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# GALACTIC EVOLUTION AND THE INTERPRETATION OF COSMOLOGICAL TESTS

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RESUME :

L'évolution galactique influence l'interprétation des tests cosmologiques en modifiant les relations entre la magnitude apparente, le diamètre angulaire, le décalage spectral, etc..., prédits par divers modèles. On considère plusieurs tests. Il se peut : (1) que l'évolution stellaire et dynamique dans les galaxies elliptiques rendent ensemble le diagramme de Hubble peu sensible au modèle cosmologique ; (2) que la relation éclat-décalage dépende non seulement de l'évolution de luminosité mais aussi de la cosmologie ; (3) que les dénombrements de galaxies à magnitude limite démontrent l'évolution galactique et renseignent sur le décalage au moment de la formation des galaxies. En général, les galaxies lointaines renseignent plus sur leur propre évolution que sur le modèle cosmologique.

## I. INTRODUCTION

Most cosmological tests involving distant galaxies (e.g. Sandage 1961) attempt to measure the deceleration of the Universe by finding, in effect, a relation between redshift and lookback time: at small redshifts the relation is linear (Hubble's law), but further out the redshifts lie above a linear relation if the Universe is decelerating. In these tests, the lookback time is given in terms of a "distance" parameter[1] such as the apparent luminosity or size of first-ranked cluster galaxies. Here I shall discuss how the evolution of galaxies affects these parameters and the inferred value of the deceleration parameter $q_o$. The tests are extremely sensitive to evolution: because a fractional error in the "distance" translates into a similar fractional error in the deceleration, a change in intrinsic galaxy luminosity or size by a few per cent per $10^9$ yr alters the apparent value of $q_o$ by unity!

Another type of test attempts to find the curvature of space (which depends on $q_o$ and the cosmological constant $\Lambda$ in the usual Friedman models) by measuring departures from the Euclidean relation between "volume" and "distance".[1] In this case, the volume parameter is the number of galaxies in a given area of sky, and the distance parameter is the limiting magnitude of the counts. This test proves to be even more vulnerable to evolution than the others: at a limiting magnitude where models with $q_o$ = 0 and 1 have counts formally differing by 25% ($\sim 22^m$), evolution is likely to cause a factor 5 or more departure from either formal relation.

My conclusion will be that some of the classical cosmological tests are better probes of galaxy evolution than probes of $q_o$. The cosmological questions should perhaps be approached in another way, via tests based on local data (density, age, etc.). A discussion of these tests would be beyond the scope of this paper (see, for example, Gott et al. [1974, and references therein], Sandage [1975], Peebles [1976]), but it is worth noting that they can in principle provide enough information to determine a unique Friedman model. For example, values of the density parameter $\Omega$, the age $t_o$, and Hubble's constant $H_o$ are sufficient. With no other

[1] The terms "distance" and "volume" are used above in a loose descriptive sense. In practice, the tests use relations between observable quantities (redshift, apparent magnitude, angular size, etc.), taking full account of the effects of expansion, deceleration, curvature, light travel-time, etc.

details at all, confirmation of a lower limit $H_o t_o > 2/3$ would establish that the Universe is open ($q_o < 1/2$) if $\Lambda$ is assumed to be zero; or if $H_o t_o > 1$, we must conclude that $\Lambda$ is positive. Of course there are difficult astrophysical problems involved in the local tests, but perhaps they will prove more tractable than trying to understand very distant galaxies in the detail needed to use them as probes of the cosmological model.

I assume throughout this paper that redshifts are cosmological, and that the Universe is adequately described by one of the Friedman models, based on General Relativity. Galactic evolution affects the interpretation of data in most alternative models; the discussion below will illustrate how such effects may be estimated.

## II. THE HUBBLE DIAGRAM: EVOLUTION OF GIANT ELLIPTICAL GALAXIES

### a) Form of the first-order correction

The best studied cosmological test is the Hubble diagram, the apparent magnitude-redshift relation for giant elliptical galaxies. The dominant effects of the cosmological model and evolution can be seen by writing a Taylor series in redshift z, although of course such a series is not accurate enough for estimating $q_o$ from a set of data. The following relation is for monochromatic magnitudes corresponding to a fixed frequency $\nu$ at emission (other functions of z would appear in alternative cases, e.g. using broad-band magnitudes, but the terms with $q_o$ and evolution would not be affected):

$$\begin{aligned} m_\nu &= M_\nu(t) + 5 \log D(z,q_o,\Lambda) + \text{const.} \\ &= \text{const.} + M_\nu(t_o) + 5 \log(cz/H_o) + 1.09z \, \frac{2-\alpha}{2} \left[q_o - \frac{2}{2-\alpha} \frac{1}{H_o t_o} \left(\frac{d\ell nL}{d\ell nt}\right)_o\right] \\ &\qquad + 1.09 \, \frac{\alpha}{4} \, z + O(z^2). \end{aligned} \tag{1}$$

Here D is the usual luminosity distance; $M_\nu(t)$ is the absolute magnitude at emission time t(z); subscripts zero refer to the present time; L(t) is the absolute luminosity equivalent to $M_\nu(t)$; and $\alpha$ is the slope of the luminosity-radius relation that enters the aperture correction (Gunn and Oke 1975). It is important to note that L and $M_\nu$ refer to that portion of the galaxy light which is emitted inside the aperture radius. The value of $\alpha$ depends on the aperture; here I use $\alpha = 0.7$, appropriate to Gunn and Oke's (1975) data.



