GALACTIC EVOLUTION WITH THE SPACE TELESCOPE

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Since almost every facet of astronomy is relevant to the evolution of galaxies, most of the topics discussed at this Colloquium are important to the field. For example, stellar populations and interstellar matter in galaxies are to be understood in the context of evolution, and when galaxies are used as probes in cosmological studies it is vital to know how their intrinsic properties vary with time. Some aspects of research on galactic evolution with the Space Telescope are discussed by several authors in the recent ESO/ESA Workshop (Macchetto et al., 1979). In this paper, I concentrate on "lookback" studies that compare present-day and younger galaxies directly. Many of the theoretical ideas mentioned here are quite speculative; the aim is to provide viewpoints from which ST (and related ground-based) studies can be planned, knowing that the real world billions of years ago will surely contain more surprises than verifications of any projections.

1. ELLIPTICAL GALAXIES

Elliptical galaxies are populated now almost entirely by old stars, raising questions about how they looked in the distant past when the stars were forming, and about the more recent, quiescent evolution of the old population.

1.1 Primeval Galaxies

Elliptical galaxies are believed to have been very bright at an early stage when most of their stars were forming - the stage of so-called primeval galaxies (PGs). The high angular resolution and faint limits attainable by the ST may help to answer questions about the angular size, redshift, and luminosity of PGs, which in turn will shed light on how elliptical galaxies form.

Various models for the formation of elliptical galaxies differ

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substantially in their predictions for the appearance of PGs (see reviews by Larson, 1976; Tinsley, 1979a). At one extreme, Partridge and Peebles (1967) presented a model in which star formation occurs fairly uniformly over the face of an extended protogalaxy before it has collapsed to its present size; this would occur at a redshift $z \sim 10 - 30$, and the objects would have angular diameters of at least 5". An alternative picture is that the maximum star formation rate (SFR) and luminosity occur after the collapsing protogalaxy is very centrally concentrated (Larson, 1974; Meier, 1976; Sunyaev et al., 1978); such PGs would be found at $z \sim 2 - 20$, with angular sizes of only $\sim 1''$. Another idea is that elliptical galaxies formed their stars in bursts resulting from violent mergers of gas-rich protogalactic fragments (Tinsley and Larson, 1979; see also Toomre, 1977); in this case, the time scales suggest $z \sim 2 - 10$, and again star formation would be in regions with small angular sizes, although the structure would be less symmetrical than in models where a single gas cloud collapses.

Whatever the details, PGs are likely to be fairly gas-rich, so that little radiation will emerge at wavelengths below the Lyman limit; detection is therefore unlikely if the observer's passband is below 912(1+z) Å, i.e. if the time of star formation is too soon after the Big Bang. Another problem is that PGs could be very dusty, so that most of the light from hot stars appears in the far infrared (Kaufman, 1976), as is the case for regions of intense star formation in a number of nearby galaxies.

Let us suppose that we are lucky, in that giant E galaxies do form most of their stars at $z \lesssim 5$ (times $\gtrsim 1$ Gyr after the Big Bang), and that most of the UV light from hot stars is not absorbed by dust. The detectability of a PG then depends on the redshift, the size of the region of star formation, and the absolute luminosity, which is proportional to the SFR. Scaling from Meier's (1976) models, I estimate that PGs corresponding to rather modest E galaxies, with present $M_V \lesssim -21$, should lie above the magnitude limit for the ST even if star formation occurs on a time scale as long as several times 10^8 years; their surface brightnesses should be bright enough if the region of star formation is smaller than ~ 10 kpc. These are only approximate, model-dependent estimates, but they suggest that the ST should have no difficulty finding PGs if their UV light is neither absorbed nor too highly redshifted. The density of bright PGs on the sky is also encouragingly high; estimates depend on many parameters, including whether the spheroidal bulge components of spiral and S0 galaxies form in the same way as ellipticals, and range from a few to a few hundred per square arc minute. The most sensitive searches for PGs to date (e.g. Partridge, 1974; Davis and Wilkinson, 1974) would have mistaken for stars any objects as small as 1", but to the ST these would be clearly resolved. Even if star formation is concentrated in a region a few kpc across, the angular size will be several times $0''.1$ at all redshifts where detection

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itself is possible. Thus if PGs are found, pictures from the ST will provide information on the morphology of young elliptical galaxies with rapid star formation, perhaps distinguishing between a symmetrical system or a chaotic collection of merging pieces.

