GALAXY FORMATION AND EVOLUTION

Richard B. Larson

Yale Astronomy Department
Box 6666
New Haven, CT 06511, U.S.A.

1 INTRODUCTION

Most of the visible matter in the universe is concentrated in galaxies, which are the basic astronomical ecosystems in which stars are born, evolve, and die. The gross structural properties of galaxies and their distribution in space are determined primarily by the processes of galaxy formation, while other properties such as the stellar and gas content of galaxies and their evolution with time depend mainly on the processes of star formation and stellar evolution. However, it can be difficult to separate the processes of galaxy formation from those of galactic evolution, and both must be considered in any effort to understand the origin of the observed properties of galaxies and the correlations among them that are embodied in the Hubble classification sequence. In this contribution, I shall review some of the current ideas about the formation and evolution of galaxies, and also discuss the extent to which they can account for the various observed properties of galaxies.

A major development in this subject during the past two decades has been the realization that if conventional physics is correct, galaxies and the universe contain much more mass than can be accounted for by their visible stars and gas. In fact, the universe is now believed to be dominated by dark matter of an unknown nature everywhere except in the inner parts of bright galaxies, and the visible galaxies are thought to be just concentrations of ordinary matter located at the centers of much more massive and extended dark halos (Tremaine 1992). We are interested here in the formation and evolution of these visible systems of stars and gas, but clearly their properties are controlled at least in part by the distribution and dynamics of the dark matter in the universe. Accordingly, following a summary of some of the systematic properties of galaxies that we wish to understand, Section 2 reviews the efforts that have been made to understand the formation of galaxies in a universe dominated by dark matter. Section 3 then discusses the collapse and fragmentation of gas clouds in dark halos and the processes that control star formation rates in galaxies. Section 4 discusses simple models of galactic evolution based on these ideas, and compares them with the available evidence; also discussed are the stellar initial mass function and some ideas concerning its origin. Finally, Section 5 reviews the fossil evidence concerning the earliest stages of galactic evolution, and some of the initial results of attempts to study galaxy formation directly by observing objects at high redshifts.

2 THE ORIGINS OF GALAXY MORPHOLOGY

2.1 Some Systematic Properties of Galaxies

Perhaps the most fundamental fact about galaxies is the existence of the two basic galaxy types, elliptical and spiral: the elliptical galaxies are relatively round in shape and are supported almost entirely by random motions, while the spirals are flat disks supported almost entirely by rotation. Most galaxies contain both spheroidal and disk-like components, and an elaboration of the simple division into two types is provided by the Hubble classification sequence, which can be regarded most fundamentally as a sequence of varying relative prominence of spheroid and disk ranging from pure spheroid for the elliptical galaxies to pure disk for the late-type spirals. Many other properties of galaxies also vary systematically along this sequence, albeit with considerable scatter; most notably, the fractional gas content and the relative present rate of star formation increase systematically along the Hubble sequence. The spiral pattern also becomes increasingly open along the sequence, but like the increase in the present star formation rate this is probably a consequence mainly of the increase in gas content, since a higher surface density of gas is expected to lead to a more open spiral pattern (see Section 3.2). Thus, there appear to be two fundamental properties of galaxies whose variation along the Hubble sequence needs to be understood, namely the disk-to-bulge ratio and the fractional gas content, both of which increase systematically along the sequence.

An important clue to the origin of the Hubble sequence is provided by the ‘morphology-density relation’, which is a correlation between the distribution of Hubble types and the local density of galaxies in different environments: in low-density regions most of the galaxies are gas-rich spirals, but with increasing galaxy density the number of gas-poor S0 and elliptical galaxies increases, and the densest clusters are dominated by S0 and elliptical galaxies (Oemler 1974; Dressler 1980; Postman and Geller 1984; Haynes 1987; Whitmore and Gilmore 1991). The formation of disks is thus clearly favored in low-density regions, while the formation of spheroids is favored in the densest regions; in addition, star formation and gas depletion processes appear to have proceeded most rapidly in the galaxies located in the densest environments. As will be discussed, both the greater prominence of spheroids and the more rapid star formation in the denser environments probably result from the greater importance of galaxy interactions at early times in these regions.

Increasing attention has been given in recent years to dwarf galaxies, and it has become clear that they differ in several important respects from the giant galaxies considered above (Wirth and Gallagher 1984; Dekel and Silk 1986; Kormendy 1987; Binggeli and Cameron 1991). In particular, the dwarf galaxies have low surface brightnesses that decrease with decreasing luminosity, unlike the trend for giants. They do not have distinct spheroid and disk components, but they nevertheless vary greatly in their content of gas and young stars, and range from gas-poor dwarf ellipticals to gas-rich dwarf irregulars. Apart from their difference in gas content, however, the dwarf elliptical and dwarf irregular galaxies appear to be similar in their other properties, and they are probably closely related types of objects (Kormendy 1987; Kormendy and Djorgovski 1989; Da Costa 1992).

Both giant and dwarf galaxies exhibit scaling relations among their basic properties such as mass, radius, virial velocity, mass-to-light ratio, and metallicity. For giant galaxies, including both ellipticals and spirals, the mass M, virial velocity V, and radius R satisfy the approximate scaling relations $M \propto V^4 \propto R^2$, where R is the radius of the visible galaxy and M is the mass within this radius (*e.g.,* Faber *et al.* 1987; Kormendy and Djorgovski 1989; Djorgovski 1992). The approximate scaling relation between M and V given here is essentially equivalent to both the Faber-Jackson (1976) relation between the luminosity and velocity dispersion of elliptical galaxies, and the Tully-Fisher (1977) relation between the luminosity and rotational velocity of spirals. The relation between M and R follows from that between M and V if virial equilibrium is assumed; note that it implies that the surface density of matter in giant galaxies is approximately constant. In addition to these basic structural relations, which must have their origin in the galaxy formation process, the mass-to-light ratios of elliptical galaxies increase slowly but significantly with mass, approximately as $M/L \propto M^{1/6}$ according to Djorgovski (1992). The mass-to-light ratios of giant galaxies depend mainly on the stellar mass spectrum, and hence on star formation processes; thus their near constancy among the giant ellipticals suggests that star formation has proceeded in a similar way in all of these galaxies, at least to the extent that a similar stellar mass spectrum has been produced in all cases.

A third type of scaling law satisfied by the giant elliptical galaxies is a relation between the metallicity Z and the mass M; the calibration of the slope of this relation is difficult, however, and dependences ranging from $Z \propto M^{1/4}$ (Tinsley 1980) to $Z \propto M^{1/2}$ (Caldwell *et al.* 1992) have been proposed. The metallicity of a galaxy depends not only on star formation processes, but also on any gas flows that may remove metal-enriched gas from the galaxy during its evolution; the generally accepted explanation of the mass-metallicity relation is that supernova-driven gas loss during early galactic evolution becomes increasingly important in galaxies of decreasing mass (Larson 1974b; Tinsley 1980).

The dwarf galaxies exhibit different scaling laws from the giants, as has been emphasized by Dekel and Silk (1986) and Kormendy (1987); the scaling relations for the dwarfs may even be better defined than those for the giants, because of the larger range in the properties of the dwarf galaxies. The basic structural scaling laws relating the mass, virial velocity, and radius for the dwarfs are, roughly, $M \propto V^3 \propto R^3$; note that the relation between mass and radius for the dwarfs corresponds more nearly to a constant volume density than to a constant surface density, as was found for the giant galaxies. More remarkable is the fact that the mass-to-light ratios of the dwarf galaxies increase substantially with decreasing mass, contrary to the trend for giants; the mass-to-light ratios of the dwarfs scale with mass approximately as $M/L \propto M^{-1/3}$, and reach values as large as ~ 100 for the smallest known dwarf ellipticals, Draco and Ursa Minor (Da Costa 1988, 1992; Kormendy 1990b; Pryor 1992). This result implies that the smallest dwarf galaxies are completely dominated by dark matter, even at their centers. This confirms and extends the trend earlier noted by Tinsley (1981a), who found that the proportion of dark matter is higher in galaxies with bluer colors, which generally are also smaller. As has been emphasized by Kormendy (1990b), the smallest dwarf galaxies contain the highest densities of dark matter known. The existence of such high concentrations of dark matter even in the smallest galaxies places an important constraint on the nature of the dark matter and implies that at least some of it must be ‘cold’, that is it must have a very small velocity dispersion, since otherwise it could not remain bound in such small systems.

Like the giant galaxies, the dwarf galaxies also show a strong dependence of metallicity on mass; the relation between Z and M is probably better calibrated for the dwarfs because it is based on metallicity measurements for individual stars, and its form is approximately $Z \propto M^{1/2}$ (Da Costa

1988, 1992; Caldwell *et al.* 1992). Here the dependence of Z on L given by these authors has been converted into a dependence on M using the relation between M/L and M given above. If this is done also for the relation between Z and L given by Caldwell *et al.* (1992) for the giant elliptical galaxies, the same dependence of Z on M is found as for the dwarfs, removing the difference in slope that was noted by these authors when Z is considered as a function of L. The extremely low metallicities of the smallest dwarfs, which are less than one percent of solar, almost certainly imply that the loss of heavy elements was of major importance during their early evolution.

2.2 Galaxy Formation in a Universe Dominated by Dark Matter

It is generally believed that galaxies were formed by the gravitational condensation or aggregation of matter that was initially much more uniformly distributed in the universe. If the universe is dominated by dark matter everywhere except in the inner parts of large galaxies, then the gravitational forces responsible for collecting the material into galaxies are due almost entirely to the dark matter, and the ordinary matter initially plays no important role but merely “goes along for the ride”. In order to understand how galaxies form, we must therefore understand something about the distribution and dynamics of the dark matter in the universe. The formation of the visible galaxies is expected to be closely associated with the formation of dense concentrations of dark matter; for example, if the dark matter first forms dark halos, visible galaxies would be expected to form in these halos as a consequence of gas infall followed by star formation where the gas attains a sufficiently high density (White and Rees 1978; Fall and Efstathiou 1980; White and Frenk 1991).

Most of the efforts that have been made in recent years to model the growth of structure in the universe have been based on the hypothesis that the observed structure originated from initial density fluctuations having a wide range of length scales. Usually the power spectrum of these initial density fluctuations has been assumed to be approximately scale-free, and such that the density fluctuations have larger amplitudes on smaller scales (Peebles 1980). As a universe with such initial density perturbations evolves, small condensed structures develop first and then cluster gravitationally into progressively larger ones, possibly in a hierarchical fashion; the galaxies that we now observe may then just represent the smallest structures that have survived as discrete units (Peebles 1974). The detailed way in which structure develops and galaxies form depends on the nature of the initial density fluctuation spectrum, so it is important to try to constrain the form of this spectrum from observations. Information about the structure of the early universe can be obtained most directly by studying the present distribution of matter on scales larger than that of clusters of galaxies, since on these scales there has not yet been time for gravitational clustering to erase the initial conditions; the observed structure on these scales is therefore still in the 'linear regime', that is, the observed density fluctuations are simply an amplified form of the initial density perturbations.

Several surveys have shown that the large-scale structure of the universe is intricate and complex, consisting of networks of filaments, sheets, and voids of various sizes (Maddox *et al.* 1990; de Lapparent, Geller, and Huchra 1991; Giovanelli and Haynes 1991). Numerical simulations of the development of large-scale structure in the universe also produce complex filamentary structures with a fractal-like appearance (Park and Gott 1991; Kates, Kotok, and Klypin 1991; Beacom *et al.* 1991). Recent analyses of the observed large-scale distribution of galaxies have shown that there are two regimes in which the distribution of matter is approximately self-similar and can be characterized by different fractal dimensions: on scales smaller than about 5 Mpc, the well-known Peebles covariance function implies a fractal dimension of $D \sim 1.2$ which reflects the approximately isothermal clustering of galaxies, whereas on scales between about 5 and 50 Mpc where the initial structure has not yet been greatly altered by gravitational clustering, a different scaling behavior is found that corresponds to a fractal dimension of $D \sim 2.2$ (Einasto 1991; Guzzo *et al.* 1991). A fractal dimension of 2.2 would be characteristic, for example, of an open filamentary or sponge-like structure, which indeed is a good description of the observed appearance of the universe on these scales. In a fractal structure of dimension 2.2, a substructure of radius R has a mass proportional to $R^{2.2}$; this is very similar to the observed scaling relation $M \propto R^2$ for giant galaxies, suggesting that this scaling relation results from the self-similar nature of the matter distribution in the pre-galactic universe.

A number of numerical simulations have been carried out to study the development of structure in a standard 'cold dark matter' (CDM) universe on scales comparable to those of groups and clusters of galaxies (Frenk *et* *al.* 1985, 1988; Zurek, Quinn, and Salmon 1988; Carlberg 1988; Carlberg and Couchman 1989). While these simulations do not have sufficient resolution to model in any detail the formation of individual galaxies, the results obtained nevertheless suggest some of the processes that are likely to be important for galaxy formation in a universe dominated by dark matter with a scale-free spectrum of initial density fluctuations. All of the simulations show that in the denser regions of the universe, small dark halos form first and then merge rapidly into larger ones, resulting in the formation of particularly large dark halos. In low-density regions, mergers are less important and dark halos grow more gradually by the accretion of diffuse matter. These results thus suggest that the merging of smaller systems into larger ones may play an important role in the formation of galaxies in the denser parts of the universe, whereas mergers are probably less important and the gradual accretion of diffuse matter more important in low-density regions. The dark halos formed in the simulations are approximately isothermal, implying that any disks that form in them would have nearly flat rotation curves, in agreement with the observations. The simulations are also able to reproduce satisfactorily the Tully-Fisher and Faber-Jackson relations between the masses and the virial velocities of galaxies (Frenk *et al.* 1988), supporting the suggestion that these scaling relations have their origin in the self-similar structure of the pre-galactic universe. Thus, these simulations appear to provide a promising framework for understanding at least some of the processes that might be important for galaxy formation, even though the validity of the standard CDM model remains unclear, and indeed has been much debated (*e.g.,* Peebles *et al.* 1991).

Some of the simulations of the development of structure in a cold-dark-matter universe have also included a schematic treatment of gas dynamics and star formation in forming galaxies (Carlberg 1988; Carlberg and Couchman 1989), or a detailed treatment of the gas alone without including any effects of star formation (Navarro and Benz 1991). In the absence of heating due to star formation, the gas is found to cool rapidly following mergers and to lose most of its angular momentum through gravitational interaction with the dark matter, causing it to sink deeply into the centers of the dark halos; as a result, no extended gas disks are formed (Navarro and Benz 1991). Moreover, too much gas ends up in small systems to be consistent with the observed luminosity function of galaxies, a conclusion that has also been reached in analytical studies of the cooling and condensation of gas in dark halos (Cole 1991; White and Frenk 1991). Thus, it is clear that the neglect of stellar feedback effects is not realistic, and that these effects must play an important role in galaxy formation. When the effects of heating by supernovae are included, most of the gas may actually end up in relatively hot diffuse form in galactic halos or in clusters of galaxies (Carlberg 1988; White and Frenk 1991). The hot gas in halos might then slowly cool and condense into the star-forming regions of galaxies, helping to sustain star formation in them, as suggested by White and Frenk (1991).