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The zero-order terms in (1) just express Hubble's law for small z. The (unspecified) second- and higher-order terms contain $\Lambda$ (if non-zero) as well as $q_o$ and the evolution L(t). The first-order term contains only the present first derivative of L(t), $q_o$, and functions of z. From the expression in square brackets, it can be seen that the main effect of evolution is to give an apparent value of $q_o$, to be denoted $q_{oa}$, which differs from the true value by the first-order evolutionary correction,

$$\Delta q_o \equiv q_{oa} - q_o = -1.54 \frac{1}{H_o t_o}\left(\frac{d\ell nL}{d\ell nt}\right)_o . \tag{2}$$

It is convenient to separate the evolutionary correction into terms for aging of the stellar population, which alters the luminosity of a fixed number of stars at the rate $(\partial \ell nL/\partial \ell nt)_*$, and dynamical evolution, which alters the number of stars within the observer's aperture at a rate $(\partial \ell nL/\partial \ell nt)_d$. Then, in obvious notation, we can write

$$\Delta q_o = \Delta q_{o*} + \Delta q_{od}. \tag{3}$$

Evidently, $\Delta q_o$ is positive ($q_o$ is really smaller than its apparent value) if L is decreasing with time. The sign is easy to understand qualitatively: if the distant galaxies are brighter, their apparent magnitudes lead to an underestimate of the distance, so a given redshift appears at too small a distance, and the past expansion rate is overestimated. *In the usual log z vs. m coordinates of the Hubble diagram, the qualitative effect* is that if galaxies at large z are too bright, they are plotted too far to the left, which gives a relation corresponding to too great a value of $q_o$.

I shall now consider the effects of stellar and dynamical evolution in turn, then show how together they affect the apparent value of $q_o$.

b) Stellar evolution

The effects of stellar evolution on L(t) and $q_o$ have been reviewed by Tinsley (1975), and further discussion and results are given by Tinsley and Gunn (1976). A summary follows.

The stellar population in giant elliptical galaxies is predominantly very old and quite metal-rich, like the old-disk population in our Galaxy. The evolution of integrated luminosity of such a population, at a fixed wavelength in the visual region, is given by a simple relation:

$$(\partial \ell nL/\partial \ell nt)_* = -(1.3 - 0.3x), \tag{4}$$

where x is the slope of the initial mass function (IMF) for stars in the

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mass range from a little below the present turnoff to the turnoff at ages seen at $z \sim 0.5$, i.e. $0.8 \lesssim m/M_\odot \lesssim 1.2$. The slope x is defined by writing the IMF in the form

$$dN/dm \propto m^{-(1+x)}; \tag{5}$$

in this notation, Salpeter's (1955) IMF for the solar neighborhood has $x = 1.35$. From equation (2) the corresponding first-order correction to $q_o$ is

$$\Delta q_{o*} = (2.0 - 0.5x)/H_o t_o; \tag{6}$$

the dimensionless product $H_o t_o$ depends on $q_o$ and $\Lambda$, and is $< 1$ if $\Lambda = 0$. This relation shows at once that evolution can affect the Hubble diagram strongly, unless elliptical galaxies have a much steeper IMF ($x \sim 4$) than does the solar neighborhood. We distort the effects of evolution somewhat by considering only the first-order correction as an initial approximation, but we do not exaggerate their importance.

The rate of evolution (4) can be understood by simple analytical approximations, and it holds quite accurately in a variety of numerical models (see references given above). These models reveal that the slope x near turnoff is far the most important quantity for $(\partial \ln L/\partial \ln t)_*$, which has the value (4) for a given x regardless of the choice of parameters used to represent many uncertainties (e.g. chemical composition, the luminosity function and colors of giant stars, and a possible sprinkling of younger stars above the turnoff point). The logarithmic rate of evolution is also essentially independent of age, after about $5 \times 10^9$ yr, strictly if the time t in (4) is replaced by $t-t_g$, where $t_g$ is the time of formation of the dominant old stars; by neglecting $t_g$ here, we underestimate $\Delta q_o$ by a factor $t/(t-t_g)$.

The major cause of the luminosity evolution given by (4) is the change in numbers of stars on the giant branch; this depends on the rate at which stars peel off the main sequence, giving approximately $(d\ln N_g/d\ln t) = -(1.0 - 0.26x)$, where $N_g$ is the number of giants. The integrated luminosity of the main sequence also evolves at a similar logarithmic rate, as stars are lost at turnoff, but this factor is less important since giant stars dominate the light. With a steeper IMF (greater x), L declines more slowly, mainly because the giant branch is fed by a richer main sequence, and partly because of the enhanced effect of "unevolving" dwarfs. (The slow evolutionary brightening of stars below turnoff has a non-negligible effect, surprisingly tending to make $\ln L$ decline faster,

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because it steepens the stellar luminosity-mass relation [Tinsley 1976a].)

Evidently, if we wish to evaluate $\Delta q_{o*}$, we must find the value of x. Several different approaches can be used; I shall summarize current results from each.

i) Analogy with the local IMF.

