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Galactic Evolution: A Survey of Recent Progress

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Summary. Current observational knowledge bearing on the evolution of elliptical and disk galaxies is reviewed. Particular emphasis is placed on identifying the factors that appear common to all galaxies of a particular type as opposed to those that seem to depend on environmental conditions. The success of various classes of galactic formation and evolution models used to confront these data is evaluated.

Since the 1920's, when a significant fraction of cataloged "nebulae" were recognized as "island universes" or galaxies external to our Milky Way, these enormous aggregates of stars, gas, and dust have been used as probes of the large-scale structure of the universe. For individual galaxies to be useful in such studies, it is necessary to understand their evolutional history so that we can estimate how their luminosity, size, and morphological appearance change with time. Lacking such information, it is impossible to use galaxies as standard candles or meter sticks in charting the shape and extent of the visible universe. It is not surprising therefore that considerable effort has been devoted to understanding the evolution of galaxies. Over the past 20 years, astronomers have gathered an impressive array of observational data bearing on this critical problem. At present, efforts to synthesize these data into a coherent picture of galactic evolution have been hindered by the unavoidable problem that the epoch of galaxy formation occurred between 10 billion and 20 billion years ago. Until recently, the study of galactic properties has been restricted to relatively nearby systems, many of which appear to be near the end of their active evolutionary phases. Our understanding of their past history is therefore to a large extent based on primitive models, many classes of which predict properties nearly identical to those found to characterize current-epoch galaxies. However, over the past few years, application of sensitive optical and infrared detectors has permitted astronomers to probe the properties of more distant, "younger" galaxies, with results which challenge evolutionary models and pose some serious new problems.

We provide here a compendium of basic properties that must be explained by any proposed picture of galaxy evolution. We attempt to sort those that appear to be "universal" properties of a particular galaxy type from those that appear to depend significantly on the environment in which a galaxy is located. Finally, we summarize the classes of evolutionary models currently believed to provide the best frameworks for interpreting these observed characteristics (*1*).

Galaxy Morphology

A necessary first step in the study of galactic evolution is to define a classification system that provides a basis for sorting galaxies into categories. By comparing the properties of galaxies of similar appearance as a function of time and environment, we hope to discern patterns of evolutionary development. Initially, such classification schemes are necessarily based partly on visual appearance. As our physical understanding of the factors that affect morphology deepens, classification criteria eventually become more refined.

The existence of two broad categories of galaxies—ellipticals and disk systems—is apparent from the most cursory examination of photographic surveys.

Elliptical or E galaxies are systems whose light distribution, deriving from the superposition of starlight along the line of sight, appears to fall off smoothly with radius and whose overall shape appears to represent the projection of a prolate or oblate spheroidal system on the plane of the sky. Typically, E galaxies are classified solely on the basis of their flattening (see Fig. 1). Detailed studies of surface brightness variations in ellipticals suggest that they can be well represented at large galactocentric distances by a variety of fitting functions; the most extensively used at present is the de Vaucouleurs law (*2*); $\log \mu = -3.33 [\log (r/r_e)^{1/4} - 1]$. Here μ is the observed surface brightness (magnitudes per arc second squared) and r and r_e are, respectively, the galactocentric distance and the effective radius within which half the luminosity of the galaxy is contained. This functional representation appears to fit well the light distribution of E galaxies in the luminosity range $-20 \lesssim M_v \lesssim -23$; the surface brightness distribution of fainter galaxies appears to fall off more rapidly at large galactocentric distances than does the de Vaucouleurs law.

Disk galaxies appear to be composed of two morphologically distinct parts—a spheroidal bulge and a flattened disk. The bulge components of disk galaxies are superficially similar to E galaxies. Disk components may exhibit a variety of appearances. Some are forming stars at the present epoch, either in relatively regular patterns (spirals; see Fig. 2) or in chaotic patterns (irregular systems; see Fig. 3); others appear to have ceased star formation (at the current epoch), either temporarily or permanently, and are characterized by relatively smooth disks (S0 systems). The relative size and luminosity of the bulge and disk components

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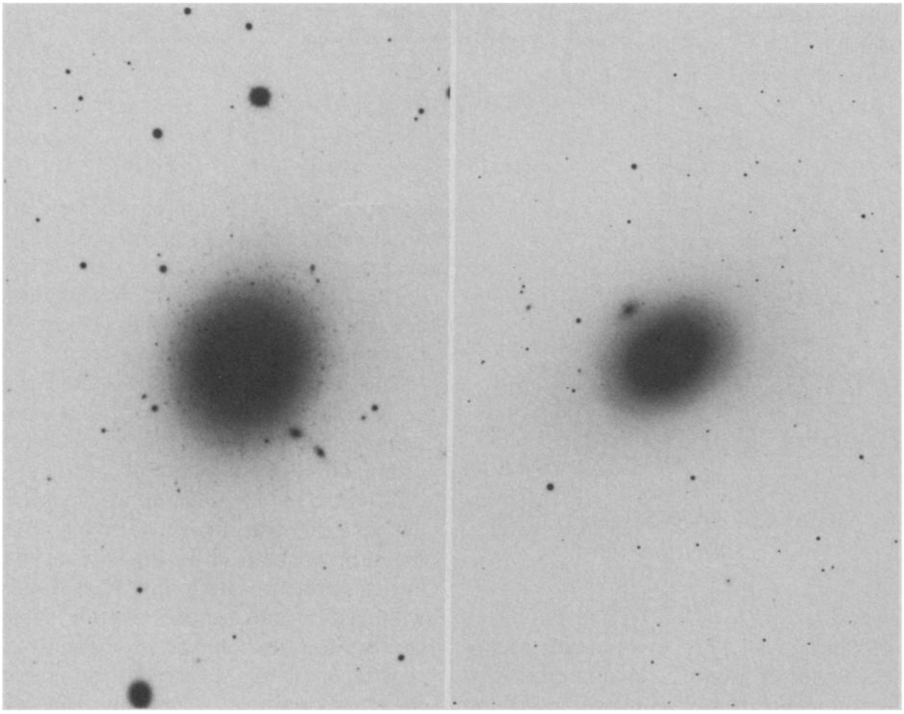

Fig. 1. Two examples of elliptical galaxies. On the left is a plate of Messier 87 (M87), a giant E0 galaxy in Virgo. Note the swarm of starlike images surrounding the galaxy; these are a population of globular clusters similar to those found in the halo of our Milky Way. On the right is a more flattened E galaxy (NGC 4406, E3).

appear to vary continuously from pure bulge systems (E galaxies) to pure disk systems (late-type spirals and irregulars and their non–star-forming analogs). Hence a useful initial description of a disk galaxy is provided by (i) the bulge-to-disk ratio characteristic of the system, (ii) the presence or absence of current-epoch star formation in the disk, and (iii) the spatial regularity of the current-epoch star-forming episodes.

Classification schemes for disk galaxies generally follow precepts that are similar in spirit to those originally articulated by Hubble (*3*). In his system, as modified and extended by Sandage (*4*), the following categories are defined:

S0: galaxies with no or little evidence of star-forming activity in the disk; some may show evidence of dust lanes or dust patches.

Sa: galaxies with a low contrast of arm to disk light, a large bulge-to-disk ratio, and tightly wound spiral arms.

Sb: galaxies with a higher contrast of arm to disk light, a smaller bulge-to-disk ratio than those in class Sa, and a more open arm pattern.

Sc: galaxies with a high contrast of arm to disk light, a small bulge-to-disk ratio, and an open spiral pattern.

Sd: galaxies with a small or absent bulge and an open, patchy, and ill-defined spiral pattern.

Sm: bulgeless systems characterized by open, poorly defined spiral patterns.

The Sa galaxies are often referred to as early Hubble types, while types Sc through Sm are referred to as late Hubble types.

As suggested above, the location of a spiral galaxy in the Hubble sequence depends primarily on the appearance ("texture") of the arms. However, other systems, such as those proposed by Morgan (*5, 6*) and by van den Bergh (*7*), rely on the ratio of the bulge and disk sizes. In most cases the systems yield comparable classifications. In our view the systems based on bulge-to-disk ratio may eventually prove more powerful because of their more direct measure of the underlying dynamics of disk galaxies.