In summary, the cosmological simulations that have been discussed suggest that the largest galaxies, and those in the densest environments, may form through the merging of smaller systems, possibly in a hierarchical fashion. In the standard CDM model, most of this merging activity is predicted to occur at moderate redshifts between about 1 and 3 (White and Frenk 1991), a prediction that may soon become testable (Section 5.5). However, mergers are probably less important in low-density environments, and the galaxies in these regions may grow more slowly and quiescently by the accretion of diffuse matter, both dark matter and gas. Gas that cools rapidly at early times may lose most of its angular momentum to the dark matter, and as a result may become highly condensed and form compact and slowly rotating stellar spheroids, while gas that is reheated may remain relatively diffuse and retain most of its angular momentum, condensing later to form extended disks. The simulations that have been discussed are mostly based on the standard CDM model, but their main features do not depend critically on either the amount or the detailed properties of the dark matter, and are generic to any cosmology in which structure develops in a bottom-up fashion (Efstathiou 1990).

2.3 Evolution of Protogalaxies: Collapse Models

Although the distinction now seems artificial, most models for the formation of individual galaxies have been based on either the ‘collapse’ picture or the ‘merger’ picture. We mention first some results of collapse calculations based on the hypothesis that galaxies form by the collapse of discrete protogalactic clouds. The role of the dark matter has usually been neglected in these calculations; in effect, it has been assumed that the protogalactic clouds have already formed at the centers of dark halos and that the dark matter plays no further important role in their evolution. The possibility that our Galaxy was formed by a collapse process was suggested by Eggen, Lynden-Bell, and Sandage (1962); these authors presented evidence for a correlation between stellar metallicity and kinematics which suggested a smooth increase in metallicity between the halo and disk populations of our Galaxy, and they proposed that this correlation could be explained by the collapse and simultaneous metal enrichment of a protogalactic gas cloud. A recent discussion of the evidence that our Galaxy formed by a collapse process has been given by Sandage (1990).

The simplest type of collapse model is one that treats only the collapse of a system of stars formed with high efficiency from the gas at an early time. Such models clearly cannot address chemical enrichment processes or account for the formation of disks, but they may nevertheless be able to account for the gross structure of typical elliptical galaxies (Gott 1977). A number of calculations have shown that the dissipationless collapse of a system of stars can indeed yield a radial density distribution resembling that of an elliptical galaxy, provided that the initial configuration is sufficiently inhomogeneous or asymmetric that the collapse is chaotic and involves interactions between clumps (*e.g.,* van Albada 1982; Villumsen 1984; Katz 1991). Instabilities occurring during the collapse may also lead to a similar outcome if the system is initially sufficiently cold (Aguilar and Merritt 1990). These results suggest that the essential requirement for generating a radial density profile like that of a typical elliptical galaxy may simply be that the collapse must be sufficiently chaotic or violent that the stars experience substantial redistribution in energy, qualitatively as in the 'violent relaxation' process suggested by Lynden-Bell (1967), although the results of the collapse calculations do not closely follow the predictions of the violent relaxation theory.

However, the dense cores and the metallicity gradients that are typically observed in giant elliptical galaxies (Kormendy 1987; Thomsen and Baum 1989; Kormendy and Djorgovski 1989) can probably be explained only if gaseous dissipation effects are included, and it is obviously necessary to include dissipation to account for the formation of disks. Collapse calculations incorporating simple treatments of gas dynamics and star formation have been made by Larson (1974a, 1975, 1976a), Carlberg (1984a,b, 1985), and Burkert and Hensler (1987, 1988). In all of these calculations the kinetic energy of the gas is assumed to be dissipated by inelastic collisions between randomly moving gas clouds, and this allows a steady contraction of the system that is generally somewhat slower than the near free-fall collapse proposed by Eggen, Lynden-Bell, and Sandage (1962). In all of the dissipative collapse models, metallicity gradients are generated by the settling of enriched gas toward the center, and also toward the equatorial plane in the case of a rotating system. Because of the assumed random motions of the gas clouds, the stars may be formed with large random velocities and can even have retrograde orbits, as are indeed observed for many of the stars in the Galactic halo.

With appropriate choices for the parameters, these dissipative collapse models can again reproduce the typical radial structure of elliptical galaxies; however, since the same can also be claimed for other types of models, this is not a good test of the models (Gott 1977). It is perhaps more instructive to note some ways in which models incorporating gas dynamics can fail to yield realistic results if certain effects are not included. For example, if viscosity or some other means of redistributing angular momentum is not included, the collapse of a rotating protogalactic cloud can lead to a system that is flattened but not centrally condensed, unlike real spiral or elliptical galaxies (Larson 1975; Burkert and Hensler 1988). Centrally condensed structures are obtained only when a significant effective viscosity is assumed, as might be expected to exist in real protogalaxies because of random gas motions (Larson 1975) or because of the gravitational torques that occur in a non-axisymmetric mass distribution (Lynden-Bell and Kalnajs 1972; Larson 1984).

When viscosity is included, models that are otherwise realistic tend to produce too large a central accumulation of gas, leading to rotation curves that peak too strongly in the inner regions of the resulting galaxy (Larson 1976a; Navarro and Benz 1991). As was noted by these authors, gas heating effects not included in these calculations might well prevent such excessive accumulations of gas at the centers of forming galaxies. The heating and expulsion of residual gas by the effects of supernovae may in fact be of quite general importance for galaxy formation (Cole 1991), and will almost certainly be very important for the smallest galaxies, causing them to lose most of their heavy elements at an early stage of evolution and thus end up with low metallicities. The models of Larson (1974b) incorporating supernova-driven gas loss predict a dependence of metallicity on stellar mass that is, in fact, very similar to the observed metallicity-mass relation for dwarf galaxies. These models did not include the gravitational effect of the dominant dark matter in dwarf galaxies, but this has been done by Dekel and Silk

(1986); these authors showed that when the dark matter is taken into account, the scaling relations for the dwarf galaxies can all be accounted for in a self-consistent way, and are consistent with those predicted by the standard CDM theory for small galaxies.

Recent efforts to account for the low metallicities of the smallest dwarf galaxies have also emphasized the likely importance of the preferential loss of heavy elements in supernova-driven winds (Vader 1986; De Young and Gallagher 1990). Franx and Illingworth (1990) have suggested, in addition, that the same mechanism that accounts for the metallicity-mass relation in galaxies may also account for the metallicity gradients in giant elliptical galaxies, since the local metallicity correlates well with the local escape velocity in these systems. This suggestion supports the possibility that supernova-driven gas loss is of quite general importance in limiting the metallicities attained by galaxies or parts of galaxies during their early evolution.

In collapse models that include gas, any gas that is not consumed by star formation or lost from the system eventually settles into a disk. Even models intended to represent the formation of elliptical galaxies tend to develop a small disk component (Larson 1975; Burkert and Hensler 1988), a prediction that seems consistent with the evidence that many elliptical galaxies do in fact contain weak disk components and thus appear to form a continuous extension of the Hubble sequence (Bender 1990). If star formation is strongly suppressed during the collapse of a protogalaxy, a large fraction of its initial gas may end up in a disk, yielding a system with both a spheroid and a prominent disk component (Larson 1976a,b; Carlberg 1985). In models of this type, the disk tends to be built up from the inside out over a relatively extended period of time; this process of disk building could even continue for a large fraction of the present age of a galaxy if the gas forming the disk falls into the galaxy from large distances (Larson 1972, 1976b; Gunn 1982, 1987). Tinsley and Larson (1978) have shown that dissipative collapse models like those of Larson (1976b) may be able to account for many of the observed structural and chemical properties of galaxies like our own.

In models like those that have been described, star formation must be much slower in proto-spiral galaxies than in proto-ellipticals if a prominent disk component is to form. This might be the case if the gas in the proto-spirals is less dense and/or less clumpy than the gas in proto-ellipticals (Gott and Thuan 1976; Larson 1976a,b); such a difference might qualitatively be expected since spiral galaxies tend to form in regions of relatively low density.

An additional effect noted above that may inhibit star formation in protospiral galaxies is that much of the gas in these relatively low-density systems may be heated and maintained in a relatively diffuse state by the effects of early star formation and supernova production; this would not only suppress further star formation but might also prevent the gas from losing most of its angular momentum to the dark matter (Navarro and Benz 1991), thus allowing it to condense later into an extended disk.

2.4 Mergers and Accretion

On the basis of evidence for strong gravitational interactions and mergers between disk galaxies, Toomre and Toomre (1972) and Toomre (1977) suggested that many, and possibly all, elliptical galaxies are formed by the merging of smaller galaxies, typically spirals. Toomre (1977) also suggested that even large spiral galaxies might be formed by mergers if the smaller systems that merge contain a large amount of gas that eventually settles into a new disk. A number of authors, including White and Rees (1978), Tinsley and Larson (1979), and Struck-Marcell (1981), have discussed how various properties of galaxies might be accounted for if they are formed by a series of mergers of smaller systems into larger ones, with dissipative settling of the residual gas and new star formation occurring after each merger. As we have seen, the cosmological simulations also strongly suggest that some galaxies, especially the largest ones and those in the densest environments, have been formed by a series of mergers. Therefore much effort has gone into simulating mergers between galaxies and comparing the results with the observed properties of those systems, particularly elliptical galaxies, that might be merger products.

The first and simplest simulations of mergers studied the merging of spherical systems of stars without dark halos (White 1978, 1979; Villumsen 1982, 1983), and they found that strongly interacting systems always merge quickly because of the effect of gravitational drag or 'dynamical friction' (Binney and Tremaine 1987), which rapidly removes energy and angular momentum from the orbits of the interacting systems and causes them to spiral together within about one orbital period. The radial structure of the merger product resembles that of a typical elliptical galaxy, although in most cases it has more rotation than is observed. The results are thus similar to those of the clumpy dissipationless collapse calculations mentioned above, illustrating again the apparently general conclusion that any sufficiently violent formation process produces a system with a structure like that of an elliptical galaxy. It therefore seems likely that the structures of elliptical galaxies have been produced at least in part by violent dynamical processes, possibly involving interactions and mergers between subsystems.

Although the overall importance of mergers for galaxy formation has been debated (*e.g.,* Ostriker 1990; van den Bergh 1990a), there is compelling evidence that mergers do sometimes occur and that some peculiar galaxies that have the basic structure of ellipticals, such as the radio galaxies Fornax A (NGC 1316) and Centaurus A (NGC 5128), are the products of recent mergers or captures of smaller galaxies by larger ones (Schweizer 1990). Mergers of pairs and even groups of spiral galaxies that have both bulge and disk components as well as dark halos have been simulated in detail by Barnes (1988, 1989, 1990), and the results show that when dark halos are included in the simulations, the visible stars rapidly lose both energy and angular momentum to the dark matter and form compact and slowly rotating systems that closely resemble real elliptical galaxies in both structure and kinematics. If the merging galaxies have metallicity gradients, these gradients will be weakened but not obliterated by the merger process, since the stars from the inner regions of the merging galaxies tend to end up in the inner part of the merger product (White 1980; Villumsen 1982).

When gas is included in such merger simulations, the gas in the interior part of the merging system rapidly loses most of its angular momentum as a result of the gravitational torque between a stellar bar and a leading gas bar that typically form in the system, and this can cause half or more of the gas to fall rapidly into the innermost several hundred parsecs of the final system (Hernquist 1989; Barnes and Hernquist 1991). Similar results have been found in simulations of galaxies that are tidally perturbed by close encounters with other galaxies (Noguchi 1990). The result of this extreme concentration of gas at the center will almost certainly be an intense burst of star formation (Larson 1987b), as is indeed frequently observed in interacting or merging galaxies. The core of the merged system will then acquire a new population of stars, and as was noted by Schweizer (1990), the resulting increase in the central stellar density may remove the earlier objection to the merger hypothesis that mergers of spirals cannot produce systems with cores as dense as those of typical elliptical galaxies.

Thus it seems likely that mergers are involved in the formation of at least some elliptical galaxies, and probably also in the formation of the bulges of early-type spirals (Toomre 1977; Schweizer 1990). The Hubble type of a galaxy may then be determined in part by the relative importance of mergers during its early history: more mergers would produce systems with larger spheroids, and hence earlier Hubble types. The densest parts of the universe, where mergers are predicted to be most frequent at early times, would thus be expected to contain a higher proportion of galaxies with early Hubble types, as is indeed observed to be the case.

We have so far considered mainly mergers of systems of comparable size, but a more common event is presumably the capture of a small galaxy by a larger one. If a large elliptical galaxy accretes a smaller galaxy, whether spiral or elliptical, the small system is violently disrupted and its stars are dispersed into transient shell-like features superimposed on the smooth outer envelope of the larger galaxy (*e.g.,* Hernquist and Quinn 1988, 1989). Such shell-like features are observed in at least half of all elliptical galaxies (Schweizer and Ford 1985) and even in some early-type spirals (Schweizer and Seitzer 1988), indicating that accretion events are indeed a fairly common occurrence. Other signs of past mergers in some early-type galaxies include dust lanes and counter-rotating nuclear disks in elliptical galaxies, and polar rings in early-type spirals (Larson 1990c). It is also possible that many of the distortions such as warps and asymmetries observed in the outer disks of spiral galaxies are the results of accretion events (Larson 1976b,c; Binney 1990; Kamphuis and Briggs 1992), although the evidence in this case is more ambiguous. In any case, it seems clear that large galaxies can continue to grow slowly by the accretion of smaller galaxies. The question of whether galaxies also continue to accrete primordial gas will be considered further in Section 4.3.

2.5 Summary

We have seen that the formation of at least the larger galaxies is likely to be a complex process involving interactions and mergers between subunits, and perhaps also the continuing accretion of smaller galaxies and diffuse matter. Elliptical galaxies and the bulges of early-type spirals are probably formed first in the densest parts of the universe, perhaps by a sequence of mergers of smaller subsystems. The disks of spiral galaxies probably form later from gas that remains relatively diffuse during the initial chaotic period of spheroid formation and then settles more gradually into a disk. As has been emphasized by Kormendy (1990a) and Larson (1990c), no clear division can be drawn between the collapse and merger pictures of galaxy formation, and elements of both are almost certainly involved in the formation of most large galaxies. Chaotic dynamical processes probably account for the basic structure of elliptical galaxies and spiral bulges, while dissipative settling of gas is probably required to account for the metallicity gradients and dense cores of elliptical galaxies as well as for the disks of spirals. The processes of galaxy building and their time dependence are likely to depend strongly on the environment; for example, the elliptical galaxies in clusters are relatively homogeneous in their properties, suggesting that they all formed at an early time, while field ellipticals show more variation in their properties and more evidence for recent capture events and for the presence of relatively young stellar populations (de Carvalho and Djorgovski 1992; Guzmán *et al.* 1992). The relative importance of the various processes must also depend on the sizes of galaxies; for example, it is unlikely that mergers have played any important role in the formation of the dwarf galaxies, whose properties are probably determined predominantly by mass loss processes.

