THE ORIGIN OF THE HUBBLE SEQUENCE

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ABSTRACT

A brief review is given of the aspects of galaxy formation and evolution that are relevant to understanding the origin of the Hubble sequence. The variation along the Hubble sequence of the gas content and related properties of galaxies is the result of a variation in the rate of galactic evolution that is probably controlled mainly by the underlying mass distribution, which is thus the most fundamental characteristic to be explained by theories of galaxy formation. Much recent theoretical work and observational evidence, including the fossil record for our Galaxy, support the view that most large galaxies are formed by the merging or accretion of smaller units. The structure of the resulting galaxy depends on the nature of the subunits: if they are mainly stellar, the result will be a bulge-dominated galaxy, while if they are mostly gaseous, the result may be a galaxy with a dominant disk. Star formation processes and mergers are both expected to proceed most rapidly in the densest parts of the universe, resulting in the formation of mostly bulge-dominated galaxies in these regions. This may account for the observed relation between morphology and environment, although continuing environmental effects including gas removal and the destruction of disks by interactions may also play an important role.

1. The Systematic Properties of Galaxies

Like all natural phenomena, galaxies exhibit a mixture of regularity and irregularity, or of order and chaos, in their properties. Hubble looked for the order among their properties, and noted several correlations that he adopted as the basis of his proposed classification scheme. As has been emphasized by Buta, Madore, and Gavazzi in this volume, galaxies may have a large number of measurable characteristics, but only a few parameters suffice to account for most of the variability in their properties. Principal component analysis shows that there are just two dominant parameters, and that they can be identified as 'scale' and 'form', or equivalently as luminosity and Hubble type (Whitmore 1984). This finding supports the utility of Hubble types as a predictor of other properties of galaxies, and also suggests that the Hubble classification scheme reflects important underlying regularities in the processes of galaxy formation and evolution.

Although the Hubble types and luminosities of galaxies are almost completely uncorrelated in the sample studied by Whitmore (1984), some correlation is found when a larger range of types is considered, the later-type galaxies generally being fainter (de Vaucouleurs 1977). Some authors have even suggested that the basic properties of galaxies are largely determined by a single parameter, which may be the total mass (Tully, Mould, and Aaronson 1982), the virial velocity (Lake and Carlberg 1988b), or just the bulge mass (Meisels and Ostriker 1984).

The classification sequence proposed by Hubble (1936) for spiral galaxies is based on three characteristics, all of which generally increase along the sequence: the disk-to-bulge ratio, the openness of the spiral pattern, and the resolution of the arms into bright knots. The resolution of the arms reflects the level of star formation activity, and this depends on the gas content, which also increases systematically along the sequence. As has been discussed by Eder in this volume, the S0 class introduced by Hubble as a transition between spirals and ellipticals can, with present data, be understood as forming a smooth extension of the spiral sequence to systems with weak or absent spiral structure and with little or no gas or present star formation. Weak disk components even appear to be present in some elliptical galaxies, which may thus constitute a further continuous extension of the sequence to systems that are almost pure bulge (Bender 1990).

The Hubble classification scheme does not, however, apply to dwarf galaxies, which differ fundamentally in several respects from the giant galaxies studied by Hubble; some of their properties have been reviewed by Ferguson in this volume. The dwarf galaxies do not exhibit distinct disk and bulge 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. The dwarf ellipticals and dwarf irregulars may in fact be closely related, and may form a sequence of objects that differ mainly in gas content (Kormendy and Djorgovski 1989; Da Costa 1992).