From counts and theoretical lifetimes of stars in the solar neighborhood, one can derive a slope $x \simeq 0.25$ in the mass interval $0.5 < m/M_\odot < 1$, and a slope $x \simeq 2.6$ in the interval $2 < m/M_\odot < 20$; the slope for masses between 1 and $2M_\odot$ depends on the past rate of star formation (Schmidt 1959; other references cited by Audouze and Tinsley 1976). For the mass interval of interest here, $0.8 < m/M_\odot < 1.2$, an average slope $x = 1 \pm 0.5$ is indicated. It would be unsafe to assume that elliptical galaxies have the same IMF as the solar neighborhood, since star formation in spheroidal systems and in disks must proceed under very different physical conditions (Larson 1976), but we can perhaps use $x \simeq 0.5 - 1.5$ as an initial guide.

ii) Population syntheses of elliptical galaxies.

The definition (5) of x indicates that the ratio of contributions of dwarf and giant stars to the light increases with x; in particular, the preponderance of late dwarfs increases with x, so the idea is that if x is great enough, the integrated spectra of elliptical galaxies should show characteristics of dwarfs at long wavelengths. Constraints can thus be set on x by means of population syntheses that incorporate spectral features whose strengths differ widely between giant and dwarf stars. Several such syntheses (Whitford 1976, Tinsley and Gunn 1976; others cited therein and in Tinsley 1975) have led to the conclusion that $x \lesssim 1$; if the IMF is steeper than that, certain features appearing most strongly in giants (especially the CO band at $2.3\mu$ [Frogel et al. 1975]) are predicted to be too weak, and features appearing mainly in dwarfs (especially the Wing-Ford band at $0.99\mu$ [Whitford 1973, 1976]) are predicted to be too strong.

Unfortunately, these apparently powerful constraints do not lead to an accurate enough estimate of x, because of two seemingly intractable problems.

The first trouble is that the strengths of spectral features depend not only on x, but also on other poorly-known properties of the stellar population. With values of x between 0 and 1, the spectrum is always so

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dominated by giants that the effects of x on feature strengths are no greater than systematic uncertainties due to the age, chemical composition, and detailed luminosity function and spectral types of the giants. The currently acceptable range, say $0 < x < 1.5$, allows values of $(H_o t_o)\Delta q_{o*}$ between 2.0 and 1.3; a great deal more needs to be learned about the spectra of giant elliptical galaxies and their constituent stars before this approach will yield $\Delta q_{o*}$ to an accuracy of a few tenths.

The second problem with the synthesis approach is that G dwarfs, the stars whose slope x we want, contribute light mainly at visual and shorter wavelengths, where the extremely composite nature of the galaxy spectrum confuses the usual stellar temperature and luminosity criteria. One achieves much better sensitivity by using features in the red - infrared, where the contributing stars are late K and M types with some very clear differences between dwarfs and giants. The value of "x" so derived is thus the average slope of the IMF between turnoff (supplying the giants) and masses $\lesssim 0.5 M_\odot$ (late dwarfs); there is no direct information on the slope just below turnoff (and of course no information on the slope <u>above</u> the present turnoff, which actually determines the past luminosity!). If the syntheses are interpreted in terms of an IMF with a constant slope (or a slope that increases towards lower masses), then the slope at turn-off is limited to $x \lesssim 1$; but we cannot rule out a steeper slope near turnoff, i.e. slower luminosity evolution, as long as there is a change of slope providing a relative deficiency of late dwarfs. There is no argument against the former interpretation, but it would clearly be preferable to devise some test for the slope of the IMF for G dwarfs themselves.[2]

iii) Colors of distant galaxies.

Theoretical models predict that the rate of color evolution increases with x. The reason is that, if x is small, giant stars dominate the light, and the integrated color of the giant branch changes only slowly; but if x is large, one notices the much faster redward evolution of the

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[2] Mass-to-luminosity (M/L) ratios give no firm constraint on the slope at turnoff. With a steep slope, an excessive M/L can be avoided by postulating a cutoff at several tenths of $M_\odot$ (to which the giant-dominated spectrum presents no objections). And with a shallow slope, M/L can be made great enough by postulating the presence of dark matter (substellar objects, etc.).

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main-sequence turnoff point. In principle, therefore, the spectral energy distributions of the galaxies used in the Hubble diagram provide a way of estimating x, and so the rate of luminosity evolution of those galaxies. And in this case, the value of x is the slope of the relevant part of the IMF. In Tinsley and Gunn's (1976) models, the color evolution is as slow as observations require (Oke and Sandage 1968, Sandage 1973, Crane 1975) if $x \leq 2$. Paradoxically, slow color evolution implies rapid luminosity evolution (because both are consequences of giant stars dominating the light). It is frustrating that our most direct evidence for a large value of $\Delta q_{o*}$ is therefore the almost null result of attempts to detect color evolution!

In summary, the critical parameter x is almost certainly less than 2, and is probably less than 1 if the slope of the IMF does not decrease between turnoff and early M dwarfs. Consequently, $\Delta q_{o*}$ is at least 1.0, and may be closer to 2.0.

c) Dynamical evolution

Central cluster galaxies are thought to accrete other cluster members by the process of dynamical friction. Thus the galaxies used in the Hubble diagram may grow brighter by acquiring an increasing number of stars, and so may be subject to an evolutionary correction of the opposite sign to the correction due to stellar evolution (Ostriker and Tremaine 1975). Since S. M. White will discuss the process of dynamical friction in the following paper, I shall review only some consequences for the Hubble diagram, basing my remarks on the papers by Ostriker and Tremaine (1975) and Gunn and Tinsley (1976).