Many of the processes that might be expected to occur during the formation of galaxies like our own are illustrated in the most recent and realistic simulations of galaxy formation by Katz and Gunn (1991), who calculated the dynamics of the dark matter and gas in protogalaxies modeled as galaxy-sized pieces of a standard cold dark matter universe, and by Katz (1992), who has extended this work by including a simple treatment of star formation. The results of these calculations show an initial chaotic stage during which mergers between clumps build a dark halo and a stellar spheroid, followed by a more prolonged period during which the remaining gas organizes itself into a disk. The formation of the disk is itself a somewhat chaotic process in these simulations, since the disk is initially irregular and clumpy and retains a significant tilt with respect to the halo. Random differences in the initial conditions are found to lead to significant differences in the final disk-to-spheroid ratio. Small satellite systems may form during the initial chaotic phase of halo formation, and they may survive for a significant time and continue to interact with the disk. As will be seen in Section 5, the current evidence regarding the early evolution of our own Galaxy is qualitatively consistent with such a picture, and provides strong support for the existence of an initial chaotic phase of halo formation.

3 LARGE-SCALE STAR FORMATION IN GALAXIES

3.1 Gas Condensation in Dark Halos

According to the general scenario discussed above, the dark halos of galaxies are formed first as part of the large-scale dynamical evolution of the universe, and gas then condenses within these halos to form the visible galaxies (White and Rees 1978; White and Frenk 1991). In most cosmological models, the dark matter is initially dominant everywhere, and the ordinary matter constitutes only a small fraction of the mass; for example, in conventional hot big bang cosmology the density of baryonic matter cannot exceed 10 percent of the closure density of the universe if the observed abundances of the light elements are to be accounted for (*e.g.,* Krauss and Romanelli 1990; Peebles *et al.* 1991; Tremaine 1992; Deliyannis, Demarque, and Pinsonneault 1992), while in the standard CDM model it is assumed that the total matter density is equal to the closure density. Even if the standard CDM model is not correct and there is not enough dark matter to close the universe, it remains true that most of the mass in galactic halos and in clusters of galaxies consists of unseen matter in some form that almost certainly predates the visible components of galaxies. If the gas that eventually makes the visible stars is initially distributed like the dark matter, as is usually assumed, then this gas is initially not self-gravitating, and it cannot begin to form stars until it has become sufficiently condensed within the dark halos that its self-gravity becomes important (White and Rees 1978).

In general, the self-gravity of the gas in dark halos is counteracted by the tidal force produced by the dominant dark matter, and therefore the most basic requirement for star formation to be possible is that the self-gravity of the gas must exceed the tidal force due to the dark matter; this is essentially the classical Roche criterion. For a spherical gas cloud in an isothermal dark halo, it is easy to show that the self-gravity of the gas cloud exceeds the tidal force due to the dark matter if the cloud density exceeds the local density of dark matter by a factor of 3. For example, if we take as a typical dark matter density the density of dark matter in the halo of our Galaxy at the solar location, which is about 0.01 $M_\odot/\mathrm{pc}^3$ according to Kuijken and Gilmore (1991), this criterion implies that star formation can occur only if the gas density exceeds about 1 atom/cm^3, which is similar to the observed density of interstellar matter in the solar neighborhood. This similarity is almost certainly not accidental, since the gas density in galactic disks is probably regulated to be close to the threshold density required for star formation (Quirk 1972; Larson 1983; see Section 3.4.)

Higher gas densities are required for star formation to occur in the cores of the dwarf galaxies, which have considerably higher densities of dark matter than the giant galaxies. The central dark matter density in the dwarf galaxies scales with galactic mass M roughly as $M^{-1/2}$ (Kormendy 1990b), and it approaches 1 $M_\odot$/pc^3 in the smallest known dwarf ellipticals, Draco and Ursa Minor (Kormendy 1990b; Pryor 1992). Star formation can therefore occur near the centers of these galaxies only if the gas density exceeds the very high average value of about 100 atoms/cm^3. This suggests that star formation may proceed differently in the cores of dwarf galaxies than in the disks of spirals, a possibility that may be relevant to early galactic evolution and the formation of globular clusters (Section 5.4).

Since the gas density in most models is initially only 1/10 or less of the dark matter density, the Roche criterion requires that the gas must be compressed by at least a factor of 30 in density relative to the dark matter before star formation can occur. The gas can attain such a high density in a gravitationally bound configuration only if its temperature is significantly smaller than the virial temperature of the dark halo. Since the gas is likely to be heated to roughly the virial temperature during the formation of dark halos, especially if this process is a violent one involving the merging of subunits, the gas must then be able to cool again if it is to become self-gravitating. The cooling of hot gas in gaseous protogalaxies was studied by Rees and Ostriker (1977) and Silk (1977), who suggested that the requirement of rapid gas cooling limits the sizes and masses that galaxies can attain. In treatments of galaxy formation in a dark-matter-dominated universe, it has likewise generally been assumed that the cooling time of the gas must be shorter than the dynamical time if sufficiently rapid star formation is to be possible (*e.g.,* White and Rees 1978; Blumenthal *et al.* 1984; White and Frenk 1991). This criterion is amply satisfied for galaxies with typical sizes and masses, but it is not satisfied for groups or clusters of galaxies (Silk 1985); thus there is a maximum mass for which rapid cooling is possible, which is about 10^{12} solar masses. A second requirement for rapid cooling to be possible is that the virial temperature must exceed about 10^4 K, which according to the scaling relations discussed above implies a galactic mass larger than about $10^7\,M_\odot$. The requirement of rapid gas cooling thus limits the range of masses with which galaxies can form to be between about 10^7 and $10^{12}\,M_\odot$, which indeed is just the observed range of galaxy masses. We recall that the distribution of matter in the pregalactic universe is usually assumed to have a roughly scale-free form, and so may contain no strongly preferred mass scale or range; thus the actual masses of galaxies may be determined, as discussed here, by the detailed physics of galaxy formation.

3.2 Stability of Gas Sheets and Disks

The configuration finally attained by the cooling gas in a dark halo will depend in detail on the initial conditions, but general arguments suggest that the gas may often form flattened structures or sheets (Lacey 1989), somewhat as has been suggested to occur on larger scales in a universe containing only gas (Zeldovich 1970), and on smaller scales in star-forming molecular clouds (Lin, Mestel, and Shu 1965; Larson 1985). In the presence of significant angular momentum, rotationally supported disks may also be formed. Any equilibrium gas layer or disk that may form in a protogalaxy will generally be much thinner than the size of the system. For an isothermal gas layer or disk with surface density μ and sound speed c, the scale height H is given by $H = c^2/\pi G\mu$; for example, if the sound speed in the gas is 10 km/s or less, as would be expected following the phase of rapid cooling, and if the gas layer has the same surface density as the local disk of our Galaxy, or about $50\ M_\odot/\mathrm{pc}^2$ (Section 4.1), then the predicted scale height of the layer is only about 140 pc or less, which is much smaller than the size of a typical galaxy. The subsequent evolution of protogalaxies containing such thin gas layers or sheets may then involve the fragmentation of these sheets into filaments or clumps, which finally collapse to form stars.

Such a picture may not apply, however, to the dwarf galaxies, which have smaller surface densities than the giant galaxies, as well as smaller sizes; as a result, any equilibrium gas configuration that may form in a dwarf galaxy will have a much larger ratio of scale height to size. The scaling relations for dwarf galaxies imply that the ratio H/R varies with mass roughly as $M^{-2/3}$ and approaches 1 for the smallest known galaxies, so that highly flattened structures may never develop in these systems.

The most basic criterion for the fragmentation of a gas sheet in a dark halo is again the requirement that the local self-gravity of the gas must overcome tidal forces, a requirement which in this case sets an upper limit on the size of any region that can collapse gravitationally. If a spherical halo producing a radial gravitational acceleration $a(r)$ contains a gas sheet with surface density perturbations of the form $\mu_1 \cos kr$, it can be shown that the regions of excess density will collapse only if the wavelength $\lambda = 2\pi/k$ is smaller than a critical wavelength

$$\lambda_{\rm crit} \ = \ 8\pi G\mu_1/(da/dr) \ .$$

In an isothermal halo with $\rho_{\rm dark} \propto r^{-2}$, this critical wavelength is just $2\mu_1/\rho_{\rm dark}$. This result is general and does not assume that the gas sheet has necessarily attained any equilibrium structure such as a rotationally supported disk.

For a thin disk in rotational equilibrium, a stability analysis for short-wavelength axisymmetric perturbations, or for non-axisymmetric perturbations in the special case of a rigidly rotating disk, yields the result that only modes with wavelengths smaller than a critical wavelength

$$\lambda_{\rm crit} \ = \ 4\pi^2 G\mu/\kappa^2$$

can grow, where κ is the epicyclic frequency (Toomre 1964). For example, if we apply this result to the local Galactic disk and assume again a surface density of 50 $M_\odot/{\rm pc}^2$, we obtain $\lambda_{\rm crit} \sim 6$ kpc, while for the present Galactic gas layer alone, which has $\mu \sim 13\ M_\odot/{\rm pc}^2$ (Section 4.1), we obtain $\lambda_{\rm crit} \sim 1.5$ kpc. The quantity $\lambda_{\rm crit}$ plays an important role in theories of spiral structure in galaxies (*e.g.,* Toomre 1981, 1990), where it determines the typical spacing of the spiral arms; since $\lambda_{\rm crit}$ for the gas layer increases with the surface density of gas in galactic disks, galaxies with more gas are predicted to show more open spiral patterns (Carlberg and Freedman 1985; Carlberg 1987; Toomre 1990), which is indeed one of the defining characteristics of the Hubble sequence.

For a gas layer with a finite temperature, there is also a minimum length scale for fragmentation which is essentially the classical Jeans length. In an equilibrium isothermal gas layer with surface density μ and effective sound speed c, density perturbations can grow only if their wavelengths exceed a minimum value

$$\lambda_{\rm J} \ = \ 2c^2/G\mu \ ;$$

the corresponding minimum unstable mass is

$$M_{\rm J} \;=\; 4.7c^4/G^2\mu$$

(Larson 1985). For example, if we consider again the initial Galactic gas disk and assume that it behaves isothermally with an effective sound speed of 10 km/s, we obtain $\lambda_{\rm J} = 0.9$ kpc and $M_{\rm J} = 5 \times 10^7\, M_\odot$. For the present Galactic gas disk which is confined to a relatively thin layer by the gravitational field of the stars, it is more appropriate to use the minimum unstable length and mass scales for an infinitely thin sheet, which are smaller by factors of 2 and 4, respectively. Adopting a velocity dispersion c of 7 km/s, as is observed for the local interstellar medium (Kulkarni and Heiles 1987), we then obtain $\lambda_{\rm J} = 0.8$ kpc and $M_{\rm J} = 1.1 \times 10^7\, M_\odot$. These results give the minimum size and mass of any structures such as large cloud complexes or spiral arm segments that might form by the isothermal fragmentation of the local Galactic gas layer.

Note that $\lambda_{\rm crit}$ and $\lambda_{\rm J}$ depend in opposite ways on the gas surface density μ: as the surface density decreases, the maximum wavelength $\lambda_{\rm crit}$ decreases while the minimum wavelength $\lambda_{\rm J}$ increases; therefore the range of unstable wavelengths decreases, and it eventually vanishes when the surface density becomes sufficiently small. Thus there is a minimum surface density that is necessary for gravitational instability to occur in a gas layer or disk that is subjected to tidal forces and also has a finite temperature. The above examples suggest that the early Galactic disk was unstable over a wide range of wavelengths, but that the present gas layer is unstable over only a relatively small range of wavelengths from about 0.8 to 1.5 kpc, and so has a surface density not much above the minimum required for instability.

The effects of both tidal forces and thermal pressure can be included rigorously in an analysis of the stability of short-wavelength axisymmetric modes in a thin disk, or of non-axisymmetric modes in a rigidly rotating thin disk. The dispersion relation for modes of the form $\exp(i\omega t + ikr)$ is, assuming again that the gas behaves isothermally,

$$\omega^2 \;=\; c^2k^2 - 2\pi G\mu k + \kappa^2$$

(*e.g.,* Larson 1985; Binney and Tremaine 1987). Note that the critical wavelength $\lambda_{\rm crit}$ and the Jeans length $\lambda_{\rm J}$ for a thin disk can both be derived from this dispersion relation by setting either $c = 0$ or $\kappa = 0$, and then setting

$\omega = 0$ for the critical non-growing mode. Instability occurs if the squared growth rate $-\omega^2$ is positive for some range of wavelengths, and this requires a minimum gas surface density, as was noted above. The criterion for disk instability that is derived from the above dispersion relation is similar to the criterion obtained by Toomre (1964) for a stellar disk, and it is usually written in the similar form

$$Q \equiv c\kappa/\pi G\mu < 1 .$$

(The criterion for a stellar disk differs from this only by the presence of a factor of 3.36 in place of π). If the gas does not behave isothermally but can still be described by a polytropic equation of state, or if the effect of a finite disk thickness is important, a criterion of the same form still applies but with a critical value for the stability parameter Q that is somewhat different from unity (Larson 1985).

Numerical simulations of the fragmentation of gas disks formed by the collapse of rotating clouds yield results that are in general agreement with the above stability theory, both with regard to the criterion for fragmentation and in the characteristic length and mass scales involved (*e.g.,* Larson 1978; Miyama, Hayashi, and Narita 1984; Monaghan and Lattanzio 1991). In particular, as was noted by Miyama *et al.* (1984), the fragmentation of a disk into clumps occurs in the numerical simulations at essentially the same critical value of Q as that for which fragmentation into rings is predicted. Thus the above stability criterion appears to be of quite general significance, and not restricted just to axisymmetric modes.

Elmegreen (1991b) has discussed the applicability of the Toomre Q criterion when magnetic fields are important, as may well be the case in the present Galactic interstellar medium. His conclusion is that, although spiral density enhancements can grow regardless of the value of Q if magnetic fields are important, these spiral density enhancements can fragment along their lengths into star-forming clumps or cloud complexes only if the above criterion is satisfied. Thus, even when magnetic fields are important, this criterion is still the relevant one determining the conditions under which large-scale star formation can occur in the disks of spiral galaxies.

It is interesting to note that the recent calculations of the collapse and fragmentation of a rotating cloud by Monaghan and Lattanzio (1991) show that the resulting fragmenting disk tends to develop a network of filaments and voids resembling the filamentary networks obtained in the cosmological simulations discussed in Section 2.2 (*e.g.,* Park and Gott 1991). Thus, this type of structure may be a very generic outcome of the effects of gravity in astrophysical systems.

3.3 Large-Scale Star Formation Processes

Many properties of galaxies depend on the rate at which gas is converted into stars during their formation and evolution; for example, the disk-to-bulge ratios predicted by the galaxy formation models of (Larson 1976a) depend on the early star formation rate, and many properties of the Hubble sequence depend on the history of star formation in galaxies as a function of Hubble type. We therefore wish to understand the processes that drive star formation in galaxies, and also the parameters that determine its rate.

