II SPIRAL STRUCTURE AND STAR FORMATION

"We do not pretend that we have a theory about every spiral galaxy."

C.C. Lin in Discussion II.4

THE EVOLUTION OF DISK GALAXIES

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1. INTRODUCTION

The past decade has witnessed dramatic changes both in our conceptual models of disk-system formation and evolution and in the power of new observational techniques to confront, challenge, and redefine these models. In this contribution, we would like to review recent optical wavelength studies of spiral and S0 galaxies which appear to influence our understanding of disk-system evolution. Particular emphasis will be placed on the effects of environment on evolutionary processes, since it appears likely that the addition or removal of gas during the lifetime of a disk system may often be dominant in controlling its appearance.

2. THEORETICAL OVERVIEW

A typical disk system is composed of two morphologically distinct components: a spheroidal component, the bulge; and a flattened component, the disk. In some cases, the disk component is forming stars at the current epoch (in galaxies of type Sa-Sc and in some irregular systems), while in others (S0 galaxies and "smooth-arm" spirals) there is no evidence of star formation. The relative prominence of bulge and disk components, expressed as a bulge-to-disk ratio (B/D), appears to vary continuously among observable systems. Among relatively luminous galaxies, disk systems appear to be the dominant morphological type in the field and in low-density groups of galaxies. In the great clusters, the frequency with which star-forming disk galaxies appear decreases dramatically; it is also possible that the frequency of all disk systems is lower in such regions. Recent theoretical efforts have been directed first toward explaining the morphological appearance of disk systems, and next toward understanding their relative frequency in differing environments.

Most prominent among recent contributions to our understanding of disk-system formation have been those of Larson (1976) and Gott and

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Thuan (1976). Both sets of models presuppose the existence of a rotating protogalactic gas cloud in which star formation accompanies collapse. Collision between gas clouds in the collapsing protogalaxy leads to dissipation of energy in the gas (through cloud heating and subsequent radiative processes) and the eventual formation of a thin disk. The prominence of the disk and bulge components is determined by the relative efficiency of star formation during the galaxy-formation epoch. Those systems in which star formation is relatively efficient at early epochs form large spheroidal components; little gas remains to form a disk. Conversely, when few stars are formed initially and when dissipative processes in the gaseous component dominate the early evolution, the disk component is most prominent. The beliefs of a decade ago, which argued that the Hubble sequence from elliptical to spiral galaxies represented a sequence of increasing initial angular momentum, are not supported by current galaxy collapse models. Current speculation centers on the initial density of the protogalactic cloud as the primary determinant of the relative time scales for star formation and for collapse of gas to a disk and thereby the B/D ratio. If the star-formation rate (number of stars formed/volume/time) $\sim \rho^{n}$, then the time scale for star formation $\tau_s \sim \rho^{1-n}$. The time scale for collapse to a disk is on the order of the free-fall time scale $\tau_{ff} \sim \rho^{-\frac{1}{2}}$. Hence, $\tau_s/\tau_{ff} \sim \rho^{1.5-n}$. The estimates by Schmidt (1959) of the star-formation rate in our Galaxy, and the more recent theoretical estimates of Talbot and Arnett (1975), suggest $1.7 \lesssim n \lesssim 2$. In protogalactic condensations of high initial density, the star-formation rate is therefore expected to be relatively high and consequently not much gas may remain to form a disk. In regions of lower density, however, the time scale for star formation may be longer than the free-fall time scale in the protogalactic cloud, and these systems may be dominated by the disk component. Gott and Thuan (1976) have argued that more spheroidal galaxies may be formed in dense clusters of galaxies if the mean density of the protogalactic clouds is in some way related to cluster-formation conditions. They believe that the "seeds" for great clusters are found in regions of above-average density enhancements. In such regions, systems of high B/D are expected to predominate.

2.1. Evolution of the disk postformation: spiral galaxies

The current epoch appearance of disk galaxies depends on three factors: 1. the amount of gas remaining (to form stars) in the disk subsequent to its formation; 2. the rate at which gas is consumed in astration events; 3. the effects, if any, of mechanisms which add or remove gas from the disk (and thereby enhance or truncate star formation).

The collapse into disk form involves collisions of subcondensations within the protogalactic cloud; the relative velocities of these subcondensations are on the order of several hundred km $\sec^{-1}$. Star formation may proceed vigorously in regions of high compression behind shocks induced in the supersonic cloud-cloud collisions. It is not yet clear, however, how much star formation takes place during these final disk-collapse phases, and what fraction of the "initial" disk is stellar or gaseous. Sandage et al. (1970) argue that the fraction of remaining gas is the dominant factor which determines the Hubble type of a galaxy. At the extremes, in their view, S0 galaxies represent systems in which little postformation gas remains, whereas Sc and irregular galaxies represent systems with initially gas-rich disks. While this suggestion may be correct, by itself it is insufficient to explain the detailed relationship between bulge prominence and arm appearance characteristic of the Hubble sequence.

Perhaps the greatest advances in understanding postformation disk evolution have come from recent theoretical studies of spiral galaxies. From inspection at optical wavelengths, the dominant features of these galaxies are regions of active star formation extending over scales of many kpc and arranged in a regular pattern of spiral arms. The regularity of the spiral patterns and their apparent persistence on time scales significant compared to a Hubble time led to the hypothesis that the arms represent a quasi-permanent, spiral wave pattern in the density distribution of the underlying old disk stars (Lindblad 1960; Lin and Shu 1964). A theory describing these density waves has been extensively developed by Lin and his collaborators over the past 15 years. In this theory, the wave pattern, which is characterized by an angular velocity of rotation, Ω_p (the pattern speed), results from a self-sustaining departure from the axisymmetric gravitational field of the disk system. The importance of star formation in spiral arms is believed to result from interaction of any remaining disk gas with the spiral wave pattern sustained by the underlying disk stars.

At present, considerable controversy surrounds discussion of the physical processes by which spiral-density waves are initially induced, and the processes which amplify and damp the waves and thereby determine the wave lifetime. However, much progress has been made both in understanding (a) the dependence of the wave pattern on galaxy mass size, and the distribution of mass within a galaxy, and (b) the role of gas-density wave interactions in triggering star formation.

The first impression of the spiral-arm pattern in a galaxy is derived from the "openness" of the pattern; this quality can be expressed in terms of the "pitch angle" i. The quantity i (the angle between the spiral wave, at any radial distance r from the center and a circle of radius r centered on the galactic nucleus) is primarily related to the degree of central concentration in the galaxy (Roberts et al. 1975). Galaxies exhibiting high central concentration or large bulges support wave patterns which have small values of the pitch angle (tightly-wound arms); open wave patterns are most easily supported in galaxies of low central mass concentration.

Another feature which directly affects the visual perception of the spiral pattern is the relative prominence and distribution of the recently-formed stellar population in the arms. Galaxy-wide shocks induced by interaction of disk gas with the density wave appear to provide a most promising mechanism for driving star-forming events in spiral arms. In this picture, gas at a given radial distance r moving at an angular speed $\Omega(r)$ encounters the density wave with an unperturbed (by the gravitational field of the arms) velocity perpendicular to the arms given by $w_{\perp_0} = (\Omega - \Omega_p)\ r \sin i$. For a typical massive spiral galaxy, the maximum circular velocity is on the order of 250 km $\sec^{-1}$; the pitch angle i is on the order of 5-15 degrees. Hence, $w_{\perp_0}$ is on the order of 25-60 km $\sec^{-1}$. For an idealized two-component (cloud-intercloud) model of the interstellar gas (Field et al. 1969), the value of $w_{\perp_0}$ exceeds the expected sound speed ($\sim$8 km $\sec^{-1}$) in the intercloud gas ($T \sim 10\ 000^{\circ}$K). Hence, as the gas encounters the spiral-wave crest supersonically, a shock wave is formed. For a given wave amplitude, the strength of the shock and the compression are proportional to $(w_{\perp_0}/a)^2$, where a is the effective accoustic speed in the gas. For large values of $w_{\perp_0}$, the shocks are strong and regions of higher compression are narrow. For small $w_{\perp_0}$, shocks are weak and the region of compression is broad. Even for $w_{\perp_0} < a$, some of the gas can nevertheless be accelerated by the spiral gravitational field near the wave crest to transonic values and produce a shock wave, if the wave amplitude is sufficiently large.

