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DISSIPATIONAL GALAXY FORMATION

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Abstract. Arguments are presented which suggest that the process of galaxy formation involves both dissipational and violent relaxation processes. A protogalaxy model is developed which consists of an aggregate of individually long-lived gas clouds and which undergoes mergers with other similar systems. Such a scenario is consistent with either the hierarchical clustering of primordial isothermal fluctuations or with the fragmentation of massive primordial adiabatic fluctuations. Dissipation only dominates in the cores of the merged systems, and it is argued that the luminous cores of ellipticals are to be identified with these regions. The individual clouds are sustained by internal star formation, and the stellar components maintain some of the initial anisotropy in the merged systems. Isolated systems develop rotationally supported bulges and disks by continuous viscous infall of clouds. Protogalaxy merging during the initial collapse of clusters and groups can account for the observed spatial distribution of spiral, *SO*, and elliptical galaxies.

1. INTRODUCTION

The theory of the formation of galaxies can be constrained in several ways. One approach is to begin with a uniform cosmological model, and seek conditions for instability. This approach has not proved successful, and will not be pursued here. Another means of attack utilizes various observational aspects to constrain and help define the theory.

One can broadly divide the types of relevant observational evidence into three categories. The search for angular fluctuations in the cosmic microwave radiation provides an indirect glimpse of galaxies at the stage of their conception. The radiation fluctuations are produced by interaction with the inhomogeneous matter component on the surface of last scattering. A second observational goal is to search for protogalaxies, or effects directly associated with the rapid evolution of galaxies during their initial collapse phase. One observable effect may be the radiation from the first stars to form, and this is discussed in another lecture. Finally, there are the characteristics of ordinary galaxies that must have arisen during their formation and early evolution. In the present lecture, it will be shown how many of these properties of galaxies help to define a model of galaxy formation. The following discussion is based on a forthcoming paper by Silk and Norman (1981), where further details and more extensive references can be found.

The gravitational instability theory of galaxy formation usually commences with a spectrum of density fluctuations that collapse and first become bound at a redshift $z \sim 100$—1000 (isothermal mode) or $z \lesssim 10$ (adiabatic mode). The characteristic mass of the first isothermal fluctuations to collapse is the Jeans mass at decoupling or $\sim 10^6\, M_\odot$, whereas the mass characteristic of the first primordial adiabatic fluctuations to collapse is constrained by radiative dissipation to be $\sim 3 \times 10^{13}$ $(\Omega h^2)^{-5/4}\, M_\odot$; here $\Omega = \varrho/\varrho_{\rm cr}$, $\varrho_{\rm cr} = 3H^2/8\pi G$, and $h = H_0/100\ {\rm km\ s^{-1}\ Mpc^{-1}}$. However the adiabatic fluctuation collapse is likely to be pressure-free (since $M \ll M_{\rm Jeans}$) and anisotropic, leading to formation of a thin sheet or pancake that is liable to continued fragmentation by thermal and gravitational instability. The final fragment mass may be $< 10^8\, M_\odot$, and the further evolution of these bound clouds will be similar to that of the clouds forming directly from primordial isothermal fluctuations. We may consider these clouds to be the basic units from which galaxies subsequently develop.

Evidence that this mass range is not entirely in the realm of speculation can be inferred from two observations. The galaxy correlation function has been modelled by N-body simulations of galaxy clustering which enable one to extrapolate back as far as the decoupling epoch and infer the initial density fluctuation spectrum. This procedure, based on the hierarchical clustering of isothermal density fluctuations, yields a fluctuation spectrum in the linear regime

$$\delta\varrho/\varrho = (M/M_0)^{-1/2-n/6}(t/t_{\rm d})^{2/3}\,.$$

The index n refers to the Fourier power spectrum of density fluctuations $[(\delta\varrho/\varrho^2 = \int \delta_k^2 d^3\vec{k},\ |\delta_k|^2 \propto k^n]$ and the simulations constrain $0 \gtrsim n \gtrsim -2$ for $1 \gtrsim \Omega \gtrsim 0.1$. Since the observed two-point galaxy correlation function $\xi(r) = (r_0/r)^{1.8}$ becomes non-linear below a mass-scale $\sim 5 \times 10^{14}$ $\Omega h^{-1}(r_0 h/4\ {\rm Mpc})^3\, M_\odot$, where r_0 $\sim 4h^{-1}$ Mpc, one infers that

$$10^6\, M_\odot \lesssim M_0 \lesssim 5 \times 10^8\, M_\odot (0.1 \lesssim \Omega \lesssim 1)\,.$$

This suggests that a primordial isothermal fluctuation spectrum would have perhaps inevitably become non-linear on scale M_0 at $z \sim 1000$, since the Jeans mass at decoupling $\lesssim M_0$.