Star formation is observed to occur mostly in giant molecular clouds, and these in turn are grouped into large complexes or spiral arm segments which appear to be the basic units of star formation in galaxies (Elmegreen and Elmegreen 1983, 1987; Efremov 1989). Even low-mass stars probably form mostly in giant molecular clouds, possibly in compact embedded clusters like those observed in the Orion A and B clouds (Evans 1991; Lada and Lada 1991; Lada, Strom, and Myers 1992). Thus, the formation of giant molecular clouds and cloud complexes is an essential aspect of star formation in galaxies, and the rate at which these processes occur must play an important role in determining the star formation rate. Since giant molecular clouds are transient structures that are continually being created and destroyed, the star formation rate should just be proportional to the cloud formation rate, assuming that each cloud converts a similar fraction of its mass into stars, as appears to be the case (see below). The short lifetimes of molecular clouds are indicated by the fact that the duration of star formation in them as inferred from the ages of the associated young stars and clusters is never more than about 10 Myr (Larson 1981). Indeed, clouds that form star clusters are evidently soon destroyed by them, since molecular clouds associated with clusters more than 5 Myr old already show significant evidence of disruption, and large clouds are no longer seen near clusters older than about 10 Myr (Leisawitz, Bash, and Thaddeus 1989). There cannot be any prolonged 'dead time' between the formation of a giant molecular cloud and the onset of star formation in it, since there are not large numbers of giant molecular clouds that are not forming stars; thus the lifetime of a molecular cloud before it is destroyed or restructured in a major way cannot much exceed the typical duration of star formation in such clouds, that is, it cannot exceed a few times 10^7 years (Elmegreen 1991a). This period is comparable to the internal dynamical timescale of these clouds (Larson 1981), so that molecular clouds apparently do not survive in recognizable form for more than about one or two dynamical times.

Thus the problem of understanding large-scale star formation in galaxies is essentially the problem of understanding the formation of giant molecular clouds and cloud complexes. Several processes that may play a role in aggregating the interstellar gas into massive clouds and complexes have been discussed by Larson (1987b, 1988b), and will be summarized briefly here; these and other processes of cloud formation have also been reviewed extensively by Elmegreen (1990a, 1991a). The basic physical effect involved is almost certainly the large-scale self-gravity of the interstellar medium, which is probably responsible for the origin of the large cloud complexes or spiral arm segments that are the basic units of star formation in galaxies (Larson 1977, 1983; Elmegreen and Elmegreen 1983). As was shown above, gravitational fragmentation of the local Galactic gas layer can produce structures with sizes of the order of 1 kpc and masses of the order of $10^7\,M_\odot$, which indeed are just the typical observed sizes and masses of the large star-forming cloud complexes. Since these complexes are typically located in spiral arms, density waves may also sometimes play a role in their origin; however, density waves are not necessary to drive large-scale star formation in galaxies, as is shown by the example of the irregular galaxies, and it is possible that their role in spiral galaxies is largely just one of organizing star formation that would have occurred anyway (Elmegreen and Elmegreen 1986; Elmegreen 1992).

Since the value of the stability parameter Q in the solar neighborhood is actually about 1.5 and thus does not satisfy the condition $Q < 1$ required for gravitational instability, the local Galactic gas layer is probably not unstable in the strict sense that an arbitrarily small perturbation in surface density will undergo unlimited exponential growth. Nevertheless, in this probably typical situation, the closely related phenomenon of 'swing amplification' can still produce substantial growth in the amplitudes of density fluctuations as they are wound up by differential rotation (Goldreich and Lynden-Bell 1965; Toomre 1981, 1990). This mechanism requires finite initial density perturbations whose amplitudes are perhaps of the order of 10 percent, since numerical simulations of swing amplification typically show growth factors of the order of 10 (Sellwood and Carlberg 1984). While the origin of these initial density perturbations is not completely understood, the many astrophysical processes (some of which are discussed elsewhere in this volume) that can structure the interstellar medium on a wide range of scales can plausibly provide density fluctuations of the required magnitude (Larson 1988b).

Given that large gas complexes or spiral arm segments can somehow be created, it is still necessary to account for the formation within them of individual giant molecular clouds. This evidently requires gas accumulation processes that operate on smaller scales, and possible mechanisms include the growth of seed clouds by gravitational accretion and the growth of clouds by random collisions and coalescence (Larson 1987b, 1988b). A more detailed treatment of gravitational accretion in a galactic shear flow has been presented by Gammie, Ostriker, and Jog (1991), who find a very similar result for the accretion rate, and a more detailed discussion of cloud growth by random collisions has been given by Elmegreen (1990a,b). Cloud growth by random collisions is predicted to take somewhat longer than the development of large-scale gravitational instabilities, and gravitational accretion in a shear flow probably also takes somewhat longer; however, both of these processes will be accelerated in regions of relatively high density and low shear such as spiral arms, where they may work together with the larger-scale aggregation processes discussed above to build giant molecular clouds.

It would appear, in any event, that the essential prerequisite for molecular cloud formation is the formation of large gas complexes by gravitational instability or swing amplification effects; the cloud formation rate is then governed essentially by the rates of these large-scale accumulation processes. If the stability parameter Q is small, the predicted e-folding time for the growth of surface density perturbations by gravitational instability in a thin disk is

$$\tau \ \sim\ c/\pi G\mu \ ;$$

the growth time for swing-amplified disturbances is similar. In the solar vicinity this timescale is about 38 Myr, or about 1.5 times the inverse epicyclic frequency of 26 Myr; note that the stability parameter Q is simply the ratio of these two times. The total time required to build major gas concentrations is probably somewhat longer than this e-folding time, and may be of the order of 50 Myr.

3.4 Star Formation Rates in Galaxies

The timescale for gas aggregation given above depends on two parameters, the surface density μ and the velocity dispersion c of the gas layer. If c is approximately constant, as is suggested by the fact that the observed velocity dispersion of the gas in galaxies generally has values between about 4 and 10 km/s (Kennicutt 1990), then this timescale depends primarily on the gas surface density μ, and is inversely proportional to μ. The time required for cloud growth by gravitational accretion or by random collisions also depends inversely on the gas surface density and only relatively weakly on other parameters (Larson 1988b). The timescale for cloud formation may then depend primarily on the gas surface density μ, and may be approximately inversely proportional to μ. The star formation rate (SFR) per unit area in a galactic disk is equal to the gas surface density divided by the timescale for converting the gas into stars; thus in this case it is approximately proportional to μ^2. This prediction is similar to the star formation law originally proposed by Schmidt (1959), except that here the SFR is predicted to depend on the surface density rather than on the volume density of the gas. (A dependence on surface density was in fact later adopted by Schmidt (1963) in a study of models of galactic evolution.) It should be noted that the present prediction refers only to the SFR averaged over regions that are at least a kiloparsec in diameter, since the gravitational aggregation processes discussed above operate only on these relatively large scales.

Several studies of star formation rates in galaxies have yielded results that are in rough agreement with the above prediction. For example Viallefond (1988), in a reanalysis of the ultraviolet measurements of Donas *et al.* (1987), found that the average SFR per unit area in a large sample of galaxies correlates well with the average surface density of atomic gas and is proportional to about the 1.6 power of the gas surface density. For a smaller sample of galaxies with more complete data on both atomic and molecular gas, Buat, Deharveng, and Donas (1989) found a similar relation with an exponent of about 1.65, although a smaller exponent is also possible if different assumptions are made about extinction. It is noteworthy that the data of Buat *et al.* (1989) show that the SFR per unit area correlates well with the total gas surface density, but not with the surface density of molecular gas alone;

this result has also been found by Kennicutt (1989). This finding is consistent with the theoretical expectations discussed above, since the aggregation processes that have been discussed depend only on the self-gravity of the interstellar medium and not on its molecular composition.

The above simple quadratic Schmidt law does not, however, provide any ready basis for understanding why galaxies with later Hubble types should convert their gas into stars more slowly than those with early Hubble types; this is one of the important properties of the Hubble sequence that needs to be understood on the basis of any theory of star formation (Larson 1983). Direct evidence for an increase in the gas depletion time with Hubble type along at least the later part of the Hubble sequence is provided by the results of Donas *et al.* (1987) for the gas depletion times in a large sample of spiral and irregular galaxies. This trend could be understood if the velocity dispersion c of the gas in galactic disks is not strictly constant, as was assumed above, but is controlled in part by the gravitational dynamics of such disks, as is found to occur in numerical simulations (Sellwood and Carlberg 1984; Carlberg 1987; Gunn 1987). In these simulations, gravitational instabilities or swing amplification effects tend to heat the disk, increasing the values of both c and Q and thus making the disk more stable; as a result, the stability parameter Q is regulated at a nearly constant value of about 1.7, which is approximately the value below which swing amplification rapidly becomes very important (Toomre 1981). If Q rather than c is assumed to be constant, then the timescale for gas accumulation $\tau \sim c/\pi G\mu = Q/\kappa$ becomes inversely proportional to the epicyclic frequency κ, and the SFR per unit area becomes proportional to $\kappa\mu$ (Larson 1988b; Silk 1988). In this case the SFR per unit area depends only linearly on the gas surface density, but it also has a dependence on epicyclic frequency that allows the variation of the star formation timescale along the Hubble sequence to be qualitatively understood: star formation would be expected to proceed more slowly in galaxies of later Hubble type, since the rotational velocity and hence the epicyclic frequency are generally smaller in galaxies of later Hubble type (Rubin *et al.* 1985).

Reality probably lies somewhere between the two cases that have been considered above. In the first case, which yielded a quadratic Schmidt law, it was assumed in effect that astrophysical processes always maintain the velocity dispersion of the gas at a constant value, presumably through a balance between energy input and dissipation. In the second case, it was assumed that the velocity dispersion is controlled by the gravitational dynamics of galactic disks and that Q rather than c is regulated at a constant value. In reality, both astrophysical and gravitational effects must operate at some level, and there will be a competition between them that results in an intermediate situation in which neither Q nor c is strictly constant but both vary moderately (Larson 1988b). Understanding better the processes that regulate these parameters will clearly be an important topic for further research. If an intermediate situation applies, then the SFR per unit area will have a dependence on gas surface density characterized by an exponent between 1 and 2, and also a dependence on epicyclic frequency with an exponent between 0 and 1.

If large-scale star formation in galaxies is driven by gravitational instability or swing amplification effects, then star formation should occur only when the surface density of the gas exceeds a threshold value corresponding to a value for Q of the order of unity (Quirk 1972; Larson 1983). Strong support for the idea that star formation is driven by the large-scale self-gravity of the gas layer in galaxies is provided by the fact that significant star formation is indeed observed to occur only where the gas surface density exceeds a threshold value corresponding to a value for Q of about 1.8 (Skillman 1987; Kennicutt 1989), which is approximately the value below which swing amplification becomes important. For surface densities above this threshold, Kennicutt (1989) finds that the SFR per unit area in galactic disks varies approximately as the 1.3 power of the gas surface density, a result consistent with the theoretical expectations discussed above. The application of plausible star formation 'laws' based on the above considerations to models of galactic evolution will be considered further in Section 4.1.

In addition to the parameter dependences of the SFR that have been discussed, it is also of interest to see whether we can understand quantitatively the rate at which the gas in galaxies is converted into stars. This requires understanding not only cloud formation rates but also the efficiency of star formation in individual molecular clouds. As reviewed by Larson (1987b, 1988b) and Franco (1992), ionization by hot stars is a major process contributing to the destruction of giant molecular clouds, and it must play an important role in limiting the efficiency of star formation in them. If it is assumed that star formation in a giant molecular cloud continues until enough hot stars have been formed to completely ionize the cloud, the implied efficiency of star formation is of the order of several percent (Whitworth 1979;

Larson 1987b; Franco 1992); this is a well-defined result because it depends only on simple physics and is not very sensitive to the details of cloud structure or dynamics. Since additional effects such as stellar winds probably also contribute to the destruction of star-forming clouds, the actual efficiency of star formation should be somewhat smaller than this simple prediction, and observational estimates of the efficiency of star formation in fact yield values that are typically only about 1 or 2 percent (Myers *et al.* 1986; Leisawitz, Bash, and Thaddeus 1989; Evans and Lada 1991). Because of this low efficiency of star formation, the time required to convert all of the gas in galaxies into stars is roughly two orders of magnitude longer than the timescale for cloud formation. For example, if the timescale for assembling the gas into molecular clouds in the local Galactic disk is 50 Myr, and if the efficiency of star formation in these clouds is assumed to be 0.02, the timescale for converting the gas into stars is 50/0.02 Myr, or 2.5 Gyr. Gas recycling increases the timescale for gas depletion by about another factor of 2 to $\sim$ 5 Gyr (Kennicutt 1992; Section 4.4). As will be seen, this prediction agrees well with the gas depletion timescales in simple models of galactic evolution that are consistent with the relevant data, so it may indeed be possible to understand on the basis of simple physics the rate at which the gas in galaxies is converted into stars.

3.5 Starbursts

It is of interest, finally, to see if we can also understand the exceptionally high star formation rates observed in starbursts. The essential characteristic of a starburst is the conversion of the available gas into stars in a time much shorter than the normal evolutionary timescale of a galaxy. Durations as short as $\sim$ 20 Myr have been inferred for starbursts in galaxies (Larson and Tinsley 1978; Kennicutt *et al.* 1987), and in some of the best studied cases such as M82 it has also been inferred that most of the gas in the starburst region is consumed by star formation during this time, at least if a normal stellar initial mass function is assumed (Rieke *et al.* 1980; Knapp *et al.* 1980; Kronberg, Biermann, and Schwab 1985). Thus, an unusually high efficiency of star formation may also be a characteristic of many starbursts.

According to the ideas discussed above, a short timescale for star formation requires either a high gas surface density or a high epicyclic frequency, or both. If the star formation timescale varies inversely with the gas surface density, a reduction by two orders of magnitude in this timescale, as is inferred for many starbursts, would require an increase by two orders of magnitude in the gas surface density in the starburst region to at least 1000 $M_\odot/\mathrm{pc}^2$ (Larson 1987b). Gas surface densities of this magnitude or even higher are indeed observed in a number of starburst systems, as reviewed by Larson (1987b) and Mirabel (1992). It is also the case that starbursts typically occur in the nuclear regions of galaxies where the epicyclic frequency is high, at least an order of magnitude higher than in typical parts of spiral disks. Thus, starburst regions typically have both a high gas surface density and a high epicyclic frequency, and both of these properties would imply a very short timescale for star formation, thus allowing the observed rapid star formation in starbursts to be understood.

The most extreme starbursts occur in the nuclei of interacting or merging galaxies, and the large central concentrations of molecular gas observed in these systems are well explained by numerical simulations of interacting or merging galaxies which show that the gas rapidly loses most of its angular momentum and falls toward the center (Noguchi 1990; Barnes and Hernquist 1991). The merger simulation of Barnes and Hernquist (1991) produces an exceedingly high gas surface density of about 4×10^4 $M_\odot/\mathrm{pc}^2$ in a central region whose radius is only about 200 pc, and this would almost certainly generate an extremely luminous burst of star formation. Similar or even more extreme concentrations of dense molecular gas have been observed in the central regions of a number of ultraluminous infrared galaxies that appear to be merging systems experiencing intense bursts of star formation (Solomon, Downes, and Radford 1992).