Accretion has two opposing effects on the luminosity (L) within the observer's aperture: the addition of stars tends to make L grow, but, to conserve energy, the core of the central galaxy must swell in size as stars fall in, so some stars move out of view at the edge of the aperture. The net effect depends on the density distributions within the central and accreted galaxies. At one extreme, if the victim is as diffuse as the central galaxy, the composite system may have a smaller average surface brightness than the initial central galaxy, so L decreases. At the other extreme, a small, compact victim will fall right to the center, adding its total luminosity to L and causing only a relatively small loss of stars by

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swelling of the giant at the aperture radius. The central densities of elliptical galaxies generally increase with decreasing galaxy luminosity, so the dominant effect in most clusters is likely to be closer to the latter case; we therefore expect that, on average, $(\partial \ell nL/\partial \ell nt)_d > 0$, and $\Delta q_{od} < 0$.

The size of the dynamical correction is very uncertain, because the rate of accretion and its effects on L depend on details that vary from cluster to cluster, and which are not well known, theoretically or observationally. In the asymptotic case, i.e. when the observed luminosity is mostly due to accreted stars, L grows as $(t-t_c)^{1/2}$, $t_c$ being the time at which accretion effectively started; $t_c$ could be a significant fraction of the Hubble time (if it is comparable to the cluster collapse time), so it cannot safely be neglected. Probably most clusters are not yet in the asymptotic regime, so the effect of accretion on L is diluted by the ratio of accreted to total luminosity; however, the dilution is offset by the fact that, at this stage, the accretion rate is faster than $(t-t_c)^{1/2}$ (White 1976). Altogether, we can expect values of $(\partial \ell nL/\partial \ell nt)_d \gtrsim 0.5t/(t-t_c)$, corresponding to an upward correction to $q_o$ by $|\Delta q_{od}| \gtrsim 0.8$.

Accretion at a significant rate may be detected via the well-known color-luminosity relation for normal elliptical galaxies (van den Bergh 1975); the accreted galaxies are presumably bluer than the central giant, which should therefore become increasingly too blue for its size as it grows. It is suggestive that Crane (1976) finds the galaxies in Gunn and Oke's (1975) sample to have a weaker color-luminosity relation than normal; maybe accretion is responsible - much more data are needed to make further tests such as correlating the amount of accretion with cluster properties.

Another point is the predicted growth (decrease towards greater z) of the contrast in magnitude between the central and other members of clusters. Ostriker and Tremaine (1975) tried to test for the occurrence of accretion by studying the variation of contrast with z, for clusters of different Bautz-Morgan types; the process should be most apparent in Type I clusters, since their cD galaxies are believed to be products of extensive accretion. Apart from the paucity of data (see footnote 3 below), several problems attend this test: (i) The evolution of contrast may affect the assignment of Bautz-Morgan class to a cluster, so it is not

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clear that one is comparing equivalent clusters at different redshifts. (ii) Other cluster members as well as the central galaxy can grow by accretion, perhaps by swallowing their satellites; magnitude contrasts may therefore evolve more slowly than the magnitudes of individual bright galaxies. (iii) Two of the originally brightest members of a cluster may merge, so the second-, third-, and higher-ranked galaxies are not necessarily equivalent objects at all redshifts.

The "Bautz-Morgan correction" to galaxy magnitudes (Sandage and Hardy 1973) is surely of the right sign to correct for dynamical evolution, but because of problems like the three above, it is unlikely to be of exactly the required amount. Altogether, the value of $(\partial \ell nL/\partial \ell nt)_d$ will be very difficult to determine either theoretically or by empirical studies of cluster galaxies.

d) The apparent value of $q_o$

In this section, I give a schematic, but not implausible, example to illustrate how stellar and dynamical evolution may together affect the Hubble diagram. Let us consider how the m-z relation would appear, to first order, under the following assumptions: (i) The cosmological constant is zero. (The value of $\Lambda$ does not affect the first-order m-z relation directly [see eq. 1], but it provides a relation between $q_o$ and $H_o t_o$ for the time-scale for evolution in equation [2].) (ii) The true value of $q_o$ lies between 0 and 1; this range is consistent with estimates that the density parameter $\Omega$ is less than $1 (\Omega = 2\, q_o$ if $\Lambda = 0)$. (iii) Stellar evolution makes the luminosity of a given number of stars decrease as a power $(-1.3 + 0.3x)$ of time, where $0 \lesssim x \lesssim 1.5$. (iv) Accretion begins at a time $t_c = \gamma H_o^{-1}$, where $\gamma \lesssim 0.5$, and varies thereafter as a power $\kappa$ of $(t-t_c)$. This rate and the luminosities L below refer to the part of the galaxy within the observer's aperture.

From assumptions (iii) and (iv), the luminosity at times $t > t_c$ is

$$L(t) = L(t_c)\left(\frac{t}{t_c}\right)^{-1.3+0.3x}\left[1 + \frac{f_o}{1-f_o}\left(\frac{t-t_c}{t_o-t_c}\right)^{\kappa}\right], \tag{7}$$

where $f_o$ is the fraction of the present light that comes from accreted stars. The derivative required in equation (2) is

$$\left(\frac{d\ln L}{d\ln t}\right)_o = -1.3 + 0.3x + \frac{f_o\kappa}{1 - \gamma(H_o t_o)^{-1}} \quad . \tag{8}$$

Since $H_o t_o$ depends only on $q_o$, we can express $\Delta q_o$ and hence $q_{oa}$ in terms of $q_o$, $f_o\kappa$, x, and $\gamma$. Figure 1 shows the results for several values of $f_o\kappa$, using x = 1 and $\gamma$ = 0.33 (similar results are obtained for other choices of x and $\gamma$ in the ranges postulated above).