A second observation that is suggestive of a fundamental mass-scale $\lesssim 10^8\, M_\odot$ for young systems is that of gas-rich dwarf galaxies. Unlike more massive galaxies, these appear to have formed recently, since one can in individual cases where the metallicity is extremely low reject the alternative possibility of a succession of separate bursts of star formation (e.g. I Zw 18, Lequeux and Viallefond 1981).

It is necessary that the clouds remain predominantly gaseous for a time long compared to the free-fall time of an individual cloud in order to lead to a satisfactory model of galaxy formation. Several properties of galaxies suggest that considerable dissipation occurred during the formation process. These properties include the radial metallicity gradients in many disks and ellipticals and in the globular cluster population around our galaxy, the degree of central concentration of ellipticals and bulge components, and the correlations between galaxies involving luminosity, central velocity dispersion, peak rotational velocity, radius, and metallicity. Other characteristics of galaxies, most notably the low rotation of ellipticals and the transition between disk and bulge components in spirals and lenticulars, indicate however that dissipation-less collapse must also have been important in preserving velocity anisotropy.

It seems evident that a hybrid approach to galaxy formation is necessary, both dissipation and violent relaxation playing important roles. Previous models of dissipational elliptical galaxy formation (e.g. LARSON 1974, BINNEY 1977) have not considered the dynamical aspects which arise if a protogalaxy is envisaged as a collection of bound gas clouds. It is first necessary to consider the longevity of individual clouds; then their mutual interaction will be described.

CLOUD SURVIVAL

Consider a bound gas cloud of mass $M_6 \equiv M/10^6\, M_\odot$. In the absence of heavy elements, the cloud will radiatively cool to $T_4 \equiv T/10^4\, K \sim 1$, although the virial temperature could exceed this if the cloud is inhomogeneous. The cloud free-fall time is

$$t_f = 10^7\, M_6 T_4^{-3/2}\ \mathrm{yr}\,,$$

and its mean radius and density are

$$R = 10^{1.8}\, M_0 T_4^{-1}\ \mathrm{pc}\ \text{and}\ n = 10^{1.4} T_4^3 M_6^{-2}\ \mathrm{cm}^{-3}\,.$$

The galaxy formation model requires the clouds to remain mostly gaseous over a time scale in excess of the galaxy collapse time, $\sim 10^8$ yr. Internal star formation can provide sufficient energy input to stabilize a cloud against collapse or fragmentation. This leads to a new difficulty, however: the most massive stars will become supernovae and eventually can lead to cloud disruption.

The cloud will be rapidly eroded if the hot interiors of the supernova remnants overlap before the shells breakup and cooling occurs. In order to avoid the overlapping of supernova remnants of maximum radius (determined by the ambient pressure) R_{SNR}, the mean time between successive supernovae t_{SN} must exceed

$$t_{\mathrm{crit}} \equiv R_{\mathrm{SNR}}^4 (R^3 v_s)^{-1} = 10^{4.6} E_{51}^{1.3} M_6^{-0.1} T_4^{-2.5}\ \mathrm{yr},$$

where R is the cloud radius, v_s the sound velocity in the ambient medium, and $E_{51} \equiv E/10^{51}$ erg is the initial energy of the supernova explosion. If M_* denotes the total mass in newly formed stars for each massive star that forms and becomes a supernova, the cloud lifetime is clearly of order $(M/M_*)t_{\mathrm{SN}}$: at this point, the gas supply is largely exhausted (since most of the matter used in star formation is presumably not returned into the interstellar medium but is locked up in long-lived low mass stars). On the least favorable assumption, that $t_{\mathrm{SN}} = t_{\mathrm{crit}}$, in which case the cloud just survives and supernova energy input provides an important source of internal pressure, the cloud lifetime is of order

$$(M/M_*)t_{\mathrm{crit}} \sim 10^{8.6}\, M_6^{0.9} E_{51}^{1.3} T_4^{-1.5} (100\, M_\odot/M_*)\ \mathrm{yr}\,.$$

In principle, a $10^6\, M_\odot$ cloud could survive in this fashion, gradually turning itself into stars, for 10^9 or even 10^{10} yr until its gas supply is finally exhausted.