One effect of compressing the intercloud gas in shock regions is to force some intercloud material into the cold-cloud phase. The greater ambient pressure in the intercloud medium in regions of high compression may trigger the collapse of both ambient and newly-formed cold clouds. The contraction of these clouds is presumed to result in star formation. [Woodward (1976) has attempted some more quantitative studies of shock-driven implosion of cold clouds located in compressed intercloud material. His results suggest in greater detail how star formation may proceed.] In galaxies characterized by high values of $w_{\perp_0}$, newly forming stars are thought to be confined to the narrow, post-shock, high-compression regions. In galaxies where $w_{\perp_0}$ is generally small, new stars may be formed in relatively broad regions of weak compression.

The hypothesis that star formation is triggered by galactic shocks is very attractive because it provides a natural explanation for the predominance of star formation in spiral arms. No other proposed mechanism can account readily for the coherence of star-forming episodes on scales of many kpc.

If the picture of galactic shock-induced star formation is correct, it suggests that the star-formation rate (and the rate of gas depletion) depends on the frequency with which disk gas encounters the density wave, $(\Omega - \Omega_p)$. Furthermore, it also seems natural to suggest that the efficiency with which stars are produced at each encounter depends on the degree of compression (greater star-formation efficiency in high-compression regions), although no direct theoretical justification for this statement is available. These beliefs have important implications for understanding the evolution of disks or galaxies of different masses, sizes, and degrees of central concentration. For example, we expect that $(\Omega - \Omega_p)$ will be largest in galaxies in which the ratio $M_{\text{galaxy}}/R_{\text{galaxy}}$ is large since $\Omega \sim \sqrt{GM/R}/R$. Furthermore, we expect that the values of $w_{\perp o}$ are largest in such galaxies and in those for which the pitch angle is relatively large, since $w_{\perp o} \sim \sqrt{GM/R}$ f(central concentration). Finally, we expect that the degree of compression is highest not only when $w_{\perp o}$ is high, but when the wave amplitude is high as well. In Figure 1, we show a typical run of the quantity $(\Omega - \Omega_p)$

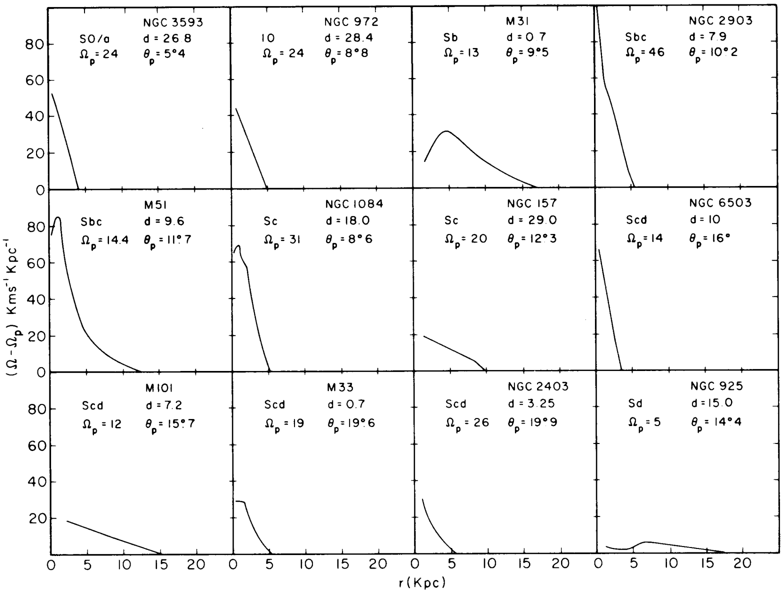

Figure 1. A plot of $(\Omega - \Omega_p)$ against galactocentric distance r for 12 spiral galaxies.

against r for a series of galaxies of differing morphological type. We expect that the formation of stars, the depletion of gas, and the chemical enrichment in the remaining gas within a given galaxy will be highest in regions of high $\Omega - \Omega_p$, $w_{\perp o}$, and wave amplitude. From Figure 1, we deduce that the gas will be depleted first in the inner regions of the galaxy and last in the outer regions. Furthermore, we expect that the chemical enrichment will be highest in the inner regions (where star formation, element production, and gas depletion rates are high) and lowest in the outer regions. In galaxies having low values of M/R (low values of $w_{\perp o}$ and weak compression), the star-formation efficiency is low and less gas is processed, and the rate of element formation is low.

In the above discussion, we assume that the evolution of the disk proceeds in isolation. However, Larson (1972a,b) has suggested the possible evolutionary significance of external gaseous material added to galactic disks over a Hubble time. The addition of such material might result from the infall of gas bound to the galaxy but located in an extensive halo several hundred kpc in size, or by direct accretion as the galaxy moves subsonically through relatively dense pockets of intergalactic material. Assuming that the high-velocity clouds observed in our Galaxy (Oort 1970) represent infalling material, Larson finds that the infall rate is sufficient to account for a large fraction of the current disk-gas content and for the average observed star-formation rate. He argues that the Hubble sequence might conceivably be understood in terms of the fraction of gas available for infall after the initial collapse and the time since the last infall episode. In this rather extreme picture, he regards the spiral features as transient, material arms produced by the combined effects of differential rotation and star formation in gas recently introduced into the disk.

The chemical evolution of the disk is also influenced by the infall of gas. If the time scale for conversion of infalling gas-to-stars is τ, then for infalling gas comprised of pure hydrogen $Z = a + (Z_0 - a)\, e^{-t/\tau}$, where a is the yield (the fraction of material going into star formation and re-ejected in the form of heavy elements), and Z_0 the initial metal abundance of the disk. Larson further argues that the evolution of disks may be different in clusters than in the field. Disk systems in clusters may be formed from denser protogalactic condensations (see Gott and Thuan 1976). These dense condensations will have shorter free-fall times and consequently less extensive halos at the current epoch. Hence, little halo gas may be introduced into the disk at the current epoch, thus explaining the relative absence of spiral galaxies in great clusters.

Removal of disk gas will also play a major role in affecting the evolution of disk galaxies. If the gas is removed from the disk, star formation will cease unless gas can be replenished. Several mechanisms for the removal of disk gas have been proposed.

2.2. Galaxy-galaxy collisions

In this process first discussed by Baade and Spitzer (1951), galaxies are assumed to collide in regions of high galaxy density. In such collisions, the stellar subsystems are relatively unperturbed, whereas the disk gas is removed from the system both (a) because the gas is heated to temperatures which exceed the effective escape temperature from the combined colliding systems, and (b) because the velocity of the remaining gas is low relative to the center of gravity of the two stellar subsystems; hence this gas is left behind as the systems move in opposite directions at velocities greater than the escape velocity from either system.

2.3. Stripping by intergalactic material

Gunn and Gott (1972) propose that as spiral galaxies move through the intergalactic medium known to pervade some rich clusters of galaxies, the disk gas can be stripped by ablation, if

$$\rho_{\rm IGM}\, V^2_{\rm galaxy} > 2\,\pi\, G\, \sigma_{\rm stars}\, \sigma_{\rm gas} \qquad (1)$$

$\rho_{\rm IGM}$ is the density of intergalactic gas; $V_{\rm galaxy}$ is the velocity of the galaxy relative to the gas; $\sigma_{\rm gas}$ and $\sigma_{\rm stars}$ are, respectively, the surface densities of the gas and stars in the disk of the spiral. For the Coma cluster, the density of the intergalactic medium can be estimated from X-ray observations, and $V_{\rm galaxy}$ from the observed velocity dispersion in the cluster; for reasonable estimates of $\sigma_{\rm stars}$ and $\sigma_{\rm gas}$, Gunn and Gott argue that no gas-bearing spirals can survive in the center of Coma. We should note that the processes which strip disk gas in clusters similar to Coma can also strip the galaxy of any halo gas thereby eleminating the evolutionary consequences of gas infall. Once a galaxy's motion carries it into environment of lower intergalactic density in the outer regions of the cluster, ablative stripping becomes unimportant. The mass loss from disk stars is expected to replenish the interstellar medium in the galaxy at a rate of $\sim$1 $M_\odot$ yr^{-1}; hence in $\sim$10^9 years, the disk gas may comprise several percent of the total mass unless other gas-removal mechanisms are important.