It is worth remarking that an intrinsically bright, blue galaxy at high redshift will almost certainly be the precursor of a present *early*-type system (an E galaxy or a large nuclear bulge of an S0 or early spiral), rather than a young irregular galaxy or late spiral. This is because the bright stage corresponds to the rapid formation of many stars, and the present colors of late-type galaxies are too blue for them to possess such a large population of old stars. Part of the fascination of PGs is thus that they will be galaxies looking extremely different from their present-day descendents. (There is a loophole in this argument: Late-type galaxies could have been bright and blue already many billions of years ago if the stellar initial mass function then included few low-mass stars that would survive to the present. However, this in turn could be reconciled with the chemical compositions of the galaxies only by introducing further artificial assumptions.)

In §3, I discuss the possibility that PGs have already been detected in faint galaxy samples, which are therefore important candidates for further study by the ST.

1.2 Evolution of the Old Stellar Population

The colors and luminosity of an old elliptical galaxy evolve as successively less massive stars peel off the main sequence, spend a brief time as giants, then disappear. A naive expectation is that the colors should grow redder with time, since the main-sequence turnoff becomes redder and the locus of the red giant branch moves slowly to cooler temperatures; models for elliptical galaxies using conventional stellar evolutionary tracks do indeed predict that the integrated colors become redder with age (Tinsley and Gunn, 1976). On the other hand, Ciardullo and Demarque (1978) have pointed out that even a metal-rich galaxy will ultimately acquire a blue horizontal branch, and its integrated colors will evolve back to bluer values, when the turnoff mass has become so low that stellar mass loss before core helium ignition leaves only a small envelope mass. The age at which this happens depends on the metallicity and on the rate of stellar mass loss, which is not well enough known for firm predictions to be made. Ciarcullo and Demarque present models allowing for mass loss at a plausible rate, in which metal-rich elliptical galaxies evolve toward bluer colors after ages of 8 Gyr.

It would therefore be interesting to test whether elliptical galaxies had bluer or redder colors a few Gyr ago, i.e. at redshifts of a few tenths. Ground-based data have been inconclusive on this

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question because of uncertainties in K corrections. For example, Kristian et al.'s (1978) plot of B-V versus z for first-ranked cluster ellipticals suggests that the colors at $z \sim 0.2$ are somewhat redder than predicted with no evolution, but the K corrections at this redshift depend on uncertain UV spectral energy distributions. Spinrad (1977) finds colors bluer than those of nearby galaxies for a few ellipticals at $z \sim 0.5$, but these are radio galaxies so could be unusual. With the ST, it should be possible to measure colors at the same wavelengths of emission out to lookback times of at least 5 Gyr ($z \gtrsim 0.5$), in a large enough sample of elliptical galaxies to determine the direction of color evolution in a typical old population.

This test will be complicated by scatter in the present colors of elliptical galaxies. One factor causing variations is metallicity, which correlates with absolute magnitude but with considerable scatter (Faber, 1977; Sandage and Visvanathan, 1978). Another source of scatter may be low-level star formation in elliptical galaxies (Oemler, this conference); if this is common, color evolution will depend partly on the rates of star formation now and in the recent past. Detailed spectra and population syntheses will be needed to sort out metallicity effects and to clarify the possible importance of blue horizontal-branch giants and young stars in the light of ellipticals. The ST will be valuable in supplementing ground-based photometry with UV data, and then in reaching galaxies with significant lookback times.

A further application of these results will be to estimate the rate of luminosity evolution of elliptical galaxies, which affects the Hubble diagram as a method for measuring q_0 (see review by Gunn, 1978). Luminosity evolution at visual and longer wavelengths depends almost exclusively on the slope of the stellar mass function, and not on metallicity or low-level star formation, but the slope itself cannot be estimated accurately from population syntheses unless the metallicity, possible young stars, and position of giants in the HR diagram are also unravelled.

1.3 Cannibalism

It has been argued persuasively that the cD galaxies found (usually) at the centers of rich clusters have grown by accretion of smaller cluster members, via dynamical friction (e.g., Hausman and Ostriker, 1978). This process not only is interesting in itself but also plays havoc with the Hubble diagram as a cosmological test (Gunn, 1978); in order to use cluster galaxies as standard candles, we must assess the effects of cannibalism on their luminosities within a given aperture, which depend on details of the accretion process that probably vary from one cluster to the next.