The high efficiency of star formation that has been inferred for some starbursts requires that the effects of ionization and winds that normally limit the efficiency of star formation in galaxies must somehow be overcome. A relevant property of starbursts in this respect may simply be the very short duration of the burst (Larson 1987b); since ionization and stellar winds exert their effects over periods of time that are fixed by stellar evolution timescales to be of the order of several million years, the feedback effect associated with ionization and winds is reduced if star formation occurs in a time that is of this order or shorter. The dynamical or free-fall time of the gas in dense starburst regions is in fact of the order of a few million years or less, and therefore a considerable fraction of the gas in such regions could be turned into stars before there has been time for ionization and winds to disperse the remaining gas, leading to a relatively high efficiency of star formation.

A high efficiency of star formation in starbursts may favor the formation of particularly massive star clusters. The formation of a bound star cluster requires a local efficiency of star formation that is of the order of 50 percent or more, and such a high efficiency is normally attained in only a very small fraction of the mass of a star forming cloud (Larson 1990b); however, in starburst regions where the average gas density and the overall efficiency of star formation are both high, a larger fraction of the stars may form in bound clusters, and relatively massive clusters may therefore be produced. Such effects may well be relevant for the formation of globular clusters (Section 5.4).

4 GALACTIC EVOLUTION AND THE STELLAR IMF

4.1 History of Star Formation

Many observed properties of galaxies depend on the relative numbers of stars with different ages, masses, and chemical compositions present, and thus on the history of star formation and chemical enrichment. In Sections 3.3 and 3.4 some of the processes responsible for determining the star formation rates in galaxies were discussed, and we now wish to see whether reasonable models of galactic evolution can be constructed that are consistent with these ideas and also with the observed properties of galaxies like our own.

We consider first the simplest type of model in which galaxies, or regions of interest in them such as annular zones in the disks of spiral galaxies, are treated as 'closed boxes' in which the initial gas is steadily converted into stars according to some law specifying the SFR as a function of gas content; such models were first studied systematically by Schmidt (1959, 1963). Normally, it is assumed that the stellar initial mass function (IMF) is universal and does not vary with time, so that the gas depletion rate is simply proportional to the star formation rate. As a typical system, we consider the local Galactic disk, or more precisely an annular zone at the Sun's distance from the Galactic center that includes the full vertical thickness of the disk. The total surface density of ordinary matter in the local disk will be assumed to be 50 $M_\odot/\mathrm{pc}^2$, based on recent dynamical estimates by Gould (1990) and Kuijken and Gilmore (1991), who found 54 and 48 $M_\odot/\mathrm{pc}^2$, respectively.

For the present surface density of gas we adopt 13 $M_\odot/\mathrm{pc}^2$, a value that includes the contribution of the diffuse components of the interstellar medium (Kulkarni and Heiles 1987; McKee 1990). We adopt an age of 10 Gyr for the local part of the Galactic disk, although it is possible that the local disk may actually be somewhat younger than this (Section 5.3). All of these disk properties are significantly revised from those assumed in earlier work (*e.g.,* Tinsley 1980, 1981b), and the effect in all cases is to make the Galactic disk a younger and less evolved system than was previously believed. As will be seen, this also reduces the differences between the predictions of the various models considered.

A model property that is of interest for comparison with data on the age composition of the local Galactic disk and of galaxies generally is the ratio $\langle\mathrm{SFR}\rangle/\mathrm{SFR}_0$ of the past average star formation rate to the present rate SFR_0; also of interest as an indicator of the rate of evolution of the system is the timescale for gas depletion, $\tau_\mathrm{g} \equiv -M_\mathrm{g}/\dot{M}_\mathrm{g}$, where M_g is the total mass of gas present. Given the total mass of ordinary matter in the system, the present gas mass, and the age of the system, these model characteristics are fixed by the assumed dependence of the SFR on the gas content M_g. Three standard assumptions for the dependence of the SFR on the gas content have been widely adopted in models of galactic evolution, and they are listed below, along with the properties of the corresponding models for the local Galactic disk:

> (1) *Constant SFR model* with SFR = constant. For this model, the ratio $\langle\mathrm{SFR}\rangle/\mathrm{SFR}_0$ is 1.0 by definition, and the gas consumption rate in the local disk is 3.7 $M_\odot/\mathrm{pc}^2/\mathrm{Gyr}$, yielding a present gas depletion timescale τ_g of 3.5 Gyr.
>
> (2) *Linear model* with $\mathrm{SFR} \propto M_\mathrm{g}$. In this model, which is the one most widely adopted, the SFR and the gas content both decline exponentially with time; for the parameters assumed above, the ratio $\langle\mathrm{SFR}\rangle/\mathrm{SFR}_0$ is 2.1 and the present gas depletion timescale is 7 Gyr.
>
> (3) *Quadratic model* with $\mathrm{SFR} \propto M_\mathrm{g}^2$. In this model, the SFR and the gas content decline more rapidly at first and more slowly at later times than in the linear model; the ratio $\langle\mathrm{SFR}\rangle/\mathrm{SFR}_0$ is 2.8, and the present gas depletion time is 10 Gyr.

Models (2) and (3), the linear and quadratic models, were first proposed and studied by Schmidt (1959). As was discussed in Section 3.4, both are plausible theoretically, and they probably bracket the range of reasonable possibilities for the dependence of the SFR on gas content. Model (1), the constant SFR model, is less plausible theoretically, but a constant SFR has been suggested by a number of authors as providing a good approximation to the star formation history of the solar neighborhood and of typical late-type galaxies (Twarog 1980; Gallagher, Hunter, and Tutukov 1984; Kennicutt 1983, 1986, 1992). A constant rate of star formation might be maintained if the gas in the region of star formation were continually replenished by an inflow from outside, a possibility that will be discussed further in Section 4.3.

In the local Galactic disk, such models can be tested by comparing them with the age distribution of nearby stars as determined by isochrone fitting. Twarog (1980) derived in this way the age distribution for a large sample of nearby F stars, and he found, under what he considered to be the most likely assumptions, that their past average formation rate was about 1.5 times the present rate. He also argued that a constant SFR is not excluded, and showed that a model with a constant SFR and gas infall can provide a good explanation of the observed stellar age-metallicity relation. However, the age distribution derived by Twarog depends on the assumed age dependence of the stellar scale height, which Twarog took to be constant for ages less than 4 Gyr and then to increase linearly with age to a value 6 times larger for the oldest stars. If it is assumed instead, perhaps more plausibly, that the scale height varies with the vertical velocity dispersion of the stars, which increases strongly with age even for ages less than 4 Gyr (Wielen 1977), then the derived age distribution shows a broad peak at an age of about 6 Gyr with a smooth decline toward both smaller and larger ages; the maximum SFR in this case is about 3.5 times the present rate, and the ratio of the past average to the present SFR is about 2.5. Clearly, there remain large uncertainties in any attempt to reconstruct the history of star formation in the Galactic disk from stellar ages, but some decrease of the SFR with time does appear to be indicated, and a value for the ratio $\langle \mathrm{SFR} \rangle / \mathrm{SFR}_0$ of the order of 2 seems at least consistent with the evidence.

Additional attempts to derive the age distribution of local field stars have been made by Noh and Scalo (1990) using chromospheric emission intensities and by Rana (1991) using chemical abundances as age indicators. In both cases, the results suggest significant short-term fluctuations in the past SFR superimposed on a long-term decline that is roughly consistent with the results discussed above. It is possible that bursts of star formation have occurred in the past history of our Galaxy, as has been suggested by Scalo (1987b), but it is not clear whether all of the fluctuations in the SFR claimed by the above authors are in fact real. If such fluctuations do occur, the models discussed here should probably be regarded as describing only average values and long-term trends.

The methods available for determining the history of star formation in other galaxies are less direct, and rely on integrated photometric properties; these methods and the results obtained from them have been reviewed extensively by Kennicutt (1986, 1990, 1992). The results generally favor roughly constant rates of star formation in the disks of typical late-type spiral galaxies like our own, although the uncertainties are again considerable, and values for the ratio $\langle \mathrm{SFR} \rangle / \mathrm{SFR}_0$ that are as large as 2, as suggested above, are not excluded. An additional piece of evidence of this type, based on a comparison of the observed colors of galaxies with the predictions of synthetic stellar population models, has been discussed by Larson (1991b). The stellar population models used were computed by Yamanaka (1987), and they assumed a standard Salpeter (1955) IMF, an age of 15 Gyr, and an exponentially declining SFR with a range of values for the decay time. When these models are compared with the observed UBV colors of galaxies given by de Vaucouleurs (1977) as a function of Hubble type, the values of $\langle \mathrm{SFR} \rangle / \mathrm{SFR}_0$ for models matching the colors of galaxies of types Sa, Sb, Sc, Sd, and Irr are found to be about 7, 3.4, 1.8, 1.1, and 0.7, respectively. Our Galaxy is usually considered to have a Hubble type between Sb and Sc (de Vaucouleurs 1983), and these results would then imply that the average value of $\langle \mathrm{SFR} \rangle / \mathrm{SFR}_0$ for our Galaxy is between 1.8 and 3.4. For the local Galactic disk, the $B-V$ color of 0.53 estimated by de Vaucouleurs (1983) implies a value for $\langle \mathrm{SFR} \rangle / \mathrm{SFR}_0$ of about 1.9, which is similar to the values estimated above from the stellar age distribution. These results suggest that even Sc galaxies have experienced some decline in their SFR with time, and that only galaxies of type Sd or later have had nearly constant star formation rates. Possible explanations for the lack of any decrease with time of the SFR in Sd and irregular galaxies might be that they have continued to accrete gas, or that some of them are actually relatively young systems that have formed the bulk of their stars only recently. However, it is also possible that the stellar population models still contain significant inaccuracies; the present uncertainty in these models is probably of the order of 0.1 in the predicted $B-V$ color, or a factor of 2 in the inferred value of $\langle \mathrm{SFR} \rangle / \mathrm{SFR}_0$.

We conclude that a value of about 2 for the ratio $\langle \mathrm{SFR} \rangle / \mathrm{SFR}_0$ in the local Galactic disk and in typical Sc galaxies is most consistent with the evidence discussed here, although the value of this ratio is probably uncertain by about a factor of 2. Thus the simple linear model, which predicts $\langle \mathrm{SFR} \rangle / \mathrm{SFR}_0 = 2.1$ for the local Galactic disk and a similar value for typical Sc galaxies, is consistent with all of the evidence that has been discussed. However, the constant-SFR and quadratic models, for which the predicted values of $\langle \mathrm{SFR} \rangle / \mathrm{SFR}_0$ are 1.0 and 2.8, respectively, seem less consistent with the data, although they cannot presently be excluded, given the uncertainties.

We recall from Section 3.4 that the linear model, which assumes that the SFR is proportional to the gas content, is expected to apply if the stability parameter Q is regulated at a constant value; in this case, the SFR is predicted also to be proportional to the epicyclic frequency. If this type of model applies to all galaxies, the timescale for star formation and gas depletion would then be expected to be proportional to the epicyclic period, or approximately to the rotation period (*e.g.,* Wyse and Silk 1989); thus the rotation period may in fact be what sets the basic clock rate for the evolution of galaxies (Larson 1983, 1988b; Silk 1988). The timescales for gas depletion that would be deduced from the observed gas contents of galaxies if the simple linear model were assumed to apply to galaxies of all Hubble types would range from about 4 Gyr for Sa galaxies to 12 Gyr for Irr galaxies; this variation in timescale by a factor of 3 along the Hubble sequence is roughly consistent with the variation in rotation period along the sequence, in agreement with the idea that the rotation period is what controls the rate of evolution of galaxies.

4.2 Chemical Evolution

A second goal of models of galactic evolution is to account for the observed heavy-element abundances in stars and their variation with stellar age (Tinsley 1980; Pagel 1981). We are here interested in whether the same models that can account for the star formation history of galaxies can also account for data such as the age-metallicity relation for stars in the solar neighborhood. Twarog (1980) derived the relation between age and metallicity (or iron abundance) for a large sample of nearby F stars, and his results have been used in many studies of Galactic chemical evolution; if the more recent results of Nissen, Edvardsson, and Gustafsson (1985) and Carlberg *et al.* (1985) are combined with those of Twarog, the scatter in the age-metallicity relation is increased but the general trend is not altered, as is illustrated in the recent reviews by Matteucci (1991) and Rana (1991).

It is instructive to display the age-metallicity relation in a linear plot of iron abundance versus time (*e.g.,* Pagel 1981) rather than in the usual logarithmic plot, since the data then exhibit a nearly linear increase of metallicity with time, except during the most recent few Gyr where this trend flattens. Such a linear increase of metallicity with time is just what is predicted by the simplest closed-box model of galactic evolution if the SFR is proportional to the gas content, as in the model favored above. The 'quadratic model' actually gives a slightly better fit to the data since it predicts a slightly more rapid initial rise in metallicity and a more gradual increase at later times, but the differences between these two models are small compared to the scatter in the data. The 'constant-SFR' model of Twarog (1980) with gas infall also provides a good representation of the data, so it appears that the available data on the stellar age-metallicity relation do not discriminate strongly between the models that have been discussed, all of which are in satisfactory agreement with these data.

However, there remain two long-standing puzzles posed by the data on stellar chemical abundances, and their resolution may have important implications for our understanding of galaxy formation and evolution. The most classical puzzle is the 'G-dwarf problem', namely a relative paucity of metal-poor stars compared the predictions of simple closed-box models: a closed-box model predicts, for example, that 28 percent of the stars should have metallicities less than half of the median value, but observations show that less than 10 percent of nearby stars have such low abundances. The most generally adopted explanation of this discrepancy is that continuing infall of primordial gas moderates the increase of metallicity with time and thus produces a narrower metallicity distribution than in a closed-box model (Tinsley 1980; Pagel 1989, 1992; Matteucci 1991). The second puzzle, which is probably related to the first, is that data on old open clusters in the Galactic disk show no evidence for any increase of metallicity with time during the past $\sim$ 8 Gyr (Demarque, Green, and Guenther 1992; Friel 1992; Chiosi 1992). It is not clear to what extent the samples of clusters that have been studied so far are representative, but if indeed there has been little or no increase in metallicity during the last half or more of the age of the Galactic disk, this would appear again to argue for an inflow of metal-poor gas to suppress the increase of metallicity with time.