2.4. Removal of gas by galactic winds

Mathews and Baker (1971) and Faber and Gallagher (1976) have proposed that gas may be removed from disk galaxies by the action of galactic winds. These winds are generated in the nuclear bulge of the disk system, driven by two heating mechanisms: 1. supernova heating; 2. heating by collisions (at velocities determined by the velocity dispersion of the stars in the nuclear bulge) between shells of gas ejected by dying stars. If the heating due to these effects is sufficient, the equilibrium temperature of the gas is so high that the gas is no longer bound to the bulge. In disk systems, winds generated in the central bulge may be sufficient to remove gas not only from the bulge region but from the inner parts of the disk as well. A recent calculation by Bregman (1976) suggests that over a wide range of B/D ratios, once a galaxy is stripped by mechanism 2.3 it remains stripped by the action of intergalactic winds.

2.5. The role of galactic halos

Ostriker and Peebles (1973) suggest that cold disk systems (whether comprised of gas or stars) are subject to large-amplitude, irreversible, bar-like instabilities. These authors propose that extended halos with $M_{\rm halo}/M_{\rm disk} \gtrsim 1$ represent plausible entities for stabilizing the disk. Such halos might be expected to have a major influence on the chemical evolution of the disk as well (Ostriker and Thuan 1975). Furthermore, energy and angular momentum exchange between spiral-density waves and the halo may significantly affect the amplification of these waves (Mark 1976).

Ostriker and Peebles suggest that the constituents of such putative halos must have large mass-to-light ratios, since halos of the proposed size and mass composed of the usual nuclear bulge population mix would not have escaped detection. Late-type M dwarfs have been put forth as plausible candidates for the dominant halo constituents. The successful detection of massive halos would be significant not only because of the implications for the structure and evolution of disks, but because the mass contained in such halos might represent the majority of the mass in the universe.

The above discussion suggests that the evolution of disk galaxies depends both on normal astration processes driven primarily by galactic shocks and on interactions with the environment.

We would like to explore now the observational evidence bearing on the evolution of disk systems. Because of the possible importance of environmental effects, we will consider separately relatively isolated, "normal" spiral galaxies and cluster disk galaxies. We shall first explore the extent to which the morphology and evolution of spiral galaxies can be understood in terms of interaction of gas with the density-wave pattern. Next, we shall discuss the nature of disk systems in which there is no evidence of recent star formation. We will focus here primarily on systems located in clusters of galaxies where environmental factors may predominate. Finally, we will discuss a class of relatively nearby spiral galaxies in which the gas content may be quite large and from which we may possibly hope to deduce the characteristics of normal spiral galaxies at much earlier evolutionary phases.

3. RECENT OPTICAL OBSERVATIONS

3.1. Spiral galaxies

The Hubble sequence. The main Hubble classification criteria for spiral galaxies are: 1. the prominence of the bulge relative to the disk; 2. the openness of the spiral arms. Galaxies of type Sa have tightly-wound arms (small pitch angle) and relatively large nuclear bulge regions, while those of type Sc have the most open-arm patterns (large pitch angle) and smallest bulges. Roberts et al. (1975) have shown that the computed pitch angle of the spiral arms is greatest for galaxy mass distributions which have a low degree of central concentration, whereas wave patterns computed for models with high central concentration are tightly wound. Hence, the relationship between bulge prominence and arm openness implicit in the Hubble classification scheme seems well understood on the basis of the wave patterns permissible for given galaxy mass distributions.

Luminosity class. van den Bergh (1960a,b) has shown that the luminosity of a spiral galaxy is related to the qualitative appearance of the spiral arms. Galaxies with prominent, narrow spiral arms are intrinsically the most luminous, while galaxies exhibiting patchy, broad arms have the lowest intrinsic brightness. Roberts et al. (1975) have argued that the width and prominence of the arms are directly related to the strength of the galactic shock induced by interaction of disk gas with the density-wave pattern. Where $w_{\perp 0} \gg a$, the degree of compression in the shock region is large and the width of the region of high compression is small. If star-forming efficiency is related to the compression suffered by the gas, and if the width of the spiral arm (as measured by the angular extent of recently-formed stars) is related to the width of the region of high compression, then one expects those galaxies characterized by large values of $w_{\perp 0}$ to have the narrowest, most prominent arms. Because $w_{\perp 0}$ is related to galactic mass ($w_{\perp 0} \sim M^{1/2}$), both this quantity and the arm appearance are expected to be correlated with intrinsic galactic luminosity as well (if $M/L \sim$ constant). This prediction has been borne out by a comparison of the luminosity classes assigned by van den Bergh with the mean value of $w_{\perp 0}$ derived from observed galaxy rotation curves (Roberts et al. 1975).

Choice of pattern speed, Ω_p. The pattern speed Ω_p cannot at present be predicted directly from density-wave theory. Therefore when comparing computed and observed wave patterns, Ω_p is treated as a free parameter. Roberts et al. (1975) have argued that an approximate value of the pattern speed can be estimated from the location of the outermost H II region in the spiral galaxy. They reason that this region indicates the approximate radius beyond which star formation cannot be initiated by galactic shocks. If we associate the outermost H II region with the "corotation radius" [at which $(\Omega - \Omega_p)$ and hence $w_{\perp 0} = 0$], we can derive Ω_p from the observed angular velocity of this region Ω. This choice of Ω_p leads to quite satisfactory fits to the wave patterns of 24 spiral galaxies for which rotation curves provide an estimate of an appropriate mass model (Roberts et al. 1975).

An independent check on the choice of pattern speed may be provided if the inner or outer Lindblad resonance in a galaxy can be located. At the inner resonance, $\Omega - \Omega_p = \kappa/2$. Here, κ is the free oscillation frequency of the stars (which can be computed directly from the observed rotation curve). A possible observational consequence of the inner Lindblad resonance in spiral galaxies is the presence of bright rings of young stars and H II regions, recently formed as disk gas encounters the tightly-wound, high-amplitude wave pattern predicted for the region just outside the resonance (Mark 1975). The galaxy NGC 5364 (Figure 2) is an excellent example of a galaxy exhibiting a prominent ring of H II regions. A rotation curve for this galaxy was derived by Goad et al. (1975). These authors conclude that the inner Lindblad resonance is located $\sim$1 kpc inward of the ring of H II regions if a value of Ω_p equal to the observed angular speed of the outermost H II region in NGC 5364 is selected. This result provides encouraging support to the Roberts et al. criterion for selecting pattern speeds.

Wave amplitudes. Schweizer's (1976) observation of a wave pattern in the old disk population of several prominent spiral galaxies provided the first direct evidence of stellar density-wave arms. The amplitudes of the waves observed by Schweizer varied from ±5 percent to ±30 percent of the background disk-surface brightness. These values are somewhat larger than the amplitudes which have been inferred from

Figure 2. A blue-light photograph (GG 385 + IIIa-J) of NGC 5364 taken at the prime focus of the Mayall 4-m telescope by C. R. Lynds. Note the prominent central ring of H II regions. North is at the top and east at the left.

analysis of stellar orbits in our own galaxy, and which have been commonly adopted in most models of density-wave-driven star formation. Currently, the amplitude of the wave pattern in a given galaxy cannot be predicted directly from density-wave theory. Yet, the departures from the axisymmetric gravitational field produced by the wave play an important role in determining the degree of compression in galactic shocks. As a consequence, it is of some importance to determine the range of wave amplitudes characterizing spiral galaxies of differing morphological type. Eric Jensen of Rice University has undertaken such a study. In order to emphasize the contribution of the underlying disk population to the observed wave amplitude, he has chosen to observe his sample of galaxies at wavelengths of 8500 Å and 1 μ. At these wavelengths, the red K giant population of the old disk dominates the young stars in the spiral arms. Thus far, he has completed an analysis of two galaxies, M51 and M101. His results suggest that as the galactocentric distance increases the wave amplitudes increase from values of ±5 percent to ±40 percent of the background-disk surface brightness, thus confirming Schweizer's conclusions (derived from observations at shorter wavelengths).