The preceding argument ignores the possibility of a single initial burst of star formation. Even this need not be fatal. Suppose that the cloud is rotationally supported and has collapsed to a disk at this stage. The supernovae will tend to heat the disk, but disruption is unlikely. In principal, gas disks could survive star formation as argued above, until the gas supply is exhausted. The lifetime depends on the highly uncertain star formation rate. Adopting the star formation rate inferred from studies of disk galaxies, proportional to n^k, with $k > 1$, the characteristic star formation time-scale $\tau_* \propto n^{1-k}$. This suggests that heat input to the disk from newly formed stars will tend to inhibit star formation by increasing the density scale height and increasing τ_*. Hence especially if a disk forms in the initial collapse, subsequent star formation is likely to be self-regulating.

DISK GALAXY FORMATION

As the bound gas clouds cluster together gravitationally, they will also undergo inelastic collisions, which in turn are likely to further enhance the rate of star formation. The system of bound gas clouds behaves like test particles in an N-body simulation, while collisions are unimportant. However collisions occur in the dense inner regions, which develop via violent relaxation over a characteristic crossing time at any given stage of clustering. A collision between any two clouds will be highly radiative and inelastic, leading to a merger. The stellar component will be ejected from the gas whenever the cloud suffers substantial loss of kinetic energy. The collision should also stimulate further star formation, possibly destroying the cloud. Successive generations of stars therefore become more centrally concentrated and also more metal enriched (because of recycling of debris from previous stellar generations). However the clouds are likely to be destroyed as a consequence of the collisions within a dynamical time t_{dyn} appropriate to the inner region. Outside the core, the cloud collision time t_{coll} will exceed t_{dyn}, and dissipation will occur more gradually as clouds eventually collide over a longer time scale. The inner region, where $t_{\mathrm{coll}} \lesssim t_{\mathrm{dyn}}$, which forms and becomes predominantly stellar over t_{dyn}, is identified with the bulge component: it need not form from predominantly low angular momentum clouds. However low angular momentum clouds may subsequently continue to feed it.

Although kinetic energy is radiated in the cloud collisions, angular momentum is conserved. Hence the gradual clustering and merging of an isolated system of clouds results in the subsequent formation of a disk, with cloud collisions providing an effective source of viscosity, over a time-scale $\gg t_{\mathrm{dyn}}$. It is possible to infer the structure of the developing disk. Two time-scales are involved: the angular momentum transfer or viscous time-scale $\sim r^2 \nu^{-1}$ and the time-scale for loss of orbital energy by cloud collisions $\sim r(\lambda v)^{-1}$, where $\nu \sim lv/3$ is the effective viscosity, l is the cloud mean free path between collisions, v is the mean cloud velocity, and λ is the fraction of cloud kinetic energy lost per collision. It seems plausible that the infalling cloud distribution must adjust itself to maintain approximate equality of these two time-scales. It follows that $\nu \propto vr$, and one can now apply the theory of accretion disks. A self-similar disk structure develops, and an exponential disk structure forms together with a rotationally supported bulge where lower angular momentum material accumulates. Massive dark halos would presumably have developed by clustering and infall simultaneously with the disks, and may possibly be identified with remnants of a more massive stellar population. If this had evolved soon after the initial gas clouds formed, one might speculate that only those gas clouds where low mass star formation predominated survived as bound clouds to eventually form the luminous regions of galaxies. Once the gas supply is exhausted and the disk becomes predominantly stellar, the viscous mechanism effectively terminates. In order of magnitude, the disk scale parameter

$$\sim \nu (rt)^{-1} \sim l(v/30\ \mathrm{km\ s^{-1}})(\lambda/0.1)^{1/2}(t/10^9\ \mathrm{yr})\ \mathrm{kpc}\,,$$

and a wide range of characteristic scales is evidently possible. It is of interest to compare the viscosity inferred for this disk formation mechanism with that found for molecular clouds in the present interstellar medium, namely $\nu \sim (1/3) lv \sim 2$ km s^{-1} kpc. For a disk formation time in the range 10^9—10^{10} yr. the effective viscosity must have been 10—100 larger than at present.