It has been recognized since Hubble's time that the morphological properties of galaxies are correlated with their environment: spiral galaxies mainly inhabit low-density field regions, while ellipticals are concentrated in dense clusters. Several studies have shown that the mix of morphological types shifts steadily toward earlier types with increasing density of the environment (Oemler 1974; Dressler 1980; Postman and Geller 1984; Haynes 1987). A related finding is that the fraction of blue star-forming galaxies in clusters decreases with increasing cluster size (Oemler 1992). The 'morphology-density relation' clearly contains important clues about the formation and evolution of galaxies, but its interpretation has continued to be a subject of much discussion (*e.g.,* Dressler 1984; Salvador-Solé, Sanromà, and Jordana 1989; Whitmore and Gilmore 1991; Oemler 1992; see also the contributions of Salvador-Solé and Whitmore to this volume). The simplest and most obvious interpretation would be that the formation of disks is favored in low-density environments, while the formation of spheroids is favored in denser regions. However, environmental effects can also influence galactic morphology; for example, the galaxies in clusters may be gas-poor and typically of earlier Hubble types than field galaxies because of gas removal processes or because of interactions with other galaxies that have triggered enhanced star formation (Kenney 1990; Oemler 1992). The sweeping away of gas envelopes in dense environments might have a similar effect if gas infall is important for galactic evolution (Larson, Tinsley, and Caldwell 1980). It is even possible, as has been suggested by Whitmore in this volume, that the destruction of disks by violent interactions in forming clusters could account for the morphology-density relation by destroying most of the late-type galaxies in dense environments; in this case, the morphology-density relation might actually be telling us more about galaxy destruction than about galaxy formation.

The challenge is thus to account for the regularities embodied in the Hubble sequence and the morphology-density relation on the basis of an understanding of the processes of galaxy formation and evolution, and perhaps destruction. It will be argued in Section 2 that the variation of some of the properties of galaxies along the Hubble sequence results from a variation in the rate of galactic evolution that mainly depends on the underlying mass distribution. The most basic property of galaxies to be accounted for by theories of galaxy formation is then the internal mass distribution, as reflected for example in the disk-to-bulge ratio. Subsequent sections will discuss some current ideas about galaxy formation that are relevant to understanding the origin of the Hubble sequence, as well as some of the supporting evidence.

2. Galactic Evolution and the Hubble Sequence

Of the properties of galaxies that vary along the Hubble sequence, the gas content and related properties such as the star formation rate and the spiral arm structure may be regarded as secondary characteristics that depend only on the rate at which galaxies deplete their initial gas supply. The early-type galaxies have evidently evolved faster than the late-type galaxies in this respect, having consumed more of their gas because of higher past rates of star formation. Direct evidence that the timescale for gas depletion increases along the Hubble sequence is provided by the results of Donas *et al.* (1987) for the star formation rates and gas depletion times in a large sample of spiral and irregular galaxies, which show that at least along the later part of the sequence, the gas depletion time increases by roughly a factor of 4 from the Sbc galaxies to the irregular galaxies. This dependence of the timescale for galactic evolution on Hubble type is an important feature of the Hubble sequence that must be accounted for by any understanding of star formation processes and star formation rates in galaxies (Larson 1983). Here we summarize briefly why the timescale for gas depletion might be expected to depend on basic structural properties such as the disk-to-bulge ratio and the underlying mass distribution.

On the largest scales, star formation begins with the formation of giant molecular clouds and cloud complexes, and the star formation rate therefore depends on the rate of formation of these massive clouds and complexes. The formation of such large gas concentrations is almost certainly due primarily to the self-gravity of the interstellar medium in galaxies, and in this case the rates of cloud formation and star formation are controlled mainly by the timescale for gravitational accumulation of the gas (Larson 1987, 1988, 1992; Elmegreen 1990a,b). The gas layer in a galaxy is gravitationally unstable if the Toomre stability parameter $Q = c\kappa/\pi G\mu$ is smaller than unity, where c is the velocity dispersion of the gas, κ is the epicyclic frequency, and μ is the surface density; such gravitational instabilities may occur, for example, in irregular galaxies, and may be responsible for driving star formation in them. In spiral galaxies like our own, a true gravitational instability probably cannot occur because Q is actually somewhat larger than unity, but large density enhancements can still be generated by the closely related phenomenon of 'swing amplification', which is a kind of truncated instability (Toomre 1981, 1990). Evidence that swing amplification is responsible for driving much of the star formation in spiral galaxies is provided by the fact that star formation is observed to occur only where the surface density of gas exceeds a threshold that corresponds to a value for Q of about 1.8 (Kennicutt 1989), which is approximately the value of Q below which swing amplification becomes important; thus star formation is observed to turn on at just the same value of Q at which swing amplification turns on.