Luminosity and color evolution across spiral arms. If star formation is triggered by passage of disk gas through the density-wave pattern, then the spiral-arm regions should exhibit the following evolutionary pattern: 1. near the concave, inner edge of the spiral arm, evidence of recent compression in the form of dust lanes in dark clouds; 2. in an intermediate zone, OB associations in H II regions formed from gas compressed at an earlier epoch; 3. on the outermost (convex) edge of the arm, aging clusters and associations (evolved from OB associations formed at an earlier epoch). B. Lynds (1970) has presented strong evidence which confirms that dust lanes are confined to the inner edge of spiral arms. Both Schweizer (1976) and Dixon et al. (1972) have computed the luminosity and color profiles across spiral arms expected from density-wave-driven star formation. The angular drift ϕ of the newly-formed stars relative to the "edge of the arm" as defined by the dust lanes is given by $d\phi(r)/dt = \Omega(r) - \Omega_p$. Schweizer's observed luminosity profiles provide some evidence in favor of "drift," although his results are not conclusive. An attempt to derive color changes indicative of an age sequence of the type described above has been made by Talbot et al. (1977) for M83. Thus far, their analysis of observed colors provides no definitive evidence which suggests aging across spiral arms in this galaxy. It should be noted that analysis of color and luminosity profiles across spiral arms is considerably complicated by the presence of dust and uncertainty in the time between compression and the appearance of observable (at visible wavelengths) young stars. Moreover, in order to estimate ages of the newly-formed stellar population, one must accurately subtract the contribution of the underlying density wave. More accurate photometric studies may eventually provide evidence of the expected age drift across spiral arms. It would be embarrassing to the shock-induced star-formation picture if such changes were not observed.

Chemical enrichment. If density-wave-driven star formation dominates postformation disk evolution, one expects that the frequency of star-forming events will depend on $(\Omega - \Omega_p)$, while the efficiency of star formation will be related to the compression suffered by disk gas as it passes through the density-wave crest. Radial changes in chemical composition can be related directly to the star-forming frequency. Regions where stars form most frequently should be those (a) where the disk gas is consumed most rapidly, and (b) in which the chemical composition of the remaining gas is high (since the ejecta from previous generations of stars easily contaminate the remaining material). In a recent study, Jensen et al. (1976) observed several abundance-sensitive emission-line ratios in H II regions located in the disks of 12 spiral galaxies. They attempted to correlate the inferred chemical composition with the star-formation frequency and efficiency inferred from density-wave models. In agreement with the predictions of galactic shock models, they find that (a) the metal abundance is highest in regions of high $\Omega - \Omega_p$, and (b) galaxies characterized by high mean values of $w_{\pm o}$ show significantly higher mean abundances. While other, more *ad hoc* models might explain the results, Jensen et al. believe that their data provide a strong consistency check on the predictions of the density-wave model.

3.2. S0 galaxies and the effects of environment on evolution of disk systems

Galaxies classified as S0 are systems having featureless disks which exhibit no evidence of spiral density waves or recent episodes of star formation. They have long been viewed as "transition" objects between the elliptical and spiral sequences. Their true evolutionary status is at present not clear. It is possible that S0 galaxies represent (a) systems in which the amount of disk gas remaining after formation was small and in which star formation consequently ceased soon thereafter, (b) former spiral galaxies in which the evolutionary processes described in the previous section have exhausted the disk gas in the relatively recent past, (c) former spiral galaxies in which disk gas has been somehow removed either by interaction with the intergalactic environment or by other processes, or (d) some combination of the above. Freeman (1970) carried out a pioneering quantitative study of the characteristics of S0 galaxies in an attempt to compare them with actively star-forming systems. He concluded that the disk light exhibits an exponential light profile of the form $I = I(o)\, e^{-\alpha r}$(see also de Vaucouleurs 1959). The exponential scale length for S0 galaxies is similar to those derived for galaxies of types Sa-Sbc ($2 \lesssim \alpha^{-1} \lesssim 10$ kpc), although different (for his sample) from the α^{-1} values characterizing Hubble types Sc and Scd (2-5 kpc).

Furthermore, his study shows that the projected central surface brightnesses derived for S0 disks are identical to those found for spiral galaxies. Freeman also notes that the bulge/disk ratios for "field" S0 galaxies are not discernably different from those of later Hubble types. Sandage et al. (1970) use these data to argue that because the intrinsic "bulk" properties of S0 galaxies are no different from spirals, it is illogical to assume that the astration rates (and hence gas depletion rates) differ between the disks of spirals and S0 galaxies. Because the fractional gas content is zero or nearly so in most S0 galaxies, while that of later-type galaxies is significantly greater, they conclude that the basic difference between S0s and spirals results from a difference in the amount of gas remaining in the disk subsequent to disk formation. However, arguments based on more recent observational studies may obviate this conclusion. First, Kormendy (1977) has demonstrated that the apparent exponential light distribution in disk systems is in part an observational artifact arising from the combined contributions of the bulge and disk regions to the observed surface brightness distributions. Several of the disk light distributions derived by Kormendy by careful subtraction of the bulge component show a distinctly non-exponential character. Moreover, the projected central surface brightnesses of the disk light distribution do not appear to have a "universal" value. Hence, it is no longer clear that (a) the bulk characteristics of spiral and S0 systems are indeed identical, and that (b) as a consequence, the rates of star formation and gas depletion in the disks must be identical as well.

It is also necessary for Sandage et al. to demand a difference in disk-system formation conditions between rich clusters and the field, since rich clusters contain a much smaller fraction of spiral galaxies (compared to S0s); disk systems in clusters must somehow be formed in a manner such that the amount of gas remaining in the disks is much lower. While this possibility is by no means ruled out, other mechanisms have been invoked which appear to offer a far less *ad hoc* explanation of the absence of spiral galaxies in rich clusters. In this section, we shall explore in some detail recent studies of the effects of environment on disk-system evolution. However, we must bear in mind that not all S0 galaxies are found in rich clusters, and that effects other than environmental influences may well be important in accounting for the simultaneous presence of spiral and S0 galaxies in the field.

Morphology of disk systems as a function of environment. Recently, Oemler (1974) investigated the frequency distributions of ellipticals, S0s, and spiral galaxies in clusters of galaxies differing in structure and appearance. He was able to discern three types of clusters: 1. cD; 2. spiral-poor; 3. spiral-rich. Spiral-rich clusters have a mixture of galaxy types most similar to the field (dominated by spirals and S0s and poor in E-type systems). They are irregular in appearance, have a low mean density of galaxies, and no tendency toward central concentration. Spiral-poor and cD clusters, on the other hand, are deficient in spiral galaxies and, according to Oemler, exhibit a much higher percentage of elliptical galaxies. cD clusters are dominated by central supergiant galaxies and tend to be dense, centrally concentrated, and spherical. Spiral galaxies are virtually absent in the cores of these clusters. Spiral-poor clusters represent cases intermediate in character between the cD and spiral-rich clusters; they are not quite as regular, compact, or centrally concentrated as the extreme cD clusters. Oemler suggests that to a large extent the difference in type results from dynamical evolution of the clusters. The high-density, short-collapse-time, spiral-poor and cD clusters are presumed to be the most dynamically evolved. Both their smooth mass distributions and high central concentration suggest a considerable period during which two-body relaxation processes have been operative. Conversely, the low density of spiral-rich clusters implies long cluster collapse times. Furthermore, the lack of central concentration and the irregular mass distribution of these clusters indicate a lack of any significant relaxation.

The predominance of S0 galaxies in cD and spiral-poor clusters is supposed to result from transmutation of spirals to S0 galaxies as a consequence of ablative stripping in the dense cores of these cluster types. Observations of the X-ray luminosity and velocity dispersion for clusters representative of these types suggest that, at least near the cluster center, the intergalactic gas density is sufficient to remove disk gas from most spiral galaxies. X-ray observations of spiral-rich clusters suggest the absence of intergalactic gas at densities sufficient to effect stripping. Evidently, dense intergalactic media can exist only in clusters already collapsed and dynamically relaxed (and possibly in those currently undergoing collapse).

It is not clear, however, that all differences in the distribution of morphological types can be attributed solely to environmental effects. If the ratio of ellipticals/(spirals + S0 galaxies) is truly different between spiral-rich and spiral-poor and cD clusters (Oemler 1974), one must accept either (a) that S0 galaxies can be transmuted to ellipticals (see Richstone 1976; Marchant and Shapiro 1977), or (b) a difference in the initial distribution of galaxy-bulge/disk ratios which depends on conditions in the protocluster environment. It is essential to determine the true fraction of ellipticals, S0s, and spiral galaxies based on quantitative analysis of galaxy profiles. It would also be important to determine the difference, if any, between S0 galaxies located in cD and spiral-poor clusters and those located either in irregular, spiral-rich clusters or in the field. Presumably, S0 galaxies in the field have completed their "normal" evolutionary development. If, for example, field S0s represent galaxies that consume their gas most rapidly (presumably those with highest $\Omega - \Omega_p$ and $w_{\perp o}$), then the distribution of B/D ratios and M/R ratios for these galaxies might differ significantly from those characterizing S0 galaxies in rich clusters where normal evolutionary development has been truncated by stripping.