High-resolution imagery of galaxies in clusters out to $z \sim 1$ will give valuable information on the occurrence of multiple nuclei and close encounters, detailed surface brightness profiles, and color maps, as a function of cluster morphology, redshift, and the location of a galaxy within its cluster. Such data will help to determine how and under what circumstances galaxies swallow each other, and to find estimators - such as surface-brightness profiles - of the extent to which individua galaxies have been affected.

Interactions and mergers among galaxies probably play other important roles in their evolution, not only for ellipticals. For example, the colors of strongly interacting galaxies suggest that collisions between gas-rich galaxies induce bursts of star formation (Larson and Tinsley, 1978). Pictures at high resolution of such systems will help to clarify the processes involved, especially in showing details of where star formation occurs. Studies of nearby gas-rich galaxies undergoing collisions will also be relevant to the suggestion that star formation in primeval elliptical galaxies occurs during mergers of protogalaxies (§1.1). More generally, broad-band images at 0".1 resolution of many galaxies will contain unprecedented information about the process of star formation, which is fundamental to galactic evolutio

2. DISK GALAXIES

Spiral and SO galaxies must have had more varied and complex histories than ellipticals, but few lookback studies have yet been made. The ST will offer opportunities to test a number of current ideas, by exploring the evolution not only of photometric properties but also of the morphology of disk galaxies. An important point is the ability to resolve structure on scales of a few kpc at redshifts of at least 1, thereby distinguishing disk galaxies from ellipticals and even measuring the relative sizes of their disks and bulges.

2.1 Disk-to-Bulge Ratios of Spirals

Star formation is still continuing in the disks of spiral galaxies, while their bulge components have old stellar populations similar to those of elliptical galaxies. The luminosities of the disk and bulge components are therefore expected to evolve at different rates. An interesting project for the ST is suggested by the fact that different time dependences of the disk-to-bulge ratio (D/B) are predicted by alternative scenarios for the formation of galactic disks (see review by Larson, 1977). One possibility is that a gaseous disk forms almost as early as the stars of the bulge component, in a rapid collapse after which stars form in the disk at a decreasing rate as the gas is consumed; if the SFR in the disk declines fast enough, its luminosity would decrease faster than that of the bulge, so the D/B luminosity ratio would decrease with time. An alternative picture is that the

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disk forms by accretion of gas on a time scale of billions of years; the SFR would then depend on the accretion rate (see also Saar and Einasto, 1977), and it could have been constant or even increasing with time in the outermost regions. Such a long time scale for disk formation is suggested by several pieces of evidence, including the young age of most stars in the solar neighborhood (McClure and Twarog, 1977), the very low metallicity of a young cluster in the galactic anticenter (Christian and Janes, 1979), the consistency of stellar kinematics with a slow collapse of the Galaxy (Tinsley and Larson, 1978; Wyatt and Cahn, 1979), and the very blue disk colors of many spiral galaxies. A constant or increasing SFR, averaged over the disk, would lead to an increasing disk luminosity and an increase with time of the D/B ratio.

What changes in D/B might be observed to $z \sim 1$ according to these alternative scenarios? Consider a model in which the bulge stars are all very old and the SFR in the disk is either decreasing exponentially (with a time constant of 5 Gyr) or remaining constant; let the age of the system be 15 Gyr at present and 7 Gyr at $z = 1$. Calculations then show that between 7 and 15 Gyr of age the bulge component becomes fainter by 0.9 mag in the V band; the disk becomes fainter by 0.9 mag in V if it has the decreasing SFR, or brighter by 0.2 mag with a constant SFR. The intrinsic D/B ratio in V light would therefore be constant in the first case, but it would increase by a factor of 3 in the second case; in other words, if the SFR in the disk is constant, the D/B ratio would be 3 times smaller at $z = 1$ than it is locally. More generally, D/B luminosity ratios are predicted to be smaller at high z than locally in galaxies with a long time scale for star formation in the disk.