The timescale for gravitational instability or swing amplification effects is approximately $\tau \sim c/\pi G\mu$, and thus it depends on both the velocity dispersion c and the surface density μ of the gas. Two possible limiting cases have been considered by Larson (1988, 1992) in discussing the implied parameter dependences of the star formation rate. One possibility is that the velocity dispersion c is constant; in this case, the timescale for gas aggregation is inversely proportional to the gas surface density μ, and the resulting star formation rate per unit area is then proportional to μ^2, which is similar to the quadratic dependence on volume density originally proposed by Schmidt (1959). This prediction does not, however, provide any ready basis for understanding why the gas depletion timescale should increase along the Hubble sequence, since the average gas surface density does not vary much along this sequence. A second, perhaps more realistic assumption is that the stability parameter Q is constant, as is found to occur in numerical simulations of galactic disks where the value of Q is regulated dynamically at a value of about 1.7 (Carlberg 1987; Gunn 1987). The timescale for gas accumulation $\tau \sim c/\pi G\mu = Q/\kappa$ then becomes inversely proportional to κ, *i.e.* proportional to the epicyclic period, which in turn is approximately proportional to the galactic rotation period; thus the rotation period may be what sets the basic clock rate for the evolution of galaxies. Since galaxies with later Hubble types generally rotate more slowly than the earlier types (Rubin *et al.* 1985), they would then be expected also to consume their gas more slowly, as is observed. Quantitatively, since the typical rotation period increases by roughly a factor of 3 along the Hubble sequence, the gas depletion timescale would be expected to increase by about the same factor along the sequence, which is roughly consistent with the evidence noted above.

We can also understand the increase in the openness of the spiral pattern along the Hubble sequence in terms of the gas content and the rotational properties of galaxies. In gravitational theories of spiral structure, the spacing of the arms depends on the quantity $\lambda_{\rm crit} = 4\pi^2 G\mu/\kappa^2$, which is the maximum wavelength of unstable axisymmetric perturbations in a thin disk (Toomre 1964); it is also approximately the arm spacing for which swing amplification is most important (Toomre 1981, 1990; Carlberg and Freedman 1985; Carlberg 1987). A more open spiral pattern is therefore predicted if a galaxy has either a higher gas surface density or a lower epicyclic frequency; since the gas surface density does not vary strongly with Hubble type while the epicyclic frequency generally decreases along the Hubble sequence, the arm spacing is then predicted to increase along the sequence, just as is observed.

The variation of the gas content, star formation rate, and spiral arm properties of galaxies along the Hubble sequence can thus be understood as depending mainly on basic structural characteristics such as the mass distribution and the rotation rate. Galaxies that rotate faster are predicted to have lower fractional gas contents and more tightly wound arms, so that two of the three defining characteristics of the Hubble sequence (the degree of resolution and the openness of the spiral arms) can be accounted for just in terms of the galactic rotation rate. If rotational shear is itself an important effect tending to drive star formation, a centrally condensed mass distribution might enhance the gas depletion rate and thus help to explain the correlation between gas content and disk-to-bulge ratio along the Hubble sequence (Larson 1983). It is clear in any case that the essential characteristic of galaxies that theories of galaxy formation should aim to account for is their internal mass distribution. To the extent that the morphology-density relation results from galaxy formation processes, it is necessary in particular to explain why galaxy formation in dense environments should produce systems with dominant bulges; also, to the extent that Hubble type correlates with mass, it is necessary to explain why bulge-dominated galaxies tend to be more massive than disk-dominated galaxies.