<u>The fraction of spiral galaxies as a function of X-ray luminosity and cluster position</u>. Galaxies presently in the center of clusters similar to Coma are moving through intracluster gas of a density apparently sufficient to effect stripping by ablation. Hence, all spiral galaxies in the cluster cores probably have been stripped. However, there is reason to suppose that the fate of spirals located in the outer regions of the cluster is not as certain. Because the density of intergalactic gas appears to decrease outward from the cluster center, the gas density in the outer regions appears too low to result in spiral stripping. Nevertheless, it is possible that some galaxies now on the outside of the cluster have passed through the cluster center in the past. However, since the typical crossing time for a rich cluster of galaxies similar to Coma is on the order of a few billion years, it seems likely that galaxies presently in the outer regions of such a cluster will not have passed through the cluster center many times during a Hubble time even if (a) their orbits are all radial or (b) the cluster relaxed at a very early epoch. Furthermore, it is not clear at what epoch the intergalactic medium achieved a density sufficiently high to strip spirals. If the medium is of relatively recent origin, or if galaxy orbits are not primarily radial, systems located in the outer regions of the cluster may remain unaffected by stripping.

Melnick and Sargent (1977) have classified galaxies in a number of clusters known to exhibit X-ray emission. Their data suggest that the fraction of spiral galaxies increases from near zero in the cluster cores to values typical of the field in the outer cluster regions. Moreover, they find that the fraction of spiral galaxies is largest in those galaxies with weakest X-ray emission and smallest in those galaxies where X-ray emission is stronger (see also Bahcall 1977). These authors regard this evidence as strongly favoring stripping caused by the ram pressure of intergalactic gas.

Although their results strongly support the idea of transmutation from spiral to S0 galaxy types, it is also conceivable that formation rather than environmental conditions might also account for the observations. For example, the conditions under which galaxies are formed in clusters may favor the production of elliptical and rapidly evolving spiral galaxies (those with relatively large bulge-to-disk ratios, high values of $\Omega - \Omega_p$ and high values of $w_{\perp o}$) in cluster cores. In order to test the importance of stripping, it would be of value to: 1. identify recently stripped galaxies; 2. search for (a) the presence of a greater fraction of (unstripped) spiral galaxies at earlier epochs (greater look-back times) in clusters similar in morphological appearance to nearby spiral-poor and cD clusters, or (b) changes with radial distance from the cluster center, indicating not only a change in the spiral fraction but in the properties of presumably stripped S0 systems as well.

Smooth-arm spiral galaxies. A possible time sequence for spiral galaxy evolution "post-stripping" might be (a) loss of Population I tracers (dust, OB associations, and H II regions), (b) weakening of the density wave in the disk population, and (c) the final S0 state in which no density waves are discernible. Because the integrated color of the disk should become redder as the mean age of the stellar population in the disk increases, recently stripped spiral galaxies should show the bluest disk colors and the strongest relic arms, while the oldest stripped systems should exhibit red disks and no arms (S0s). A few years ago, Strom et al. (1976a) identified two smooth-arm galaxies in which no evidence of Population I tracers was found. In both cases, the galaxies were located in known X-ray clusters and appear to be ideal candidates for identification as stripped spirals. The absence of a Population I component in the arms was demonstrated not only from the appearance of the galaxy, but from a quantitative comparison of arm and disk colors. No difference between arm and disk $(U - R)$ colors was observable. More recently, Wilkerson et al. (1977) have identified nearly 25 smooth-arm spirals located in clusters known to be X-ray sources. In Figure 3, we present photographs of three smooth-arm spiral systems representative of the range in observed arm amplitudes for systems of this class. The results of a preliminary study of the 25-galaxy sample suggest that the spiral waves of largest amplitude are found in disks having the bluest colors, as might be expected if these systems were stripped most recently. In systems with weak arm amplitudes, the disk colors appear reddest, a result consistent with the belief that systems stripped relatively long ago should show lower arm amplitudes.

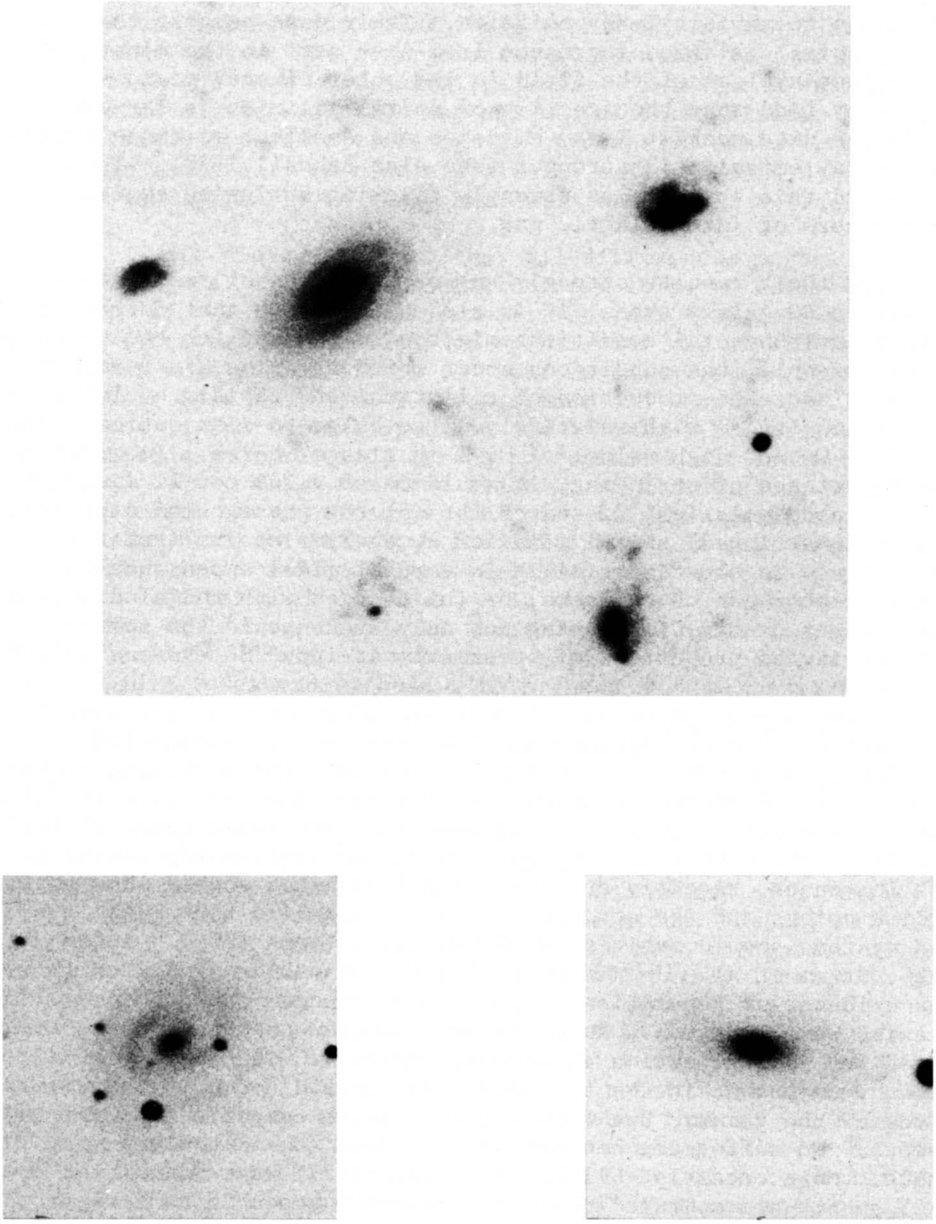

Figure 3. Ultraviolet(U)-band (UG 2 + IIIa-J) photographs of three smooth-arm spiral galaxies taken with the Mayall 4-m telescope. Top (a): NGC 3860 located in the cluster Abell 1367; bottom left (b): NGC 1268, Perseus cluster; bottom right (c): IC 2951, Abell 1367. Note the progressive decrease in wave amplitude from galaxy (a) to galaxy (c). The orientations of individual galaxies are arbitrary.

