DISK AND SPHEROIDAL COMPONENTS OF EXTERNAL GALAXIES: AN OVERVIEW

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A brief review of current theoretical views on how disk and spheroidal galaxies form and evolve provides the background for a summary of recent optical observations of external galaxies. Primary emphasis is placed on a discussion of the large-scale distribution and chemical composition of the stellar and gaseous constituents of relatively isolated galaxies. New studies of halo and disk surface-brightness distributions in spiral and S0 galaxies are summarized. The "missing mass" in galactic halos, the relationship between disk size and luminosity, the nonexponential character of disk light distributions and very low-surface-brightness disk systems are highlighted in this section. Next discussed are observations which may provide insight into the factors which regulate the star-forming history of galactic disks and the post-astration appearance of spiral galaxies. Finally, the observed properties of relatively isolated disk galaxies are compared with those located in dense groups. It appears from this comparison that environment plays a significant role in governing the evolutionary history of a galaxy.

1. INTRODUCTION

The Milky Way Galaxy is a relatively luminous, star-forming disk system of intermediate Hubble type located in a region of comparatively low galaxy density. From our vantage point in the solar system, we have, over the past half century, built up considerable understanding of the kinematics, chemical compositions, and ages of the Galaxy's stellar constituents. The past two decades have witnessed a rapid growth in our knowledge of the varied physical conditions and dynamical interactions in the plasmas pervading the disk and halo. From these investigations, astronomers have attempted syntheses aimed at developing plausible models for the formation of the Galaxy, and the evolution, with time, of its stellar and interstellar constituents. Our views of galactic structure and evolution are to a large extent based on an

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appreciation of the range of phenomena accessible to observation near our "local swimming hole." However, the development of more cosmopolitan outlooks necessitates studies of the large-scale characteristics of external galaxies. Determination of the scales and masses of disk and halo components, the properties of near-nuclear regions, the nature of wave phenomena in galactic disks, the factors influencing the rates of star formation and chemical-element production are among those problems which depend to a great extent on observations of other galactic systems.

Furthermore, it has become increasingly clear in recent years that a proper understanding of the evolutionary history of any particular galaxy cannot be achieved until we learn whether and how the galactic environment affects the gaseous and stellar components of that system. Only by examining galaxies located in regions characterized by significantly different physical properties can we hope to evaluate the effects on galactic evolution of close gravitational encounters among galaxies and interactions between galaxies and the intergalactic medium. A careful synthesis of "local" and "cosmopolitan" experiences appears to offer the best hope for refining our knowledge of the main factors which determine the structure and evolution of both the Milky Way and external galaxies.

We would like to take this opportunity to summarize recent, primarily optical work on the disk and spheroidal components in external galaxies located in a variety of environmental settings. In the course of this review we will attempt to identify a series of problems which appear, to our prejudiced eyes, to be critical and ripe for solution.

2. THEORETICAL OVERVIEW

At present, we believe that the bulge and disk components of a typical disk galaxy form from a rotating protogalactic cloud in which star formation accompanies gravitational collapse. Current models (cf. Gott and Thuan 1976; Larson 1976) suggest that the relative prominence of the bulge and disk is determined by the efficiency of star formation during collapse. Systems in which star formation is highly efficient at early epochs form large spheroidal components (since the stellar system undergoes an essentially dissipationless collapse). When the early star-forming efficiency is low, the collisions between gas clouds in the protogalaxy lead to the dissipation of energy in the gas and the eventual formation of a thin disk; presumably, stars begin to form in this disk when the average gas density is sufficiently large. The factors which determine the initial star-forming efficiency in a protogalactic cloud are currently unknown. Speculation centers on the initial protogalactic density or the distribution of angular momentum in the protogalactic cloud as the agents responsible for differences in early star-forming history. Although existing models appear to rule out differences in initial angular momentum as the overriding factor which determines whether or not a galaxy forms a dominant bulge or disk, recent observational work (Bertola and Capaccioli 1978) suggests that disk galaxies have larger values of angular momentum per unit mass than do elliptical galaxies. The significance of this observation in the context of current galaxy-formation theory is not at all well understood.

The star-forming history of a protogalactic cloud also determines the degree of element production and the distribution of heavy elements in the collapsing cloud. Clouds in which star formation is rapid, relative to the time scale for collapse of the gas, produce significantly different "abundance profiles" than do slow star-forming clouds (Larson 1974).

The star-forming history of a galaxy immediately following the appearance of a gaseous disk may be critical to determining the current epoch morphological appearance of the system. Sandage et al. (1970) argue that the fraction of gas remaining after the formation of the first generation of disk stars is essentially determined at the time of formation. The efficiency with which star formation consumes disk gas in these initial phases determines whether a galaxy becomes an S0 system, or a spiral or irregular galaxy. Whether this view — the "genetic" outlook — is correct is as yet not clear; moreover, it is difficult to test.

Advocates of the "evolutionary outlook" appeal to a continuous range in the rates of disk astration activity as the prime determinant of galaxy appearance. As our understanding of the factors influencing star-forming efficiency improves, the evolutionary outlook can be put to more and more severe tests. A derivative of the density-wave theory (DWT) of spiral structure, the "spiral-shock" model (Roberts et al. 1975) appears to offer a particularly promising starting point for understanding the evolution of galactic disks.