According to this scheme, isolated galaxies are spiral or irregular galaxies, and have been fueled with gas by continuous infall. This late accumulation of disk material resolves the long-standing problem concerning the absence of a large number of low metallicity stars in the solar neighborhood. It also naturally leads to a metallicity gradient, as the freshly acquired and relatively unenriched material falls into the outermost regions of the disk. Globular clusters can acquire a metallicity gradient relative to the parent galaxy because the cloud collision rate and inferred rate of star formation and enrichment undergone by a surviving cloud will be increased towards the galactic center. Presumably only the few clouds that avoid total disruption form the observed globular clusters. Gas-rich dwarf galaxies can be identified with isolated clouds that have not yet exhausted their initial gas supply, but have recently been triggered into a more active burst of star formation. Such systems should be weakly enriched because of continuous star formation. Dwarf spheroidal galaxies are often associated with spiral galaxies, and presumably have had their gas supply exhausted or interrupted by interaction with their massive companions.

BULGE FORMATION

Bulge components form in the cloud-collision dominated regime, where $t_{\rm coll} \lesssim t_{\rm dyn}$. This leads to an effective truncation: star formation is enhanced within the galaxy core. A simple argument yields the dependence of core mass $M(r_{\rm core})$ on central velocity dispersion. If μ is the mean surface density of an individual cloud (all assumed for simplicity to be identical), the total mass interior to radius r of a self-gravitating system can be expressed as

$$M(r) \sim \frac{3\sigma^4}{4\pi G^2 r \varrho} \sim \frac{\sigma^4}{G^2 \mu} \frac{t_{\rm dyn}(r)}{t_{\rm coll}(r)} .$$

Hence the core mass must satisfy $M(r_{\rm core}) \sim \sigma^4/G^2\mu$. Note moreover that $M(r_{\rm core}) \sim \mu r^2_{\rm core}$, providing an understanding of Fish's law (if we assume that core mass is related to mean luminosity and core radius to, say, the de Vaucouleurs radius). Since $\mu \sim 300 T_4^2 M_6^{-1} M_\odot\ {\rm pc}^{-2}$, one infers that surface densities characteristic of elliptical galaxy cores are readily attainable. It is interesting to speculate that a similar truncation could operate for the old disk population in the direction perpendicular to the disk. This collision limit would then also lead to a characteristic disk (M, σ) relation, the existence of which is inferred from the correlation between near infrared luminosity and rotational velocity.

ELLIPTICAL GALAXY FORMATION

In regions of higher than average density, such as in groups and clusters of galaxies, protogalaxy mergers and collisions play an important role in galactic evolution. As hierarchical clustering proceeds, systems of comparable mass merge from marginally bound, low angular momentum orbits. In general, the initial collapse of a group or cluster of galaxies will involve sufficiently low velocities before virialization occurs, comparable to the internal velocity dispersion of individual galaxies, that mergers between protogalaxies are inevitable. Each protogalaxy consists of a system of bound clouds that are slowly forming stars and merging into a centrifugally supported disk. The loosely bound dark halos will be shared commonly, and the two galaxies will eventually merge together. Models of the interaction are available in the form of *N*-body simulations of galaxy mergers. The resulting system is round, and resembles an elliptical galaxy. A natural consequence of such merger models is that violent relaxation leads to the development of a Hubble-law ($\sim r^{-3}$) density profile. The merger refuels the core with clouds that form stars. Hence both the central density and the total luminosity are considerably increased relative to that expected when the bulge of an isolated galaxy formed.