A particularly intriguing case of a smooth-arm spiral was found in the cluster Abell 1367 and is illustrated in Figure 3 (a). For this galaxy (NGC 3860), not only do we observe a high amplitude, smooth-arm spiral pattern, but also a number of irregular "blobs" scattered about the galaxy. It is conceivable that these blobs might represent shreds of material stripped from the galaxy and in which star formation was recently induced. Further spectroscopic study is required in order to confirm this speculation.

To further test the belief that smooth-arm spirals have been stripped, it would be of great importance to determine the neutral hydrogen content for galaxies of this class (since we presume that hydrogen has been removed from the disk!). Without confirmation of low hydrogen content, it is not possible to dismiss the possibility that the lack of Population I constituents in smooth-arm galaxies results not from the absence of disk gas but from physical conditions in the gas (high temperature, large velocity dispersion) which preclude (temporarily?) star formation at the current epoch (see Strom et al. 1976a; Scott et al. 1977).

If we are correct in believing that smooth-arm spirals represent the initial stages in the transmutation of a spiral to an S0 galaxy, it is important to note that we demand a decrease in the wave amplitude when the gas is removed and star-forming events in the disk cease. The physical cause for the decay of density waves under such conditions is at present not understood and merits careful theoretical treatment.

It is possible that smooth-arm spiral galaxies might also be found in the field. In such cases, one might speculate that a galactic wind or normal evolution has significantly reduced the gas content in these galaxies. In Figure 4, we present a photograph of a system (NGC 4622) which appears to have smooth arms in the inner regions and clumpy complexes of OB stars and H II regions in its outer parts. This system might well be one in which gas has been exhausted through evolutionary processes or removed by galactic winds in the inner parts of the disk and might therefore be intermediate in character between normal and smooth-arm spiral systems. Some of the galaxies classified as "anemic" by van den Bergh (1976) may be similar representatives of galaxies in transition between the normal spiral and smooth-arm evolutionary stages.

Disk colors as a function of cluster position. Strom and Strom (1977) have recently studied the disk $U - R$ colors of edge-on S0 galaxies in the Coma cluster. In Figure 5, we present histograms which depict the color distribution among (a) disks located within 18 arcmin (0.7 Mpc) of the cluster center, and (b) those located outside 18 arcmin. We deduce from Figure 5 that many more blue S0 disks are found in the outer region of the cluster. This result can be interpreted by assuming (a) that a larger fraction of the outer region S0 disks have been stripped more recently than those located in the inner parts of the cluster or (b) that the outer-region S0 galaxies have completed their disk evolution relatively unaffected by environmental effects;

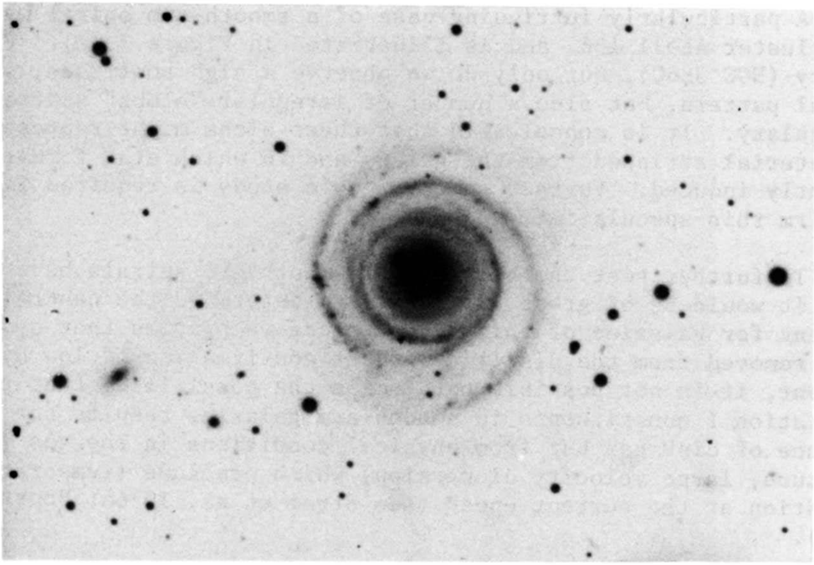

Figure 4. A blue-light photograph (GG 385 + IIIa-J) of NGC 4622 (Centaurus cluster) taken with the CTIO 4-m telescope.

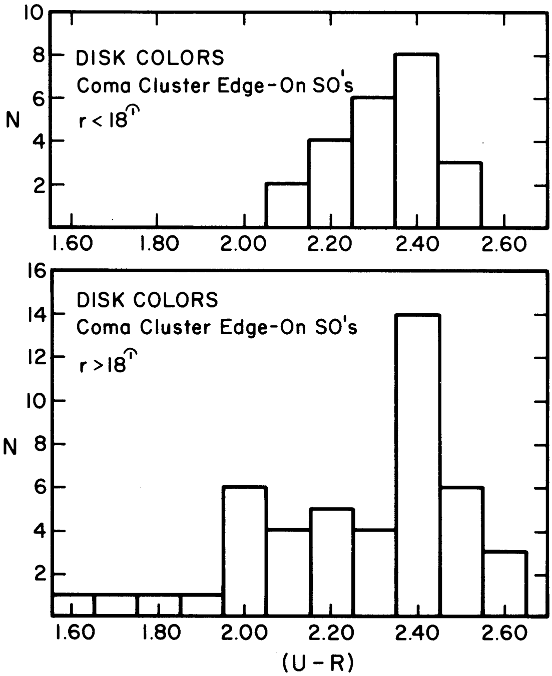

Figure 5. Histograms depicting the distributions of disk colors [$(U - R)$] for (top) disk systems located within 18 arcmin of the Coma cluster core and for (bottom) those located in the outer regions (r > 18') of Coma.

hence, the observed color distribution reflects a (variable) range of timesbetween the present and the last episode of disk-star formation. Hypothesis (b) can be checked by comparing the disk color distribution observed in the outer parts of Coma with that of field S0s. In either case, these data provide an important confirmation of the Melnick and Sargent (1977) hypothesis that stripping rather than initial conditions account for the increase in spiral fraction with increasing distance from the cluster center.

Disk colors in distant clusters of galaxies. Butcher and Oemler (1977) have studied the distribution of galaxy colors in two distant, rich, and centrally condensed clusters (3C 295, z = 0.46; Cℓ 0024 +1654, z = 0.39) similar in structure to the Coma cluster. They conclude that in distinct contrast to nearby clusters of this type (which contain galaxies primarily of the E and S0 type) between one-third and one-half of the galaxies in the distant clusters have blue colors similar to those characterizing spiral galaxies. Moreover, the fraction of blue galaxies increases with increasing distance from the center of these clusters. Butcher and Oemler's data support the belief that a smaller fraction of spirals has been stripped at the epoch corresponding to z = 0.4 as compared to the present epoch, and that the fraction of stripped spirals decreases with increasing distance from the cluster center.

Disk sizes. Larson (1972a,b) has argued that infall from low-density, gaseous halos (possibly remaining from protogalactic condensations several hundred kpc in size) significantly affects disk-system evolution over a large fraction of a Hubble time. If such extensive halos are common, it is conceivable that the outer regions of disk systems were formed during the last several billion years. A possible indirect indication of the importance of relatively recent disk-star formation resulting from the collapse of the outer regions of extensive halos might be afforded by the examination of disk sizes as a function of radial position in rich clusters. Ablative (or possibly tidal and collisional stripping) should remove halos surrounding disk galaxies located in the central regions of the clusters; some disk systems in the outer-cluster region might be unaffected owing to the lower density of intergalactic gas and of other galaxies. Strom and Strom (1977) have begun to examine disk-galaxy sizes for edge-on S0 galaxies in the Coma cluster. Sizes of S0 disks (as measured to an isophote corresponding approximately to μ_R = 25 mag per square arcsec) were measured for a sample of nearly 70 galaxies in Coma. A significant increase in the fraction of "large" disk systems was noted for those disk galaxies located beyond 18 arcmin from the cluster center. While this result is preliminary at present (and subject to analysis of such selection effects as (a) systematic differences in the true orientation of the galaxies and (b) the relative contribution of disk and bulge to the total observed surface brightness), it suggests that formation of the outer regions of disk systems may be truncated in the dense cores of rich clusters. It is, of course, also possible that initial conditions favor the formation of galaxies having high bulge-to-disk ratios in the central cluster regions. It would be of considerable interest to know how disk sizes and B/D ratios vary from spiral-rich to spiral-poor clusters in order to assess the relative effects of environmental and formation conditions on the bulge-to-disk ratio.