A large number of disk galaxies (possibly all) appear capable of sustaining density-wave patterns in their disks during a significant fraction of their evolutionary history. The manner in which the wave pattern is initially induced remains controversial. However, the susceptibility of systems of a given mass distribution to the growth of particular wave modes has been studied extensively in recent years (Mark 1976), and, as a result, many theoretical objections to the DWT appear to be diminishing. Compression of disk gas in spiral shocks induced by acceleration of gas in the vicinity of the density-wave crests (the spiral arms) is believed capable of inducing star formation (see Roberts et al. 1975 for a review). The frequency of star formation and the degree of post-shock gas compression are related to the angular speed of the wave pattern in the disk and to the circular velocity of the disk gas at a given galactocentric distance; in turn, these quantities are related to the distribution of mass in the galaxy. Galaxies with a relatively high degree of central concentration tend to form stars more frequently and possibly more efficiently. Consequently, one expects that an Sb galaxy with a prominent nucleus will form stars and deplete its disk gas more rapidly than will an Sc-type system. The chemical-enrichment patterns should also reflect differing rates of star formation across the disk. It is not yet clear to what degree the differences in star-forming activity along the Hubble sequence can be explained in the context of the spiral-shock picture. For example, do S0 and irregular galaxies represent extrema in the range of disk star-forming histories? Are the former, systems in which astration has proceeded so rapidly that no disk gas remains? If so, what has happened to the density-wave pattern in their disks? Are irregulars galaxies in which star formation has not been triggered "efficiently" by spiral shocks but rather has proceeded chaotically (perhaps because these systems, for some reason, cannot support the growth of a dominant wave pattern or because the gas-to-stellar-density ratio is insufficiently small)?

The roles of injection and removal of gas from the disks of evolving galaxies may also be essential factors in determining the current epoch appearance of galaxies and the chemical histories of their disks. Not nearly enough data are yet available regarding the distribution and velocity fields of gas in galactic halos surrounding disk systems. Yet, in our own Galaxy, we believe that the amount of gas injected from halo-gas clouds is sufficient to account for a large fraction of the current disk-gas content and possibly much of the star formation occurring at present. It will be extremely important to our understanding of galactic evolution to pursue high-sensitivity searches (Sargent and Knapp, private communication) for neutral hydrogen located in galactic halos and in the intergalactic medium.

Removal of gas by the action of galactic winds emanating from nuclear-bulge regions has been studied by Mathews and Baker (1971) and later by Faber and Gallagher (1976). The combined effects of supernova explosions and collisional heating of ejecta from dying stars raise the bulge-gas temperature to values sufficiently high to drive a wind of outflow velocity sufficient to escape the bulge region. [However, Chevalier and Oegerle (1978) argue that, at least in our own Galaxy, conditions appear to favor the establishment of a hot, bound corona rather than an outflowing wind.] If the density of disk gas is sufficiently low and if the density and velocity of the outflowing material is high enough, a galactic disk may be swept free of interstellar gas. Furthermore, the wind continually purges the disk of gas ejected by evolving low-mass stars. Because winds should be "stronger" in bulges of high mass, systems with large bulges (Sa or Sb spirals) may be more susceptible to early removal of disk gas than are galaxies that have small bulges (late-type spirals and irregulars).

External factors, such as collisions with other galaxies and with intergalactic clouds of hydrogen, as well as interactions of galaxies with intergalactic gas, may also affect the course of post-disk-formation evolution. Particular attention, in recent years, has been paid to the role of "ram-pressure stripping" in removing disk gas from galaxies. As a spiral galaxy traverses a rich cluster of galaxies, it encounters the hot gas (10^8 °K gas, 10^{-4} atoms cm^{-3}) believed to pervade such clusters at the current epoch. When the velocity of the galaxy, with respect to the intracluster gas and the density of the gas, is high enough, compared with the density of gas in a galactic disk, gas may be "stripped" from the system. Unless gas from dying stars is produced at a rate sufficient to replenish the disk before the system undergoes further stripping (either through repeat passage through the cluster medium or by action of galactic winds), further star formation in the disk cannot be sustained.

The above represents a brief summary of "mainstream" wisdom regarding disk-system evolution. Recent work has emphasized the possible significance of massive, unseen halos in affecting disk galaxy evolution. Stability arguments (Ostriker and Peebles 1973) suggest that cold disks are unstable to the growth of bar-like instabilities. An attractive mechanism for stabilizing the disk against the formation of a bar is to surround the system with an extensive, "hot" halo component of mass comparable to, or even much greater than, the disk mass. At present, optical and radio searches are aimed at determining whether halos have a mass (and mass distribution) great enough, first, to stabilize the disk and, second, to explain the mass discrepancy between galactic masses and the virial masses of rich clusters. If optical counterparts of halos cannot be observed, even after careful searches at all wavelengths, we must entertain the hypothesis that invisible constituents (e.g., neutral stars, black holes) contribute most of the halo mass (and indeed most of the mass in the universe!). If so, when did these currently invisible objects form, and what effect did they have on the early star-forming and heavy-element-producing history of a galaxy? Some very recent theoretical work (White 1978) has explored the possibility that luminous components of galaxies formed significantly after the aggregation of "invisible" material. It is becoming increasingly clear that the formation of galaxies may not be well understood without first understanding much more about the distribution of nonluminous material in galaxies.

The next sections review the current highlights of optical studies of disk and halo components of galaxies. We have tried, except insofar as continuity demands, to avoid duplication of the material presented in our recent review of disk galaxy evolution presented last summer in Bonn (Strom and Strom 1978d). The reader should refer to the more extensive Bonn review for additional details and reference material.

3. SPHEROIDAL COMPONENTS OF DISK GALAXIES

Kormendy's (1977) study of S0 galaxies suggests that the surface-brightness distribution for the spheroidal component (SC) of disk systems can be well represented by the de Vaucouleurs (1959) law. In this respect the SC's resemble elliptical galaxies. Recent work on the edge-on spiral NGC 4565 suggests that, at least in some cases, the SC light distribution can fall off much more rapidly than a de Vaucouleurs law. However, because this latter result is also true for E galaxies (Strom and Strom 1978a,b), its significance cannot be evaluated as yet.