Tests for this effect will not be entirely straightforward. For one thing, spiral galaxies have a wide range of present D/B ratios, so it is not possible a priori to identify "equivalent" galaxies at different redshifts. Another point is that the apparent D/B ratios, if measured in the same observer's passband at low and high z, will depend on the colors as well as the luminosities of the components. In particular, bulges are redder than disks so they will suffer more K-dimming, and D/B will tend to appear too big at large z; if D/B were measured at an observed wavelength of, say, 7200 Å in the above model with a constant disk SFR, the apparent ratio would be 30% larger at $z = 1$ than locally, instead of 3 times smaller. Thus it will be necessary to compare the observations with quite detailed models for the expected distributions of D/B ratios in samples of spirals at different redshifts. A careful study could lead to valuable information on the time scales for disks of spiral galaxies to form.

2.2 The History of S0 Galaxies

S0 galaxies have disks, but no spiral structure and normally no signs of ongoing star formation. There has long been a controversy as to whether S0s are former spirals that were stripped of their interstel matter, or an intrinsically separate class of galaxies. Recent data have put this problem into a new light, and I shall summarize the situation then suggest how the ST can provide further information on the origin of S0 galaxies.

That "stripping" of spirals produces S0s is strongly suggested by the large numbers of S0s relative to spirals in dense clusters (Spitzer and Baade, 1951). The dependence of galaxy populations on environment has been strikingly documented by Butcher and Oemler(1978b), who find that among nearby clusters only those with negligible central concentration are spiral-rich, while condensed clusters are all spiral-poor. In addition, Butcher and Oemler (1978a) find two condensed clusters at z $\sim$ 0.4 with large proportions of blue galaxies, suggesting that about 5 Gyr ago the disk galaxies in such clusters were mostly spirals, whereas today they are S0s. The picture is not entirely simple, however. Dressler (1979) notes that the S0/S ratio in clusters exceeds its value in the field even in regions with only a slight excess density, where it appears impossible to sweep the interstellar matter from the disks of spirals - either by collisions between galaxies (Spitzer and Baade, 195 or by ram pressure of the intergalactic medium (Gunn and Gott, 1972). Another argument against the stripping hypothesis is that S0 galaxies are no bluer than ellipticals, at a given absolute magnitude, which suggests that their disks do not contain relatively young stars (Sandage and Visvanathan, 1978). Moreover, S0s have certain structural differences from spirals: their average bulge size is larger (Sandage et al. 1970; Dressler, 1979), their average D/B ratio is smaller (Burstein, 1978; Dressler, 1979), and they may have faint "thick disks" that are not found in spirals (Burstein, 1978).

These structural differences show that stripping of typical present day spirals will not produce typical present-day S0s. However, the more relevant question is *whether spirals and S0s have common ancestors*. This question is considered by Larson et al. (1979), with the following results. We ask first what would happen to spiral galaxies if they continued to form stars at their current rates using only the gas content of their disks; the answer is that 90% of spirals would run out of gas within 7 Gyr and 50% would do so within 4 Gyr; the solar neighborhood has enough gas to last for only $\sim$ 1 Gyr. These short time scales imply that star formation in spirals has been sustained by accretion of external gas, and we suggest that spirals have possessed for most of their lives extended gas-rich envelopes - including tidal debris and companion galaxies as well as leftover primordial gas - which have been gradually accreted to build the disk. S0s are then disk galaxies that used up or lost such envelope material at an early stage. After loss of the envelope, star formation would continue for a few Gyr until the gas in the disk itself was consumed.

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This modified "stripping" hypothesis appears to account for the observations mentioned above: (1) A diffuse outer envelope can be stripped much more easily than the dense gas in a disk, so it is not surprising that S0s appear in regions with only a slight density enhancement. (2) S0s are expected to have metal-rich disks, which would be redder than observed if they were as old as elliptical galaxies; when this factor is considered, the colors of S0s are consistent with their being former spirals in which most star formation ceased a few Gyr ago. (3) The envelope gas would be stripped from cluster galaxies during the cluster's collapse, but continuing star formation from gas left in the disk accounts for the blue colors of galaxies in Butcher and Oemler's (1978b) condensed clusters at high z. Estimates of the time scales for cluster collapse and for star formation to consume the disk gas lead further to a prediction that most of these blue galaxies will run out of gas shortly after they are seen, and so evolve by the present time into S0s with normal red colors. (4) The formation of S0s by truncation of star formation in a disk implies that S0s *should* have D/B ratios smaller than those of spirals, by the observed amount. (5) It has been suggested that spheroidal systems form by violent mergers among gas-rich protogalaxies (§ 1.1), in which case elliptical galaxies and disk galaxies with the largest bulges would tend to form in the densest regions of space, where indeed they are found (Dressler, 1979); since the disk galaxies in dense regions are those most likely to lose their surrounding gas and become S0s, this explains why S0s have larger bulges than spirals.