The light distribution of the bulge appears, at first glance, to be well fitted by a de Vaucouleurs law (*8*). More careful study suggests that this may not be the case (*9*) universally. The light distribution in the disk appears to follow an exponential law, although such a simple description for all systems has been questioned.

Properties of E Galaxies

Frequency distribution in differing environments. Five years ago, Oemler (*10*) presented the first modern study of galaxy morphological types in clusters. This work suggested the existence of three representative classes of galaxy clusters: (i) cD clusters—dense aggregates of galaxies characterized by a core-halo distribution of galaxies and dominated by a centrally located cD system, (ii) spiral-poor clusters—dense aggregates somewhat less centrally concentrated than cD clusters, and (iii) spiral-rich clusters—irregular, moderate- to low-density groups.

The three cluster classes exhibit significantly different proportions of galaxy types. The ratios of ellipticals to S0's to spirals (Sp's) for the three types are (i) 3:4:2, (ii) 1:2:1, and (iii) 1:2:3. Subsequent studies by Melnick and Sargent (*11*), Butcher and Oemler (*12*), and Dressler (*13*) confirm the dependence of galaxy content on cluster morphology.

Dressler notes that the Oemler classes are not discrete but rather representative of a continuous range of cluster morphologies. He also remarks that the E:S0:Sp ratio appears to vary continuously with current-epoch local density. Hence, within clusters of all types and among clusters of different types, the proportion of E and S0 galaxies is highest in regions of the highest local galaxy density. The cluster population studies of Melnick and Sargent are consistent with this result, although their sample is strongly biased toward dense, rich clusters of galaxies.

The best available modern data suggest that E (along with S0) galaxies are found most frequently in regions characterized by high galaxy density.

Sizes and luminosities. Over the past several years, Strom and Strom have published a survey of E-galaxy properties for a large sample of elliptical systems located in a variety of environmental settings [for example, see (*14*)]. They have presented ultraviolet and red surface photometry for nearly 600 galaxies, permitting quantitative discussion of the size, shape, and chemical composition of these galaxies. Two fundamental parameters that describe E galaxies are their size and luminosity. Strom and Strom used two measurements of size: the de Vaucouleurs effective radius r_e and the radius r_{26} at which the red surface brightness reaches a value of 26 mag (arc sec)$^{-2}$. The former quantity represents a metric size, whereas the latter is an isophotal size. As might be expected from cursory examination of galaxy photographs, they found that the more luminous galaxies were bigger. Their study permitted a quantitative comparison of the size-luminosity relationship (r,L) for E galaxies located in clusters of differing Oemler types. The (r,L) relationships for the spiral-rich clusters and for the low-density outer regions of all clusters are identical; however, galaxies located in the central region of rich clusters of galaxies appear to be smaller. Strom and

Strom (*15*) attribute this difference to the effects of multiple gravitational encounters in the denser regions of the clusters included in their sample. Tidal stripping of stars from the outer regions of E galaxies appears to offer a reasonable explanation for the decrease in E-galaxy size in such regions.

The frequency distribution of E-galaxy luminosities appears to depend on environment. From Dressler's study (*16*), there appear to be several clusters, most of them characterized by high galaxy density, in which the number of galaxies as a function of luminosity differs significantly from the Schechter (*17*) relationship characteristic of the field. Whether this difference can be explained entirely in terms of postformation interactions [for example, tidal stripping and galaxy mergers (*18*)] is not yet clear.

Shape. The shape is another fundamental characteristic of E galaxies. Originally, it was believed that E galaxies were either prolate or oblate spheroids in which flattening was induced by rotation. Current results cast doubt on these assumptions (*19, 20*). It now appears that most ellipticals are triaxial (*20*) ellipsoids of revolution, although close in appearance to oblate spheroids (*21*). Their shape results primarily from anisotropies in the velocity field of their constituent stars rather than from rotation.

Strom and Strom (*14*) reported that the frequency distribution of ellipticities appears to depend on the shape of the cluster of galaxies in which E galaxies reside; there are more flattened ellipticals in flattened clusters. In some but not all cases the major axis of the E galaxies tends to be aligned along the major axis defined by the cluster galaxy distribution. Hence the environment in which an elliptical is located may determine its shape. The critical question we must face is whether this environmental difference results from relatively recent inter-

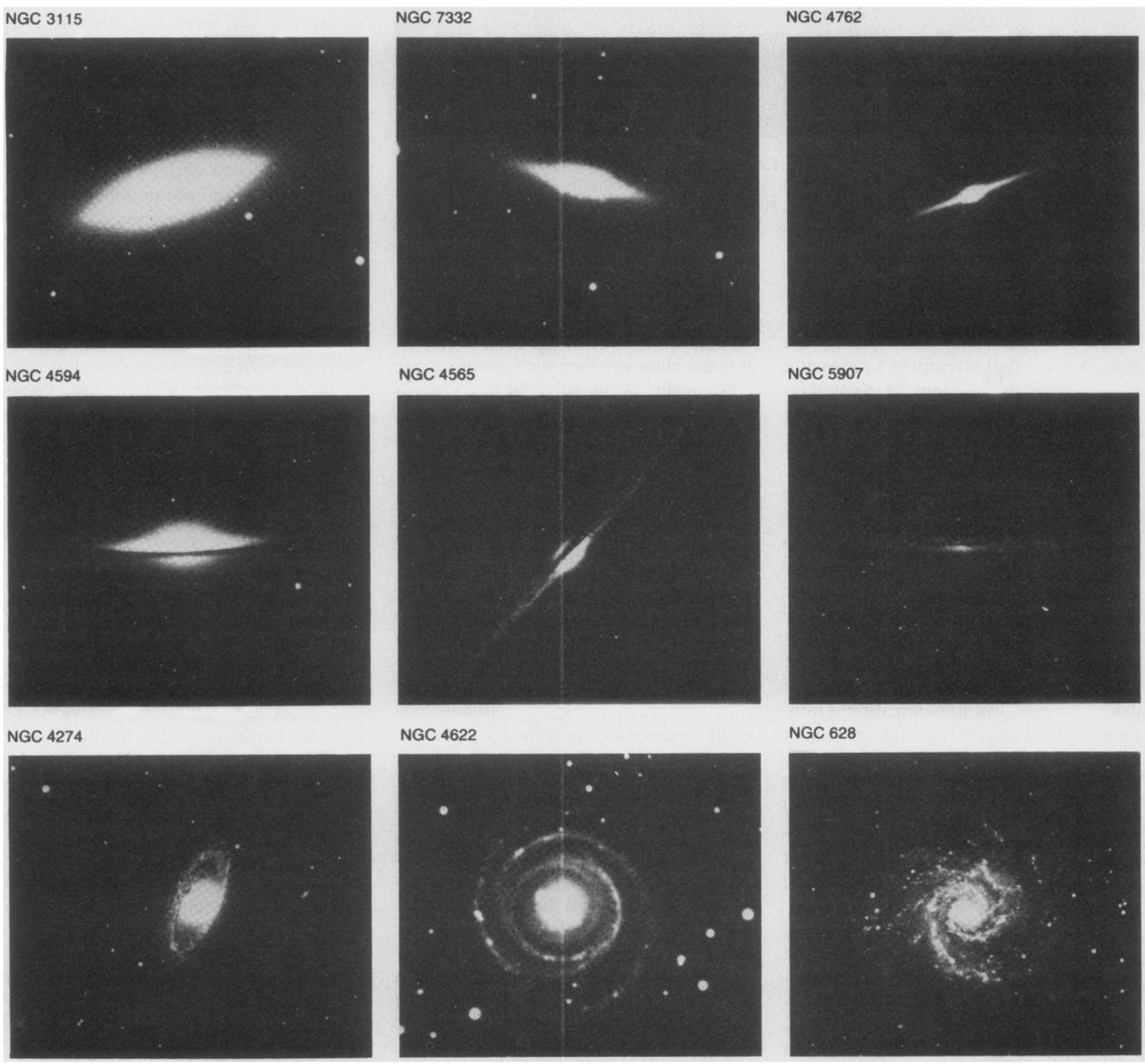

Fig. 2. Luminous disk galaxies can be divided into two broad categories: spiral systems and S0 systems. Both kinds of galaxy have a central bulge and a surrounding disk. The disks of spiral galaxies have visually prominent arms because they are studded with complexes of bright, newly formed stars. The disks of S0 galaxies, in contrast, are smooth, show no spiral structure, and are devoid of young stars. The three photographs in the top row depict S0 systems viewed nearly edge-on, arranged in order of the decreasing prominence of their bulge with respect to their disk. No evidence of recent star formation is visible. The photographs in the middle row show three galaxies of the spiral type, also seen edge-on and in order of decreasing bulge-to-disk ratio. The galaxies in the bottom row illustrate the probable face-on appearance of spiral galaxies in the middle row. The bright knots in the spiral arms of the galaxies represent newly formed stellar complexes.