Little is known about the distribution of mean ellipticities for SC's. Kormendy and Bruzual (1978) note that not all SC's appear spheroidal in form; "box-like" nuclear bulges, similar to that of NGC 128, are not uncommon. This observation suggests that SC's may not be analogous to E galaxies, either morphologically or dynamically.

Strom et al. (1976b) find that the nuclear bulge regions of the edge-on S0 galaxies NGC 3115 and NGC 4762 show large abundance gradients extending over scales of many kpc, in contradiction to the small halo gradients observed for a large majority of E galaxies (Strom and Strom 1978a,b). NGC 7332 (Strom and Strom 1978c) and our Galaxy also appear to show halo abundance gradients. If the frequent occurrence of large-scale (extending over many kpc's) halo composition gradients is confirmed for a more significant sample of disk-system SC's, it would suggest a star-forming and chemical-element-producing history significantly different from that characterizing most E galaxies. Interpreted in the context of Larson's (1974) gas-dynamical models, this result would imply that spiral bulges might have been formed from lower-density protogalactic clouds.

No evidence is yet available to permit a test of the similarity between the color(composition)-luminosity relation for E's and disk galaxy SC's. T. Boroson of the Steward Observatory is just beginning such a study.

A number of recent studies have attempted to extend observations of disk system SC's to extremely low light levels. The desire to better understand galactic halos is motivated in large measure by the hope of discovering the objects responsible for the missing mass in galaxies. Most notable among recent studies have been those of Hegyi and Gerber (1977; NGC 4565), Spinrad et al. (1978; NGC 4594, NGC 4565, and NGC 253), and Kormendy and Bruzual (1978; NGC 4565). Their studies reveal the presence of halos out to galactocentric distances well beyond 50 kpc. Assuming a mass-to-light ratio characteristic of the inner regions of either disk galaxy SC's or E galaxies ($M/L_B \sim 10$), the mass contained in the ratio of halo-to-disk mass for NGC 4565 is estimated to be comparable to or greater than the disk mass. Similar results were found by Strom et al. (1977) for NGC 3115 and Rubin et al. (1978) for NGC 4378. In all cases the observed halo surface brightness falls off more rapidly than r^{-2} at large galactocentric distances. We conclude that the halo mass in visible objects may be sufficiently large to preclude the development of bar-like instabilities in the disk. However, there is no evidence indicating the presence of an optically detectable massive ($M_H/M_D >> 10$) component for which the surface brightness falls off less rapidly than r^{-2}. Hegyi and Gerber report that the V - I color at the faintest isophotal level observed in their study is suggestive of an increase in the population of faint, red stars (possibly dwarfs later in type than K7 V). However, in our opinion their result requires careful reexamination before it can be accepted. Spinrad et al. find their (B - R) photometry to be consistent with either no color changes or with a slight "bluing" at large galactocentric distances. Strom et al. (1977) find that the halo colors for NGC 3115 become blue [in the (U - R) color system] out to galactocentric distances r ∿ 10 kpc. Moreover, an infrared (λ ∿ 2.2 μ) study of this galaxy (Strom et al. 1978) suggests that the (V - K) color index also decreases with increasing galactocentric distance; however, their infrared results extend only to r ∿ 2 kpc.

We conclude this section with a list of questions, the answers to which may be of some importance to furthering our understanding of disk galaxy SC's.

1. How do the light distributions measured along the minor axes of the nuclear bulges in edge-on disk galaxies compare with those of E galaxies? At a fixed luminosity, are their characteristic sizes similar?

2. What is the distribution of ellipticities among the nuclear-bulge components of edge-on disk systems? How frequent are box-like nuclei?

3. Is the relationship between velocity dispersion and luminosity the same in disk galaxy SC's as in E galaxies?

4. Is the color-luminosity relation the same for E galaxies and disk galaxy SC's?

5. Do all disk galaxy SC's exhibit extensive composition gradients? If so, does this property imply a fundamental difference in the protogalactic clouds which gave birth to spiral and E galaxies?

4. THE DISK COMPONENT

4.1 Distribution of the Stellar Light

Both de Vaucouleurs (1959) and Freeman (1970) argue that the disk light distribution for spirals and S0 galaxies can be well fitted by an exponential law. Characteristic distances for a 1/e decrease in surface brightness range between 2 and 10 kpc. Freeman also observes that the extrapolated central surface brightnesses (obtained by evaluating the best-fit exponential law at a galactocentric distance of zero) for most disk galaxies are identical to within 30 percent [B(0) = 21.65 mag arcsec^{-2}]. An extensive discussion of disk-system light distributions by Kormendy (1977) leads to significantly different conclusions. Kormendy states that it is essential to subtract the contribution of the bulge component prior to fitting an exponential law to the combined disk-bulge light distribution. By following a prescription in which a best-fit de Vaucouleurs profile to the bulge light distribution is subtracted from the observed surface-brightness profile, he finds that very few disk components can be represented by an exponential law. In many cases the disk components contribute insignificantly to the system light near the galactic nucleus; indeed, it is not clear to what extent a disk component exists in the near-nuclear regions of some of Kormendy's sample galaxies. There appears to be little evidence of a universal central or even a "mean" disk surface brightness.

Further evidence, which contradicts the concept of a universal B(0), has been presented recently by Romanishin et al. (1977). They discuss the properties of a group of "low-surface-brightness" (LSB) spiral galaxies in which the projected central surface brightness (adopting Freeman's definition) ranges between a factor of 2 and 6 smaller than the "canonical" value of B(0).

Recent work by B. Peterson of the Steward Observatory has led to an increased understanding of the extent of galactic disks. From measures of the light distribution in the disks of 36 Virgo and 30 Hercules cluster spiral galaxies, he finds that, to an isophotal level, $\mu_B = 26.6$ mag arcsec^{-2} (the level used to define the Holmberg radius), $\log r(\mathrm{kpc}) = -0.166\ M_B - 2.150$ (if $H_0 = 50$ km s^{-1} kpc^{-1}); M_B is the blue absolute magnitude of a galaxy. From a study of the Virgo systems, he finds that $r(\mu_B{=}28.6)/r(\mu_B{=}26.6) = 1.4$. Thus the most luminous spiral galaxies of disks with observable light extend to radii of more than 100 kpc.