4.3 Gas Depletion and Infall

Because of the potential importance of gas flows for galactic evolution, the question of whether primordial gas continues to fall into galaxies at a significant rate has long been of interest. A number of authors, including Oort (1970), Larson (1972, 1976b), Gunn (1982, 1987), and Toomre (1990), have suggested that primordial gas may continue to rain into galaxies for a long time following their formation; this might be expected to occur as part of the continuing growth of galaxies by accretion in an expanding universe. The cosmological simulations mentioned in Section 2.2 illustrate such accretion processes, and suggest that they may be most important in the less dense regions of the universe that are now inhabited mainly by spiral galaxies. It has also been suggested a number of times that continuing gas infall is needed to replenish the interstellar gas in spiral galaxies and to prevent them from running out of gas in a time less than the Hubble time. Here we briefly review the estimates that have been made of the rates of gas depletion in galaxies and of the inferred role of gas infall.

van den Bergh (1957) initially estimated that the time required for depletion of the gas in the local Galactic disk is only 0.7 Gyr (for an assumed disk age of 5 Gyr), and suggested that the gas is replenished by a radial flow in the Galactic disk. Larson (1972) later estimated a gas depletion time of about 3 Gyr which he still regarded as being uncomfortably short, and suggested that the gas is replenished by infall from outside the Galactic plane. Larson, Tinsley, and Caldwell (1980) again estimated short gas depletion times of about 2 Gyr for the local Galactic disk and 4 Gyr for typical spiral galaxies, and suggested that the gas in these systems is replenished by infall. However, the timescales estimated by the latter authors should probably be increased by a factor of 2 because they were derived assuming an IMF that puts as much mass into brown dwarfs as into visible stars, a possibility that is probably now excluded (Section 4.4). Also, the estimated gas depletion time for the local Galactic disk was based on a lower gas surface density than that adopted above, and would be further increased to about 6 Gyr if a gas surface density of 13 $M_\odot/\mathrm{pc}^2$ were adopted. Kennicutt (1983) estimated gas depletion times for a larger sample of spiral galaxies and obtained a median value of about 5 Gyr, assuming a standard IMF with no brown dwarfs; similarly, Donas *et al.* (1987) estimated gas depletion times for a large sample of spiral galaxies, and obtained a median value that is about 7 Gyr when calculated using the same assumptions as Kennicutt (1983). Sandage (1986) has also estimated gas depletion times of about 4 to 20 Gyr for a number of mostly dwarf galaxies in the Local Group and the Virgo cluster. All of these authors considered their results to pose a problem for simple models in that the estimated gas depletion time is nearly always shorter than the Hubble time, suggesting that either gas infall or a non-standard IMF is required. However, these estimated timescales are actually not very different from those that would apply in simple closed-box models in which both the gas content and the SFR decay exponentially with time, so it is not clear that either infall or a non-standard IMF is really needed. For example, the linear model of Section 4.1 for the local Galactic disk has a gas depletion timescale of 7 Gyr; this is essentially the same as the revised estimate of 6 Gyr noted above for the local Galactic disk, so there is no compelling need to invoke gas infall to account for the present properties of the local Galactic disk. This reversal of previous conclusions arises from a combination of revisions in the assumed parameters for the local Galactic disk, including a smaller total surface density, a higher gas surface density, and a smaller age, all of which make the local disk a less evolved system than was previously believed.

Nevertheless, there is still some evidence for an inflow of gas into our Galaxy in the form of high-velocity clouds that appear to be falling into the Galactic disk (van Woerden, Schwarz, and Hulsbosch 1985; Songaila, Cowie, and Weaver 1988; Mirabel 1989; Wakker 1991); some other galaxies also show evidence for high-velocity clouds that may represent infalling gas (Sancisi *et al.* 1990; van Gorkom *et al.* 1990; Kamphuis and Briggs 1992). According to Mirabel (1989), the total rate of infall of gas into our Galaxy deduced from the high-velocity cloud observations is between 0.2 and 0.5 $M_\odot$/yr, although this estimate is very uncertain because of the unknown distances of most of the high-velocity clouds. If this gas falls in uniformly over a disk of radius 15 kpc, which is also a very uncertain assumption, the local infall rate per unit area is then between 0.3 and 0.7 $M_\odot/\mathrm{pc}^2/\mathrm{Gyr}$. This estimated infall rate may be compared with the present rate of gas depletion in the linear model of Section 4.1, which is 1.8 $M_\odot/\mathrm{pc}^2/\mathrm{Gyr}$; the estimated infall rate is thus only between 15 and 40 percent of the present gas depletion rate, making infall a minor but not completely negligible effect at the present time.

Since the infall rate is expected to decrease with time, it remains possible, and perhaps even likely, that gas infall was important at earlier times in the evolution of the Galactic disk. A number of authors have considered models in which the infall rate declines exponentially with time, and this work has been reviewed, for example, by Matteucci (1991). A particularly simple case of such a model is one in which the disk is built entirely by infall and the time-constant τ for decay of the infall rate is the same as the timescale for gas depletion in the absence of infall. The star formation rate can then be shown to have a time dependence of the form $t \exp(-t/\tau)$, implying a rapid initial rise followed by a slower decline, in qualitative agreement with the evidence regarding the history of star formation in the solar neighborhood. With a value for τ of 4 Gyr and a disk age of 12 Gyr, such a model satisfactorily represents the data on the local SFR discussed in Section 4.1 and predicts a value for the ratio $\langle \mathrm{SFR} \rangle / \mathrm{SFR}_0$ of 1.8. The present gas infall rate in this model is 0.7 $M_\odot/\mathrm{pc}^2/\mathrm{Gyr}$, which is consistent with the evidence mentioned above. The model predicts a linear increase of metallicity with time, just as does the linear closed-box model, and therefore it gives an equally good representation of the observed age-metallicity relation, although it again does not account for the flattening of this relation at recent times. The fraction of stars with metallicities less than half of the median value is predicted to be 19 percent, compared with 28 percent for a closed-box model and less than 10 percent as observed. Thus such a model, in which infall effects are modest at the present time, does better than a closed-box model but still does not fully solve the G-dwarf problem, nor does it explain the slow or nonexistent increase in metallicity at recent times. Thus additional effects, such as more infall at recent times, are still required to account for the existing data on chemical abundances. More data will clearly be needed to resolve the still very uncertain issue of the role of gas infall in galactic evolution.

4.4 The Initial Mass Function

The observed properties of stellar systems depend not only on the history of star formation in them, but also on the spectrum of masses with which the stars are formed; indeed, the star formation history and the stellar mass spectrum are often so closely interrelated in their observational implications that we cannot determine one without making some assumption about the other. Up to this point we have assumed that the IMF is a universal function with a standard form similar to that first proposed by Salpeter (1955). However, it has often been suggested that the IMF may vary with time or location in galaxies, and a number of models of galactic evolution have been proposed that are based on a variable or non-standard IMF. For example, Schmidt (1963) proposed that the G-dwarf problem can be solved if the IMF varies with time in such a way that a higher proportion of massive stars was formed at earlier times. In deriving the IMF from the present-day mass function of field stars, it has generally been assumed that the SFR is constant (*e.g.,* Miller and Scalo 1979), while in deriving the SFR as a function of time, a standard form has been assumed for the IMF (Twarog 1980); thus efforts to derive information about these two functions from the data have been to some extent circular, and it is possible that other sets of assumptions might also be consistent with the observations.

If it is not demanded that the IMF be a monotonically decreasing function of mass for masses near one solar mass, then models become possible in which the SFR decreases strongly with time and the IMF is double-peaked or bimodal (Quirk and Tinsley 1973; Scalo 1986; Larson 1986). Scalo (1986) and Larson (1986) discussed some pieces of evidence suggesting that the IMF may not be a monotonically declining function of mass near one solar mass. One such piece of evidence was the presence of a small dip in the mass function of nearby stars at a mass of about 0.7 $M_\odot$, which might represent the minimum between the two peaks of a bimodal IMF. Another piece of evidence was the apparent deficiency of stars with masses below about one solar mass in the mass spectra of many star clusters; van den Bergh (1972) had suggested on this basis that there might be two modes of star formation, one that produces field stars and makes mostly stars with masses below 1 $M_\odot$, and a second that operates only in clusters and makes mostly stars more massive than 1 $M_\odot$. Suggestions that star formation is bimodal have also been made on other grounds by Güsten and Mezger (1983) and by Sandage (1986), and a model of galactic evolution based on this idea was proposed by Larson (1986). In this model, the low-mass mode of star formation was assumed to form stars at a constant rate, thus maintaining consistency with the evidence that the SFR for solar-type stars has not varied much with time, while the high mass mode was allowed to form stars at a rate that decreases strongly with time. Like the model with a variable IMF earlier considered by Schmidt (1963), this model provides a possible solution to the G-dwarf problem, but the main reason for proposing it was that the unseen mass that was thought to exist in the local Galactic disk (Bahcall 1986) could readily be accounted for by the remnants of the many intermediate-mass and high-mass stars formed during early stages of Galactic evolution.

None of the evidence suggesting a bimodal IMF is conclusive, and the evidence noted above may well have other explanations, such as features in the stellar mass-luminosity relation (D'Antona and Mazzitelli 1986) and incompleteness of the data for clusters (Stauffer *et al.* 1991). Some difficulties with models having a strongly bimodal IMF, such as the fact that most of the predicted white dwarfs should probably have been seen, have also been pointed out by Olive(1986), Scalo (1987a), and Meusinger (1989). In any case, this type of model may now be excluded by the fact that the more recent data of Kuijken and Gilmore (1989), as analyzed by Gould (1990) and Kuijken and Gilmore (1991), no longer require any significant amount of unseen mass in the solar neighborhood. If the local surface density of matter in the Galactic disk is 50 $M_\odot/\mathrm{pc}^2$ and the gas surface density is 13 $M_\odot/\mathrm{pc}^2$, as adopted above, and if the surface density of visible stars and white dwarfs is 35 $M_\odot/\mathrm{pc}^2$, as adopted by Kuijken and Gilmore (1989), then this leaves only an insignificant 2 $M_\odot/\mathrm{pc}^2$ of mass not accounted for. This would imply that any high-mass mode of star formation must be much less significant than in the model of Larson (1986), in which case bimodality is no longer an important effect and a more conventional model can account satisfactorily for the data.

All of the present evidence appears to be consistent with an IMF that has the same basic form everywhere, and is characterized by a typical stellar mass of the order of one solar mass and a possibly universal power-law tail toward higher masses (Larson 1991a; Hunter 1992). Current constraints on the amount of mass in the local Galactic disk exclude any major contribution from either stellar remnants or brown dwarfs, and this implies that neither the upper nor the lower end of the IMF can ever have been greatly enhanced over this standard form. A similar constraint is placed on the IMF by determinations of the mass-to-light ratios of the disks of other spiral galaxies, for which values of only ~ 1.6 to 3.2 are obtained that again leave little room for unseen mass (Kent 1987). There is apparently some local variability of the lower IMF in different regions of star formation, since the observed T Tauri stars appear to have somewhat larger masses in the larger and warmer clouds (Larson 1982; Myers 1991). However, there does not appear to be any general lack of low-mass young stars in massive clouds such as the Orion molecular clouds, where large numbers of low-mass stars are found in several dense embedded clusters (Lada and Lada 1991). In fact, the Trapezium cluster, in which high-mass star formation might have been expected to be favored according to some speculations (Larson 1985, 1986), actually contains many hundreds of low-mass stars with a mass function that continues to rise down to masses as small as $\sim 0.3\ M_\odot$, showing no clear indication of any departure from a standard IMF (McCaughrean *et al.* 1991).

If it is assumed, therefore, that the stellar IMF is universal and does not vary with time or location, and if it is also assumed that the past average SFR in the local Galactic disk was twice the present rate, as was suggested in Section 4.1, then the IMF for the more massive stars is increased by a factor of 2 over that derived on the assumption of a constant SFR (*e.g.,* Scalo 1986; Hunter 1992), and this results in an IMF that is somewhat flatter than the Salpeter function in the vicinity of one solar mass and below. The increased fraction of massive stars in this IMF leads to a somewhat larger gas recycling rate than has usually been assumed: about 48 percent of the gas that goes into stars is predicted to be returned to the interstellar medium in this case. The gas depletion timescale is therefore increased by almost a factor of 2 by the effect of gas recycling, a result that was already used in Section 3.4 in estimating the local gas depletion time.

4.5 Some Ideas on the Origin of the IMF

Two basic features of the stellar IMF that appear to be of fundamental significance are the existence of a characteristic stellar mass of the order of one solar mass, and the existence of a possibly universal power-law form for the upper IMF. Here we mention some possible ways of understanding these features; recent reviews of this subject have been given, for example, by Zinnecker (1987) and Larson (1989, 1991a).

The characteristic stellar mass of about one solar mass may reflect a typical mass scale for cloud fragmentation that is approximately the Jeans mass. Although the original analysis by Jeans of the stability of an infinite uniform medium was not mathematically self-consistent, a rigorous stability analysis which leads to a dimensionally equivalent result can be made for an equilibrium sheet, disk, or filament (Larson 1985). The minimum fragment mass or Jeans mass for such a configuration depends on its temperature and surface density, and if the values of these quantities typically observed in dark clouds are assumed, a mass of about 1.5 $M_\odot$ is obtained (Larson 1985). Another approach to estimating a mass scale for fragmentation, which again leads to a similar result, is to assume that protostellar clumps form in pressure balance with a surrounding medium; the minimum collapsing mass is then $M_\mathrm{J} = 0.85c^4/G^{3/2}P^{1/2}$, where P is the ambient pressure (Spitzer 1968). As discussed by Elmegreen (1992), this result applies even in a cloud supported by magnetic fields or turbulence, since the internal magnetic or turbulent support of a protostellar clump must be dissipated before the clump can collapse. The fact that molecular clouds all tend to have similar column densities implies that they also have similar pressures if they are self-gravitating structures (*e.g.,* McKee and Lin 1988); if we adopt the typical cloud pressure implied by the data of Myers and Goodman (1988), which these authors suggest is largely magnetic and characterized by a field strength of about $30\,\mu$G, the above relation predicts a critical mass of about $0.7\,M_\odot$. Although other physical processes such as stellar winds may also play a role in limiting the masses that stars can attain, the relatively high efficiency of star formation observed in the embedded clusters in the Orion clouds (Lada and Lada 1991) suggests that typical stellar masses are limited more by the scale of cloud fragmentation than by the effects of stellar winds (Larson 1992).

What might account for the apparently universal power-law form of the upper IMF? Two possibilities, which are not necessarily mutually exclusive, are the formation of the more massive stars by a scale-free accretion process (Zinnecker 1982), and the formation of stars in a self-similar clustering hierarchy in which their masses are related to the masses of the subclusters in which they form (Larson 1978, 1991a, 1992). The latter possibility receives some support from the evidence that star-forming clouds are hierarchically structured on a wide range of scales (Scalo 1985, 1990; Herbertz, Ungerechts, and Winnewisser 1991), that stars commonly form in groups or clusters (Larson 1982; Evans 1991; Lada, Strom, and Myers 1992), and that young star clusters often show internal subclustering (Elson 1991).

Several recent studies have produced evidence that molecular clouds are not only hierarchical but also self-similar or fractal in structure over a wide range of scales (Scalo 1990; Dickman, Horvath, and Margulis 1990; Falgarone and Phillips 1991; Falgarone, Phillips, and Walker 1991; Zimmermann 1992). It is possible that the power-law form of the upper IMF has its origin in this approximately scale-free character of the structure of molecular clouds. If stars form from the subunits of a fractal cloud, and if their masses scale in a simple way with the sizes of these subunits, then the stellar mass spectrum will be a power law whose slope x is related to the fractal dimension D of the cloud (Larson 1992). For example, one possibility is that stars form from linear cloud structures such as filaments or strings of clumps, and that their masses are proportional to the lengths of these filaments. Molecular clouds are frequently observed to be filamentary in structure (Scalo 1990; Bally *et al.* 1991), and evidence that stars often form in filaments is provided by the fact that the cloud cores in which stars form are typically elongated and often appear to be parts of filaments (Schneider and Elmegreen 1979; Myers *et al.* 1991). If the filaments are approximately isothermal equilibrium configurations, as might be expected if they are formed by the fragmentation of isothermal gas sheets or disks (Miyama, Narita, and Hayashi 1987), then they are predicted to have a constant mass per unit length of about $2c^2/G$; if stars form with a reasonably high efficiency from such filaments, they will then have masses approximately proportional to the lengths of the filaments from which they form.