3. Protogalactic Collapse and the Hubble Sequence

According to the conventional view, galaxies like ours were formed by the collapse and simultaneous chemical enrichment of extended protogalactic gas clouds. Evidence suggesting that our Galaxy was formed by a collapse process was presented in an influential paper by Eggen, Lynden-Bell, and Sandage (1962), and a recent discussion of this evidence has been given by Sandage (1990). Inspired by this idea, many efforts have been made to model numerically the collapse of protogalaxies and to explain on this basis the basic properties with which galaxies are formed. In particular, much attention has been given to modeling the formation of disks and bulges and to trying to account for the variation of the disk-to-bulge ratio along the Hubble sequence. Collapse calculations yielding both bulges and disks have been made by Larson (1976a), Gott and Thuan (1976), Carlberg (1985), Lake and Carlberg (1988a), Burkert and Hensler (1988), and Katz (1992); reviews of the early work were given by Larson (1976b) and Gott (1977), and a more recent review of the subject has been given by Larson (1992).

Larson (1976a) and Gott and Thuan (1976) suggested that the disk-to-bulge ratio of a galaxy is determined primarily by the star formation rate in the initial protogalactic cloud: if star formation is sufficiently fast that most of the gas is turned into stars before the collapse is completed, the resulting galaxy will have a dominant spheroid, while if star formation is much slower or is delayed, most of the gas may settle into a disk before forming stars. Thus, an earlier Hubble type would be predicted to result when star formation proceeds more rapidly in relation to the collapse time. If the star formation rate depends on the gas density in accordance with the Schmidt law or a similar relation, then the ratio of the star formation timescale to the collapse time decreases with increasing gas density, so that one might expect galaxies of earlier Hubble type to form in regions where the density is higher. This effect might account qualitatively for the observed morphology-density relation (Larson 1976b; Gott 1977), although the results of Larson (1976a) suggest that the magnitude of the effect is not quantitatively sufficient to account for the full observed range in disk-to-bulge ratio.

Larson (1976a) and Gott and Thuan (1976) also noted that star formation would be expected to proceed more rapidly in protogalaxies if their gas is strongly clumped. The clumpiness of a protogalaxy might then be important in determining the morphological type of the resulting galaxy. Clumping might also play an important role in the dynamics of the collapse through its effect in redistributing energy and angular momentum and thus allowing the formation of a dense and slowly rotating spheroid (Lake and Carlberg 1988a). Simulations of the collapse of systems of stars have in fact shown that gravitational interactions in a clumpy or inhomogeneous system tend quite generally to produce a structure like that of an elliptical galaxy or spiral bulge (*e.g.*, van Albada 1982; Villumsen 1984; Katz 1991). An extreme case of the effect of interactions on morphology is provided by galaxy mergers, in which the transfer of energy and angular momentum from the visible stars to the dark matter is found to be very effective in producing a centrally condensed and slowly rotating stellar system closely resembling an elliptical galaxy (Barnes 1988, 1989, 1990). The cosmological models and the observational evidence to be reviewed below make it appear very likely that interactions between subsystems are indeed involved in the formation of many elliptical galaxies and spiral bulges. Recent protogalaxy calculations based on current cosmological models will be discussed further in Section 5, following a brief review in Section 4 of the cosmological context of galaxy formation.

4. The Cosmological Context of Galaxy Formation

Most of the calculations mentioned above have adopted simple and idealized initial conditions for protogalaxies, but there has been much progress in recent years in understanding the structure and evolution of the universe and the likely initial conditions for galaxy formation. It is now recognized that the universe is inhomogeneous and hierarchical on a wide range of scales, and most current cosmological models assume that the universe was initially inhomogeneous on subgalactic scales as well. The presently observed galaxies and clusters of galaxies may then have been formed by the progressive merging of smaller structures into larger ones, and galaxies may simply be the smallest structures that have survived as discrete units (Peebles 1974, 1980; Press and Schechter 1974).