More detailed studies of the light distribution in the underlying disk component of spiral galaxies have been carried out recently by Schweizer (1976) and by Jensen (1977). Both authors report the presence of spiral wave patterns which appear to be surface density crests in the "old-disk" population. The study of "smooth-arm" spiral galaxies (Strom et al. 1976a; Wilkerson et al. 1977) also supports the notion that spiral arms not only manifest themselves in the distribution of newly formed stars, but also in the underlying disk population. Hence, at least to these reviewers, the case for a spiral wave pattern rooted in the overall mass distribution of spiral galaxies is overwhelming.

The following observations appear essential to furthering our understanding of the distribution of stars in galactic disks:

1) obtain bulge light distributions from photometry along the minor axes of edge-on disk systems. This will reduce uncertainties in "modeling" the bulge component implicit in Kormendy's deconvolution of bulge and disk light.

2) compare the light distributions of a much larger sample of disk systems of spiral, S0, and irregular types. Although Freeman's study suggests that the ranges of disk parameters overlap among these types, a more careful treatment seems in order. In addition to contributing to our empirical understanding of the differences among disk galaxies of differing type, these data might well shed some light on the question of why some disk systems (spirals) can support stable wave patterns and why others (S0's and irregulars) cannot.

3) carry out harmonic analyses of the wave patterns in spiral

galaxy disks in order to learn which modes can grow (and at what rate) in galaxies characterized by differing mass distributions. Efforts should concentrate on those galaxies for which accurate rotation curves and surface photometry can be obtained. Such analyses could be quite valuable in testing the newly developed wave-mode approach of the MIT group.

4) obtain disk photometry carried out at wavelengths ($\lambda \gtrsim 6000$ Å) which primarily map the underlying old stellar population rather than the combined new and old populations. Such observations should provide a better measurement of the true mass distribution, independent of changes in the ratio of young-to-old stars across the disk.

4.2 Mass Distributions in Galactic Disks

It is commonly assumed that, to a first approximation, the observed surface-brightness profile in an appropriately chosen bandpass provides an indication of the true mass distribution in the system. Based on an analysis of rotation curves and surface photometry of galaxies, Nordsieck (1973) concludes that the mass-to-light ratio within individual disk galaxies is indeed constant. More recent optical studies, however, appear to contradict this result. For example, both Schweizer's (1978) analysis of the Sombrero galaxy (NGC 4594; Sa) and Rubin et al.'s (1978) study of NGC 4378 (Sa) suggest that the ratio of mass-to-photographic-luminosity increases with increasing galactocentric distance, at least in galaxies of early Hubble type. Rotation curves derived from neutral hydrogen studies (which extend to greater galactocentric distances) by Krumm and Salpeter (1978) and Sancisi (1978) also point to larger values of M/L in the outer parts of disk galaxies. The increase in M/L is most commonly attributed to the effects on the rotation curve of the inner regions of a massive halo characterized by M/L. However, the possibility of changes in the population mix in the disk stars has not been thoroughly investigated.

Gas motions can be used as a probe of the gravitational field of the underlying disk stars. Recent 21-cm maps of M81 made at Westerbork (Visser 1978) provide strong evidence that gas motions in the vicinity of spiral arms can be well understood if one adopts as a potential field that inferred from the combined effects of the observed, smooth, axisymmetric disk light distribution and of the spiral wave crests observed by Schweizer (1976). Optical work by Rubin and Ford (private communication), who used the very high spectral and spatial resolution available with the KPNO and CTIO Cassegrain spectrographs, also suggests that the gas flows near the arms are consistent with the presence of a spiral disturbance in an otherwise axisymmetric gravitational field; more quantitative results may be available within the next year or two. Surface photometry directed at the determination of the variation of wave amplitude with position, in a bandpass ($\lambda > 6000$ Å) sensitive primarily to the distribution of the old-disk population, will be a necessary complement to the Rubin-Ford study.

4.3 Bulge-to-Disk Ratios in Spiral Galaxies

In Sec. 1 we reviewed current speculation regarding the factors which influence the star-forming histories of spiral galaxies. If star formation is driven by spiral shocks, then systems with a high degree of central concentration (such as Sa- and Sb-type galaxies) should exhibit higher star-formation and gas-depletion rates. Moreover, systems that have massive nuclear bulges should be most susceptible to disk-gas removal by galactic winds emanating from the bulge. These two predictions lead to the following working hypothesis: If there is an evolutionary progression from actively star-forming spiral galaxies to "inactive" S0 galaxies, then the systems most likely to have undergone such transmutation are those with the highest ratio of bulge-to-disk mass. A recent study by Burstein (1977) of bulge-to-disk ratios inferred from photometry of spirals and S0's (located in regions of relatively low galaxy density) reveals that the frequency of large bulge-to-disk ratios is highest among galaxies of the S0 type. Relatively few S0's have small bulges, while few actively star-forming spirals have large bulge-to-disk ratios. While Burstein's result is entirely consistent with the above working hypothesis, we cannot rule out the possibility that genetic factors influence both the bulge-to-disk ratio and the initial consumption of gas by star-forming events in the disk.