Several aspects of this picture could be tested by ST observations. One possibility is to test whether S0s have had no star formation in their disks for many billions of years, or whether they had the same ancestors as spirals until typically a few Gyr ago. The observations required are broad-band images with the best possible angular resolution, to give colors and to distinguish disk from elliptical galaxies out to $z \sim 1$. If the disks of S0s are all very old, the proportion of disk galaxies with colors as red as ellipticals should not vary with redshift, but if S0s were spirals until recently there should be many more blue disk galaxies at redshifts of a few tenths than there are at present. Butcher and Oemler's (1978a, b) cluster data strongly suggest that this is the case in dense clusters, and a first test should be to verify that the blue galaxies in distant clusters are indeed disk galaxies. O'Connell (1979) has made the alternative suggestion that they are young ellipticals; if so, they should appear spheroidal and (probably) bluest at their centers, readily distinguishable from galaxies with red bulges and blue disks.

Absorption lines in quasar spectra may also contain information on the past history of disk galaxies. If much of the material that is now in the disks of spirals used to be in extended gaseous envelopes, the effective cross-section of these galaxies for producing absorption lines

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at high z would be much greater than the present optical disk diameters The proposed origin for S0s implies that they also had gaseous envelope like those of spirals, so the comoving density of gas-rich galaxies at high z would be greater than locally. This picture will therefore receive some support if the statistics of quasar absorption lines imply very extended and/or numerous intervening galaxies, as has often been suggested (e.g. Bahcall, 1978; Boksenberg, 1978; Weymann and Williams, 1978).

3. GALAXY COUNTS

Several of the studies of galactic evolution suggested above are o a statistical nature, and closely related to some recent ground-based work on counts of galaxies as a function of apparent magnitude and colo

The results of recent 24th-magnitude surveys are reviewed by Kron (1979), and their interpretation is discussed in more detail by Kron (1978), Bruzual and Kron (1979), and Tinsley (1979b). Briefly summarized, these papers find that models for galaxy counts are consistent with the data only if substantial amounts of galactic evolution are allowed for. Kron's (1978) data show an excess of very blue galaxies at a photographic J magnitude $\sim$ 23; their colors are bluer than any nearby galaxies, and are in the range expected if a young stellar population is seen in the redshift range $\sim$ 1 - 4. The absolute luminosities of these galaxies are then in the range expected for primeval galaxies of the type described in § 1.1 - early-type galaxies seen during the rapid formation of stars in a spheroidal system. The count already show clear signs of evolution at J = 21, where the models predict that most galaxies would have z $\sim$ 0.2 - 0.3 in the absence of evolution but redshifts up to at least 0.5 (and possibly a few greater than 1) with consistent evolutionary models.

One source of uncertainty in the models is a lack of reliable K corrections for all types of galaxy. At present, one has to use scant satellite UV photometry, supplemented by synthetic spectral energy distributions based on the hot stars that are predicted to contribute most of the UV light of galaxies; these syntheses are uncertain, especially because interstellar extinction could affect the spectra strongly. A survey of UV spectral energy distributions of nearby galaxies of many types would therefore be an important contribution by the ST to the interpretation of counts and color distributions; of course, the data would also give valuable information on the stellar and interstellar contents of the galaxies themselves.

Redshifts and high-resolution images of a sample of the very blue 23rd-magnitude galaxies would also be especially interesting. The present data, giving just numbers and colors, cannot distinguish

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between alternative models in which they are (1) mostly elliptical galaxies and the bulges of early-type spirals and S0s, undergoing a primeval burst of star formation, or (2) mostly spirals at a later stage of evolution, with vigorous star formation in their disks. The latter alternative is inconsistent with the scenario of slow disk formation discussed in § 2, since in this picture the disks would not be much brighter at $z > 1$ than they are now. It is therefore possible that Kron's faint blue galaxies *are* the long-sought primeval galaxies. In any case, their redshifts will provide unique data on time scales for galaxy formation; and morphological information from pictures with 0".1 resolution will be an exciting new dimension in lookback studies of galactic evolution.

