of very dense cores evidently requires gaseous dissipation, but with realistic initial amounts of angular momentum, it also requires a mechanism to remove angular momentum from the gas condensing at the center. In the protogalactic collaspe models of Larson (1975, 1976*a*), dense cores were readily obtained if the fluid of randomly moving clouds was assumed to have a significant viscosity. Another likely possibility is that if trailing spiral density fluctuations are present, gravitational torques will act to transport angular momentum outward (Lynden-Bell and Kalnajs 1972; Larson 1984). In some circumstances spiral waves in nuclear disks may play a role in transporting angular momentum outward and in driving gas inflows (Norman 1987).

Tidal interactions and mergers are particularly effective in redistributing angular momentum in galaxies and in driving gas toward their centers. Numerical simulations of interacting galaxies containing gas show that interactions can enhance the gas viscosity and, more importantly, they can generate strong gravitational torques that remove angular momentum from the gas and cause some of it to become highly condensed at the center (Noguchi 1988; Combes 1988; Hernquist 1989). In agreement with this prediction, observations of interacting galaxies show that they often have very massive and dense concentrations of molecular gas near their centers (Scoville *et al.* 1989). Interactions and mergers frequently trigger strong bursts of star formation in galaxies (Larson and Tinsley 1978), and this enhanced star-formation activity is, like the gas, usually concentrated at the center (Joseph and Wright 1985; Keel *et al.* 1985; Bushouse 1986). In some of the best studied cases, the molecular gas and the starburst activity are both confined to a nuclear region less than a kiloparsec in diameter; this is true, for example, in M 82 (Lo *et al.* 1987; Sofue 1988), Arp 220 (Scoville *et al.* 1986), and NGC 520 (Sanders *et al.* 1988*a*). Clearly, a major episode of nuclear star formation is taking place in these galaxies, and we are observing the development of dense cores in them.

Similar but less extreme phenomena appear to occur commonly in the central regions of barred spiral galaxies, where dense gas and vigorous star formation are often observed (Hawarden *et al.* 1986; Puxley, Hawarden, and Mountain 1988). In this case, gravitational interaction between the gas in the disk and the stellar bar rapidly removes angular momentum from the gas, causing it to spiral inward and accumulate near the center. The effectiveness of tidal interactions in triggering nuclear starbursts may also be due partly to tidally induced barlike deformations in the inner disks of interacting galaxies (Combes 1988; Noguchi 1988, 1990).

As Schweizer (1990) has noted, the fact that mergers are often observed to be accompanied by nuclear starbursts may remove some of the earlier objections to the merger formation of elliptical galaxies that had been based on the difficulty of accounting for dense cores on the basis of mergers. Although it does not seem likely that mergers of typical present-day spirals made most elliptical galaxies, it is nevertheless plausible that mergers of some sort, perhaps involving relatively compact subsystems at early times (see Sections 7 and 8), were important in the formation of spheroidal systems, and that processes like those discussed above played a role in the formation of their cores.

There is also increasing evidence for a connection between central starbursts and quasar activity in galaxies. Like starbursts, quasar activity often appears to be triggered by tidal interactions or mergers (Yee 1987; Hutchings and Neff 1988; Stockton 1990). In some of the most extreme "starburst" systems, a considerable fraction of the total luminosity may even come from a central quasar, and it has been suggested that such systems provide evidence for the evolution of some starburst nuclei into quasars (Sanders *et al.* 1988*b*,*c*). Such an evolutionary connection might exist if massive black holes are already present in galaxies whose central regions are supplied with gas by interactions; some of the same gas that fuels a starburst could then also be accreted by the black hole, producing quasar activity and increasing the mass of the black hole. Initially the quasar may be heavily obscured by dust, but as the starburst subsides and the gas and dust are cleared away, the central quasar will increasingly dominate the observed properties of the system; at later times it may continue to be fed by gas lost from young stars formed in the starburst (Norman and Scoville 1988).