If spiral galaxies can become S0's following the depletion of disk gas, what is the fate of the spiral wave pattern in the disk stars? For a while, the wave pattern may persist. Strom et al. (1976a) and Wilkerson et al. (1977) find spiral wave patterns in the disks of galaxies in which active star formation has ceased. The colors of the spiral arms and of the disks in their sample of "smooth-arm spiral galaxies" are identical and tend to be more typical of S0 and E galaxies than of actively star-forming spiral galaxies. These authors believe these systems to be the immediate descendents of spiral galaxies in which disk gas has been removed, either through astration, galactic winds, or by stripping in rich clusters. However, since S0 galaxies show no evidence of spiral structure, it must be presumed that the wave pattern cannot persist for very long after gas has been removed. Lin (private communication) suggests that the spiral wave amplitude at first increases, since the damping provided by galactic shocks no longer curtails the growth of the dominant modes (see also Dekkar 1974). When the wave amplitude becomes sufficiently large, the motions of the disk stars may become significantly perturbed. An increase in the random velocities of the disk stars ensues which, in turn, eventually damps the wave.

Further theoretical work on the growth and damping of spiral waves in gas-free systems will be required in order to check these speculations. Such work would represent a critical step in our understanding of the Hubble sequence, since at present the hypothesis that spirals can be transmuted to S0's rests directly on the belief that the spiral density waves can be damped subsequent to the removal of disk gas.

4.4 Star Formation in Disk Galaxies

Understanding the factors which control star-formation efficiency as a function of time is fundamental to synthesizing plausible models of galactic evolution. Because spiral galaxies are systems which (a) are forming stars at the current epoch and (b) contain within their disks regions of significantly differing chemical and physical conditions, they appear to be attractive "laboratories" in which we can "test" various proposed mechanisms for triggering star formation.

Sargent et al. (1973) attempt to derive estimates of the star-forming history of disk galaxies from analysis of available wide-band photometry of such systems. They assume that the star-forming history of a galaxy can be represented by two separable terms: (a) an exponential birth-rate function characterized by a decay time, β^{-1}, and (b) an initial mass function (IMF) of the form $\phi(m) = Cm^{-\alpha}$. Except for irregular galaxies where the IMF may be weighted more toward the formation of massive stars, Sargent et al. find α lies close to the estimated solar-neighborhood value of $\alpha \sim 2.45$. Values of β were found to range widely; small values ($\beta^{-1} \sim 10^9$ yr) are characteristic of early-type spirals, while large values ($\beta^{-1} \gtrsim 10^{10}$ yr) are characteristic of late-type spirals and irregulars.

While these results may be correct for the galaxies as a whole (disk and bulge), the Sargent et al. analysis cannot properly describe the disk star-forming histories, since the aperture photometry available to them is affected to varying degrees by contributions from bulge light; for early-type spirals, the bulge contribution to the total system light may be very large. It is believed almost universally that star formation in the bulge is completed on a time scale $\lesssim 10^9$ years after "formation" and probably well prior to the bulk of disk star formation. Hence it is perhaps not surprising that small values of β^{-1} characterize early-type systems, since light from old bulge stars dominates. To learn more about disk star-forming histories, it would seem best to follow the spirit of the Sargent et al. analysis of integrated colors but to measure these colors as a function of disk position. Obtaining the required broad-band surface photometry of a large sample of disk galaxies is well within the capabilities of modern techniques.

Aaronson (1978) summarizes the potential of UVK photometry for making more precise estimates of plausible star-forming histories than is possible with the UBV system (see also Larson and Tinsley 1978). Measurements in this system are particularly helpful in sorting the relative contributions of newly formed stars and old-disk population. In fact, for galaxies in which the majority of star formation has taken place at recent epochs, measurement of a color similar to (V - K) may provide the only means of detecting early generations of stars.

Recent work has centered on studies of proposed mechanisms for initiating star formation in galactic disks. Models in which star formation is induced by compression behind shocks propagating in the interstellar medium have been studied extensively (see, for example, Roberts et al. 1975; Woodward 1976; Elmegreen and Lada 1977). Perhaps because of its "global" predictive powers, the spiral-shock model has received considerable attention in the last several years. First, the rate of star formation in this picture depends upon the rate at which disk gas encounters the density-wave pattern. Second, the efficiency of star formation is assumed to be related to the degree of compression suffered by disk gas in the post-shock region. Both the rate and efficiency of star formation across the disk are ultimately linked to the mass and size of a galaxy and the distribution of matter within the system. Hence, for a galaxy in which the above quantities can be estimated, it is possible to predict (qualitatively) relative star-formation rates across the disk.

Based on such reasoning, Oort (1970) suggests that the "holes" in the distribution of neutral hydrogen observed in the central regions of several nearby galaxies resulted from rapid depletion of disk gas in regions in which the encounters between the gas and the wave pattern are very frequent. However, recent observations (Burton and Gordon 1978, and references therein) of the CO distribution in our Galaxy suggest that the hydrogen holes might not represent minima in galactic gas density distribution but result instead from the predominence of H_2 compared with neutral hydrogen in the inner disk region. If so, then we must also explain why the inner disk regions in external galaxies do not appear to give birth to massive stars capable of producing observable H II regions. Can only low-mass stars form the inner disks of Sa and Sb galaxies at the current epoch, or are the massive stars and H II regions obscured by optically opaque dust clouds?

An indirect test of the spiral shock model was attempted by Jensen et al. (1976). These authors reason that in regions of high expected-star-formation rate, the rate of gas depletion and heavy element enrichment would be highest. They therefore selected a group of 14 galaxies which, on the spiral-shock picture, should exhibit a wide range of star-forming rates and efficiencies. From a comparison of emission-line strength ratios believed to be indicative of metal-to-hydrogen ratios in the gas, Jensen et al. find that the indicated heavy element abundances were indeed highest in regions expected to suffer high rates of star formation at high efficiency.