4. LOW SURFACE BRIGHTNESS SPIRAL GALAXIES: EARLY STAGES OF SPIRAL EVOLUTION?

Examination of 48-inch Schmidt and 4-m plate material has revealed a class of spiral galaxies characterized by apparently low values of disk surface brightness μ_d. In Figure 6, we present *U* and *R* photographs of two such systems, NGC 4411 (a) and (b).

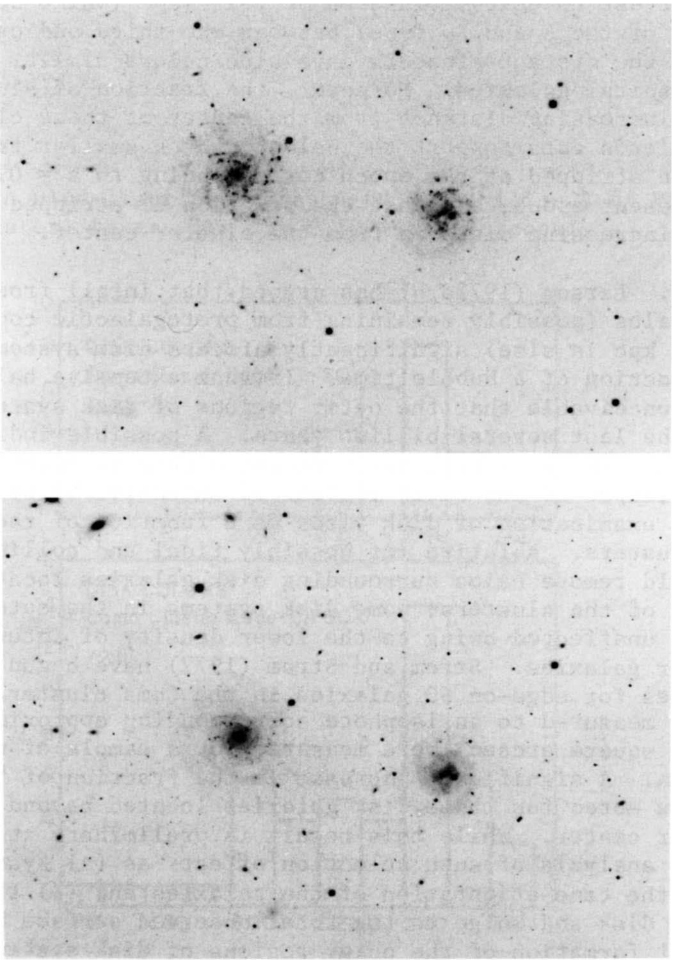

Figure 6. Mayall 4-m telescope prime focus, ultraviolet (UG 2 + IIIa-J; top) and red (RG 610 + 127-04; bottom) photographs of the low surface brightness spiral galaxies NGC 4411 (a) (right) and NGC 4411 (b) (left). North is at the top and east is at the left.

Low values of μ_d suggest that the total number of stars formed in the disk over a Hubble time has been small. We felt that an examination of such systems might be of considerable importance since they may represent (a) galaxies in which stellar formation is either inefficient, or (b) "young" galaxies in which the bulk of star formation has taken place only during the last few billion years. Romanishin et al. (1977) have undertaken an optical study of 12 such galaxies. Our major results to date suggest that (a) disk surface brightnesses in these systems are approximately 2-5 times smaller than those typical of bright, prominent spirals such as M81, M51, or M101; (b) the disks are unusually blue; and (c) the surface brightness μ_d is correlated with the disk color index. Those galaxies of lowest μ_d are also the bluest galaxies.

The blue disk colors may result from the dominant contribution of stars formed at a comparatively recent epoch. If so, either the average disk stars are relatively young or the initial mass function of older stellar generations is such that these stars have few descendents currently detectable at optical wavelengths. Alternatively, blue disk colors could result from the dominance of older, metal-poor disk populations.

Whether low surface brightness spiral galaxies are young, metal-poor, or both, it seems reasonable to assume that the fraction of gas converted to stars and heavy elements might be low. As a consequence, the neutral hydrogen content of the disk should be large. In collaboration with N. Krumm and E. Salpeter, we have obtained preliminary values of the ratio of total hydrogen mass M_H to photographic luminosity L_{pg} for three low surface brightness spirals; M_H/L_{pg} appears to lie in the range 0.5 to >2. These values are larger than those characteristic of normal disk galaxies and suggest that a smaller fraction of the gas in these low surface brightness systems may have been processed in star-forming episodes.

We are currently seeking indirect evidence bearing on the possible age of these systems. In collaboration with G. Knapp, Strom, Strom, and Romanishin are attempting to search for extensive neutral hydrogen clouds surrounding these systems. If such clouds are discovered, their presence might suggest that star formation on a galactic scale was initiated in these clouds at a relatively recent epoch.

If the galaxies are not intrinsically young, why is the disk gas content relatively high? One hint may come from the M/R ratio as estimated from the observed system luminosities and Holmberg radii for these galaxies. These ratios are smaller by factors of between 3 and 10 as compared to those characteristic of normal spiral systems. As discussed in Sec. 2.1, galaxies showing small values of M/R should be characterized by low values of $\Omega - \Omega_p$ and $w_{\perp 0}$. Consequently, the star-formation rate in low surface brightness systems, as compared to prominent, "normal" spiral systems, may be significantly lower. Hence, the number of disk stars formed over a Hubble time in such galaxies will be smaller, the disk surface brightness lower, and the amount remaining neutral hydrogen larger. To test the "low star-formation rate" hypothesis, we have compared the amplitude of the spiral waves as derived from ultraviolet (*U*) plates of several low surface brightness galaxies with the *U* amplitude for normal spiral systems. The measured *U* amplitude should provide a crude index of the current star-formation rate in the arms, since the OB associations and H II regions contribute predominantly to the total light observed at this wavelength. Our results show that the low surface brightness galaxies exhibit *U* amplitudes 2-3 times smaller than those which appear to characterize "normal" spirals, therefore suggesting a lower rate of star formation at the present epoch.

Does the existence of very low amplitude arms in these systems suggest an *M*/*R* below which no spiral structure is possible? Is the dominance of irregular systems among low luminosity a manifestation of the inability of low-mass disk systems to support spiral waves?

Whether low surface brightness spiral galaxies are young or systems in which star formation has proceeded slowly over a Hubble time, their relatively high hydrogen content suggests that they might give some hint of the initial gas distribution characteristic of normal spirals at earlier stages in their evolutionary history. High resolution studies at 21 cm therefore seem merited for a few examples of this class. Moreover, if few stars are forming in their disks at present, observations of low surface brightness galaxies may provide crude limits on the fraction of hydrogen converted to stars during the first burst of star formation following the collapse of a protogalactic cloud to disk form.

5. OPTICAL AND INFRARED SEARCHES FOR MASSIVE HALOS

Attempts to detect at optical wavelengths a massive halo component in external galaxies have thus far proven unsuccessful (Davis 1975; Freeman et al. 1975). Perhaps the most sensitive test thus far reported is that of Gallagher and Hudson (1976). They attempted to observe the halo of edge-on spiral galaxy IC 2233. This system has a thin disk which exhibits no discernable bar or other instabilities. By using the chopping secondary of the University of Minnesota-University of California (San Diego) telescope, they were able to switch rapidly between halo and sky locations thereby cancelling short-time-scale variations in sky brightness. No halo component, to the level of 1-5 percent of the central disk surface brightness, was detected at wavelengths between 0.4 to 0.8 μ. They conclude that the *M*/*L* ratio for the halo component must therefore exceed 100.

Strom et al. (1978) have obtained scans out to galactocentric distances of $\sim$5 kpc of the bulge components of NGC 3115 (E7/S0) and NGC 2768 (E6) at a wavelength of 2.2 μ. These observations should be extremely sensitive to any increase of the M dwarf population in the halo regions of these galaxies; if such a change in population mix were present, a color index such as (*V* - *K*) should become redder at increasing galactocentric distances. Instead, Strom et al.'s data suggest that the ($V - K$) color index grows monotonically bluer outward from the galaxy centers. The observed ($V - K$) color index at the outermost points excludes a halo M/L greater than 50 if the bulk of the halo mass is contained in stars of type M8 V (see also Strom et al. 1976b).