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REFERENCES

Bahcall, J.N.: 1978, Physica Scripta 17, 229.
Boksenberg, A.: 1978, Physica Scripta 17, 205.
Bruzual A., G., and Kron, R.G.: 1979, in preparation.
Burstein, D.: 1978, Ph.D. thesis, University of California at Santa Cruz.
Butcher, H., and Oemler, A.: 1978a, Astrophys. J. 219, 18.
Butcher, H., and Oemler, A.: 1978b, Astrophys. J. 226, 559.
Christian, C.A., and Janes, K.A.: 1979, Astron. J. 84, 204.
Ciardullo, R.B., and Demarque, P.: 1978, in A.G.D. Philip and D.S. Hayes (eds.), IAU Symposium No. 80, 'The HR Diagram,' Reidel, Dordrecht, p. 345.
Davis, M., and Wilkinson, D.T.: 1974, Astrophys. J., 192, 251.
Dressler, A.: 1979, preprint.
Faber, S.M.: 1977, in B.M. Tinsley and R.B. Larson (eds.), 'The Evolution of Galaxies and Stellar Populations,' Yale University Observatory, New Haven, p. 157.
Gunn, J.E.: 1978, in A. Maeder, L. Martinet, and G. Tammann (eds.), 'Observational Cosmology', Geneva Observatory, Sauverny, p. 3.
Gunn, J.E., and Gott, J.R.: 1972, Astrophys. J. 176, 1.
Hausman, M.A., and Ostriker, J.P.: 1978, Astrophys. J. 224, 320.
Kaufman, M.: 1976, Astrophys. Space Sci. 40, 369.
Kristian, J., Sandage, A.R., and Westphal, J.A.: 1978, Astrophys. J. 221, 383.
Kron, R.G.: 1978, Ph.D. thesis, University of California at Berkeley.
Kron, R.G.: 1979, Physica Scripta, in press.
Larson, R.B.: 1974, Monthly Notices Roy. Astron. Soc. 166, 585.
Larson, R.B.: 1976, Comments Astrophys. 6, 139.
Larson, R.B.: 1977, in E. Basinska-Grzesik and M. Mayor (eds.), 'Chemical and Dynamical Evolution of Our Galaxy,' Geneva Observatory,

Sauverny, p. 3.
Larson, R.B., and Tinsley, B.M.: 1978, Astrophys. J. 219, 46.
Larson, R.B., Tinsley, B.M., and Caldwell, C.N.: 1979, preprint.
Macchetto, F., Pacini, F., and Tarenghi, M.: 1979 (eds.), 'Astronomical Uses of the Space Telescope,' ESA-ESO, Geneva.
McClure, R.B., and Twarog, B.A.: 1977, in E. Basinska-Grzesik and M. Mayor (eds.), 'Chemical and Dynamical Evolution of Our Galaxy,' Geneva Observatory, Sauverny, p. 193.
Meier, D.L.: 1976, Astrophys. J. 207, 343.
O'Connell, R.W.: 1979, preprint.
Partridge, R.B.: 1974, Astrophys. J. 192, 241.
Partridge, R.B., and Peebles, P.J.E.: 1967, Astrophys. J. 147, 868.
Saar, E., and Einasto, J.: 1977, in E. Basinska-Grzesik and M. Mayor (eds.), 'Chemical and Dynamical Evolution of Our Galaxy,' Geneva Observatory, Sauverny, p. 247.
Sandage, A., Freeman, K.C., and Stokes, N.R.: 1970, Astrophys. J. 160, 831.
Sandage, A., and Visvanathan, N.: 1978, Astrophys. J. 225, 742.
Spinrad, H.: 1977, in B.M. Tinsley and R.B. Larson (eds.), 'The Evoluti of Galaxies and Stellar Populations,' Yale University Observatory, New Haven, p. 301.
Spitzer, L., and Baade, W.: 1951, Astrophys. J. 113, 413.
Sunyaev, R.A., Tinsley, B.M., and Meier, D.L.: 1978, Comments Astrophys 7, 183.
Tinsley, B.M.: 1979a, Proc. Roy. Soc., in press.
Tinsley, B.M.: 1979b, preprint.
Tinsley, B.M., and Gunn, J.E.: 1976, Astrophys. J. 203, 52.
Tinsley, B.M., and Larson, R.B.: 1978, Astrophys. J. 221, 554.
Tinsley, B.M., and Larson, R.B.: 1979, Monthly Notices Roy. Astron. Soc 186, 503.
Toomre, A.: 1977, in B.M. Tinsley and R.B. Larson (eds.), 'The Evolutio of Galaxies and Stellar Populations,' Yale University Observatory, New Haven, p. 401.
Weymann, R.J., and Williams, R.E.: 1978, Physica Scripta 17, 217.
Wyatt, S.P., and Cahn, J.H.: 1979, preprint.