The cloud collisions will generally lead to coalescence, and the compression will trigger further star formation. In an encounter between clouds, the stars present initially will escape. The bulk of the matter is still gaseous and will form new stars. In a subsequent encounter, these too will escape. A cloud could in principle survive several encounters before exhausting its gas supply. At sufficiently high relative velocity, however, the radiative cooling time will exceed the time-scale for the shock to traverse the cloud, and the clouds will disrupt. This leads to a limiting binding energy in the cores of elliptical galaxies: once clouds are disrupted, star formation effectively terminates. Truncation of the galaxy core by the exhaustion of star-forming cloud-cloud collisions within a core crossing time yields relations between M, σ, and r_{core} similar to those derived for the bulge components.

The evolving stars continuously eject enriched matter into the cloud, hence successive generations of stars become progressively more enriched. As clouds collide, they lose orbital energy and fall towards the galactic centre. In this fashion, a gradient in metallicity develops, because the distribution of enriched stars becomes more centrally concentrated than the distribution of less enriched stars. At the same time, cloud collisions are sufficiently infrequent that the velocity distribution, especially of the stars, remains anisotropic and reflects the radial distribution of the initial orbits. Consequently the resulting elliptical galaxy should be flattened because of its initially anisotropic velocity distribution; rotational support is likely to play a minor role in systems resulting in mergers from encounters with low orbital angular momentum. A simple explanation also arises for the correlation between luminosity and mean metallicity, if we assume that the efficiency of massive star formation progressively increases with increasing relative velocity of the colliding clouds. The more massive galaxies accordingly acquire a greater degree of enrichment. This process obviously saturates once cloud-cloud collisions become highly disruptive, at encounter velocities characteristic of the potential wells of very luminous elliptical galaxies.

SO GALAXY FORMATION

One may speculate on the origin of *SO* galaxies as follows. The initial merger between two disk systems is likely to leave intact a sufficient number of clouds to form a disk in the merged system, if it subsequently undergoes no further collisions. Subsequent mergers or collisions will convert all remaining clouds into stars. The inference is therefore that while ordinary spirals form in low density regions and ellipticals predominate in dense regions, a third type of galaxy, with bulge-to-disk ratio larger than that characteristic of spirals will form frequently at intermediate densities. These galaxies are identified as *SO* galaxies. There may be no necessity to invoke such effects as supernova-driven winds, ram-pressure stripping, or evaporation to convert spirals into *SO*'s: these mechanisms fail in any event to account for *SO* bulge-to-disk ratios and for the spatial distribution of *SO*'s, although they are likely to be important at the present epoch in accounting for the lack of gas accumulation in ellipticals and *SO*'s as a consequence of stellar mass loss.

There is one complicating factor that must be considered however. This involves the relative velocities of the colliding protogalaxies. If the relative velocity is too great, a merger will not occur, although a protospiral may be depleted of gas to form an *SO*. In rich clusters, mergers are not presently occurring when galaxies collide. Mergers are very likely to occur, of course, during the initial collapse phase, prior to cluster virialization. Later mergers, betweeen proto *SO*'s, and mergers involving ellipticals will occur with decreasing probability because of virialization.

Table 1

Merger Scheme

1. $\mathrm{Sp+Sp} \rightarrow \mathrm{SO}$

2. $$\begin{tikzcd}\mathrm{Sp+SO} \arrow[r, "a"] \arrow[dr, "1-a"'] & \mathrm{E} \\ & \mathrm{SO+SO}\end{tikzcd}$$

3. $$\begin{tikzcd}\mathrm{SO+SO} \arrow[r, "b"] \arrow[dr, "1-b"'] & \mathrm{E} \\ & \mathrm{SO+SO}\end{tikzcd}$$

4. $$\begin{tikzcd}\mathrm{E+Sp} \arrow[r, "c"] \arrow[dr, "1-c"'] & \mathrm{E} \\ & \mathrm{E+SO}\end{tikzcd}$$

5. $$\begin{tikzcd}\mathrm{E+SO} \arrow[r, "d"] \arrow[dr, "1-d"'] & \mathrm{E} \\ & \mathrm{E+SO}\end{tikzcd}$$

6. $$\begin{tikzcd}\mathrm{E+E} \arrow[r, "f"] \arrow[dr, "1-f"'] & \mathrm{E} \\ & \mathrm{E+E}\end{tikzcd}$$

A simple merger scheme that allows for many of these possibilities is indicated in Table 1. We assume that protospirals collide to form proto *SO*'s with unit probability, since these systems represent the basic units. Suppose that a protospiral and proto *SO* collide, to merge into a proto-elliptical with probability $a(<1)$ or else to result in two proto *SO*'s (the protospiral being effectively stripped). Two proto *SO*'s collide, to merge into a protoelliptical with probability $b(<1)$. Similarly, protoellipticals merge with protospirals, proto *SO*'s or protoellipticals to form protoellipticals with respective probabilities c, d, f. In all cases, a collision results in change in morphological type either when a protospiral collides or when a merger occurs.