Fig. 3. An example of an irregular galaxy, the Large Magellanic Cloud. Note the bright patches of newly formed stars and associated nebulosity superposed randomly on the smooth disk population of relatively old stars. Irregular star-forming patterns are common among disk galaxies of low luminosity.

actions among galaxies or was "built in" at the time of galaxy formation.

Gas content and star formation. Knapp *et al.* (*22*) attempted to measure the neutral hydrogen content of E galaxies. They concluded that the gas content of most ellipticals does not exceed 0.1 percent of their total mass.

Gisler (*23*) recently analyzed the results of all available observations of forbidden singly ionized oxygen, [O II], 3727-angstrom line emission in E and S0 galaxies located in a variety of environments. After correcting for observational selection effects and biases in the heterogeneous data sets, he found a higher percentage of [O II] emission among E galaxies located in low-density environments than in dense, rich clusters. Gisler suggested that the relative infrequency of observed ionized gas in clusters of E galaxies results from either thermal evaporation of intragalactic gas by electron conduction in the hot intracluster medium (*24*) or ablation by ram-pressure stripping (*25*).

Studies of the color distributions in E galaxies suggest that in most cases the galaxy becomes bluer at larger galactocentric distances (see the following section on chemical composition), suggesting a decrease in metal abundance in the outer parts of ellipticals. However, a small fraction of ellipticals exhibit blue colors in their nuclear region (*26*). Moreover, examination of the nearby E galaxy NGC 205 in the Local Group reveals a population of luminous blue stars near its nucleus. These observations suggest that some E galaxies are forming a limited number of stars at the current epoch. It is not clear whether such events occur episodically in all ellipticals or are restricted to a small subset of the class. Stauffer (*27*) and Gallagher (*28*) noticed the presence of dust clouds in ultraviolet and blue photographs of ellipticals. Their presence suggests that currently inactive systems contain material that could conceivably be assembled into stars. Faber (*29*) is attempting to map a sample of E galaxies of a variety of luminosities in a set of photometric indices sensitive to both metal abundance and the presence of a young stellar component. From her observations, it should be possible eventually to estimate the frequency and extent of star-forming events in elliptical galaxies.

Chemical composition. Perhaps the most solidly based result regarding the composition of E galaxies is the observed correlation between absorption-feature strength and luminosity; luminous E galaxies tend to have stronger absorption features (*30*) than do fainter systems. Although the exact relationship between absorption-feature strength and metal-to-hydrogen ratio *Z* may be questioned, it appears certain that the dominant factor influencing the observed variations in line strength is, in fact, the galaxian metallicity.

Faber (*30*) established that galaxian color varies directly with line strength (luminous E galaxies are redder), and subsequent studies (*31*) further refined the arguments which suggest that luminous E galaxies are more metal-rich. Integrated colors are available for a large number of E galaxies located in a variety of environments (*14, 26, 32*). In general, the relationship between color and luminosity is identical, independent of environment.

[*Note added in proof*: Caldwell (*32a*) notes that the dispersion in the color-luminosity relationship increases in regions of lower galaxy density. He attributes this difference to an increase of star-forming activity in E galaxies located in such environments.]

The variation of metallicity with position in a galaxy appears to provide a measure of star formation, element production, element dispersal, and gas flows that occurred during the early evolutionary history of an E galaxy. Unfortunately, the only extensive data available that measure $Z(r)$ are those of Strom and Strom (*14*). Their surface photometry in the ultraviolet and red permits estimates of $Z(r)$ for $r \gtrsim 1$ kiloparsec (that is, for regions well outside the nucleus). In their sample of cluster E galaxies only 20 percent exhibit observable halo ($r \gtrsim 1$ kiloparsec) color gradients (almost without exception, the galaxies that do are bluer and hence more metal-poor at larger galactocentric radii). The remainder show no observable variation of color with radius outside the nuclear regions. Whether this result applies to E galaxies in lower density environments is not known.

Globular Clusters Surrounding E Galaxies

High-quality photographs of E galaxies located within 20 megaparsecs reveal that they are surrounded by systems of globular clusters similar to the system populating the halo of the Milky Way. A photograph of the giant Virgo E galaxy M87 shows an excellent example of such a system (Fig. 1). Until recently, it was thought that the properties of the globular cluster system were identical to those of the stellar system that produces the smooth halo-light distribution in E galaxies. However, a recent study by Strom *et al.* (*33*) suggests otherwise. They find that at a given galactocentric distance the globular clusters are, on average, bluer and perhaps more metal-poor stars composing the spheroid. Moreover, the spatial distribution of the globular clusters differs from that of the halo stars in the sense that the globular clusters are more distended. Hence the dynamical and chemical history of the globular clusters surrounding E galaxies appears different from that characterizing the halo population in such galaxies.

Mass-to-Luminosity Ratio in E Galaxies

It has recently become feasible to measure the velocity dispersion σ_V for the stellar component of E galaxies. For the most part, these studies have been restricted to the nuclear regions of ellipticals, although data concerning the radial dependence of σ_V are becoming more abundant. Faber and Jackson (*34*) established that over a range of 100 in L, $\sigma_V \approx L^{1/4}$. Photometry and measurements of σ_V lead to an estimated mean value of the ratio of mass to blue luminosity of $M/L_B \approx 8.5$ for E galaxies (*35*).

Sargent *et al.* (*36*) compared the run of σ_V and of surface brightness with position near the nucleus of M87. They argue that an object of mass $\approx 5 \times 10^9$ solar masses ($M_\odot$) and $M/L \approx 60$ occupies a region within 110 parsecs of the center of the elliptical, and they believe the object to be a massive black hole. However, more recent studies (*37, 38*) suggest that this interpretation does not provide a unique description of the data.

For regions well beyond the nucleus, little direct evidence is as yet available regarding mass-to-light ratios. A number of E galaxies have been observed to possess halos of hot ($\approx 10^7$ K) gas. If these hot halos are gravitationally bound to the galaxies and in hydrostatic equilibrium, the necessary mass predicts an M/L_B ratio of approximately several hundred (*39*).

Another estimate of M/L for E galaxies is provided by the virial-theorem masses for rich clusters such as Coma in which E galaxies are the dominant constituent. The distribution of Coma galaxies on the plane of the sky suggests that the inner regions of the cluster have reached virial equilibrium. If so, then the cluster mass estimated from the observed velocity dispersion for the galaxies provides a mean value of $M/L_B \approx 300$ for a typical E galaxy.

E-Galaxy Evolution

Empirical evidence. Recent optical and near-infrared measurements (*40–42*) have provided empirical evidence regarding color and luminosity evolution of E galaxies. For galaxies with redshifts $z > 1$, infrared observations are necessary in order to compare the observed spectral energy distribution of galaxies with the optical spectra of nearby galaxies. Moreover, such observations are far less sensitive to the presence of small admixtures of young stars than are measurements of distant galaxies made in the visible region of the spectrum. Grasdalen (*41*) was the first to exploit the possibility of using infrared measurements to assess E-galaxy evolution. His preliminary results suggest "mild" color evolution at $z \approx 0.5$. For a simple open-universe cosmology ($q_0 = 0$) the infrared measurements suggest measurable luminosity evolution. More complete surveys of E-galaxy colors and luminosities, particularly those based on infrared measurements, will place important constraints on evolution and on the "cosmic scatter" in galaxy evolutionary properties.