How might a central black hole have been formed in the first place? Black-hole formation must occur at an early time in most cases, since many quasars have redshifts greater than 2, and some have redshifts above 4. Central black holes can be formed by a variety of processes, including gas condensation and runaway coalescence of stars or stellar remnants, but the actual mechanisms are not presently known (Rees 1984). However, similar processes may also occur in dense forming star clusters that are more accessible to study, and they may contribute to the formation of very massive stars and possibly even black holes near the centers of such clusters. Some young clusters have exceedingly dense cores dominated by central subgroups containing some of the most massive stars present; the best known examples are the Trapezium cluster in Orion and the 30 Doradus cluster in the Large Magellanic Cloud. Gravitational drag effects analogous to dynamical friction but involving both stars and gas can cause forming clusters of stars to develop dense cores and will also cause the most massive stars to become strongly concentrated in these cores, where they may continue to grow rapidly in mass by accretion (Larson 1989, 1990*b*). If a particularly massive star should collapse to a black hole, it might continue to gain mass by accreting surrounding matter, both gas and stars. Some evidence that a black hole did indeed form at the center of the well-studied globular cluster M 15 is provided by the fact that the velocity dispersion in this cluster increases strongly toward the center, indicating a large central dark mass (Peterson, Seitzer, and Cudworth 1989).

7. The Fossil Record

One way to gain more information about how galaxies like ours may have formed is to make use of the fossil record provided by the oldest stars and star clusters, which date from very early times when galaxies were still taking shape. The most useful fossils are the globular clusters, which are the oldest and most massive star clusters in galaxies like our own. There appear to be two distinct populations of globular clusters in our Galaxy: the majority belong to a nearly spherical, relatively metal-poor halo that has little rotation, while the most metal-rich ones form a flattened and rapidly rotating disklike system with properties similar to those of the oldest disk stars (Zinn 1985; Armandroff and Zinn 1988; Armandroff 1989). Thus, the globular clusters may trace not only the formation of the galactic halo but also the early history of the galactic disk.

The ages of the globular clusters can be measured and used, within the limits of their precision, to establish a chronology for the early evolution of our Galaxy. Relative ages can be determined more reliably than absolute ages, and they are typically quoted with uncertainties of about 2 Gyr, which is good enough to provide important constraints on the time scales for halo and disk formation. A question of major interest, which has also been a subject of some controversy (Freeman 1989), is whether there is a measurable age spread among the galactic globular clusters; if there is not, this would support the possibility that our Galaxy formed by a rapid collapse, whereas if a real age spread of several Gyr or more could be demonstrated, this would be evidence for a more prolonged and more chaotic process of galaxy formation, possibly involving mergers of smaller systems. In the latter case it would clearly be of great interest to try to learn something about the nature of the merging systems.

Despite the controversies that have existed, the recent results of several groups for the ages of some of the best-studied globular clusters are actually in reasonable agreement (see Larson 1990*a* for a summary), and it seems likely that measurable age differences of several Gyr do exist in at least a few cases. The best established cases are Pal 12, which has been found to be about 4 Gyr younger than the typical cluster age of ~ 15 Gyr (e.g., Stetson *et al.* 1989), and the pair of clusters NGC 288 and NGC 362, which have similar metallicities but have been found by several groups to differ in age by ~ 3 to 5 Gyr (Demarque *et al.* 1989; Bolte 1989; Green and Norris 1990). Evidence for an age spread of perhaps 5 Gyr among the galactic globular clusters has also been found in a study of 31 clusters by Sarajedini and King (1989), who in addition found evidence for a correlation between age and metallicity, the younger clusters being more metal rich.