A number of surveys have shown that the large-scale structure of the universe is complex and intricate, consisting of a network of filaments, sheets, and voids of various sizes (*e.g.,* Maddox *et al.* 1990; Giovanelli and Haynes 1991). On scales larger than those of clusters of galaxies, this structure still reflects that of the pre-galactic universe, since there has not yet been time for gravitational clustering to erase the initial conditions on these scales; the observed density fluctuations are thus simply an amplified form of the initial fluctuations. On scales between about 5 and 50 Mpc, the observed galaxy distribution is found to be hierarchical and approximately self-similar, with a fractal dimension of about 2.2 (Einasto 1991; Guzzo *et al.* 1991); such a fractal dimension would be characteristic, for example, of an open filamentary network 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 subunit of radius R has a mass proportional to $R^{2.2}$, a dependence similar to the approximate scaling law $M \propto R^2$ relating the masses and radii of giant galaxies. The corresponding relation between galactic mass and virial velocity, $M \propto V^4$, is essentially equivalent to both the Tully-Fisher (1977) relation observed for spirals and the Faber-Jackson (1976) relation for ellipticals. Thus these basic scaling laws for galaxies may be explainable if the pre-galactic universe was self-similar in structure with a fractal dimension of ~ 2 on scales down at least to those of individual galaxies.

Numerical simulations of the growth of structure in the universe, mostly based on the popular 'cold dark matter' (CDM) model, have successfully reproduced many aspects of the the large-scale distribution and clustering of galaxies, and even some of the gross properties of individual galaxies; for example, they predict approximately flat rotation curves, and can also account roughly for the Tully-Fisher and Faber-Jackson relations (*e.g.,* Frenk *et al.* 1985, 1988; Zurek, Quinn, and Salmon 1988; Carlberg 1988; Carlberg and Couchman 1989; Navarro and Benz 1991; Evrard, Summers, and Davis 1992). All of these simulations predict that in the densest parts of the universe, small concentrations of dark matter or dark halos rapidly merge to form larger ones. Gas condenses into these merging halos to form compact galaxy-like objects, which in the most detailed simulations (Evrard *et al.* 1992) are sometimes disks. These 'galaxies' also sometimes merge when their halos merge, but because of their smaller cross sections they experience less merging and thus tend to form groups or clusters of objects embedded in common dark halos. By contrast, merging is much less frequent in the low-density parts of the universe, and the dark halos and embedded galaxies that form in these regions grow only slowly by the accretion of diffuse matter. These results suggest that considerable early merging of smaller systems into larger ones may have occurred in the densest parts of the universe, while merging was much less important in low-density regions. Although the validity of the standard CDM model has been a subject of debate (*e.g.,* Peebles *et* *al.* 1991), the qualitative results of these simulations do not depend critically on the details of the model but are generic to any cosmology in which structure develops in a bottom-up fashion (Efstathiou 1990).

These results may account for the morphology-density relation if the products of the mergers can be identified as elliptical galaxies and bulge-dominated spirals. The possible formation of elliptical galaxies by the merging of smaller systems, as suggested by Toomre (1977), is supported by considerable observational evidence (Schweizer 1990) and extensive numerical simulations (Barnes 1990), as again reviewed in this volume by Schweizer and Barnes. In the simulations reported here by Evrard, about half of the 'galaxies' in proto-cluster regions have experienced mergers with objects of comparable mass, while only about one-quarter of the objects in small groups have experienced such mergers and only about 15 percent of those in field regions have merged. These numbers are similar to the present fractions of elliptical galaxies in these different types of environments, suggesting that mergers may indeed be able to account for the correlation of morphology with environment. Because mergers also increase the sizes of galaxies, elliptical galaxies and early-type spirals would be expected to be more massive on the average than later-type galaxies; this prediction is again consistent with the available evidence (*e.g.,* Binggeli 1987), and might account for the correlation between Hubble type and luminosity noted in Section 1.

Environmental effects such as those mentioned in Section 1 may, of course, also play an important role in accounting for the observed morphology-density relation. Clarifying the relative importance of the various processes involved will be an important topic for further research.