Kaufman (1978) attempts a more sophisticated test. She models the star-forming history in our Galaxy by assuming that two primary mechanisms operate: (a) supernova (or H II region) shock and (b) spiral shock-induced star formation. From optical observations of the distribution of H II regions in our Galaxy, she concludes that most stars did not originate in star-forming events triggered by galactic shocks; rather, over two-thirds of the stars were formed as a consequence of compression behind supernovae or H II region induced shocks. No attempts have been made to apply Kaufman's analysis to other galaxies.

Jensen et al. (1978; private communication with E.B.J.) have embarked on an ambitious project to map the current-epoch star-forming efficiencies across the disks of a number of spiral galaxies. Their results will be based on analysis of U, B, V, and R maps of galactic disks. From such maps, they believe that the number and ages of newly formed stars can be accurately charted. As yet, results are available in preliminary form only for the southern, barred spiral galaxy M83 (Jensen et al. 1977). They find that while most newly formed stars are found near spiral arms, there is evidence for significant star formation outside arm regions. Hence spiral shock-induced star formation cannot be the sole agent for triggering new generations of stars. Thus far, Jensen et al. find no strong evidence from their age maps for a "drift" of newly formed stars relative to the spiral wave pattern [see Schweizer (1976) for a description of a similar attempt]. However, it appears possible that the spread in formation times subsequent to compression by the spiral shock is sufficient to obscure the theoretically expected variation of age with angular position relative to the spiral arm.

Until very recently, it has been assumed that star formation in disk galaxies has proceeded continuously from the epoch when the disk gas was first assembled until the present. However, several authors (Sargent et al. 1973; Huchra 1977) argue that the star-forming histories of some disk galaxies may be extremely chaotic and characterized by bursts of star formation followed by long quiescent periods.

Even more surprising is the recent work on the ages of disk stars in our own Galaxy (Demarque and McClure 1977) and in the Large Magellanic Cloud (Butcher 1977). This latter work suggests that most stars did not start to form in the Milky Way until nearly 5 x 10^9 years following the formation of the SC, while in the LMC most star formation may have been delayed until only 3 to 5 billion years ago. Some of the LSB spiral galaxies discussed by Romanishin et al. (1977) appear to have formed the majority of their disk stars within the last 5 billion years.

5. EFFECTS OF ENVIRONMENT ON DISK GALAXY EVOLUTION

Astronomers have gradually begun to realize the importance of environment on the evolution of disk galaxies. The theoretical and observational works described in Secs. 1 through 4 have implicitly assumed that galactic evolution proceeds in isolation. However, conditions in the central regions of rich clusters of galaxies may greatly alter the course of galactic evolution. Because galaxies are moving through a hot plasma, disk and halo gas can, in principle, be removed by the effects of ram-pressure stripping (Gunn and Gott 1972) or by evaporation (Cowie and Songaila 1977). If halo or disk gas extends to galactocentric distances in excess of ∿100 kpc. collisions between galaxies will remove some of this gas. Tidal encounters in the dense central regions may be important in (a) "heating" the stellar subsystems in disk galaxies (Richstone 1976; Marchant and Shapiro 1977), (b) stripping stars from the outer regions of their disks and halos, and (c) inducing star formation. How efficacious these processes are depends upon the density and temperature of intracluster gas, the galaxian density, the cluster velocity dispersion, and the time since the cluster was first assembled. Evaluating the interplay between these factors and the natural evolutionary processes in galaxies presents a significant challenge. However, observations of galaxies in differing environmental settings appear to offer the possibility of both testing many pictures of disk galaxy evolution and deriving a sounder understanding of cluster evolution.

The possible effects of ram-pressure stripping on disk galaxy evolution have received the most observational attention in the last few years. In this picture it is implicitly assumed that stripping of gas from a spiral or irregular galaxy will result in a transmutation to a system of the S0 type. Recent work (Melnick and Sargent 1977; Bahcall 1977) regarding the distribution of spiral and S0 types in rich clusters demonstrates that (1) S0's dominate those clusters in which the 2-10 kev X-ray luminosity and the cluster velocity dispersion are highest, and (2) spirals are most frequently found in the outskirts of rich clusters where the density of intracluster material is expected to be lowest. These observations are consistent with the stripping hypothesis, since removal of disk gas by this process takes place most effectively when the velocity of a galaxy, relative to the intracluster medium, and the density of the medium are highest. Other optical studies (cf. Strom and Strom 1978d) also support the stripping hypothesis.

Sullivan (1978) reports the results of a survey of the neutral hydrogen content of disk galaxies in two X-ray clusters (Coma and Abell 1367). He concludes that the hydrogen mass-to-luminosity ratios for spirals in these clusters are significantly below those expected for field galaxies of similar morphology, and suggests that ram-pressure stripping has removed some of the disk gas in these systems.

Butcher and Oemler (1977) discuss observations of galaxy colors in two distant ($Z \sim 0.4$), rich clusters of galaxies similar in morphological appearance to the Coma cluster. They find a large excess of blue galaxies compared with Coma, and conclude that in these clusters stripping has not yet removed sufficient gas to preclude active star formation. W. Rice of Harvard is presently compiling data on the galaxian color distribution in ten nearby galaxy clusters of differing morphological types. When more information on distant clusters becomes available, his data should form the basis for a sound comparison of colors of nearby and distant clusters.

Gisler (1978) at Kitt Peak suggests that the rate at which gas is expelled from dying disk stars is sufficiently high during much of a typical galaxy's lifetime to preclude stripping in a cluster of properties similar to Coma until relatively recent epochs. Until the gas-expulsion rate from dying stars decreases sufficiently, Gisler finds that ram-pressure stripping cannot remove all the gas from a galaxy. Hence, in the context of his computations, the Butcher-Oemler inference of a large number of "unstripped" galaxies at look-back times of $\sim 5 \times 10^9$ years is not terribly surprising. Gisler adds an important caveat:

the IMF cannot be biased too heavily in favor of the production of low-mass stars else stripping should take place relatively soon after the formation of a rich cluster.