These results are consistent with the suggestion of Rood and Iben (1968) and Searle and Zinn (1978) that age is the second parameter (after metallicity) governing the structure of the horizontal branch in globular clusters, and that the observed variations in horizontal-branch structure are best explained if the galactic globular clusters have an age spread of the order of a few Gyr (see also Lee, Demarque, and Zinn 1988, 1990). Searle (1977) and Searle and Zinn (1978) suggested that such an age spread could be understood, along with the large dispersion in metallicity among the globular clusters, if these clusters were formed in a number of "protogalactic fragments" that evolved independently for a time before being merged to make the galactic halo. In support of such a picture, Larson (1987, 1988*a*) argued that the remarkable internal homogeneity of the iron abundance in globular clusters can be readily understood only if these clusters were formed in much larger protogalactic subsystems. If the efficiency of formation of globular clusters was as small as the observed efficiency of formation of open clusters (Larson 1990*b*), these subsystems must have had masses exceeding $10^8\ \mathfrak{M}_\odot$, that is, masses comparable to those of small galaxies; some of them may even have resembled present gas-rich compact galaxies like I Zw 18. In like vein, Freeman (1990) has suggested that the clusters in the outer halo originated in accreted satellite galaxies possibly similar to present nucleated dwarf ellipticals. While these suggestions all involve some version of a merger scenario for the formation of the galactic halo, the merging units involved might for the most part have been smaller than the "sizeable" ones earlier envisioned by Toomre (1977).

An important characteristic of the second-parameter effect is that it correlates with location in the Galaxy (Zinn 1986); the clusters in the inner halo, i.e., within about 8 kpc of the galactic center, show little or no variation in the second parameter, while the clusters in the outer halo show a much larger second-parameter dispersion that may increase systematically with distance from the galactic center. If the second parameter is age, this result implies that the clusters in the inner halo are all very old and have only a small age spread, while the clusters in the outer halo have an age spread that extends increasingly toward younger ages with increasing galactocentric distance. It is consistent with such a trend that the clusters mentioned above as showing age differences are all located in the outer halo. If the age interpretation of the second parameter is confirmed by additional age measurements for distant clusters, the inference will be that cluster formation began at about the same time throughout the galactic halo but then ceased relatively early in the inner halo, while continuing for progressively longer times at greater distances from the galactic center. This could be understood if the subsystems in which the globular clusters formed survived for only a short time in the inner halo before being destroyed, perhaps by collisions with each other, while subsystems at greater distances from the center survived for longer times, as might be expected because of the longer orbital periods and lower collision rates at larger galactocentric distances.

It is possible, then, that the halo of our Galaxy was built up from the inside out by the addition at progressively larger radii of stars and clusters from disrupted subsystems that had for a time evolved like separate small galaxies. If these subsystems were still very gas rich at the time of their disruption, the remaining gas would presumably have fallen into the central bulge or into the galactic disk, perhaps building up the disk along with the halo from the inside out, a process that might be visualized as a gradual emergence of order from chaos. The capture and disruption of the Magellanic Clouds may continue this process of building up the halo and the disk of our Galaxy, the stars and clusters from the Clouds being added to the halo, and their gas to the disk. Such an inside-out process of galaxy formation would be diametrically opposite in its sequence of events to the outside-in process of spheroid formation implied by the dissipative collapse models of Larson (1975, 1976*a*), in which the innermost part of the spheroid forms last as the culmination of a progressive condensation process. This difference reflects the fact that, in all likelihood, substructure plays a much more important role in reality than in the collapse models. More information about the chronology of early galactic evolution will obviously be crucial for clarifying whether an outside-in or an inside-out picture of galaxy formation, or some combination of both, is closest to reality.

An important aspect of this problem will be to understand the origin of the central bulge of our Galaxy and its relation to the halo. No ages are yet known for any bulge clusters, but what is known about the field stars in the bulge suggests that they are mostly very old and very metal rich (Frogel 1988). The high metallicity of the central bulge almost certainly excludes the possibility that it is merely the debris of disrupted globular clusters or captured smaller galaxies, since such systems would be too metal poor; the only place where comparably high metallicities are seen is in the inner regions of large galaxies. Therefore, the bulge stars probably formed *in situ* from highly enriched gas that settled into the central regions of our Galaxy at an early time. Possibly the bulge formed even before most of the halo was in place and then served as a nucleus around which the rest of the Galaxy was built up from the inside out, as sketched above.