If $f_o\kappa = 0$, the only evolution is stellar. $\Delta q_o$ is positive, and its value increases with $q_o$ because $H_o t_o$ is a decreasing function of $q_o$. So in this case, evolution enhances the separation of models with different

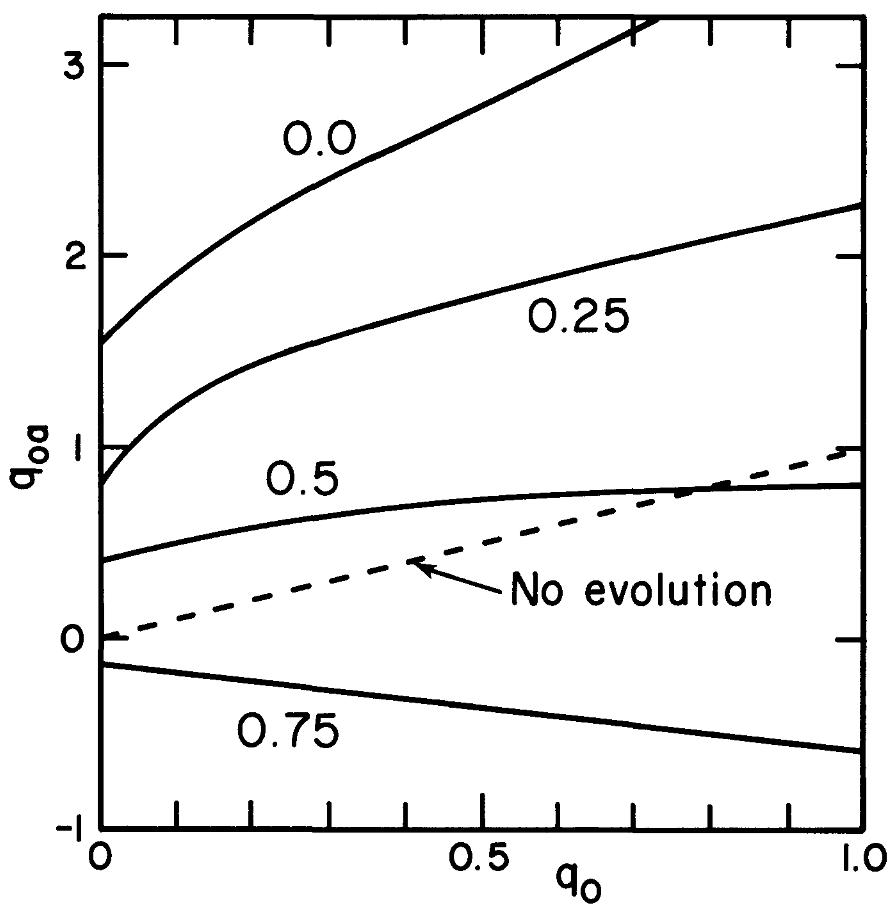


FIG. 1.- The apparent value of $q_o$ versus its true value, using the first-order evolutionary correction given by the schematic model of § IId. The dashed line is for no evolution ($q_{oa} = q_o$), and the other lines are labelled with the parameter $f_o\kappa$ representing dynamical evolution.

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values of $q_o$.

But if $f_o\kappa$ is great enough, the net correction $\Delta q_o$ is negative. Its absolute value again increases with $q_o$, so now $q_{oa}$ changes only very slowly with the true value of $q_o$. For example, in the asymptotic case ($f_o$ = 1, $\kappa$ = 0.5), $q_{oa}$ is about 0.5 for all values of $q_o$ between zero and 1. Alternatively, if we adopt $q_{oa} \simeq 0$ (Gunn and Oke 1975), we see that (with this choice of x and $\gamma$) $f_o\kappa$ must be 0.7, with little uncertainty, but that the true value of $q_o$ is indeterminate.

More realistic treatments of dynamical evolution will alter the details, but they are not likely to alter the severity of the problem. Clearly, it will be very difficult to derive $q_o$ from the Hubble diagram, unless some way can be found to choose galaxies that are not affected by dynamical evolution. Cluster galaxies other than the central member are not perfectly safe, since, as noted above, they can accrete at least their satellites; a warning is that Oemler (1976) finds the third brightest galaxy in the Coma cluster to be a cD.

It is tempting to conclude this discussion of the Hubble diagram by reversing the roles usually played by cosmology and evolution in its interpretation: the m-z relation seems to be an excellent way of determining effects of stellar and dynamical evolution on the luminosities of elliptical galaxies, requiring relatively minor corrections for uncertainties in the cosmological model.