5. Protogalactic Collapse Revisited

The most recent and detailed simulations of protogalactic collapse by Katz and Gunn (1991) and Katz (1992) have calculated the evolution of protogalaxies modeled as galaxy-sized pieces of a standard cold-dark-matter universe. As in the cosmological simulations discussed above, much small-scale structure is present during the early stages of evolution, and there is a chaotic period during which interactions and mergers between clumps build up an extended dark halo. Stars that have formed by gas condensation in the dense cores of these clumps are at the same time dispersed to form a stellar spheroid. The remaining gas then organizes itself more gradually into a disk in a process that is itself somewhat chaotic, since the disk is initially irregular and clumpy and retains a significant tilt with respect to the halo. These results illustrate that in reality it is probably not possible to draw a sharp distinction between the collapse and merger pictures of galaxy formation, since elements of both are almost certainly involved in the formation of most large galaxies (Kormendy 1990; Larson 1990b).

A result of particular interest for the origin of the Hubble sequence is that random differences in the initial conditions can lead to substantial differences in the final disk-to-bulge ratio: protogalaxies that by chance contain more large clumps produce galaxies with larger spheroids. This result supports the earlier suggestions noted in Section 3 that the clumpiness of a protogalaxy may play an important role in determining the Hubble type of the resulting galaxy. Since this clumpiness is subject to statistical variations, the Hubble type of a galaxy might in part be of random origin, and this might account for some of the scatter in the correlations discussed in Section 1.

Another result found by Katz (1992) is that small satellite systems sometimes form during the initial chaotic stage of evolution, and they may survive as separate small galaxies for several orbits before merging with the main galaxy. The accretion of such satellite systems may account for the origin of the globular clusters in the outer halo of our Galaxy (Searle and Zinn 1978; Freeman 1990), a possibility that is strengthened by the evidence that these clusters have a significant age spread (see Section 7). Satellite accretion during the early stages of disk evolution might also account for the origin of the 'thick disk' component of our Galaxy (Freeman 1990, 1991; Katz 1992; Section 7).

6. Effects of Accretion and Interactions

While they appear to have many realistic features, the protogalaxy models described above are still simplified in that they include only the matter that was initially located inside an artificial spherical boundary. A real forming galaxy will be surrounded by additional matter that may continue to interact with and be accreted by it for an extended period of time. The infall of additional dark matter may build up the dark halos of galaxies (Gunn 1977), while the accretion of stars may build up galactic spheroids (Gott 1977) and the infall of gas may build up disks (Oort 1970; Larson 1972, 1976b; Gunn 1982, 1987). These authors all imagined the infalling matter to be diffuse and smoothly distributed; however, in an inhomogeneous and hierarchical universe like that described above, it seems more likely that much of this infalling matter will already have condensed into galaxies, in which case the accretion will take the form of captures or mergers. Evidence that elliptical galaxies grow by capturing smaller galaxies is provided by the frequent occurrence in their outer envelopes of shell-like features (Schweizer and Ford 1985; Prieur 1990) which are very similar to those predicted by numerical simulations of such captures (*e.g.*, Hernquist and Quinn 1989). The evidence that spiral galaxies also grow by accretion is less clear, but some of the disturbances observed in the outer parts of spiral disks might be the result of accretion events (Larson 1976c; Binney 1990; Sancisi *et al.* 1990; Kamphuis and Briggs 1992; Sancisi, this volume).

The accretion of new material and the disturbances caused by interactions with surrounding galaxies may significantly influence the morphological types of galaxies. The acquisition of new gas may build up disks, but the effects of interactions are more likely in general to drive the morphology of galaxies toward earlier types by disrupting disks, removing gas, and building up spheroids. Such effects may help to explain the continuous shift in the morphology distribution of galaxies toward earlier types with increasing density of the environment (*e.g.,* Haynes 1987), especially if this shift is partly caused by effects acting over the entire lifetimes of galaxies, as suggested by Oemler (1992).