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DISCUSSION

Heidmann: A remark about the question of primaeval galaxies : yesterday I referred to the existence of supergiant HII regions, which are 100 times larger than giant HII regions. They were found in what we called clumpy irregular galaxies, which contain 5-10 such supergiant HII regions. My suggestion is that these clumpy irregulars, which possess a tremendous rate of star formation, may serve as live models for primaeval galaxies. At present their properties may be investigated by ground-based means :spectroscopy for chemical abundances, the Westerbork radio-telescope for neutral hydrogen distribution, the VLA for ionized hydrogen, I-R for dust, CO line for molecules, the Einstein X-ray telescope for end products of short-lived stars. Later on they could be probed with the ST and shed light on the problem of galaxy evolution.

Tinsley: The colliding galaxies may be even better models for primaeval galaxies.

King: Objective-prism exposures in the UV with ST can potentially determine individual redshifts from the position of the Lyman break. Do you expect galaxies to be bright enough in the UV that we can really do this ?

Tinsley: IUE observations of normal galaxies have shown that they are very much brighter in the far ultraviolet than would be predicted by models which account for the optical spectrum. There is a good chance this may be possible.

Westphal: The problem with galaxies is that they are extended and consequently features in objective prism images are smeared out.

King: We can now take limiting IV-N plates and get infrared magnitudes of faint galaxies. Do you expect that observations with J, F, and N plates can solve these problems from the ground without waiting for ST ?

Tinsley: Kron and Bruzual believe it is possible to get redshift information from these plates.

Gunn: It is well-known that the redshift-magnitude relation for brightest cluster galaxies as a cosmological test is bedevilled by evolutionary corrections to the luminosities of galaxies. There are two corrections to be made. The stars of a galaxy evolve and it can be readily shown that the correction depends only on the slope of the initial main sequence mass function. This is difficult to estimate but probably can be done with effort. The more difficult correction, first described by Tremaine and Ostriker, results from cannibalism in which the brightest cluster galaxy eats less massive galaxies. In a simple theory, it can be shown that, if energy is conserved and if the galaxies are homologous,

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the core (or characteristic) radius $r_c \propto M^{\beta}$ where $\beta \approx 1 - 2$, being 1 if the galaxy eats members of mass similar to its own mass and 2 if very much less massive members are eaten. One can work out what happens to the luminosity of a galaxy seen through an aperture of fixed radius as function of added mass and it depends only on β and $\alpha = d(\log L)/d(\log$ The galaxy grows in size and it follows that, for β constant, the amoun by which the galaxy grows depends only on α. Therefore, if we can measure α, we can hope to make a correction for cannibalism according t this very simple theory.

Hoessel and I have studied the correlation of absolute magnitude with α for the brightest galaxies in 107 Abell clusters and there is a clear trend in the data which is in very encouraging agreement with the simple theory. The dispersion in absolute magnitude of the brightest cluster galaxies is reduced from 0.4 to 0.2 magnitudes. Thus, if one can measure α for distant galaxies with ST, it may be possible to make this most difficult correction.

Concerning the correction for stellar evolution, it is well known that the surface brightness of a galaxy is independent of the cosmological model. Thus, if there were only the stellar evolution correction to be made, this could be done by measuring the surface brightness of distant and nearby galaxies. This is obviously complicated by variations in the sizes of galaxies due to cannibalism. However, these corrections can be made by measuring α and corrections for stellar evolution measured directly. Surface brightnesses for distant galaxi are very difficult to measure from the ground but, from ST, it will be very easy with the WFC or with the higher resolution cameras.