Under these simple assumptions, we can now write down a set of kinetic equations for morphological type evolution as a consequence of galaxy mergers. The equations for morphological type evolution can be expressed in the following form:

$$\frac{1}{\gamma}\frac{dn_{sp}}{dt} = -2n_{sp}^2 - n_{s0}n_{sp} - n_e n_{sp}\,,$$

$$\frac{1}{\gamma}\frac{dn_{s0}}{dt} = n_{sp}^2+(1-2a)n_{sp}n_{s0}-2bn_{s0}^2+(1-c)n_e n_{sp}-dn_e n_{s0}\,,$$

and

$$\frac{1}{\gamma}\frac{dn_e}{dt} = bn_{s0}^2+an_{s0}n_{sp}-fn_e^2\,,$$

where n_e, n_{s0}, and n_{sp} denote the number densities of elliptical, *SO*, and spiral (together with irregular) galaxies. All of these collisional mergers are understood to occur during the initial phases of cluster collapse or in regions where the relative collision velocities are less than the internal velocity dispersion of the colliding systems.

By considering the ratios of these equations, first integrals of the system can be obtained. These directly yield the relative abundances of different types of galaxies. It is convenient to introduce the variable $X \equiv n_{sp}/n_{s0}$, which decreases monotonically with increasing galaxy density. Implicit solutions can easily be obtained for n_{sp}, n_{s0}, and n_e in the limit that collisions of protospirals and proto *SO*'s with protoellipticals are neglected.

We assume that $n_e = 0$ as $x \to \infty$ (i.e. in the field where $n_{sp} \gg n_{s0}$). This is required by our simple model, which however could obviously be generalized if necessary to include an additional uniform component of ellipticals. In Figure 1, we display our

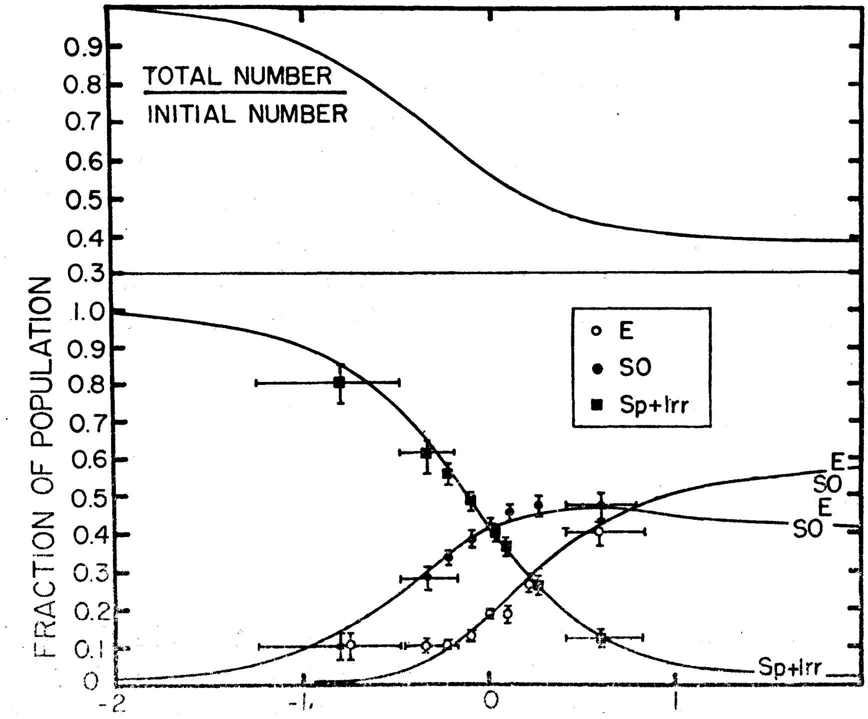

Fig. 1. Fractional abundance of elliptical, spiral, and *SO* galaxies, expressed as a function of the ratio of *SO* to spiral (and irregular) galaxies and computed from a simple merger model. Solid lines are calculated (see text) for $a = 1$, $b = 0$

solution for $a = 1$, $b = 0$, and for comparison, show also data obtained from the study by Dressler (1980).