## III. SURFACE BRIGHTNESS AND RELATED QUANTITIES

### a) The "ideal" surface brightness test for evolution

The relation between surface brightness (SB) and redshift is regarded as a promising way of measuring evolution, because of the fact that the ratio of observed to intrinsic SB of a source depends on redshift but not on the cosmological model. The observed monochromatic SB of a galaxy at redshift z, measured at an angular radius $\theta$ and frequency $\nu_o$, is given by

$$b_\nu(\theta,\nu_o,z) = B_\nu(r,\nu,t)/(1+z)^3, \qquad (9)$$

where $B_\nu$ is the intrinsic SB at emission time t(z), at the frequency $\nu = \nu_o(1+z)$, and at radius $r = \theta D/(1+z)^2$; D is the function of z, $q_o$, and $\Lambda$ used in equation (1). With some assumptions about the dependence of evolution on $\nu$ and r, the run of $b_\nu$ with z should give the evolution of $B_\nu$

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with z, and hence the evolution of luminosity L. Ideally, it should be possible to derive an empirical evolutionary function,

$$E(z) \equiv L/L(t_o), \qquad \text{where } L = L[t(z)], \tag{10}$$

from a relation of the form

$$b_\nu \propto E(z)/(1+z)^3, \tag{11}$$

independently of the cosmological model. (In this schematic relation, $b_\nu$ is either the SB at angular radius $\theta$, or the average SB within $\theta$.)

Unfortunately, this simple plan founders on the need to specify a radius $\theta$ at which or within which the SB is to be measured, because galaxies are not uniformly bright surfaces.

b) Sensitivity of practical surface brightness tests

Several recent analyses (e.g. Gudehus 1975, Sandage 1974, Petrosian 1976, Tinsley 1976b) have emphasized the need for very detailed data and interpretation in SB tests. The central problem is the definition of $\theta$.

One suggestion is to measure the average SB within an isophotal radius (Petrosian 1976). In this case, one must consider the effects of evolution on the levels of isophotes within the galaxy, which imply that the metric radius corresponding to $\theta$ depends on E(z). It can be shown that the effects of evolution on the flux and isophotal radius almost cancel in the expression for observed SB, so the test is insensitive to the evolution it was meant to measure: instead of the linear dependence of $b_\nu$ on E(z) given by (11), one predicts a power only $\sim$ 0.1 to 0.3, depending on how the magnitudes entering the SB are defined (Tinsley 1976b). This problem is a quirk of the fact that the galaxies have approximately inverse-square SB profiles at the relevant radii; it could be circumvented by photometry with very high angular resolution.

Another possibility is to measure the SB at a value of $\theta$ that would correspond to a fixed metric radius r if $q_o$ had a chosen fiducial value (H. Spinrad, private communication). Then the actual value of r at which the SB is measured varies with z in a way that depends on the unknown true $q_o$. It turns out that in this case, the $b_\nu$-z relation provides a function of E(z) and the cosmological model which is almost the same as the function provided by the Hubble diagram. In fact the SB test is relatively <u>less</u> sensitive to evolution than is the Hubble diagram, by a factor $\sim 2/(2-\alpha) \sim$

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1.5 ($\alpha$ being defined as in eq. [1]). This is a rather ironic reversal of the sensitivities usually ascribed to the tests - the Hubble diagram supposedly giving $q_o$ and SB giving evolution, with "corrections" for the other parameters.

For an SB test to be as sensitive to evolution as promised by the schematic relation (11), the metric scale of each galaxy in the sample must be determined by detailed surface photometry. One would have then, in effect, both an "ideal" SB test for evolution and a metric diameter - redshift relation for $q_o$. Very high angular resolution, presumably using a space telescope, will be needed to realize this possibility (Sandage 1974, Petrosian 1976).

SB relations as a test for the expansion of the Universe are discussed by Sandage (1974) and Crane (these proceedings); this test requires less precision than a measurement of the rate of evolution.

c) Isophotal diameters

The isophotal diameter - redshift relation is another standard test for $q_o$. Because of the evolution of isophote levels, this relation gives information on both cosmology and evolution which is very similar to the information given by the Hubble diagram (Tinsley 1972, Gudehus 1975). The near equivalence of the two tests is related to the problems of SB tests using isophotal radii, mentioned above. Dynamical evolution could have complicated effects on isophotal diameters; detailed study is needed.[3]

## IV. GALAXY COUNTS

Counts of galaxies to faint limiting magnitudes are in principle a test for $q_o$. We can be warned to expect large evolutionary effects because this is the optical counterpart of radio source counts - which have notoriously always shown gross departures from simple expectations, indicating an overwhelming importance of evolution at radio wavelengths. The formal advantage of counts, over other optical tests, is that they sample

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[3] The study of accretion effects on magnitude contrasts (see § IIc) was based on relative magnitudes estimated from ratios of isophotal diameters - the only available magnitudes for second- and third-ranked cluster galaxies. Because accretion affects the diameters in an unknown way, photometric magnitudes are badly needed to define the contrasts properly.

distances too great for the types or redshifts of many galaxies to be determined, and different cosmological models have divergent predictions at great distances; the corresponding disadvantage is that interpretation of counts involves the luminosity functions, spectral energy distributions, and rates of evolution of all types of galaxies.