Thus, contrary to my previous views, I now believe that cosmological studies for q_o using brightest cluster members are a viable enterprise using ST.

Spinrad (Discussion leader): The Space Telescope will tell us a great deal about the evolution of galaxies with cosmic epoch but there are problems. For example the predicted V magnitudes of giant elliptical galaxies at redshift $z \approx 1.0$ vary considerably with the assumptions made about how their luminosities have evolved with time. ST can do precise photometry at V = 24 but spectroscopy will be very difficult, partly because of the aperture of the telescope and partly because the apertures of the FOS are all small. There may be ways of obtaining redshifts using ST, for example, by multicolour photometry, or it may be necessary to measure these redshifts from the ground.

The direct imaging mode is the most important and this will provid much crucial data for studying the evolution of galaxies, for example, the disc-to-bulge ratios for galaxies and their angular diameters at large redshifts.

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A serious problem is how to find standard candles, especially giant elliptical galaxies, for cosmological tests. I list few possibilites, two of which are old and two new.

(i) Optical identification of distant radio galaxies. These are similar in absolute magnitude to the brightest galaxies in clusters and some indeed are brightest cluster members.

(ii) The search for distant rich clusters of galaxies. This will be difficult with ground-based electro-optical devices and with those on board ST because of the small field of view. If they are found by chance, it is essential to make sure that they are the same types of objects observed nearby.

(iii) Some quasars are now known to be in clusters. By searching for these companion clusters, brightest cluster members in the normal sense may be discovered.

(iv) At faint magnitudes, $V > 21$, it can be shown that only giant ellipticals in the redshift range $0.4 \lesssim z \lesssim 0.9$ have colours $J-F \gtrsim 2.0$. Such tests are just beginning from the ground now. An interesting approach would be to use a combination of (iii) and (iv) for quasars in the range $0.5 \lesssim z \lesssim 0.9$

Two final comments : studies of the UV continua of elliptical galaxies can give information about the epoch of the last major burst of star formation. Surface brightness tests and associated tests of galaxy luminosity evolution (similar to those described by Gunn) will be very much better with ST than from the ground because of the very high angular resolution of ST.

N.A. Bahcall: The dynamical evolution of galaxies in dense clusters can be studied with Space Telescope. This evolution is closely related to the observed X-ray emission from clusters. Essentially all rich clusters are found to be X-ray emitters. The X-ray emission comes from a hot intracluster medium, most of which is believed to have originated in the galaxies (the iron X-ray lines correspond to roughly solar abundance). Therefore, a correlative study of the galaxy properties such as type, color, and spectra (with ST) in comparison with the observed properties of the intracluster gas such as density, temperature, and structure (X-ray satellites) should yield important information regarding the dynamical evolution of galaxies and clusters.

It has been shown (Bahcall, N.A., 1977a. Ap. J. Letters, 217, L77; 1977b. Ap. J. Letters, 218, L93) that for nearby clusters ($z \lesssim 0.2$) strong correlations exist between the X-ray luminosity of a cluster (i. e., intracluster gas density and temperature) and the stage of dynamical evolution of the cluster. In particular, it has been shown that X-ray luminosity is, on the average, highest (i.e. gas density and temperature for compact cD-B type clusters and lowest for irregular clusters. The X-ray luminosity was found to increase with central galaxy density in clusters, as expected, and to strongly decrease with increasing spiral fraction in the cluster. This latter correlation agrees well with a ram-pressure stripping model in which the spiral galaxies are converted to SO (or E) by the dense ($\sim 10^{-3}$ cm^{-3}) intracluster medium. Similar correlations should be carried out at higher redshifts in order to bette understand the evolution of galaxies. The blue galaxies found in two $z \sim 0.4$ clusters by Butcher and Oemler (1978. Ap. J., 219, 18), and the relatively strong extended X-ray emission detected from at least one of these two clusters (Henry et al. 1979. Ap. J. Letters, in press) are other manifestations of the interactions between the intracluster gas and the galaxies that can be studied at large redshift.

Collin-Souffrin: I would like to add to Dr. N. Bahcall's talk that it would be also interesting to correlate the optical and X-ray studies of clusters of galaxies with 21 cm observations. Indeed Chamarant has recently shown, that the HI deficiency of spiral galaxies is well correlated with the richness and with the intensity of the X-ray emission of clusters.

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