8. Look-Back Observations

A unique advantage enjoyed by astronomers is the possibility of observing directly, if only with difficulty, the early evolution of galaxies by looking at large redshifts where objects are seen as they were at much earlier times. Normal bright galaxies can presently be observed out to redshifts of the order of $z \sim 1$ that correspond to times when the universe was between one-third and one-half of its present age, while certain exceptionally luminous objects, primarily radio galaxies and quasars, can be observed out to redshifts of 3 or more that probe the first few Gyr of the history of the universe. Thus, it is possible to observe at least the most luminous galaxies at much earlier stages in their evolution when galaxy-building processes were almost certainly going on at a much higher rate than at the present. If the globular clusters in our Galaxy have an age spread of several Gyr, then such high-redshift observations can probe the epoch when at least the youngest globular clusters in galaxies like our own were still forming.

Observable changes have taken place in the properties of some galaxies during just the past $\sim$ 6 Gyr, i.e., at redshifts of $\sim$ 0.5 or less. The first evidence for this was the discovery by Butcher and Oemler (1978, 1984) that the fraction of blue, actively star-forming galaxies in condensed clusters increases systematically with redshift over this range; at low redshifts these clusters contain almost entirely elliptical and S0 galaxies with little or no active star formation. A similar trend appears to exist among field galaxies, whose colors typically become bluer toward fainter magnitudes and greater distances (Koo 1986*b;* J. A. Tyson 1988). At present, no explanation for the Butcher-Oemler effect has been firmly established, but it appears likely that several mechanisms are involved (Oemler 1987); these include the rapid evolution of spirals into S0 galaxies in clusters (Larson, Tinsley, and Caldwell 1980), starbursts triggered by galaxy interactions in forming clusters (Lavery and Henry 1988), and enhanced star formation in spirals triggered by dynamical interaction with a hot intracluster medium (Gunn 1989). Some of these processes may contribute to galaxy building, so the Butcher-Oemler effect may provide evidence for an enhanced rate of galaxy forming processes even in the relatively recent past.

More extreme color and spectral anomalies have been discovered in some giant radio galaxies observed at redshifts greater than $z \sim 1.5$, which have exceptionally high ultraviolet luminosities and strong emission-line spectra dominated by the Lyman-α line (Spinrad 1986, 1988; Djorgovski 1987, 1988). The optical structures of these objects are barely resolved, but typically they appear to be clumpy and elongated on scales of the order of 100 kpc. These properties do not correspond to those of any known type of object at low redshifts, but they suggest that spectacular and spatially extended starburst activity could be taking place in these galaxies. A few additional Lα galaxies have been found that are companions of high-redshift radio galaxies or quasars, and it has been suggested that at least some of the Lα galaxies are primeval galaxies in which the first major episodes of star formation are taking place (Djorgovski 1987, 1988). The clumpy appearance of these objects is in fact consistent with models of galaxy formation by hierarchical mergers accompanied by bursts of star formation, as suggested by Tinsley and Larson (1979) and studied in detail by Baron and White (1987). However, it is by no means certain that these objects are really primeval galaxies; as cautioned by Djorgovski (1988), they could also turn out to be fool's gold. In fact, infrared observations have shown that at least one of them contains a luminous already old population of stars (Lilly and McLean 1989), indicating that it is not a newly formed system. Probably both an old population and a young population with a less regular spatial distribution are present in these objects.