The evidence for fractal structure in molecular clouds mentioned above, combined with the evidence for filamentary structure, suggests that star-forming clouds may consist of, or may contain, fractal networks of filaments. A fractal structure is one that is made up of substructures similar to the whole, and these substructures have a distribution of linear sizes given by

$$dN/d\log l \ \propto \ l^{-D} \ ,$$

where D is the fractal dimension. For a fractal network of filaments, the substructures are the various branches and sub-branches of the network, and this equation gives the distribution of sizes of the branches; if the branches are made of filaments, it also gives the distribution of filament lengths in the cloud. If stars form from these filaments with masses proportional to their lengths, then the distribution of stellar masses m has the same form as the distribution of filament lengths:

$$dN/d\log m \ \propto \ m^{-D} \ .$$

This predicted mass distribution has the same form as the stellar IMF expressed in terms of the exponent x of Tinsley (1980), and becomes identical to it if $x = D$; thus, under the above assumptions, the slope x of the IMF is identical to the fractal dimension D of the star-forming cloud (Larson 1992). (Note that $x = -\Gamma$ in the notation used by Scalo (1986) and by Hunter in this volume.)

Several of the studies quoted above found that the boundaries of molecular clouds on contour maps are fractal curves with dimensions of about 1.3, and this suggests that the surfaces of these clouds are fractal surfaces with a dimension of about 2.3. If the three-dimensional structure of molecular clouds is actually very open, so that their internal structure is closely reflected in their surface structure and can be characterized by a similar fractal dimension, then an IMF slope of $x \sim 2.3$ is predicted (Larson 1992). This may be compared with the observed slope of $x = 1.7 \pm 0.5$ for the upper IMF (Scalo 1986). It is not certain that this difference is significant, but a smaller value of x might be predicted if, for example, stars form with masses proportional to a higher power than unity of the linear sizes of the basic cloud structures in which they form, as would not seem implausible. It will clearly be of great interest to establish in more detail not only the degree to which star-forming clouds show self-similarity in their structure, but also the nature of the cloud subunits in which stars form and the way in which the masses of stars are related to the properties of these basic cloud subunits.

5 EARLY GALACTIC EVOLUTION AND THE FORMATION OF GLOBULAR CLUSTERS

5.1 Properties of the Galactic Halo

We consider finally the earliest stages of galactic evolution, namely those that formed the halo and bulge components of galaxies like our own. We are interested particularly in the formation of the halo of our own Galaxy, since this is the system for which we have the most detailed information. Since the spheroids of spiral galaxies have properties similar to those of elliptical galaxies of the same luminosity, the processes that formed the spheroids of spirals were presumably similar to those that formed many elliptical galaxies.

A basic and long-debated question about the structure of our Galaxy is whether the Galactic halo and disk are distinct systems with separate origins, or whether they are just the extremes of a continuum of stellar populations formed by a single continuous process. In recent years, most research has favored the conclusion that the halo and the disk are discrete systems and are not part of a continuum. For example, studies of the Galactic globular clusters have demonstrated the existence of distinct halo and disk subgroups which are apparent as two peaks in the cluster metallicity distribution (Zinn 1985, 1990; Armandroff 1989); the more metal-poor group has a nearly spherical spatial distribution with large random motions and little net rotation, while the more metal-rich group has a flattened spatial distribution with rapid rotation and relatively small random motions. A clear separation between halo and disk populations is also found in studies of the kinematics and metallicities of nearby field stars (*e.g.,* Carney, Latham, and Laird 1990): when the velocity of rotation of these stars around the Galactic center is plotted versus stellar metallicity, the halo and disk populations are found to occupy distinct regions of the diagram, with little overlap. Further evidence for a discontinuity in properties between the halo and the disk of our Galaxy has also been presented by Norris and Ryan (1991) and Majewski (1992). All of this evidence suggests that the halo and the disk were formed by separate processes, and perhaps at different times. The fact that the halo has little rotation and is dominated by random motions suggests, in particular, that the halo was formed in a much more chaotic way than the disk.

One important clue to the processes involved in the formation of the halo of our Galaxy, and of galactic spheroids generally, may be the presence in these systems of large numbers of globular clusters, which are typically much more massive than the open clusters that have formed more recently in galactic disks. The presence of such massive clusters in galactic spheroids suggests that, in addition to being a more chaotic process, the formation of spheroids may have involved much larger star-forming subunits than are now found in galactic disks.

5.2 Implications of Galaxy Formation Simulations

We recall that simulations of the evolution of a universe dominated by cold dark matter predict an early period of rapid merging of smaller structures into larger ones in the densest regions (*e.g.,* Frenk *et al.* 1988). When simple treatments of gas dynamics and star formation are included in such simulations, compact galaxy-sized clumps of gas and stars form, and they may survive as separate systems when their dark halos merge (Carlberg 1988). In the simulations these clumps represent galaxies in forming groups or clusters, but similar processes might also be involved in the formation of the halos of individual galaxies, and globular clusters that form in protogalactic clumps or subsystems might similarly survive destruction because of their small sizes. After an initial chaotic period of mergers has made a spheroid, a more quiescent period of settling of diffuse gas may then build up a disk. Such a two-stage galaxy formation process, characterized by an initial rapid phase of spheroid formation followed by the more gradual building up of a disk from residual gas, is seen in the dissipative collapse calculations of Larson (1976a) and also in the more realistic simulations of galaxy formation by Katz (1992); in the latter calculations, the spheroid is formed by mergers between protogalactic clumps in a process closely resembling the mergers between galaxy-sized objects that occur on larger scales in the cosmological simulations.

In some of the protogalaxy simulations of Katz (1992), a few compact stellar subsystems survive for a considerable time as small satellite systems; this result is suggestive because many spiral galaxies, including our own, have a number of dwarf satellites. The eventual fate of most such satellites is almost certainly to be accreted by the main galaxy, in which case their stars and clusters will be merged into the halo of the main galaxy and their gas will be added to the disk. The accretion of satellite systems early in the evolution of our own Galaxy might account for the origin of the globular clusters in the outer Galactic halo, as has been suggested by Searle and Zinn (1978) and Freeman (1990). The accretion of small satellites might also disrupt or perturb a forming galactic disk, and this might account for the relatively thick older components of the disks of spiral galaxies like our own (Freeman 1990; Katz 1992).

5.3 The Galactic Fossil Record

If the formation of the halo of our Galaxy and of other galactic spheroids was a chaotic process, as has been suggested, it is not amenable to simple modeling like the relatively orderly evolution of galactic disks discussed in Section 4. We must therefore rely on observations to provide a picture of how the halo of our Galaxy evolved; specifically, we must rely on the fossil record provided by the oldest stars and star clusters. Reviews of some of the recent work in this field and its implications been given by van den Bergh (1990b) and Larson (1990c).

A question of central interest concerns the chronology of halo formation, as reflected in the age distribution of the globular clusters. A small age spread among the globular clusters would be consistent with a rapid 'monolithic' protogalactic collapse, as was envisioned by Eggen, Lynden-Bell, and Sandage (1962), whereas a large age spread would indicate a more prolonged and chaotic process of halo formation, possibly involving the merging of smaller systems. Although this subject has been controversial (as reviewed, for example, by Freeman 1989 and Hesser 1991), it is now generally accepted that age differences of several Gyr do exist among the Galactic globular clusters (VandenBerg, Bolte, and Stetson 1990; Sarajedini and Demarque 1990; Demarque, Deliyannis, and Sarajedini 1991; Lee 1992b). A brief summary of some recent age determinations has been given by Larson (1990a), and ages for larger samples of clusters have been given by Sarajedini and King (1989), Carney, Storm, and Jones (1992), and Chaboyer, Sarajedini, and Demarque (1992). The typical age of the Galactic globular clusters is $\sim$ 15 Gyr, but some clusters have ages as small as 12 Gyr, and the youngest clusters presently known, the small outer halo clusters Pal 12 and Ruprecht 106, are only about 10 or 11 Gyr old (Stetson *et al.* 1989; Chaboyer *et al.* 1992). Although the absolute ages of the globular clusters may be subject to some revision, the age differences between them are relatively well determined. For example, it now seems well established that the comparison pair of moderately metal-rich clusters NGC 288 and NGC 362 have ages that differ by about 3 Gyr (VandenBerg, Bolte, and Stetson 1990; Sarajedini and Demarque 1990), while the more metal-poor comparison pair NGC 6397 and Ruprecht 106 have ages that differ by about 4 Gyr (Buonanno *et al.* 1990; Demarque *et al.* 1991). There is a correlation between age and metallicity in the expected sense that the more metal-rich clusters tend to be younger (*e.g.,* Chaboyer *et al.* 1992), but the correlation is dominated by a scatter in age which is at least as large as the trend and is of the order of several Gyr at all metallicities. The total age spread is at least $\sim$ 5 Gyr, or one-third of the Hubble time. Thus the formation of globular clusters in the halo must have continued for at least the first one-third of Galactic history, and our Galaxy must have looked very different during that period than it does now.

Additional information about halo chronology is provided by the horizontal branch structure of the globular clusters, which depends on metallicity and also on a second parameter that is probably age. The age interpretation of the second parameter was suggested by Rood and Iben (1968) and Searle and Zinn (1978), and is supported by the work of Sarajedini and King (1989), Lee, Demarque and Zinn (1988, 1990), and Lee (1992a,b); in particular, it is supported by the age differences found between the comparison pairs mentioned above, since the horizontal branches of these clusters differ in just the way that would be expected theoretically on the basis of the known age differences. The second parameter has a dispersion among clusters that increases with distance from the Galactic center, and this suggests that the age spread among the globular clusters also increases with distance from the center. Moreover, the average cluster age inferred from the second parameter effect decreases with increasing Galactocentric distance from about 15 Gyr for clusters within 8 kpc of the Galactic center to only about 10 Gyr for clusters more than 24 kpc from the center (Lee 1992a,b). A similar trend is also seen in the direct age determinations of Chaboyer *et al.* (1992). These results thus suggest that the innermost part of the Galactic halo formed first and within a relatively short period of time, while the formation of the outer halo took progressively longer with increasing distance from the center; in other words, the evidence suggests that the Galactic halo was built up from the inside out.

If the process of halo formation was chaotic and involved the merging of subunits, the residual gas probably could not begin to settle into a disk until this initial chaotic phase was completed. In agreement with this expectation, the age of the local Galactic disk appears to be comparable to or smaller than the ages of the youngest globular clusters. A relatively young disk age is indicated, for example, by the steep drop in the luminosity function of the nearby white dwarfs at low luminosities, which can only be understood on the basis of current white dwarf theory if star formation in the local Galactic disk did not begin until about 7 to 11 Gyr ago (Iben and Laughlin 1989; Noh and Scalo 1990; Van Horn 1991; Wood 1992). Also, the oldest known Galactic open cluster, NGC 6791, has an age of only about 7 to 9 Gyr which is consistent with the age of the disk inferred from the white dwarf luminosity function (Demarque, Green, and Guenther 1992). The disk globular clusters may be older than this, since the best studied such object, 47 Tucanae, is about 14 Gyr old; however, since the disk globular clusters are concentrated in the inner part of the Galactic disk, this age may be more representative of the inner disk than of the local region. If the inner disk is indeed older, all of the evidence would then be consistent with a picture in which both the halo and the disk of our Galaxy were built up from the inside out, the formation of the disk occurring after the formation of the halo was completed at each radius.

The evidence thus argues against the classical picture in which the Galactic halo was formed by a rapid collapse, and is more consistent with the picture suggested by recent cosmological simulations in which the formation of galactic halos is a relatively prolonged and chaotic process that involves mergers among subunits and the continuing accretion of smaller systems. A similar picture of halo formation by the merging of protogalactic fragments was suggested by Searle (1977) and Searle and Zinn (1978) as a way to account for the properties of the Galactic globular clusters, including not only the second parameter effect but also the large dispersion in metallicity among the clusters. If the hypothetical protogalactic subsystems had a spatial distribution that was concentrated toward the center of the protogalaxy, they would have merged first in the dense central regions and progressively later with increasing distance from the center because of the lower densities and longer dynamical timescales at larger galactocentric distances. It might then be expected that the halos of galaxies would be built up from the inside out, just as is suggested by the evidence discussed above. If the disks of spiral galaxies are made from gas left over from the process of halo formation, then both the spheroids and the disks of galaxies may be built up from the inside out in a process that might be visualized as a gradual emergence of order from chaos (Larson 1990c).

If this inside-out picture of galaxy formation is correct, the central bulge of our Galaxy might be expected to be the oldest part of the Galaxy. No ages are yet known for any bulge clusters, but Lee (1992a,b) has recently shown that there is evidence from the metallicity distribution of the RR Lyrae stars in the Galactic bulge that the radial variation of the second parameter observed in the Galactic halo continues all the way into the central bulge; interpreted as an age effect, this implies that the bulge of the Galaxy is older by about 1 Gyr than even the oldest halo clusters. If the Galactic bulge was indeed the first part of our Galaxy to form, it may then have served as a nucleus around which the rest of the Galaxy was built up from the inside out, as sketched above.

This process of galaxy building may continue in the future with the accretion by our Galaxy of the Magellanic Clouds, which are apparently now in the process of being tidally disrupted by interaction with our Galaxy. If the Magellanic Clouds eventually merge with our Galaxy, their stars and clusters will be added to the Galactic halo and their gas will be added to the disk, and both the halo and the disk will then grow somewhat in size and mass. Such a process of slow galaxy building by the occasional accretion of smaller galaxies may in fact be a rather common process, as is suggested in the case of the elliptical galaxies by the frequent presence of shell-like structures in their outer regions (Schweizer and Ford 1985), and in the case of the spiral galaxies by the frequent occurrence of disturbances such as warps and asymmetries in the outer parts of their disks (Binney 1990; Kamphuis and Briggs 1992).

5.4 Formation of Globular Clusters

Globular clusters are clearly of crucial importance as galactic fossils, not only because they can provide information about the chronology of early galactic evolution but also because of what they may be able to tell us about the conditions that existed at the time of their formation; for example, they may contain clues about the nature of the star-forming subunits from which galactic spheroids were formed. It is therefore of great interest to understand something about the origin of the globular clusters themselves.