Evolutionary models. Theoretical models of E-galaxy evolution fall into three broad categories:

1) Merger models, in which E galaxies are assembled from slow collisions and the merger of disk galaxies (*43*).

2) Gravitational assembly models, in which an E galaxy is produced by assembly of preexisting stars or clusters of stars.

3) Gas dynamical models, in which E galaxies begin as primordial gas clouds in which star formation proceeds rapidly and accompanies the collapse of the cloud (*44*). The collapse is essentially dissipationless, and the E-galaxy structure is established within a few free-fall times.

All models successfully account for the luminosity profile of ellipticals. However, beyond this, each model encounters some degree of difficulty (*45, 46*). In general, gas dynamical models have proven most successful in predicting the overall properties of E galaxies. In such models the massive stars in initial stellar generations evolve and inject synthesized elements into the collapsing gas; successive generations of stars are thereby enriched in metals, thus producing a systemwide composition gradient. However, if the heating from supernovae and cloud-cloud collisions is sufficiently high to overcome the self-gravity of the protogalactic system, all of the enriched protogalactic gas can be ejected from the system in its later evolutionary stages, thus precluding the production of metal-rich stellar generations (*47*). Since lower mass systems are more susceptible to losing supernova-heated gas, their mean metallicity is expected to be smaller than that of more massive galaxies. Thus the observed metallicity-luminosity relationship can be explained in a natural way. While more successful in confronting observations than other evolutionary models, the gas dynamical picture is at present heuristic at best. Its greatest uncertainties derive from our meager knowledge concerning the factors that influence star formation efficiency. Hence a critical factor in the evolutionary history of model E galaxies—the ratio of conversion of gas into stars as a function of gas density—is treated as an adjustable parameter. Moreover, the gas dynamical models computed to date suppose that rotation is the dominant factor controlling E-galaxy shape—in contradiction to the best current evidence. No models in which initial velocity anisotropies are assumed have been used to compute the chemical history of E galaxies.

Disk Galaxies

Frequency distribution in differing environments. Earlier we discussed the distribution of galaxy types in each of the Oemler cluster types; E and S0 galaxies dominate in the relatively regular and dense cD and spiral-poor clusters, while spirals dominate lower density irregular clusters and the field. Melnick and Sargent (*11*) and Bahcall (*48*) have studied the distribution of actively star-forming disk systems (spirals and irregulars) and non–star-forming disks (S0's) in several rich, dense system clusters known to be x-ray emitters. The ratio of Sp's to S0's increases monotonically with increasing distance from the center of the clusters in their sample. Melnick and Sargent also found that Sp:S0 is dependent on the velocity dispersion of the cluster. Dressler (*13*) argued that this systematic behavior is representative of a more general correlation between Sp:S0 and local galaxy density that applies not only to rich clusters but to all regions of space. He cites only one possible deviation from the smooth trend of Sp:S0; this ratio appears, at a marginal level, to be systematically smaller at given densities in clusters known to be x-ray emitters.

Dressler also finds the luminosity of the bulge component of disk galaxies to depend on local galaxy density; in regions of higher density, the bulge luminosity tends to be higher as well.

The frequency distribution of bulge sizes for actively star-forming and S0 disk systems has been found to differ by both Dressler (*13*) and Burstein (*49*). Systems with a large bulge-to-disk ratio are more likely to be S0's than spirals. S0 systems with small bulge-to-disk ratios are virtually absent.

Size. There are as yet no published comprehensive studies (analogous to those available for E galaxies) of disk system sizes located in a variety of environments. Peterson *et al.* (*50*) examined the size-luminosity relationship for spirals and S0 galaxies in the Hercules and Virgo clusters. For Hercules, they found that the isophotal diameters of disk systems exhibit a relationship to luminosity identical to that of the field galaxies studied by Holmberg (*51*). The Virgo disks appear to be approximately 20 percent smaller at constant luminosity. Strom and Strom (*52*) also studied the relationship between isophotal diameter and position for S0 galaxies in the Coma cluster. They found that the disk sizes for these galaxies tend to be smaller in the central, dense regions of this cluster, in analogy with their findings for E galaxies.

Shape and alignment. There are as yet no data that provide measurements of the frequency distribution of ellipticity for disk system bulges, although Kormendy (*53*) believes the average disk system bulge to be more flattened than the average elliptical. In contradistinction to E galaxies, Kormendy and Illingworth (*54*) find that rotation is sufficient to account for the flattening of disk system bulges.

Recent work by Adams *et al.* (*55*) suggests that the major axes of disk galaxies are aligned in two preferred directions: either along or perpendicular to the cluster major axis. Their results add to the list of clusters in which galaxy alignment has been noted (*16, 56*) for disk systems, ellipticals, or both. It appears as if galaxies in clusters may somehow reflect the effects of the cluster environment either at the time of galaxy formation or later, as a consequence of postformation interactions.

Gas content and star formation—spiral and irregular galaxies. All current models of disk galaxies presume that the bulge region forms within a few free-fall times of the initial collapses of a protogalactic cloud. In analogy to E galaxies, star formation in the bulge is supposed to occur rapidly, so that the subsequent evolution of this region is dominated by nondissipative, stellar-dynamical processes. Bulges are consequently presumed to have been inactive in the star-forming sense for nearly the entire lifetime of the disk galaxy. In discussing the evolutionary history of a disk galaxy, it is necessary to take into account the (possibly) large difference in characteristic time scale for star formation in the bulge and disk subsystems; the evolutionary behavior of each component must be evaluated separately.

Assessment of star formation in disk galaxies at present depends on interpretation of integrated colors. Qualitatively, the bluest galaxies are believed to contain the largest fraction of newly formed stars. However, the observed colors include a nonnegligible contribution from the bulges; the relative contribution of the bulge is, of course, larger for earlier Hubble types. Hence if one sets out to compare the relative numbers of new and old stars in the actively star-forming region of the galaxy—the disk—the use of integrated colors will result in underestimating the young star contribution in systems of early Hubble type.

Taken at face value, the observed colors of spirals (*57, 58*) suggest that the ratio of new ($t \lesssim 10^8$ years) to old ($t \gtrsim 10^9$ years) stellar populations increases toward later Hubble types; the largest fraction of new stars is found in irregular galaxies. It is therefore believed that star formation was extremely efficient at early epochs in early Hubble types but is relatively inefficient at present; the opposite is believed true for late Hubble types. However, this conclusion rests heavily on the assumption that the metallicity of disk stars is constant with type.

A further difficulty in the discussion of disk system star-forming histories is presented by the one-dimensional classification scheme currently in use by most astronomers. For E galaxies, we now recognize that the observed colors depend on luminosity, presumably because they reflect a systematic variation of metallicity with galaxy mass (see earlier section on chemical composition). Such a luminosity-dependent phenomenon should serve as a warning to compare galaxy properties at constant luminosity in disk galaxies as well; physical arguments presented here will reinforce this intuitive belief. In this context Strom (*59*) has emphasized [see also van den Bergh (*7*)] that the Hubble sequence is also, in part, a luminosity sequence. Late-type galaxies are found to persist at lower luminosities than do the earlier types. Moreover, there are no high-luminosity representatives of types Sd and Sm. Consequently, a statement such as "galaxy colors become bluer at later Hubble types" contains information regarding the star-forming history of galaxies not only as a function of type but of luminosity as well. It will be critical in future discussions of the evolution of disk galaxies to establish an objective two-dimensional galaxy classification system.

Combined with an assessment of new and old population ratios, the relative mass in gas and stars provides another indication of the evolutionary status of a galaxy. The ratio of hydrogen mass to luminosity (M_H/L_B) appears to increase toward later Hubble types (*60*), suggesting that such galaxies are less advanced in an evolutionary sense than are earlier types. However, the total hydrogen mass rarely exceeds 20 percent of the total stellar mass. Hence in most disk galaxies a large fraction of the initial gas appears to have been converted into stars. Maps of the neutral hydrogen column density and the surface brightness of the stellar disk suggest that within a galaxy the ratio of gas to stellar mass increases outward. This suggests that the conversion of gas to stars is slower in the outer regions of disk galaxies, a result consistent with the radial distribution of chemical abundance described in the forthcoming section on chemical composition.