Wilkerson et al. (1977) claim to have detected a class of galaxies, smooth-arm spirals, which appears to be a good candidate for spiral systems stripped in the relatively recent past. Hence, not only do we find the presumed ultimate descendents of stripped spirals — S0 galaxies — but the transition cases as well.

Sandage and Visvanathan (1978), however, argue that S0 galaxies are not formed by stripping. From a study of the integrated colors of a sample of over 300 S0 galaxies, they find no evidence for systematic differences between S0 colors in the field or in clusters. If stripping were preferentially operative in clusters, one might expect cluster galaxies to show less evidence of recent star formation in their integrated colors; they do not. It is difficult, however, to evaluate the Sandage and Visvanathan results. First, some of their "cluster" samples are not located in regions thought to be pervaded by a sufficiently dense intracluster medium. Second, as with the Sargent et al. study of galaxy-integrated colors, it is not clear what fraction of the observed light arises from a bulge component (in which star formation has presumably been long inactive) as opposed to the disk. Systems in which the observed light is dominated by the bulge component will tend to have similar colors (to the extent that their mean metallicity is similar) despite the star-forming activity, recent or otherwise, in the disk. The Sandage-Visvanathan result seems to these reviewers neither damning nor supportive of the stripping hypothesis.

The effects of stripping in rich clusters can be used to test the efficacy of this proposed mechanism for S0 galaxy formation. Burstein (1977) finds that for field and low-density groups and clusters the distribution of bulge-to-disk ratios (B/D) for S0 galaxies tends to be weighted toward higher values than that found for spirals. If stripping "truncates" star formation by removing disk gas and if stripped spirals eventually become S0 galaxies, then the distribution of B/D for a sample of cluster S0 galaxies should include more small B/D ratio systems than the Burstein field S0 sample. Moreover, the distribution of S0 B/D ratios should vary both with position with the cluster (cf. Melnick and Sargent 1977) and from cluster to cluster (cf. Bahcall 1977).

Not only do the distribution of morphological types, integrated colors, and hydrogen mass-to-light ratios differ between disk galaxies located in rich clusters and in the field, but disk sizes appear to be smaller as well. Strom and Strom (1978d) report that S0 galaxies located in the central region of the Coma cluster appear smaller than those found in the cluster outskirts or in lower-density regions. It is not clear whether this results from the effects of tidal stripping of stars in the outer disk, or from the indirect effects on disk-system star-forming histories of ram-pressure stripping or galaxy collisions.

It is also possible that close encounters between galaxies or with intergalactic clouds can stimulate star-forming events (Toomre and Toomre 1972; Larson and Tinsley 1978; Lynds and Toomre 1976). As yet, it is not clear to what extent these events may affect the star-forming history in systems located in groups of differing density and velocity dispersion.

We should not ignore the possibility that the difference in galaxy-type distributions between rich clusters and lower-density galaxy regions might be an artifact of formation conditions rather than evolution. However, this view presupposes that galaxies "know" they will be cluster members from the time of formation. We feel that considerable effort should be invested in delineating not only morphological but also detailed structural differences between cluster and field galaxies. For example, are the bulge components of cluster disk galaxies different from those characteristic of the field? Can these differences plausibly be ascribed to differences in initial conditions? Do composition gradients in disk-system, spherical components differ significantly from those in the field? From answers to these questions, we may hope to begin to understand and separate genetic and environmental effects.

REFERENCES

Aaronson, M.: 1978, *Astrophys. J.* (in press).
Bahcall, N. A.: 1977, *Astrophys. J. Letters* 218, pp. 93-95.
Bertola, F. and Capaccioli, M.: 1978, *Astrophys. J. Letters* 219, pp. 95-96.
Burstein, D.: 1977, Univ. of California, Santa Cruz, (Ph.D. Thesis).
Burton, W. B. and Gordon, M. A.: 1978, *Astron. Astrophys.* 63, pp. 7-27.
Butcher, H.: 1977, *Astrophys. J.* 216, pp. 372-380.
Butcher, H. and Oemler, A.: 1977, *Astrophys. J.* 219, pp. 18-30.
Chevalier, R. A. and Oegerle, W. R.: 1978, *Astrophys. J.* (in press).
Cowie, L. L. and Songaila, A.: 1977, *Nature* 266, pp. 501-503.
Dekkar, E.: 1974, in Proc. CNRS Int. Colloquium, *La Dynamique des Galaxies Spirales*, Bures-Sur-Yvette, France.
Demarque, P. and McClure, R. D.: 1977, in B. M. Tinsley and R. B. Larson (eds.) *The Evolution of Galaxies and Stellar Populations*, Yale Univ. Obs., New Haven, pp. 199-217.
de Vaucouleurs, G.: 1959, *Handbuch der Physik* 53, pp. 311-372.
Elmegreen, B. G. and Lada, C. J.: 1977, *Astrophys. J.* 214, pp. 725-741.
Faber, S. M. and Gallagher, J. S.: 1976, *Astrophys. J.* 204, pp. 365-378.
Freeman, K. C.: 1970, *Astrophys. J.* 160, pp. 811-830.
Gisler, G.: 1978, *Astrophys. J.* (in press).
Gott, J. R. and Thuan, T. X.: 1976, *Astrophys. J.* 204, pp. 649-667.
Gunn, J. E. and Gott, J. R.: 1972, *Astrophys. J.* 176, pp. 1-19.
Hegyi, D. and Gerber, G. L.: 1977, *Astrophys. J. Letters* 218, pp. 7-11.
Huchra, J. P.: 1977, *Astrophys. J.* 217, pp. 928-939.
Jensen, E. B.: 1977, Univ. of Arizona (Ph.D. Thesis).
Jensen, E. B., Strom, K. M., and Strom, S. E.: 1976, *Astrophys. J.* 209, pp. 748-769.