A preliminary feeling for the sensitivity of counts can be obtained from the number - apparent luminosity relation for one type of galaxy, expressed as a Taylor series in powers of a quantity $\zeta$, which is the ratio of the zero-order luminosity distance to the Hubble distance $c/H_o$: $\zeta \equiv (L_{Vo}H_o^2/4\pi\ell_V c^2)^{1/2}$, where $L_{Vo}$ is the present absolute visual luminosity and $\ell_V$ is the apparent visual luminosity. The number of galaxies brighter than $\ell_V$ is

$$N(\ell_V) = \frac{4\pi n_o}{3}\frac{c^3}{H_o^3}\zeta^3 \left\{ 1 - \frac{3}{2}\zeta\left[1 + \frac{1}{H_o t_o}\left(\frac{d\ell n L_V}{d\ell n t}\right)_o + k_V\right] + O(\zeta^2)\right\}, \quad (12)$$

where $n_o$ is the local number density and $k_V$ (a partial K correction) depends on the spectral energy distribution. The quantity outside the brackets is just the Euclidean expression for counts. The (unspecified) second-order term in brackets depends on L(t), the spectral energy distribution, $q_o$, and $\Lambda$; $\Lambda$ actually enters in the combination $(\frac{3}{2}\Omega-q_o-1)$, which is the dimensionless curvature. Thus, in principle, counts to faint enough magnitudes would be a test for curvature. But the trouble is the first-order term in (12): it does depend on evolution, but the effects of $q_o$ have cancelled out in this order. Galaxy counts are thus expected to be much more sensitive to evolution than to the cosmological model - just as radio source counts are.

More detailed calculations bear out this prediction (Brown and Tinsley 1974, Tinsley 1976c; the following examples are from Tinsley 1976c).

Figure 2 shows theoretical galaxy counts, in the form log $N/N_o$ vs. $m_r$, where $m_r$ is a red apparent magnitude and $N_o$ is the number in a static, Euclidean model; i.e. $N_o \propto \mathrm{dex}(0.6m_r)$. The lower two curves are for a mixture of all galaxy types, with luminosity functions and spectral energy distributions based on empirical data, but with no evolution. These curves fall below the horizontal line $N = N_o$ because with increasing redshift, the r band (effective wavelength 6700Å) is viewing light emitted at shorter wavelengths, where most galaxies are fainter (this is the usual K correction effect). As predicted, the value of $q_o$ makes little difference: the model with $q_o = 1.0$ has smaller counts than the model with $q_o$ =

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0.02, but the difference is only 25% at $m_r = 22$.

Evolution alters the picture drastically. The upper four curves in Figure 2 incorporate models for the evolution of all types of galaxies. These models are of course highly schematic, but they should be much more realistic than using no evolution at all. The most important parameter for the counts (out of numerous parameters for cosmology, evolution, etc. considered in Tinsley [1976c]) proves to be the redshift $z_F$ of galaxy formation, defined as the redshift of first extensive star formation. The cases plotted here correspond to $z_F = 3.5$ in each cosmological model, and to the redshift at time $t_F = 2 \times 10^9$ yr in each model. With a given $z_F$, the counts are greater in the model with greater $q_o$ (reversing the trend found with no evolution), because galaxies at a given z appear brighter. For a given $t_F$, the model differences are even more striking because the corresponding $z_F$ (given in the caption to Fig. 2) is much smaller in the model with greater $q_o$.