7. The Fossil Record for Our Galaxy

The above picture of galaxy formation by the merging and accretion of subunits can be tested for our Galaxy using the fossil record provided by the oldest stars and clusters, especially the globular clusters of the Galactic halo. Recent reviews of the evidence concerning the early evolution of our Galaxy have been given by van den Bergh (1990) and Larson (1990a, 1992). A central and much debated issue has been whether the globular clusters show a measurable age spread significantly exceeding 1 Gyr, since a smaller age spread would be consistent with the near free-fall protogalactic collapse proposed by Eggen, Lynden-Bell, and Sandage (1962), while a larger age spread would provide evidence for a more prolonged and chaotic process of galaxy formation, possibly involving the merging of smaller systems. The formation of the Galactic halo over a period of several Gyr by the accumulation of 'protogalactic fragments' was originally suggested by Searle (1977) and by Searle and Zinn (1978) to account for the chemical properties of the globular clusters, and also for the 'second parameter effect' (see below).

It is now generally accepted that at least a few of the globular clusters in the Galactic halo differ in age from others by several Gyr (VandenBerg, Bolte, and Stetson 1990; Sarajedini and Demarque 1990; Demarque, Deliyannis, and Sarajedini 1991; Da Costa, Armandroff, and Norris 1992). 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 total spread in age indicated by these data is of the order of 5 Gyr, or about one-third of the Hubble time. There is a correlation between age and metallicity in the expected sense that the more metal-rich clusters tend to be younger, and there is also a suggestion that the inner Galactic halo experienced a more rapid rise in metallicity than the outer halo; however, these correlations are dominated by a scatter that is at least as large as the trend, and is of the order of several Gyr at all metallicities.

An important result that is now seen for the first time in direct age determinations is that the age dispersion increases and the mean cluster age decreases with increasing distance from the Galactic center (Chaboyer *et al.* 1992). These trends had earlier been inferred from studies of the horizontal branch structure of globular clusters, which depends on metallicity and on a second parameter that is probably age (Rood and Iben 1968; Searle and Zinn 1978). If the second parameter is indeed age, as is supported by the recent work of Lee, Demarque, and Zinn (1988, 1990), it can be inferred that the clusters in the inner Galactic halo are all relatively old, while the clusters in the outer halo scatter increasingly toward younger ages with increasing Galactocentric distance. According to Lee (1992a,b), the typical age decreases 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. There is also evidence from the properties of the RR Lyrae stars in the Galactic bulge that the radial variation of the second parameter continues all the way into the central bulge, implying that the bulge contains stars that are about 1 Gyr older than even the oldest halo clusters (Lee 1992a,b).

The fossil record thus suggests that the halo of our Galaxy was built up from the inside out over a period of perhaps 5 Gyr or more. The central bulge appears to be the oldest part of the Galaxy, and it may therefore have served as a nucleus around which the rest of the Galaxy was built up by accretion. The evidence that the bulge contains the oldest Galactic stars does not necessarily conflict with the evidence discussed by Rich in this volume that most of the stars in the bulge are actually younger than the halo, since the continuing accretion of subsystems during the formation of our Galaxy would probably have deposited much new material into the bulge. Together with the evidence mentioned in Section 6 that many galaxies continue to grow by capturing smaller galaxies (see also Larson 1990b), these results make a strong case that typical large galaxies experience a prolonged formation process involving the continuing accumulation of smaller units. The youngest globular clusters in the Galactic halo, which are about 10 Gyr old, may date from the last major accretion event contributing to the formation of our Galaxy. This event may have strongly disturbed the still forming Galactic disk and thus created the 'thick disk', which appears to be a discrete Galactic component whose stars and clusters are all older than about 10 Gyr (Freeman 1991).

The 'thin disk', which contains the bulk of the Galactic disk mass, appears to have formed only after the chaotic phase of halo formation was over. Several indicators of the age of the local disk population all yield ages that are of the order of 10 Gyr or less; for example, the age inferred from the white dwarf luminosity function is between about 7 and 11 Gyr (Wood 1992), while the oldest known open cluster, NGC 6791, has an age of about 7 to 9 Gyr (Demarque, Green, and Guenther 1992). The thick disk seems to be older than this, as noted above, and the 'disk globular clusters' that appear to belong to the thick disk population (Zinn 1990) have ages similar to those of the halo clusters; for example the best studied such cluster, 47 Tucanae, has an age of about 14 Gyr. However, since these disk globular clusters are strongly concentrated toward the Galactic center, this age may be more representative of the inner part of the disk than of the local region. If the inner disk is in fact older than the local region, both the halo and the disk of our Galaxy may then have been built up from the inside out, the disk forming mostly after the formation of the halo was completed at each radius. Since there is some evidence for chemical continuity between the halo and the disk, the disk may have been formed largely of material left over from, and chemically enriched by, the halo-forming subsystems (Larson 1991).