Indirect optical evidence in support of massive halos can be found in Schweizer's (1977) study of the rotation curve and light distribution in the disk of the Sombrero galaxy. His data suggest a monotonic increase in M/L from the center to the edge of the observable disk. A similar result has been obtained in a study of NGC 4378 by Rubin et al. (1977).

We wish to thank Dr. E. Jensen, W. Rice, W. Romanishin, and M. S. Wilkerson, who have collaborated with us on a number of the research programs reported in this review. Their insight and diligence as well as their tolerance of our demanding personalities are acknowledged with gratitude. We also wish to note the many hours of stimulating and at times critical discussions with a number of our colleagues: Drs. H. Butcher, S. Faber, J. Gallagher, J. Goad, J. R. Gott, G. Illingworth, R. Larson, G. Oemler, L. Thompson, and B. Tinsley. Finally, we thank Dr. Don Wells of KPNO for his contributions to the development of the basic interactive picture processing system (IPPS). Without his work many of the new data discussed here could not have been reduced and analyzed.

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DISCUSSION FOLLOWING REVIEW II.1 GIVEN BY S.E. STROM

WAXMAN: Shouldn't we expect star formation to be occurring between the co-rotation point and outer Lindblad resonance on the leading edge of the wave in trailing wave systems?

STROM: Yes, there do exist galaxies which have a prominent spiral pattern on the inside, a gap which you might associate with co-rotation, and a spiral pattern on the outside. I have no quantitative data on such galaxies.

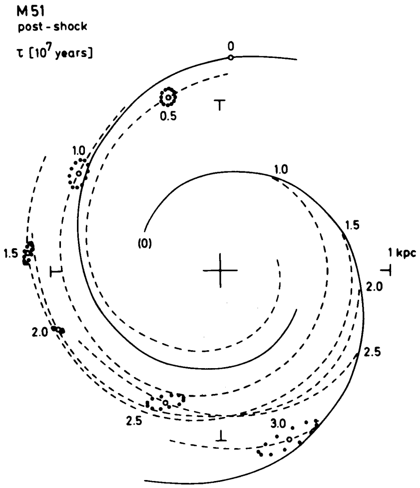
SHU: I find the discovery of the smooth-arm spirals to be extremely intriguing. It would be very important to determine exactly how much gas is in such systems to settle the old question of whether gas is a *sine qua non* for spiral structure. What are the future observing plans in this regard?

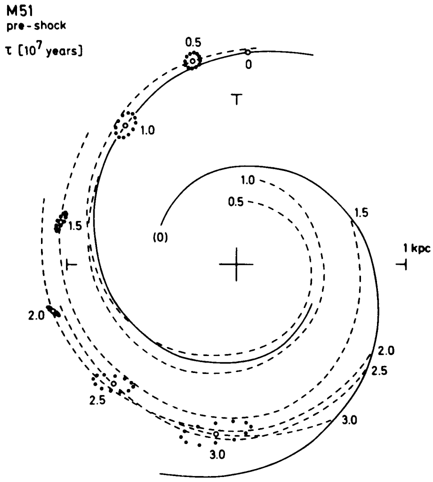
STROM: Currently observations are going on at Arecibo in order to look for HI gas in low surface brightness systems and in some of the smooth arm systems. Unfortunately, many of the systems we have identified are located outside the Arecibo declination range. I hope some people will be interested in observing these systems elsewhere.

MEBOLD: Together with Australian collaborators we have made a 21-cm line survey of the low surface brightness galaxies that have been detected with the Schmidt telescope at Siding Spring. Out of a total of about 160 galaxies approximately 70% have been detected in HI. The ratio M_H/L_B of these galaxies is exceedingly high. We have mapped several of the sufficiently large systems, and we find that in these systems HI is generally more centrally peaked than is usual for spiral galaxies.

WIELEN: DRIFT AND BROADENING OF AGEING SPIRAL ARMS

In order to study the ageing of spiral arms, H. Schwerdtfeger and I have calculated the drift and broadening of ageing spiral arms in the frame of density-wave theory. An aged spiral arm is defined by the positions of stars of a common age which have been migrated away from the zero-age spiral arm. We assume that the stars are formed at the global spiral shock front. For the initial systematic velocities of





the stars, we consider two cases: In the "post-shock case", the stars reflect the motion of the gas immediately after the shock. In the "pre-shock case", the average initial velocity is the gas velocity before the shock. Orbit calculations for many test stars, including a velocity dispersion at birth (10 km/s in the figures), then provide the desired evolution of ageing spiral arms. As examples we show the results for the inner part of M51. The drift and broadening are very complicated, neither linear nor monotonic with age τ. In the post-shock case, the stars even move back to the inner side of the shock front. The pre-shock case seems to agree better with observations. In both cases (and in other galaxies with strong shocks), the newly born stars move essentially along the spiral shock front for a rather long period (about 40% of the circular rotation period at half the corotation radius), thus minimizing the drift at the beginning.

GROSBOL: I would like to report on the calculation of birthplaces of 100 - 200 B5-A0 stars in different density-wave potentials with pattern speeds ranging from 10 to 37 km s^{-1} kpc^{-1}. It shows that for two pattern speeds, namely $\sim$ 14 km s^{-1} kpc^{-1} and $\sim$ 32 km s^{-1} kpc^{-1} more birthplaces are located in the arms than expected in a random model.

GALLAGHER: COMMENTS ON NGC 3312, NGC 1291 AND NGC 1079

In the preceeding paper by Dr. Strom, a scenario for stripping of cluster galaxies by the intracluster medium (ICM) was presented. I would like to suggest that NGC 3312 in the Hydra I cluster of galaxies (Abell 1060) is an example of a galaxy that is presently experiencing ram-pressure-stripping. On a limiting IIIaJ exposure obtained by Drs. M. Smith and D. Weedman, a series of faint, filamentary extensions are seen to the southeast of the disk of NGC 3312. These seem to be material which has been removed from the galaxy. Tidal collisions, internal activity, a low velocity interaction with an intergalactic cloud, or ram pressure stripping by an ICM are possible interpretations. However, since Hydra I is a known X-ray cluster, the ablation hypothesis appears consistent with both the properties of the cluster and the morphology of the disturbance in NGC 3312, although other models at present cannot be rigorously excluded.

I will also briefly comment on spiral-like structures that are found in a limited sample of galaxies which have been classified as S0 or S0/a and have been detected in the HI 21-cm line. NGC 1291 and NGC 1326 are usually classified as RSB0/a and are both good examples of "θ" galaxies. As G. de Vaucouleurs has emphasized, NGC 1291 is probably the best example of such galaxies. Based on a blue IIIaJ photograph obtained with the CTIO 4-m telescope, the inner region which contains the lens and bar, has a rather smooth light distribution. This and the colors are in agreement with the presence of an old stellar population. The outer ring, however, shows many condensations which are very similar to the knotty structures found in spiral arms of Sb or Sa systems. In fact the entire outer ring structure appears to primarily result from the overlap of 2 spiral arms with very small pitch angle and low surface brightness. Thus the global characteristics of NGC 1291 may not be so different than those of normal Sb spirals which have similar hydrogen mass to luminosity ratios. It also seems possible that the dominant bar has produced significant changes in star formation patterns as compared to normal galaxies.

Another interesting case is NGC 1079, which has a relative HI content appropriate to a typical Sc. A CTIO 4-m plate shows a moderately high surface brightness "S" shaped bar imbedded in a very low surface brightness disk. There is little evidence for star formation activity beyond some condensations in very faint outer arms. Thus this galaxy may be related to the low surface brightness spirals that were discussed by Strom. Like these spirals NGC 1079 has abnormal disk properties. The Kitt Peak Interactive Picture Processing System has been used to produce a mean surface brightness profile and there is no exponential disk to a level of 4 magnitudes below the blue sky brightness.

SHOSTAK: Could you describe the HI profiles for the two "revealed spirals" you have shown?

GALLAGHER: No, we were unable to use the HI profile to classify NGC 1291 as the profile is very sharp due to the face-on orientation of the galaxy.