A remarkable property of radio galaxies with redshifts greater than $z \sim 1$ is that the optical structure tends to be aligned with the radio jets (McCarthy and van Breugel 1989; Chambers and Miley 1990). Again, this is a characteristic not seen at low redshifts. The only plausible explanation of such an effect is that the elongated optical appearance is in some way caused by the radio jets, probably via interactions with ambient gas; the most popular hypothesis has been that the jets trigger star formation in the ambient gas. Other possible contributing sources of the extended optical emission include shock excitation by the jets, photoionization by ultraviolet radiation from the active nucleus escaping along the jets, and scattering of light from a central source by dust along the jets (see also Miley 1990; McCarthy 1990). If the optical morphology is a result of the jet activity, then the interpretation of the observations in terms of mergers and starbursts that are part of the galaxy formation process is weakened, although not excluded. The radio jet phenomena may instead be analogous to the bipolar outflows produced by newly formed stars: These outflows generate strings of bright knots known as Herbig-Haro objects, whose light is partly due to shock excitation and partly represents reflected light from the central star. As with the Herbig-Haro objects, the ultraviolet light from the distant radio galaxies is polarized, indicating that at least some of it is scattered radiation from a central source (di Serego Alighieri *et al.* 1989; Scarrott, Rolph, and Tadhunter 1990), i.e., that the optical extensions are partly galactic-scale reflection nebulae.

One conclusion that does seem to be clear is that the high-redshift radio galaxies are surrounded by much more gas than is seen around similar galaxies at low redshifts. Additional evidence for the presence of dense gas around some high-redshift radio quasars is provided by the fact that the radio jets of quasars with $z > 1.5$ are often bent, apparently by interaction with large and dense gas clouds (Barthel and Miley 1988; Miley 1990). This suggests that there is an abundance of raw materials available for galaxy formation, or at least for disk formation, at redshifts greater than 1.5. The quasar activity itself is probably caused by the infall of some of this gas, or of gas-rich small galaxies, into larger galaxies that already possess spheroids with central black holes.

Evidence for considerable amounts of intergalactic gas at high redshifts is provided by studies of quasar absorption lines, which indicate a strong increase with redshift in the space density of intergalactic clouds (Sargent 1988). The absorbers with the highest column densities, characterized by very broad or "damped" Lα absorption lines, may constitute a separate population of objects that have column densities comparable to those of spiral disks (Wolfe *et al.* 1986; Wolfe 1988; Turnshek *et al.* 1989). The total mass of gas contained in these "damped Lα" systems is actually greater than the total amount of gas presently in galactic disks, and is comparable to the total mass of stars in disks. Therefore, these systems may contain most of the gas from which galactic disks are eventually built. They could be very young disks with large radii, as suggested by Wolfe and collaborators, or perhaps more plausibly, they could represent a more numerous population of gas-rich dwarf galaxies (N. D. Tyson 1988; Hunstead and Pettini 1989) from which larger galaxies may later be made by mergers. The damped Lα systems have low metal abundances (Pettini, Boksenberg, and Hunstead 1990) and at most moderate rates of star formation (Smith *et al.* 1989), as might be expected either for small gas-rich galaxies or for large disks at early stages of their evolution. Some quasar absorption-line systems showing evidence for a wide range of ionized species have properties similar to those observed in regions of active star formation, and they may represent Magellanic-type dwarfs or large star-forming regions in young galaxies (York *et al.* 1986; York 1988).

It would appear, therefore, that observations at redshifts between ~ 1.5 and ~ 3.5 are probing an era when luminous spheroids with active nuclei had already formed, but much uncondensed gas remained and galactic disks were still at a very early stage of development. This was also approximately the same period, about 3 to 6 Gyr after the big bang, when most of the globular clusters in our Galaxy had already formed but the youngest outer halo clusters like Pal 12 and NGC 362 were still forming. The local disk of our Galaxy apparently formed soon afterward, approximately 10 Gyr ago (Larson 1990*c*), which would correspond to a redshift between about 1.0 and 1.5. The evidence reviewed above suggests that disk formation was not a very rapid or spectacular process, and that early star-formation rates in disks were not very much higher than present rates; this inference is consistent with current views about the evolution of galactic disks, according to which the star-formation rates in disk-dominated galaxies have not varied strongly with time (Kennicutt 1986; Larson 1990*c*).