If $z_F$ is small, a peak is predicted in the quantity log $N/N_o$, in the

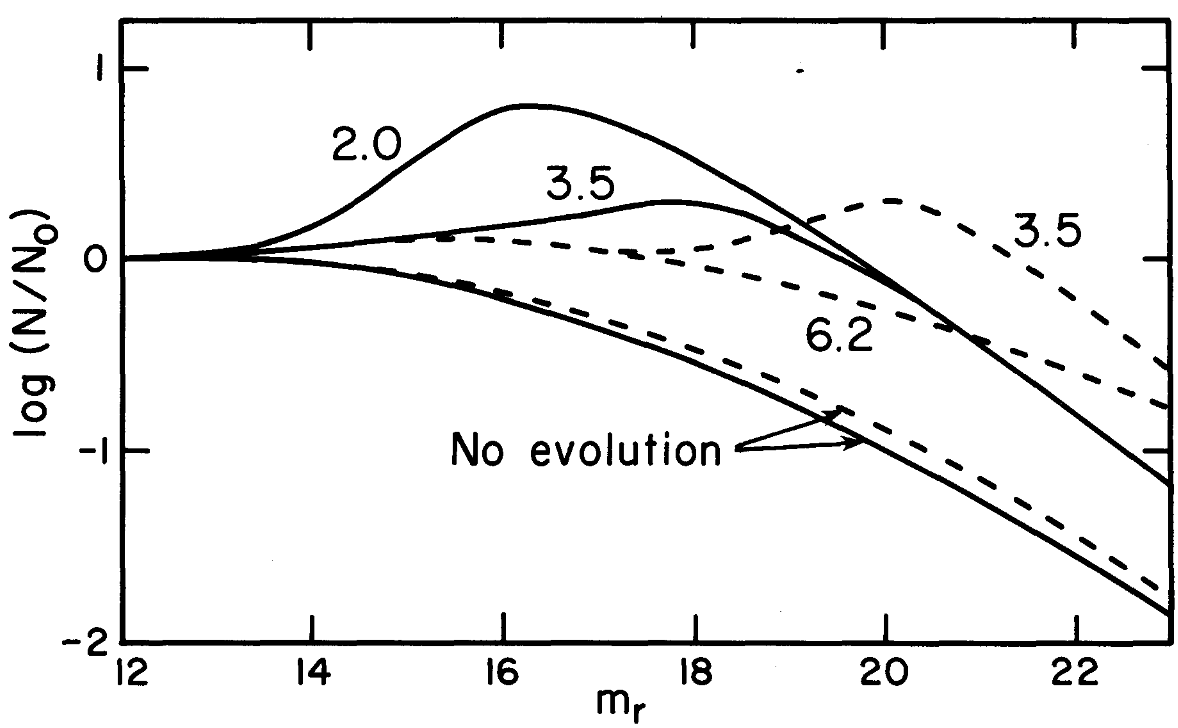


FIG. 2.- Magnitude-limited galaxy counts, relative to the "static, Euclidean" number $N_o$, as described in the text. Solid lines: $q_o$=1.0, $H_o$=50 km/s/Mpc. Dashed lines: $q_o$=0.02, $H_o$=50. The upper four curves are labelled with the redshift $z_F$ of galaxy formation. Corresponding values of $z_F$ and the formation time $t_F$ are, for $q_o$=1: (3.5, 1.0), (2.0, 2.0); for $q_o$=0.02: (3.5, 3.5), (6.2, 2.0), where $t_F$ is in units of $10^9$yr.

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magnitude range (depending on $z_F$ and $q_o$) at which young galaxies appear. The galaxies comprising the peak have a wide range of redshifts, from a few tenths (the redshifts of "normal" galaxies at those magnitudes) to $z_F$.

For values of $z_F \gtrsim 5$, the counts vary smoothly with magnitude, since the young galaxies are too faint to show at the magnitudes of interest. Nevertheless, the counts at $m_r > 20$ are always a factor 3 or more above the curves for no evolution. The enhancement is due about equally to evolution of luminosity and of color. The typical redshifts increase smoothly from $\sim 0.02$ at $m_r = 12$ to $\sim 1$ at $m_r = 22$, with a wide spread due to the width of the luminosity function. Curves similar to that shown for $z_F = 6.2$ are predicted also in cases with small values of $z_F$, if for any reason very young galaxies are not counted (e.g. if they are obscured by internal dust or have starlike photographic images). A general prediction, for any reasonable estimate of the evolution of galaxies at $z < 1$, is that the observed counts should be significantly above the values they would have with no evolution.

Preliminary data, kindly made available to me by A. Oemler (private communication), suggest that counts already provide the first positive evidence for galaxy evolution at optical wavelengths. Oemler's counts agree, within the substantial uncertainties of theory and data, with the predictions in a variety of cases that include evolution; but they are clearly discordant with the curves for no evolution. It is too soon to say whether there is a peak in log $N/N_o$ that could be attributed to young galaxies. If such a peak is found, an interesting experiment would be to obtain redshifts and photometric data for a sample of galaxies at the magnitudes within the peak, for the sample should be rich in very young objects.

Altogether, galaxy counts seem to be a very promising test - not for the value of $q_o$, but for the evolution of galaxies.

## V. CONCLUSION

Most of the cosmological tests involving distant galaxies seem to be so sensitive to evolution that they cannot provide useful estimates of the parameters defining the cosmological model. This conclusion is not altogether disappointing, for it opens alternative prospects: the data on distant galaxies will help to answer some key questions related to the

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evolution of stellar populations, the epoch of first star formation in galaxies, and interactions among galaxies in clusters.

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## DISCUSSION

J.C. PECKER: You gave reasons for pessimism with respect to the determination of $q_o$ or of evolutionary facts. I feel that we should be still more pessimistic, as much as young objects radiate an enormous amount of UV radiation, for which predictions are difficult and which strongly influence everything, and every test! The EARLY times of galactic evolution are badly known, and essential. I am afraid that other facts of galactic "quiet" evolution, at later stages, are of a much less cosmological significance.

B.M. TINSLEY: Dr Pecker is right that early stages of galactic evolution, and radiation at short wavelengths (redshifted into the observer's part of the spectrum) are extremely important for some cosmological observations. An example is the galaxy count-magnitude relation; the results I have reported here include both of these effects. A paper on the subject (Astrophys. J., in press) will discuss the parameters used and their uncertainties in detail. I agree that early stages of galactic evolution are poorly known. I have attempted to make a realistic assessment of the effects of uncertainties on galaxy counts and related quantities; time did not allow me to mention such details here.

Observations of elliptical galaxies to redshifts less than about 0.6, however, depend chiefly on the "quiet" stages of evolution. This statement is supported by the agreement of model spectral energy distributions with detailed scans of galaxies at redshifts near 0.5. An example was shown in figure 2 of my letter in Astrophys. J. 1972, 173, L 93.

G.O. ABELL: One of our students at UCLA, G. Rainey, has recently made counts of galaxies as a function of magnitude, complete to $m_v = 19.5$, in three regions of the sky, each covering about one square degree. All of his integral counts give curves indistinguishable from the calculated curves for Friedmann models with $\Lambda = 0$, for $q_o$ in the range 0 to + 1 and for no evolution. (As pointed out by Dr. Tinsley, log N ($\leq$m) vs m is very insensitive to $q_o$ in this range of $q_o$ and m.) Rainey's careful observations suggest that we can not be seeing appreciable evolution or galaxy formation within a magnitude limit of $m_v = 19.5$.

B.M. TINSLEY: My models predict fairly small effects at $m_v = 19.5$, if galaxy formation is not at too small a redshift. The predictions (even for no evolution) are quite sensitive to the luminosity functions, spectral energy distributions, and relative space densities of various types of galaxies, so it will be interesting to learn further details about Mr. Rainey's calculations. Oemler's data, out to $m_r = 21.5$, are clearly discordant with my models for no evolution.

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