Some attempts (*61*) to study M_H/L_B as a function of luminosity suggest that the ratio increases toward lower luminosities within a given Hubble type. The highest values of M_H/L_B are found for irregular galaxies. Following the reasoning in our discussion of galaxy colors, it would be instructive in comparing the relative hydrogen content of galaxy types to compute the ratio of hydrogen mass to (red) disk luminosity and to compare systems of comparable disk luminosity.

Another difficulty in quantitatively assessing these M_H/L_B ratios is the possibility that a significant fraction of the gas content of a galaxy may be in the form of molecular as opposed to atomic hydrogen. Maps of some external galaxies (*62*) suggest that $M_{H_2}/M_H \gtrsim 1$ over a significant fraction of the galactic disks in late-type galaxies. Until we are able to estimate this quantity for a wide range of galaxy types and luminosities, it will be difficult to provide a definitive discussion of the relative degree of gas consumption in disk galaxies.

A further question regarding the gas content of spirals is the mass of gas contained in galactic halos. Larson *et al.* (*63*) suggested that halo gas "reservoirs" play a significant role in the evolution of disk galaxies. They proposed that removal of such halos in dense regions through galaxy-galaxy collisions may be responsible for the dominance of S0 galaxies in such regions. Neutral hydrogen (H I) maps of edge-on, isolated disk galaxies and careful observations of H I velocity dispersion in face-on systems should be made in order to assess the importance of gaseous halos.

A final concern regarding the star-forming histories of disk galaxies arises from recent observations (*64, 65*) which suggest that the oldest stars in the disk of the Milky Way may be no older than 6×10^9 years and in the Magellanic Clouds no older than 4×10^9 years. If true, these results suggest that the bulk of disk star formation may have begun more than 5×10^9 years after the formation of globular clusters and halo stars. Consequently, disk systems should exhibit significant changes in luminosity and color at relatively modest look-back times. Detailed population surveys of nearby galaxies with Space Telescope should provide definitive information regarding the age range of the constituents of the "old" disk population.

Gas content and star formation—S0 galaxies. Biermann *et al.* (*66*) have made searches for neutral hydrogen in S0 galaxies. In most cases the results have been negative, although some systems do contain small amounts of neutral hydrogen (1 percent of the total mass). In most cases detailed examination of the gas-bearing S0 galaxies reveals some evidence of recent star formation.

Searches for [O II] emission analogous to those carried out for E galaxies have also been conducted for S0 galaxies located in a variety of environments. The surveys to date provide primarily an indication of whether ionized gas is present in the nuclear bulge region. As for E galaxies, the frequency of [O II] emission is lower for the S0's located in rich clusters than for those in the field (*23*).

Wilkerson *et al.* (*67*) discussed an unusual class of spiral galaxies that appear not to be forming stars at the current epoch. They have smooth arms and no evidence of ionized hydrogen (H II) regions, OB complexes (associations of spectral type O and B stars), or dust and are found primarily, although not exclusively, in dense, rich clusters. Wilkerson *et al.* observed a sample of these galaxies and found that M_H/L_B is deficient, compared with normal spirals of similar bulge-to-disk ratio and arm winding, by more than a factor of 5 in all cases studied to date. They concluded that these systems are hydrogen-poor and suggested that some mechanism has accelerated the consumption of gas or removed most of the disk hydrogen.

A question related to the gas content of disk galaxies is whether the star-forming rates in actively star-forming galaxies vary as a function of environment. To answer this question, it will be necessary to observe the disk colors of spiral galaxies and compare the colors of systems of similar Hubble type located in a variety of settings. No such data are available at present.

Data are available that permit comparison of the integrated colors of S0 galaxies located within and outside rich clusters. From a sample of over 400 galaxies, Visvanathan and Sandage (*32*) argued that the colors of S0 galaxies are independent of environment. It should be noted that their result applies to the combined light of the bulge and disk. If the bulge light dominates the observed colors, then the test suggests that the bulge colors are environment-independent; the disk colors could be different. That this may be the case was suggested by Strom and Strom (*52*), who found the disk colors of S0 galaxies in the outer parts of the Coma cluster to be bluer than those in dense central regions. Their result suggests that star formation ceased more recently for galaxies located in the outer parts of the cluster.

Another indication of the star-forming history of disk systems located in rich clusters comes from recent work of Butcher and Oemler (*12*). From an examination of the frequency distribution of galaxy colors in two clusters similar to Coma but located at $z = 0.4$, they infer that a much larger fraction (compared with Coma) of the galaxies in the two distinct clusters are actively star-forming systems (presumably spirals). Their result has, however, been challenged recently by Eastwood and Grasdalen (*68*), for example. If the Butcher-Oemler effect is real, it suggests that some mechanism acts to truncate star formation in such systems on a time scale comparable to 5 billion years. Alternatively, disks may be formed relatively recently.

Chemical composition—bulges. Burstein (*69*) recently completed an initial survey of S0 bulges and believes them to differ significantly from E galaxies in the sense that the nuclear region metallicity of S0's is greater at a fixed luminosity. Boroson (*70*) has challenged these results and attempted to extend the study of the bulge luminosity-composition relationship to actively star-forming disk systems. At present, the samples are too small to provide a definitive comparison of E galaxies and S0 and spiral bulges.

Wirth (*71*) has reported the first results of a survey of composition gradients in disk system bulges. He finds that the frequency and magnitude of detectable composition gradients are significantly higher among disk system bulges than in ellipticals. Combined with the Kormendy and Illingworth (*54*) results suggesting higher rotation for disk system bulges as compared with ellipticals, Wirth's observations seem to suggest that the evolutionary history of a disk system bulge may differ significantly from that of an E galaxy.

Chemical composition—disks. Considerable effort has been invested in the study of metal abundances in galactic disks [for example, see (*72*)], primarily through analysis of H II regions. All investigators agree that the metal-to-hydrogen ratio is greatest near the galactic center and decreases outward; disagreements regarding the magnitude of the composition gradients persist. Such gradients are predicted naturally in the context of gas dynamical models (*73*). Jensen *et al.* (*72*) attributed the gradients and the differences in mean metal abundances among galaxies of a given type to differences in star formation, element production, and gas depletion rates induced by galactic shocks.

Infrared properties of disk galaxies. The integrated light from actively star-forming disk galaxies derives both from newly formed stars and from an "old disk" population. Most discussions of disk properties such as scale length and total luminosity have been based on blue-light photometry. This is in hindsight an unfortunate choice, since the reported properties depend on the fractional contribution of young and old stellar populations. At wavelengths of 1.6 and 2.2 micrometers, however, the observed luminosity is normally dominated by the old disk population. Hence observations at these wavelengths provide a direct measurement of the underlying structure of the stellar component of disk galaxies. Aaronson (*74*) has provided the most extensive survey of disk galaxies to date. His work clearly demonstrates that light arising from old disk K giants dominates the luminosity observed in the near-infrared. Potentially, a comparison of near-ultraviolet and infrared maps of disk galaxies offers the possibility of separating the contributions of new and old populations and of leading thereby to an assessment of the ratio of present to past star-forming rates as a function of position. As yet this potential for explaining the star-forming behavior of disk galaxies has not been exploited fully.

Infrared observations at long wavelengths (≈ 10 micrometers) have thus far been restricted primarily to the nuclear regions of disk galaxies. The results suggest the presence in some galaxies of large complexes of newly formed stars (of mass 10^7 to 10^8 $M_\odot$) still surrounded by molecular cloud complexes (*42*). The cause of such extremely vigorous star formation in the nuclear region is at present unknown. However, the existence of such stars is an important consideration in attempts to model active disk galaxy nuclei.