Current theoretical ideas about galaxy formation thus appear to receive strong support from the fossil record for our Galaxy. Not only is there evidence that the Galactic halo was formed from subsystems, but there is evidence that our Galaxy was built up from the inside out by the accretion of material from progressively greater distances. Thus, some additional support is given to the idea that the Hubble sequence can be understood as originating from the formation of galaxies from varying numbers and sizes of subunits.

8. Summary

The morphological characteristics of galaxies depend partly on the way in which they were formed, and partly on their subsequent evolution. Basic structural properties such as the disk-to-bulge ratio are determined mainly by the formation process, while more superficial features such as the gas content and the spiral arm characteristics depend on the internal dynamics and the evolutionary history of galaxies. It was suggested in Section 2 that these 'evolutionary' characteristics are themselves determined mainly by the galactic mass distribution through basic dynamical timescales such as the rotation period. Environmental effects can also influence the structures of galaxies by adding or removing material, and they may be difficult to separate from formation processes. Nevertheless, it is clear that the galactic mass distribution and the disk-to-bulge ratio are fundamental properties whose variation along the Hubble sequence must be explained by any understanding of galaxy formation processes.

Early attempts to model the formation of galaxies assuming homogeneous initial conditions concluded that the disk-to-bulge ratio is determined mainly by the star formation rate in the initial collapsing protogalaxy. It is now recognized, however, that the structure of the universe is inhomogeneous and hierarchical on a wide range of scales, and it seems likely that it was initially inhomogeneous on subgalactic scales as well. Interactions and mergers among subunits must then have played an important role in the formation of most large galaxies, as suggested by Toomre (1977). Of particular importance for the origin of the Hubble sequence is the fact that the early merging of smaller systems into larger ones is expected to have occurred most frequently in the densest parts of the universe; if the products of the mergers are bulge-dominated galaxies, dense regions should then contain a relatively high proportion of such galaxies, as is in fact observed. Various environmental effects might also act to drive the morphology of galaxies toward earlier types in denser environments. Thus, the basic morphological properties of galaxies and their correlation with the environment might be accounted for at least qualitatively if inhomogeneities play an important role in their formation and if continuing interactions influence their subsequent evolution.

However, a fully quantitative understanding of the Hubble sequence is not yet in hand, since the structure of a galaxy formed by the merging of subunits will depend in detail on the nature of the subunits: if they consist mainly of stars, the result will be an elliptical galaxy or an early-type spiral, while if they are mainly gaseous, the resulting galaxy may have a dominant disk. It is therefore necessary to understand better the processes of star formation in protogalaxies, but star formation is still treated in a simple *ad hoc* manner even in the most detailed models. It is also important to treat carefully the physics of the gas, since some of the protogalactic gas may be heated by collisions and may thus form a hot diffuse medium that cannot directly participate in star formation. The feedback effects of star formation can also be important in heating the residual gas and thus inhibiting or delaying further star formation (Cole 1991; Navarro and Benz 1991; White and Frenk 1991). Since the thermal behavior of the gas depends strongly on its density, these effects might enhance the effective dependence of the protogalactic star formation rate on the gas density, for example by introducing a critical star formation rate such that the gas is efficiently heated and dispersed and further star formation is suppressed if this rate is exceeded (Larson 1974). If the result is that denser and more massive subsystems convert more of their gas into stars, as seems likely, then the size and density of the substructures from which a galaxy is formed may be the main factors determining the Hubble type of the galaxy.

In any case, it would appear that at least some of the processes responsible for the origin of the Hubble sequence have been identified, and we can look forward to further progress in understanding this subject as the various models and hypotheses that have been described are further refined and tested by comparison with the many relevant observations.

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