When did most of the star formation in galactic spheroids take place? The activity observed in the Lα galaxies at redshifts between 1.5 and 3.5 could in part represent the final stages of spheroid formation; however, even the highest-redshift radio galaxies have visual and near-infrared colors that indicate the presence of a dominant older stellar population that is already at least ~ 1 Gyr old, according to Lilly (1989), or at least ~ 0.3 Gyr old, according to Chambers and Charlot (1990). If these galaxies are already at least 1 Gyr old at the time of observation, then the bulk of their star formation must have occurred at redshifts greater than 5 and so has not yet been directly observed. Observations of high-redshift quasars also set a lower limit on the redshifts by which at least some spheroids with central black holes must have formed. The space density of quasars peaks at a redshift of about 2 to 2.5 (Schmidt 1989), possibly because of a peak in the merger rate at that time (Carlberg 1990); therefore, many galaxies with massive central black holes must already have been in existence by then. Some quasars have redshifts greater than 4, and the largest redshift now known is 4.73 (Schneider, Schmidt, and Gunn 1989*a*); thus, in at least a few cases, the conditions necessary to produce quasars had already been created within the first 1 or 2 Gyr after the big bang. If much of the star formation in spheroids occurred at such early times, i.e., at redshifts greater than 5, this would help to account for the mostly negative results to date of searches for primeval galaxies (Koo 1986*a;* Cowie 1988). Even if the Lα galaxies should turn out to be true primeval galaxies, they may be too rare to represent more than a small population of late stragglers.

A very recent result of observations of the most remote quasars is the discovery of strong quasi-continuous absorption at wavelengths below that of the Lα emission line, indicating that the amount of intergalactic atomic hydrogen increases markedly with redshift at around a redshift of 4 (Schneider *et al.* 1989*a*). It will obviously be of great interest to understand what happens to this atomic gas at lower redshifts: Most of it must either condense into galaxies or else become ionized, perhaps by hot stars in forming galaxies. In either case, it would appear that major galaxy-building activity was taking place at these highest presently known redshifts.

Clearly, only a few tantalizing glimpses of the early stages of galactic development have yet been obtained from look-back observations, but these glimpses strongly suggest that at least the later stages of galaxy formation can indeed be directly observed at currently accessible redshifts.

9. Summary

Many processes have contributed to building the galaxies we see, including the collapse of pregalactic gas clouds, continuing gas infall, dissipative settling of gas into disks and bulges, violent interactions between clumps in protogalaxies, and a variety of possible types of merger or capture events that can build larger galaxies from smaller ones. Disks can only form through the continuing action of gaseous dissipation, and the disks of spiral galaxies are probably built up over a prolonged period of time from the gas that is seen in abundance around galaxies at high redshifts. Disks can also be built from gas acquired via mergers or captures, and evidence for recent disk formation is seen in some systems like the radio galaxy Cen A, which shows evidence for a recent capture event. The stars acquired in such events also contribute to building up galactic spheroids, and considerable evidence supports the possibility that many elliptical galaxies have been formed by mergers of some kind, possibly involving smaller disk systems.

However, elliptical galaxies differ from spiral disks in that they contain many more globular clusters, most of which presumably date from the first several Gyr of the history of the universe. Observations of radio galaxies and quasars at high redshifts also suggest that most of the star formation in spheroids occurred within the first few Gyr after the big bang. The presence of some younger globular clusters in the halo of our Galaxy suggests that residual star formation in spheroids continued for perhaps 5 Gyr or more. The globular clusters were probably formed in protogalactic subsystems that evolved independently for a time, and that possibly resembled compact galaxies. Dynamical interactions and mergers of such subsystems at early times probably played an important role in building galactic spheroids, and gravitational drag effects involving both gas and stars could have contributed to the formation of dense cores containing massive central black holes.

While our understanding of how galaxies form remains rudimentary, the study of galaxy-building processes has matured rapidly in recent years, owing to the growing body of relevant observational information and to parallel progress in the theoretical modeling of these observations. Instead of being limited to debates about speculative grand scenarios, the study of galaxy building is becoming a true empirical science founded upon a solid basis of observational facts. In the era of the Hubble Space Telescope, we can look forward to a vast increase in our still meager collection of pertinent facts.

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