Efforts to map the disks of actively star-forming galaxies in the 10-micrometer region have just begun (*75*). Such observations will clearly be of importance in assessing the contribution of newly formed stars that are presently obscured from optical detection by optically thick dust clouds. Until such a census is available, the range of star-forming activity in galaxies in the current epoch will not be known with certainty.

Disk Galaxies as Laboratories for Understanding Star Formation

The apparent difference in the rates at which disk systems convert gas to stars suggests that by identifying systems of high M_H/L_B we may be able to gain some insight into the star-forming process as it operated at earlier epochs. Searches for such systems appear most profitably directed at lower luminosity, irregular systems, although in some cases relatively luminous galaxies of high M_H/L_B have been found (*76, 77*).

From studies of the relationship between observed metallicity and relative gas content M_H/M_{total} in such systems, it may be possible to estimate the yield of heavy elements per stellar generation. For closed systems with a constant yield per stellar generation, metallicity $\sim \ln(M_H/M_{total})$ (*78*). In more complex models the functional relationship will differ. The metal yield and its variation with M_H/M_{total} provides insight into the number of stars born as a function of mass—the initial mass function (IMF)—at least at the high-mass end. Attempts to evaluate the yield and place limits on the variation of IMF with age have been made by Lequeux *et al.* (*79*) and others (*80–82*). Thus far, the number of systems analyzed and the precision of metal abundance determination have not been sufficient for a definitive statement regarding yield (and hence IMF behavior) as a function of gas consumption fraction.

Observations of the *range* in observed current-epoch star formation as a function of M_H/M_{total} and of metallicity may yield important information about the frequency and efficiency of star-forming events in gas-dominated systems. Such a statistical study is rendered difficult because our census of gas-rich, low-luminosity systems is woefully incomplete and naturally biased toward systems that at present are bright. If "bursts" of star formation followed by long nascent periods are the rule, then large numbers of systems will be faint most of the time [for example, see (*58*)]. Nevertheless, studies of a complete sample of low-luminosity galaxies may prove to be critical in understanding the nature of star-forming events in the earlier evolutionary phases of more luminous galaxies.

Mass-to-Luminosity Ratios

Evidence that the stellar population producing the visible light observed for disk galaxies represents only a fraction of the total system mass has been growing over the past decade [for a review, see (*35*)]. The primary evidence supporting this view derives from rotation curves that, after an initial rise near the nucleus, reach a maximum and remain flat to very large galactocentric distances (*83*). If such rotation curves measure the true circular velocity of the stars and gas, the observations suggest a linear increase of mass with radius. As noted previously, the light distribution in disk galaxies decreased exponentially. Hence the mass-to-luminosity ratio in the outer parts of disk galaxies increases outward; local values of M/L exceeding 100 have been reported. Typical systemwide mean values for M/L_B range from 2 to 10. In computing the average M, only mass interior to isophotes of blue surface brightness $B = 26.5$ mag (arc sec)$^{-2}$ is included (*35*).

Average mass-to-luminosity ratios for disk galaxies have been derived from studies of binary pairs of disk galaxies (*84, 85*). However, it is not yet possible to compare with confidence the M/L ratios derived from binary galaxies with those estimated from rotation curves (*86*).

Whitmore *et al.* (*87*) compared the velocity dispersion of the nuclear bulge of disk galaxies with the peak rotational velocity. From such a comparison, they deduced that the unseen material constitutes a third, "hot" component independent of bulge and disk.

Attempts to isolate the agent responsible for the unseen mass have, to date, proved unsuccessful. Stringent limits on contributions from very red, low-mass stars have been derived from near-infrared measurements. Such objects appear incapable of supplying the missing mass. However, attempts to uncover the nature of the remaining mass continue to be a major challenge to students of galactic evolution, since the constituents of the unseen halo may play a critical role in the chemical and dynamical history of disk galaxies.

Interpretation

To understand these results, we must first attempt to understand the factors that affect the evolution of isolated disk galaxies. Most models (*73*) assume that disk galaxies begin as rotating protogalactic clouds containing large numbers of gaseous clumps. If the mass of cloud is large enough, its self-gravity "wins" over the Hubble expansion and the cloud begins to collapse. The collapse proceeds nonhomologously. In the denser central regions of the cloud, star formation proceeds vigorously, rapidly consuming the gas. This region evolves into the stellar-dominated nuclear bulge on a time scale comparable with a free-fall time ($\sim 10^8$ years for a Milky Way system). Star formation in the lower density outer regions proceeds far less efficiently. In collisions between gas clumps, the kinetic energy of motion is converted into heat, which is then radiatively lost to the system. Such collisions occur most easily along the rotational axis of the system. By dissipating the energy in random motions through gas-cloud collisions, the outer regions eventually settle into a cold, rotating disk. The subsequent changes in disk system appearance will depend primarily on the star-forming history of the disk component. Perhaps the major factor that determines the ability of a disk to form stars is the availability of gaseous material. In turn, the amount of gas available at any time depends on the initial gas content of the disk, the rate of injection from dying stars in the disk or possibly in a halo, and the rate of depletion through star-forming events. Self-sweeping mechanisms such as winds emanating from the nuclear bulge region can also deplete disk gas. Suppose that initially disk galaxies are born with a wide range of bulge-to-disk ratios—from the small values characterizing late-type spirals to the large values found today for only the most extreme Sa galaxies and for S0 systems. At birth, each Hubble type starts out with comparable ranges of initial disk gas content.

Two models for the subsequent star-forming history of the disk have been suggested in recent years. One proposes that astration in the disk is driven by galactic shocks, while the other posits that star formation occurs stochastically.

The galactic shock model (*88*) presupposes the existence of a spiral density wave in the old disk stars. The wave pattern propagates through the disk with a characteristic angular speed Ω_p, the pattern frequency. The disk gas is supposed to be in circular orbit about the galaxy center with an angular speed $\Omega(r)$ at galactocentric distance r. At any r, the spiral arm intersects a circular path at an angle i called the pitch angle. The velocity of gas normal to the spiral pattern is

$$w_\perp = [\Omega(r) - \Omega_p]\, r \sin i$$

The galactic shock model then presumes that if $w_\perp$ exceeds the acoustic speed a in the gas, the gas will be shocked and compressed behind the shock; the compression is supposed sufficient to initiate the collapse of gas clouds and the formation of stars. Hence the model predicts that star-forming events will occur each time the disk gas "encounters" the spiral wave pattern, provided the circular velocity of the gas is sufficiently high to produce a shock. Moreover, the star-forming regions are predicted to lie adjacent to the density wave crests. This picture appears to be highly successful in predicting the star-forming patterns and gas flows in well-defined, luminous spiral galaxies [for example, see (*89*)]. However, there are classes of galaxies at all luminosity ranges in which no obvious underlying density wave pattern is found and in which the star-forming pattern is less obviously spiral.

Seiden and Gerola (*90*) posit that star formation initially begins at random in a differentially rotating disk. Each initial star-forming event has a probability of "stimulating" star formation in a nearby region (for example, through a supernova explosion and subsequent compression of "nearby" gas behind the supernova shock). They find that for a narrow range of random and stimulated star-forming probabilities the differential rotation of the galaxy naturally produces patterns quite similar to those observed in nature. In one sense their model is purely mathematical. However, if the values derived for random and stimulated probabilities in a wide variety of types occupy relatively small ranges, we may be able to deduce important constraints on the factors influencing the star-forming history of galaxies, although at present we lack even a crude outline of an adequate model of star-forming physics.