Jensen, E. B., Talbot, R. J., Davis, J. C., and Dufour, R. J.: 1977, *Bull. Am. Astron. Soc.* 9, 648.

Kaufman, M.: 1978, *Astrophys. J.* (in press).

Kormendy, J.: 1977, *Astrophys. J.* 217, pp. 406-419.

Kormendy, J. and Bruzual, G.: 1978, *Astrophys. J. Letters* (in press).

Krumm, N. and Salpeter, E.: 1978, in R. Wielibinski (ed.), Proc. IAU Sym. 77, *Structure and Properties of Nearby Galaxies*, Reidel, Dordrecht.

Larson, R. B.: 1974, *Monthly Notices Roy. Astron. Soc.* 166, pp. 585-616.

Larson, R. B.: 1976, *Monthly Notices Roy. Astron. Soc.* 176, pp. 31-53.

Larson, R. B. and Tinsley, B. M.: 1978, *Astrophys. J.* (in press).

Lynds, C. R. and Toomre, A. R.: 1976, *Astrophys. J.* 209, pp. 382-388.

Marchant, A. B. and Shapiro, S. L.: 1977, *Astrophys. J.* 215, pp. 1-10.

Mark, J. W-K.: 1976, *Astrophys. J.* 205, pp. 363-378.

Mathews, W. G. and Baker, J. C.: 1971, *Astrophys. J.* 170, pp. 241-259.

Melnick, K. and Sargent, W. L. W.: 1977, *Astrophys. J.* 215, pp. 401-407.

Nordsieck, K. H.: 1973, *Astrophys. J.* 184, pp. 735-751.

Oort, J. H.: 1970, *Astron. Astrophys.* 7, pp. 381-404.

Ostriker, J. H. and Peebles, P. J. E.: 1973, *Astrophys. J.* 186, pp. 467-480.

Richstone, D. O.: 1976, *Astrophys. J.* 204, pp. 642-648.

Roberts, W. W., Roberts, M. S., and Shu, F. H.: 1975, *Astrophys. J.* 196, pp. 381-405.

Romanishin, W., Strom, K. M., and Strom, S. E.: 1977, *Bull. Am. Astron. Soc.* 8, 538.

Rubin, V. C., Ford, W. K., Strom, K. M., Strom, S. E., and Romanishin, W.: 1978, *Astrophys. J.* (in press).

Sancisi, R.: 1978, in R. Wielibinski (ed.), Proc. IAU Sym. 77, *Structure and Properties of Nearby Galaxies*, Reidel, Dordrecht.

Sandage, A. R., Freeman, K. C., and Stokes, N. R.: 1970, *Astrophys. J.* 160, pp. 831-844.

Sandage, A. R. and Visvanathan, N.: 1978, *Astrophys. J.* (in press).

Sargent, W. L. W., Searle, L., and Bagnulo, W. G.: 1973, *Astrophys. J.* 179, pp. 427-438.

Schweizer, F.: 1976, *Astrophys. J. Suppl.* 31, pp. 313-332.

Schweizer, F.: 1978, *Astrophys. J.* 220, pp. 98-106.

Spinrad, H., Ostriker, J. P., Stone, R. P. S., Chiu, L. G., and Bruzual, G.: 1978, *Astrophys. J.* (in press).

Strom, K. M. and Strom, S. E.: 1978a, *Astron. J.* 83, pp. 73-134.

Strom, K. M. and Strom, S. E.: 1978b, *Astron. J.* (in press).

Strom, K. M. and Strom, S. E.: 1978c (unpublished).

Strom, K. M., Strom, S. E., Jensen, E. B., Moller, J., Thompson, L. A., and Thuan, T. X.: 1977, *Astrophys. J.* 212, pp. 335-346.

Strom, K. M., Strom, S. E., Wells, D. C., and Romanishin, W.: 1978, *Astrophys. J.* 220, pp. 62-74.

Strom, S. E., Jensen, E. B., and Strom, K. M.: 1976a, *Astrophys. J. Letters* 206, pp. 11-14.

Strom, S. E. and Strom, K. M.: 1978d, in R. Wielibinski (ed.) Proc. IAU Sym. 77, *Structure and Properties of Nearby Galaxies*, Reidel, Dordrecht.

Strom, S. E., Strom, K. M., Goad, J. W., Vrba, F. J., and Rice, W.: 1976b, *Astrophys. J.* 204, pp. 684-693.

Sullivan, W. B.: 1978, *Astrophys. J.* (in press).
Toomre, A. and Toomre, J.: 1972, *Astrophys. J.* 178, pp. 623-666.
Visser, H. C. D.: 1978, Rijksuniversiteit te Groningen (Ph.D. Thesis).
White, S. D. M.: 1978, *Comments Astron. Astrophys.* (in press).
Wilkerson, M. S., Strom, S. E., and Strom, K. M.: 1977, *Bull. Am. Astron. Soc.* 9, 649.
Woodward, P. R.: 1976, *Astrophys. J.* 207, pp. 484-501.

DISCUSSION

Ostriker: You quoted a paper by Spinrad et al. with regard to the mass ratio M_{Disk}/M_{Halo}. In that paper, which was based on two dimensional photometry, we derived ratios of the light L_{Disk}/L_{Halo} for several spiral galaxies. No information about mass ratios is obtainable from photometry without unwarranted assumptions about mass to light ratios. There are dynamical arguments that may be made concerning the ratio M_D/M_H and these, which will be noted in my talk, indicate a ratio $\lesssim$ 1.

Strom: Agreed. I should emphasize that M_H/M_D was deduced from the observation of visible light only and involved the assumption that $(M/L)_H = (M/L)_D$. However it is of some interest that M_H/M_D deduced from optical photometry under these assumptions suggests that the halo mass may be sufficient to stabilize the disk.