One would obviously prefer a solution of the merger equations in which mergers between protoellipticals and disk systems were not neglected. There are sufficiently many parameters in the full system of equations that it seems fruitless to pursue this point, other than to note that the asymptotic behaviour is as follows: define $y = n_e/n_{s0}$, then for large x and small y,

$$xy = a, \; n_{sp} \sim \exp(-2/x)$$

and for small x and large y,

$$y \sim x^{-(d-f)/(1-d)}, \; n_{sp} \sim x^{1/(1-d)} .$$

This solution has the same asymptotic behaviour as the solution to the restricted set of equations plotted in figure 1, provided that $d > f$.

How reasonable are the restrictions imposed on the merger parameters? Clearly, the progression towards virialization makes it seem plausible that $a > b > c > d > f$. One cannot really say any more without recourse to the complications of a dynamical model. In general theory and observation are in remarkably good agreement apart from one data point, namely that for field ellipticals. Allowance for an unclustered distribution of ellipticals, possibly due to dynamical escape from denser regions, while detracting from the simplicity of the merger model, could completely reconcile model and data points if the uniform component amounts to a fractional population $\lesssim 0.1$. The fact that the fractional populations of galaxy types are determined over a wide range of density ($10^{-2} - 10^{+2}$ galaxies Mpc^{-3}) strongly supports the merging hypothesis. Figure 1 indicates that the initial number density of galaxies is reduced by ~ 60 percent as a consequence of mergers. This implies that the characteristic elliptical should be about one magnitude more luminous than the spheroidal component of a typical spiral. Moreover v_p/σ is decreased by a factor of $\sim 2.5^{3/2} = 4.0$, with bulges forming an intermediate class. In general, a continuous sequence of properties is expected between ellipticals and the spheroidal components of *SO*'s and of spirals. This should also include metallicity, as well as bulge rotation and luminosity.

IMPLICATIONS

Disk formation occurs slowly over $\gtrsim 10^9$ yr and tends to be inhibited within rich clusters, where the clouds of enriched material that otherwise would form the disk are ejected into the intergalactic medium. The formation time-scale of elliptical galaxies is characterized by a cluster crossing time, also $\sim 10^9$ yr, since after a collapse time, virialization prevents any further mergers at the high random velocities characteristic of clusters.

No dominant burst of star formation is expected, since much pregalactic star formation occurs in the isolated clouds. Indeed, the galaxies are assembled out of preenriched matter comparable in abundance to that of extreme population II. The long-lived supply of gas into disk systems helps ensure that metal-poor stars do not dominate the stellar distribution. In a cluster where mergers occur, the bulk of this gas undergoes collisions with gas in other clouds. This stimulates further star formation and enrichment, and also heats the gas, which must eventually fill the intracluster medium. Presumably field ellipticals formed in groups that have since dispersed. These should have undergone fewer mergers than ellipticals in rich clusters. Not only should there be more *SO*'s and a higher fraction of spirals, but further observational implications are that field ellipticals should be less luminous and have higher specific angular momentum than cluster ellipticals.

These properties depend on the merger rate and therefore on local density (and also on velocity dispersion, mergers being enhanced in lower velocity dispersion systems). Hence a weaker effect should also be present in comparing the outskirts and the central regions of a rich cluster.

Finally, one fascinating consequence of the hypothesis that isolated clouds can be very long-lived is that formation of small galaxies and globular clusters could be occurring at the present epoch. No external trigger is needed to convert clouds into galaxies. In fact, the isolated clouds supported by star formation that our theory utilizes and its basic building blocks are recognizable, after $\sim 10^9 - 10^{10}$ yr, as gas-rich dwarf galaxies.

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