Both models predict that the mass (luminosity) of the galaxy should play a major role in determining star-forming patterns. The galactic shock model demands that $w_\perp \gtrsim a$ in order that star-forming events may be induced. Let us define a quantity

$$w_\perp(\max) = V_{\max} \sin i$$

where $V_{\max}$ is the maximum value of the quantity $(\Omega - \Omega_p)r$. For a galaxy of mass m and characteristic radius R

$$V_{\max} \approx (M/R)^{1/2}$$

Assuming that the luminosity L of a galaxy is proportioned to M and that, from observation (*50*), $R \sim L^{0.4}$,

$$w_\perp(\max) \approx L^{0.3} \sin i$$

For a fixed pitch angle $w_\perp$ therefore decreases with decreasing L until, at some critical luminosity $L_{\min}$, $w_\perp = a$. Below $L_{\min}$, $w_\perp$ is too small to initiate star-forming events in galactic shocks, and hence star formation will no longer take place in spiral patterns unless the amplitude of the wave pattern is extremely large. The pitch angle of the arms i is larger for open-armed, late Hubble-type systems (Sc and later) than for tightly wound spirals of early Hubble type (Sb and earlier). Hence $L_{\min}(\text{Sa}) > L_{\min}(\text{Sc})$, and we expect to see spiral star-forming patterns begin to die out at higher luminosities for Sa galaxies than for Sc's. Below $L_{\min}$, only irregular star-forming patterns are expected.

Indeed, observations show that spiral patterns are present in late-type systems at much lower luminosities than in early-type galaxies; irregular galaxies dominate low-luminosity systems. This picture also suggests that for systems of luminosity below $L_{\min}$ star formation can no longer be driven. As a result, we expect the formation of stars and the consumption of gas to proceed more slowly, at least if shock-driven star formation plays an important role in the star-forming history of spiral galaxies. Hence the ratio of new to old stellar population and gas content should be a function of galaxy luminosity—a result in qualitative agreement with observations.

The stochastic model attributes the decrease in average star-forming activity and the tendency toward irregular patterns in low-luminosity galaxies to (i) a decrease in system scale (and the consequent low-average rotational velocity) and (ii) the apparent rigid (as opposed to differential) rotation of low-luminosity systems. The scale determines the number of star-forming "cells" that can be active at any given time—the smaller the number of cells, the smaller the average star-forming rate. The lack of differential rotation prevents the development of a spiral pattern, since all star-forming cells move at the same rate relative to one another. Hence a "snapshot" at any time reveals only a random pattern.

Observers are faced with two major tasks at present. The first is to determine the relationship between star-forming patterns and the underlying density wave pattern, if any. Strong coupling between the two would strongly suggest a causal relationship of astration events and the density wave pattern. Such studies should be carried out for all Hubble types at constant system luminosity. Quantitative measurements of spiral pattern shape and the relationship of the pattern to the distribution of matter in the galaxy will be especially valuable in providing insight into the physical basis for the underlying spiral patterns.

The second task is to determine quantitatively the ratio of new to old stellar populations and the fractional gas content as a function of luminosity for fixed Hubble types. Overall galaxy dynamics may play an essential role in determining the evolutionary history of disk systems. If so, such effects will become apparent through a classification scheme that provides an appropriate measure of disk system dynamics.

At some point in the history of a system, a significant fraction of disk gas must be depleted in star-forming events. As noted previously, in most luminous galaxies the neutral hydrogen mass constitutes less than 10 percent of the total system mass. Suppose, for the sake of argument, that at some point in a system's evolutionary history the disk gas content drops below the point critical to sustain star formation. What happens when the disk gas is depleted? It seems logical to assume that a gas-free spiral should appear similar to the smooth-arm systems discussed by Wilkerson *et al.* (*67*). In such systems the underlying arm pattern is readily visible; however, there appear to be no accompanying star-forming events, and moreover the gas content is unusually low. It is tempting to speculate that such systems evolve into S0's. However, no convincing models as yet predict whether smooth-arm systems evolve naturally into featureless S0 disks.

Dressler (*13*) notes that S0's tend to have significantly larger bulge-to-disk ratios than do actively star-forming spirals. Suppose rapid astration is the major cause of disk gas depletion. If so, the currently available data suggest that among still star-forming systems, types with large bulge-to-disk ratios (Sa and Sab) have depleted their disk gas mass most rapidly. It seems natural to extrapolate this behavior to systems with even higher bulge-to-disk ratios and to posit that such systems have already consumed their available disk gas. A satisfactory explanation of why large bulge/disk systems should be more likely to form stars more rapidly is, however, not available.

The evolutionary fate of disk systems located in a rich cluster may be affected by interaction both with other galaxies and with the intracluster medium. Gravitational encounters may tidally strip the gaseous halos and the outer disks of individual galaxies, perhaps resulting in the observed decrease of disk sizes in the central region of the Coma cluster (note that such a reduction will increase the apparent bulge-to-disk ratios for such systems). As galaxies traverse clusters containing intracluster gas of sufficient density, ram-pressure stripping may remove their disk or halo gas (*25*); partially stripped galaxies may continue active star formation although they possess less disk gas. In some cases, for galaxies bathed in hot intracluster gas, thermal evaporation may also remove disk gas. If gas is removed by either process, we must again ask, what is the fate of an actively star-forming system? It seems logical that the evolutionary path followed by such galaxies should be similar to that followed by isolated disk galaxies that deplete their disk gas; the spiral will at first appear as a smooth-arm system and later as an S0. If gas removal by evaporation or ram-pressure stripping is important in driving evolution from spirals to S0's, two major effects should be observed: (i) the ratio of Sp's to S0's should be smaller in x-ray clusters, and (ii) the fraction of S0's with small bulge-to-disk ratios may be larger in such clusters. Dressler's data (*13*) are marginally supportive of the first effect and say little about the second. However, it is noteworthy (*13*) that the median bulge luminosity in dense regions (although not necessarily those pervaded by hot gas) is actually larger, suggesting that the bulge size may reflect initial conditions at the epoch of galaxy formation that may, in turn, be somehow related to the current-epoch environment.

Gisler (*91*) noted that the gas densities in disk galaxies were probably higher at earlier epochs. Consequently, they would have been more resistant to ram-pressure stripping. Hence, even if the intracluster gas density at earlier epochs was as high as it is at present, many actively star-forming systems (particularly of later Hubble type) could have resisted stripping. Therefore the presence of a large admixture of blue galaxies in the Butcher-Oemler clusters is not surprising. However, we must keep in mind that the Butcher-Oemler data may also be telling us that star formation in galactic disks may be a more recent phenomenon than currently popular thought would have it (*64, 65*).

Finally, Dressler's results on the dependence of bulge luminosity on environment and the variety of work suggesting that the shape and orientation of both disk and elliptical galaxies reflect the properties of their host clusters both argue strongly that we heed the possibility that environment-dependent initial conditions greatly influence the course of galaxy evolution.

References and Notes

1. Because of space limitations we have not been able to adequately discuss several subjects of active research, including the role of active nuclei and "heavy halos" in galactic evolution and the role of bars in disk system evolution. Moreover, in a limited bibliography we have almost certainly been unable to do justice either to the pioneers or the current active practitioners in the field.
2. G. de Vaucouleurs, *Mon. Not. R. Astron. Soc.* **113**, 134 (1953).
3. E. Hubble, *Astrophys J.* **64**, 321 (1926).
4. A. R. Sandage, *The Hubble Atlas of Galaxies* (Carnegie Institution of Washington, Washington, D.C., 1961).
5. W. W. Morgan, *Publ. Astron. Soc. Pac.* **70**, 372 (1958).
6. ———, *ibid.* **71**, 394 (1959).
7. S. van den Bergh, *Publ. David Dunlap Obs.* **2** (No. 6) (1960).
8. J. Kormendy, *Astrophys. J.* **217**, 406 (1977).
9. H. Spinrad, J. P. Ostriker, R. P. S. Stone, L.-T. G. Chiu, G. Bruzual A., *ibid.* **225**, 56 (1978).
10. A. Oemler, Jr., *ibid.* **209**, 693 (1976).
11. J. Melnick and W. L. W. Sargent, *ibid.* **215**, 401 (1977).
12. H. Butcher and A. Oemler, Jr., *ibid.* **219**, 18 (1978).
13. A. Dressler, *ibid.* **236**, 351 (1980).
14. S. E. Strom and K. M. Strom, *Astron. J.* **84**, 1091 (1979).
15. ———, *Astrophys. J. Lett.* **225**, L93 (1978).
16. A. Dressler, thesis, University of California, Santa Cruz (1976).
17. P. Schechter, *Astrophys. J.* **203**, 297 (1976).
18. M. A. Hausman and J. P. Ostriker, *ibid.* **224**, 320 (1978).
19. P. L. Schechter and J. E. Gunn, *ibid.* **229**, 472 (1979).
20. T. B. Williams and M. Schwarzschild, *ibid.* **227**, 56 (1979).
21. A. B. Marchant and D. W. Olsen, *Astrophys. J. Lett.* **230**, L157 (1979).
22. G. R. Knapp, F. J. Kerr, B. A. Williams, *Astrophys. J.* **222**, 800 (1978).
23. G. R. Gisler, *Mon. Not. R. Astron. Soc.* **183**, 633 (1978).
24. L. L. Cowie and A. Songaila, *Nature (London)* **266**, 501 (1977).
25. J. E. Gunn and J. R. Gott, III, *Astrophys. J.* **176**, 1 (1972).
26. W. G. Tifft, *Astron. J.* **74**, 354 (1969).
27. J. Stauffer, personal communication.
28. J. S. Gallagher, personal communication.
29. S. M. Faber, paper presented at the Aspen Physics Workshop (1981).
30. ———, *Astrophys. J.* **179**, 731 (1973).
31. J. A. Frogel, S. E. Persson, M. Aaronson, K. Matthews, *ibid.* **220**, 75 (1978).
32. N. Visvanathan and A. Sandage, *ibid.* **216**, 214 (1977).