While the formation of star clusters as massive as typical globular clusters has not yet been clearly observed, and so cannot be studied empirically, there appears to be no sharp division in properties between the globular and open clusters; thus it may be possible to learn something about the formation of globular clusters by studying the formation of open clusters, especially such relatively massive ones as are found in the Magellanic Clouds. Our knowledge about how and where open clusters form has been considerably advanced in recent years with the advent of infrared array photographs which have revealed the presence of compact, centrally condensed clusters of newly formed stars embedded in or closely associated with the dense cores of many giant molecular clouds; some examples of such clusters include the Trapezium cluster (Herbig and Terndrup 1986; see also McCaughrean 1989) and the clusters associated with NGC 2024 (E. A. Lada *et al.* 1991), M17 (C. J. Lada *et al.* 1991), S106 (Hodapp and Rayner 1991), and LkHα 101 (Barsony, Schombert, and Kis-Halas 1991). Most stars may in fact be formed in such systems, many of which probably do not survive as bound open clusters but disperse soon after their formation (Lada and Lada 1991); only about 10 percent of stars are estimated to form in systems that survive as bound open clusters (Von Hoerner 1968; Miller and Scalo 1978). The efficiency with which the matter in giant molecular clouds is converted into bound clusters has been estimated to be about $(1-2)\times10^{-3}$ (Larson 1990b), which again is only about 10 percent of the overall efficiency of star formation. The very low efficiency of cluster formation is probably due to the fact that bound clusters form only in exceptionally dense regions where the average gas density is of the order of 10^5 molecules per cm^3 or more (Larson 1990b); only in such regions does the local efficiency of star formation appear to be high enough to allow the formation of a bound cluster.

If a similarly low efficiency of cluster formation applies to the formation of globular clusters, which have typical masses of a few times $10^5\,M_\odot$, then the formation of a globular cluster would require a cloud or star-forming complex whose mass exceeds $10^8\,M_\odot$, which is the mass of a dwarf galaxy (Larson 1987a, 1988a). The chemical properties of the globular clusters are also easiest to understand if they were formed in separate protogalactic subsystems with masses of perhaps $10^8\,M_\odot$ or more, as was first suggested by Searle (1977) and Searle and Zinn (1978). For example, an important constraint on the origin of the globular clusters is set by their observed internal chemical homogeneity, which requires that the protocluster gas must have been chemically well homogenized prior to the formation of the observed cluster stars; this could plausibly have been done only by turbulence generated by previous episodes of star formation in a much larger star-forming system (Larson 1987a, 1988a). Some support for the idea that the globular clusters were formed in systems with masses of the order of $10^8\,M_\odot$ or more is provided by the fact that the 30 Doradus cluster in the Large Magellanic Cloud, which is probably the most massive young cluster in the Local Group, is located in a massive star-forming complex that has a mass of at least $5\times10^7\,M_\odot$ (Rohlfs *et al.* 1984).

Although the cluster-forming protogalactic subsystems may have had masses comparable to those of dwarf galaxies, they probably did not closely resemble typical present-day dwarf galaxies. The cluster-forming systems must have had relatively high rates of star formation, and as was discussed in Sections 3.4 and 3.5, this requires that they had higher densities and shorter dynamical timescales than typical present-day dwarf galaxies. The possibility that they were relatively compact is also suggested by the fact that some of these systems apparently managed to survive and continue to form globular clusters in the Galactic halo for several Gyr, or perhaps up to ~ 10 orbital periods, before being disrupted. They must therefore have had sufficiently small cross sections to avoid colliding with each other during this time, and this implies that they must have had diameters of no more than a few kiloparsecs.

If the cluster-forming subsystems had masses comparable to those of dwarf galaxies but were relatively compact and had higher rates of star formation, they may have resembled more closely the relatively rare 'blue compact dwarfs' or 'H II galaxies' (Thuan 1987; Kunth 1989; Melnick 1987, 1992; Mirabel 1992). These objects have diameters of about 1 to 3 kpc and masses between 10^8 and a few times $10^9\,M_\odot$, and they typically contain very massive gas clouds with masses up to $10^7\,M_\odot$, associated with which are extremely luminous H II regions. An example of such an object is the compact galaxy I Zw 18 = Mkn 116, which with a metallicity of about 1/40 solar is the most metal-poor such object known; it has a mass of about $10^9\,M_\odot$ and a diameter of about 3 kpc, and contains a massive central clump of gas with a mass of about $5 \times 10^6\,M_\odot$ and a luminous H II region containing an estimated $10^6\,M_\odot$ of young stars (Viallefond, Lequeux, and Comte 1987). Another example is NGC 1705, which contains several concentrations of young stars including an exceptionally luminous nuclear 'super star cluster' whose estimated mass of $1.5 \times 10^6\,M_\odot$ is comparable to that of the most massive globular clusters (Melnick, Moles, and Terlevich 1985; Meurer *et al.* 1992). This globular-like young cluster also appears to be powering a very energetic bipolar gas outflow, which might eventually disrupt the galaxy and in any case must have important consequences for its evolution (Meurer *et al.* 1992). Thus there is evidence that compact starburst galaxies can form globular-like clusters, and also that the formation of such clusters may have a destructive effect on the systems in which they form.

Similar phenomena on a larger scale may have occurred in the nuclear regions of the peculiar giant elliptical galaxy NGC 1275, where Hubble Space Telescope observations have recently revealed the presence of a population of very luminous young star clusters, at least some of which may eventually evolve into typical globular clusters (Holtzman *et al.* 1992). There is some evidence that this galaxy has recently experienced a merger event, and the inferred ages of the luminous young clusters are consistent with the possibility that they were formed in a starburst at the time of the merger (Holtzman *et al.* 1992). The inner regions of this galaxy still contain a considerable amount of molecular gas which is probably still forming new stars (Lazareff *et al.* 1989).

If a compact dwarf galaxy experiences a strong burst of star formation and as a result loses most of its gas and perhaps some of its stars as well, it may become a gas-poor dwarf elliptical galaxy of low surface brightness. The dwarf spheroidal galaxies surrounding the Milky Way and M31 may have originated in this way, and they may represent the last surviving remnants of a once much more numerous population of protogalactic subsystems. A good example of such a leftover 'building block' of the Galactic halo may be the Fornax dwarf spheroidal galaxy, which is the most luminous and massive of the dwarf spheroidal satellites of our Galaxy, with a mass of about $10^8\,M_\odot$ (Mateo *et al.* 1991); it also contains five apparently normal globular clusters (Buonanno *et al.* 1985), so that the accretion of such systems by the Galactic halo could account for the origin of many of the globular clusters in the halo. In fact, the entire halo of our Galaxy could be accounted for if it had been formed by the merging of some 30 Fornax-like dwarfs, although some of the subsystems that merged to form the Galactic spheroid must have been more metal-rich and hence presumably larger than any of the surviving dwarf spheroidal satellite galaxies.

The ability of the compact dwarf galaxies to develop very dense and massive concentrations of gas that can form globular-like clusters may be related to the exceptionally high density of the dark matter in these systems. It was noted in Section 3.1 that the density of dark matter at the centers of the smallest dwarfs approaches $1\ M_\odot/\mathrm{pc}^3$, which implies that very high gas densities of the order of $100\ \mathrm{cm}^{-3}$ are required for the gas in these systems to become self-gravitating and form stars. The gas in such galaxies may therefore become highly condensed before forming stars, and star formation may as a result occur in denser and more massive clouds than are found in the disks of typical spiral galaxies; this may in turn favor the formation of very massive clusters. Another effect that may well play a role in the formation of the massive central gas concentrations that are observed in many of the blue compact or H II galaxies is that most of these objects show evidence for interactions or mergers with companions (Mirabel 1992; Melnick 1992).

5.5 Lookback Observations

The evidence discussed above suggests that the initial chaotic period of halo formation lasted for perhaps the first one-third of Galactic history, and that during this period vigorous star formation activity was taking place in halo subsystems. If this sort of early history is typical of galaxies generally, some of the early star formation in galactic spheroids might be directly observable in galaxies with sufficiently large redshifts. The redshift range corresponding to the first third of the Hubble time extends down to redshifts as small as 1 or 2, depending on the density of the universe, and so comes within the range of observable redshifts for very luminous objects. Thus it might be possible to observe directly at least the later stages of spheroid formation in very luminous galaxies, as well as the subsequent epoch of disk development. We review here some recent results of lookback observations that may be relevant (see also Larson 1990c).

Considerable evidence has been found for changes in the properties of galaxies and galaxy populations with redshift, even at redshifts smaller than 1. The best established result is the discovery by Butcher and Oemler (1978, 1984) that the fraction of blue, actively star-forming galaxies in dense clusters of galaxies increases with increasing redshift; there is also evidence for an increasing fraction of galaxies that have experienced recent starbursts (Dressler 1987). Several different phenomena have been suggested to account for these observations (Oemler 1987), including the rapid evolution of spirals into S0 galaxies in clusters (Larson, Tinsley, and Caldwell 1980), and bursts of star formation triggered by interactions of galaxies with close companions (Lavery 1990) or with a hot ambient medium (Gunn 1989). Similar trends with redshift may exist among the field galaxies, whose colors typically become bluer at fainter magnitudes (Tyson 1988). However, it has recently been discovered that many of the faint blue objects found in deep surveys are not luminous galaxies at large redshifts but instead are dwarf galaxies with moderate redshifts of only a few tenths (Ellis 1990; Cowie, Songaila, and Hu 1991). This discovery is unexpected because the inferred space density of the dwarf systems at moderate redshifts is much larger than the local density of dwarf galaxies, and is high enough that the dwarfs at moderate redshifts may contain as much matter as the giant galaxies (Cowie *et al.* 1991). Apparently most of the star-forming dwarf galaxies observed at moderate redshifts have since disappeared; some of them may have been merged into larger galaxies, and perhaps many have been destroyed by bursts of star formation (Cowie *et al.* 1991). In the latter case, the importance of mass loss from dwarf galaxies may be even greater than has been believed, in that many dwarfs may not even survive until the present time as bound systems.

A very recent discovery from Hubble Space Telescope observations is that many of the blue star-forming galaxies in distant clusters appear to be large irregular galaxies with little central concentration (A. Oemler, private communication), a result not anticipated or explained by any of the scenarios mentioned above. Apparently these observations have revealed the existence of a new population of objects in the distant clusters whose relation to present galaxies is not clear; perhaps many of these extended irregular galaxies are destroyed by interactions in the clusters and do not survive to the present as bound systems.

Observations at higher redshifts have yielded more surprises, but again it is not clear how to interpret many of these observations, or what they may be telling us about galaxy formation. One difficulty is that the galaxies that have been observed at high redshifts are not typical galaxies but are systems with extreme and unusual properties: they are among the largest and most luminous objects in the universe, and most of them have active nuclei. Radio emission has often been used as beacon for finding high-redshift objects, and as a result high-redshift radio galaxies have been particularly extensively studied, partly in the hope that they might tell us something about galaxy formation (Spinrad 1988; Djorgovski 1987, 1988). The high-redshift radio galaxies typically have extremely large ultraviolet luminosities with spectra dominated by the Lyman-α line, and they are clumpy and elongated in optical appearance; an example of such an object is the radio galaxy 3C 326.1 at a redshift of 1.8 (Djorgovski 1987). The properties of these objects suggest the occurrence of intense starbursts, possibly in merging systems, and it has been suggested that we could be witnessing some of the first major episodes of star formation in galaxies forming by the merging of smaller systems (*e.g.,* Baron and White 1987; Djorgovski 1987, 1988). However, there is also evidence that many of the high-redshift radio galaxies contain an older and more symmetrically distributed stellar population whose age is at least 1 Gyr (Lilly 1990; Rigler *et al.* 1992); this would imply that they are not true 'primeval' galaxies experiencing their first star formation, but are already well-formed elliptical-like galaxies experiencing subsequent episodes of activity.

A discovery that has attracted much attention is the finding that the elongated optical structure of the high-redshift radio galaxies tends to be aligned with the radio jets; this strongly suggests that the emission from the optical extensions is somehow caused by the jet activity (van Breugel and McCarthy 1990; Chambers and Miley 1990). Examples of this alignment effect are provided by the double-lobed radio galaxy 3C 368 at a redshift of 1.1, whose optical and near infrared structures are closely aligned along the radio axis (Chambers, Miley, and Joyce 1988), and by the most distant galaxy presently known, the radio galaxy 4C 41.17 at a redshift of 3.8, whose elongated structure has a roughly similar appearance at all wavelengths from ultraviolet to radio (Chambers, Miley, and van Breugel 1990). If the optical appearance of these high-redshift radio galaxies is somehow caused by the jets, then the case for starbursts in merging systems is weakened, although galaxy interactions may still be involved in supplying fuel to the active nucleus and perhaps also in providing dense ambient gas for the radio jets to interact with (McCarthy 1990). The actual mechanism producing the optical emission is not yet clear; the most popular hypothesis has been that it is due to star formation triggered by the jets, but other possibilities include photoionization of the gas by ultraviolet radiation from the active nucleus, and scattering of radiation from a central source. Recent discussions of some of the possible mechanisms have been given by Daly (1992) and Rigler *et al.* (1992). In some cases there is evidence for scattering of radiation from a central source in the form of polarization of the light from the optical extensions, indicating that these features are at least in part galactic-scale reflection nebulae (Scarrott, Rolph and Tadhunter 1990).

It therefore appears that observations of the high-redshift radio galaxies may be telling us more about the effects of nuclear activity and energetic bipolar outflows in young galaxies than about how galaxies form (Miley and Chambers 1990; McCarthy 1990). The situation may be analogous to the history of efforts to observe star formation in molecular clouds; observers looking for evidence for collapse or infall found instead that the observed properties of even the youngest stellar objects were dominated by the effects of energetic outflows. We now understand that the actual accumulation of gas into stars is probably a relatively undramatic, low-velocity phenomenon whose observable effects are swamped by the much more conspicuous effects of the high-velocity outflows that begin as soon as any kind of stellar object is present. Perhaps the process of accumulating matter into galaxies is also less spectacular than some of its immediate consequences, especially if an active nucleus is present. Clearly, the observational study of galaxy formation at high redshifts is still at an embryonic stage, but we can look forward to major progress in this area in the coming years.

Possibly indicative of developments to come is the recently announced discovery that the ultraluminous infrared galaxy IRAS 10214+4724 at a redshift of 2.3 contains a very large amount of molecular gas (Brown and Vanden Bout 1991), for which a revised mass estimate of $\sim (2-6)\times 10^{11}\ M_\odot$ has been given by Solomon, Radford, and Downes (1992). The high luminosity of this object could be produced either by a starburst or by an active nucleus, but Brown and Vanden Bout (1991) and Solomon, Radford, and Downes (1992) favor star formation as the origin of most of the infrared emission from this object because of the large mass of molecular gas present. In some less distant and less extreme ultraluminous infrared galaxies, Solomon, Downes, and Radford (1992) have found large amounts of dense molecular gas, and they suggest that the high luminosities of these systems can be understood as a consequence of the star formation activity to be expected in this dense gas. Brown and Vanden Bout (1991) and Solomon, Radford, and Downes (1992) note that the molecular mass of IRAS 10214+4724 is comparable to its total dynamical mass, and they suggest that this object is a very young, vigorously star-forming galaxy whose mass is still mostly in gaseous form. Thus, it may be the best candidate yet found for a still forming or ‘primeval’ galaxy.

Clearly, we have so far obtained only a few tantalizing glimpses of earlier stages in the evolution of a few unusual galaxies. Nevertheless, it appears that the ‘dim boundary’ of the visible universe described by Hubble (1936) has been pushed out into a realm where the universe has a very different appearance from the familiar local region, and where galaxies are observed as they were in their more energetic and extravagant youth. The challenge to observers to advance the frontiers of this subject and turn the study of galaxy formation into a true observational science is clear.

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