32a. E. N. Caldwell, thesis, Yale University (1982).

33. S. E. Strom, J. C. Forte, W. E. Harris, K. M. Strom, D. C. Wells, M. G. Smith, *Astrophys. J.* **245**, 416 (1981).
34. S. M. Faber and R. E. Jackson, *ibid.* **204**, 668 (1976).
35. S. M. Faber and J. S. Gallagher, *Annu. Rev. Astron. Astrophys.* **17**, 135 (1979).
36. W. L. W. Sargent, P. J. Young, A. Boksenberg, K. Shortridge, C. R. Lynds, F. D. A. Hartwick, *Astrophys. J.* **221**, 731 (1978).
37. A. Dressler, *Astrophys. J. Lett.* **240**, L11 (1980).
38. M. Duncan and C. Wheeler, *ibid.* **237**, L27 (1980).
39. J. N. Bahcall and C. L. Sarazin, *ibid.* **213**, L99 (1977).
40. J. Kristian, A. Sandage, J. A. Westphal, *Astrophys. J.* **221**, 383 (1978).
41. G. L. Grasdalen, in *Proceedings, IAU Symposium 92, Objects of High Redshift*, G. O. Abell and P. J. E. Peebles, Eds. (Reidel, Boston, 1980), p. 269.
42. G. H. Rieke and M. J. Lebofsky, *Annu. Rev. Astron. Astrophys.* **17**, 477 (1979).
43. A. Toomre, in *The Evolution of Galaxies and Stellar Populations*, B. M. Tinsley and R. B. Larson, Eds. (Yale University Observatory, New Haven, Conn., 1977).
44. R. B. Larson, *Mon. Not. R. Astron. Soc.* **166**, 585 (1974).
45. J. P. Ostriker, *Comments Astrophys.* **8**, 177 (1980).
46. J. R. Gott, III, and T. X. Thuan, *Astrophys. J.* **204**, 649 (1976).
47. R. B. Larson, *Mon. Not. R. Astron. Soc.* **169**, 229 (1974).
48. N. A. Bahcall, *Astrophys. J. Lett.* **218**, L93 (1977).
49. D. Burstein, *Astrophys. J.* **234**, 435 (1979).
50. B. M. Peterson, S. E. Strom, K. M. Strom, *Astron. J.* **84**, 735 (1979).
51. E. Holmberg, *Medd. Lunds Astr. Obs. Ser. 2 No. 136* (1958).
52. S. E. Strom and K. M. Strom, in *Proceedings, IAU Symposium 77, Structure and Properties of Nearby Galaxies*, E. M. Berkhuijsen and R. Wielebinski, Eds. (Reidel, Dordrecht, Netherlands, 1978).
53. J. Kormendy, personal communication.
54. ——— and G. Illingworth, in *Photometry, Kinematics and Dynamics of Galaxies*, D. S. Evans, Ed. (Department of Astronomy, University of Texas, Austin, 1979), p. 195.
55. M. T. Adams, K. M. Strom. S. E. Strom. *Astrophys. J.* **238**, 445 (1980).
56. L. A. Thompson, *ibid.* **209**, 22 (1976).
57. G. de Vaucouleurs, A. de Vaucouleurs, H. G. Corwin, *Second Reference Catalogue of Bright Galaxies* (Univ. of Texas Press, Austin, 1976).
58. L. Searle, W. L. W. Sargent, W. G. Bagnuolo, *Astrophys. J.* **179**, 427 (1973).
59. S. E. Strom, *ibid.* **237**, 686 (1980).
60. M. Roberts, in *Galaxies and the Universe*, A. Sandage, M. Sandage, J. Kristian, Eds. (Univ. of Chicago Press, Chicago, 1975), vol. 9. p. 309.
61. C. Balkowski, *Astron. Astrophys.* **29**, 43 (1973).
62. N. Scoville and J. R. Young, *Astrophys. J.*, in press.
63. R. B. Larson, B. M. Tinsley, C. N. Caldwell, *ibid.* **237**, 692 (1980).
64. P. DeMarque and R. D. McClure, in *The Evolution of Galaxies and Stellar Populations*, B. M. Tinsley and R. B. Larson, Eds. (Yale University Observatory, New Haven, Conn., 1977).
65. H. Butcher, *Astrophys. J.* **216**, 372 (1977).
66. P. Biermann, J. N. Clarke, K. J. Fricke, *Astron. Astrophys.* **75**, 7 (1979).
67. M. S. Wilkerson, S. E. Strom, K. M. Strom, *Bull. Am. Astron. Soc.* **9**, 649 (1977).
68. K. Eastwood and G. L. Grasdalen, *Astrophys. J. Lett.* **239**, L1 (1980).
69. D. Burstein, *Astrophys. J.* **232**, 74 (1979).
70. T. A. Boroson, thesis, University of Arizona (1980).
71. A. Wirth, *Astrophys. J.*, in press.
72. E. B. Jensen, K. M. Strom, S. E. Strom, *ibid.* **209**, 748 (1976).
73. R. B. Larson, *Mon. Not. R. Astron. Soc.* **176**, 31 (1976).
74. M. Aaronson, thesis. Harvard University (1977).
75. G. Wynn-Williams, personal communication.
76. W. Romanishin, thesis, University of Arizona, Tucson (1980).
77. B. L. Webster, W. M. Goss, T. G. Hawarden, A. J. Longmore, U. Mebold, *Mon. Not. R. Astron. Soc.* **186**, 31 (1979).
78. L. Searle and W. L. W. Sargent, *Astrophys. J.* **173**, 25 (1972).
79. J. Lequeux, M. Peimbert, J. F. Rayo, A. Serrano, S. Torres-Peimbert, *Astron. Astrophys.* **80**, 155 (1979).
80. D. Talent, thesis, Rice University (1980).
81. T. D. Kinman and K. Davidson, *Astrophys. J.* **243**, 127 (1981).
82. H. B. French, thesis, University of California, Santa Cruz (1979).
83. V. C. Rubin, W. K. Ford, Jr., N. Thonnard, *Astrophys. J. Lett.* **225**, 107 (1978).
84. E. L. Turner, *Astrophys. J.* **208**, 304 (1976).
85. P. D. Noerdlinger, *ibid.* **229**, 877 (1979).
86. H. Rood, *ibid.*, in press.
87. B. C. Whitmore, R. P. Kirshner, P. L. Schechter, *ibid.* **234**, 68 (1979).
88. W. W. Roberts, Jr., M. S. Roberts, F. H. Shu, *ibid.* **196**, 381 (1975).
89. H. C. D. Visser, *Astron. Astrophys.* **88**, 159 (1980).
90. P. E. Seiden and H. Gerola, *Astrophys. J.* **233**, 56 (1979).
91. G. R. Gisler, *ibid.* **228**, 385 (1979).

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