THE EVOLUTION OF GALAXIES: EVIDENCE FROM OPTICAL OBSERVATIONS

Beatrice M. Tinsley
Yale University Observatory

The clearest evidence that galaxies evolve comes from the Milky Way: here we see stars with ages and lifetimes differing by 4 orders of magnitude, and with chemical compositions indicating a hundred-fold enrichment in metals between the times of formation of the halo and most disc stars. The general resolution of Olbers' Paradox also gives evidence for cosmological change: the sky is dark because galaxies turned on a finite time ago (Harrison, 1974). Here I discuss some of the further evidence for galactic evolution that is emerging from observations probing billions of years in lookback time.

1. COLOR CHANGES

Color evolution gives the least ambiguous evidence for changing stellar populations in galaxies, but the changes are expected to be slow since the types of stars contributing most light vary slowly if star formation is proceeding at a gradually decreasing rate or if it has stopped. The latter case, corresponding to normal elliptical galaxies, is predicted to give the faster rate of evolution - with bluer colors in the past because of the earlier main-sequence turnoff - but still only an overall decrease to redshift $z \sim 0.7$ of about 0.15 mag in U-B (intrinsic) and about 0.07 in B-V. Spinrad (1977) has reviewed the current status of searches for color evolution in ellipticals. In summary, the only clear positive result comes from Spinrad and his colleagues, who find about the predicted change in a U-B index derived from spectrophotometry; null results in other cases are consistent with the predictions.

There is, however, statistical evidence for some much more dramatic cases of color evolution. Butcher and Oemler (1977) have measured color distributions for galaxies in rich, centrally condensed clusters at z = 0.39, 0.46, and 0.95 (see also Spinrad, 1977, Fig. 10). The range of color in each case is consistent with that expected for normal galaxies from irregulars to ellipticals. But, surprisingly, the colors are spread broadly across the range, in marked contrast to the morphologically sim-

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ilar Coma cluster where the color distribution is sharply peaked at the red end. Presumably the distant cluster members are blue because of active star formation, so if the clusters are to become like Coma most members are destined to stop forming stars. This idea agrees with the standard picture in which SOs (the dominant type in Coma) form from spirals by loss of interstellar gas in a dense cluster environment, but the remarkable discovery is how late the cutoff occurs: the nearer clusters are seen with only $\lesssim$ 6 Gyr (6×10^9 yr) lookback time, and all three have already collapsed to a condensed form. Further evidence for some galaxies being much bluer in the past appears in Kron's (1977) deep counts: he finds that between $m_B = 22$ and $m_B = 24$, the mean color of counted galaxies gets bluer by 0.35 mag. Possibly some early period of rapid star formation is coming into view, as will be discussed below.

Sandage (1973) based an interesting argument for an evolutionary universe on colors of elliptical galaxies. He estimated the spread of colors that would result from the age distribution of galaxies in a Steady State universe. This was much wider than the observed narrow color range, which suggests that E galaxies are approximately coeval.

2. LUMINOSITY CHANGES

Cosmological tests using lookback observations to derive the past expansion rate (i.e. the deceleration) of the universe provide in fact functions of both q_o and galactic evolution. The standard approach has been to determine an apparent value of q_o and then to apply an evolutionary correction. Results have so far been inconclusive, partly because the so-called "correction" is theoretically of the same order of magnitude as q_o and uncertain by a similar amount! An alternative approach is to use local cosmological data (density, stellar ages, etc.) to estimate q_o, so that the lookback tests give information on luminosity evolution (Tinsley, 1977b, c; Spinrad, 1977).

It is interesting to see what parameters dominate the results of such tests. Here I extend some earlier results to include a particular form of dynamical evolution: the growth of central cluster galaxies by accretion of smaller members (Ostriker, this conference), under the simplifying assumption that the shape of the cannibal galaxy remains invariant while its characteristic scale (specifically, the Hubble core radius a) grows. Only first-order results will be given; they indicate all the information that can reasonably be sought at $z < 1$.

The rate of dynamical evolution can be expressed in terms of the derivative (at $z = 0$) $f_a \equiv d \ln a/dz$. Note that $f_a < 0$, and may be very roughly estimated as ~ -1 (from the crude model in Tinsley [1977b]). Ostriker and Hausman (1977) give detailed models of this type of evolution and note two empirical tests: (1) changes in a are related to changes in α, the logarithmic slope of the luminosity-radius relation at a given radius r, and (2) qualitatively, more evolved clusters have a greater magnitude contrast between the first and second brightest galaxies, i.e. a lower Bautz-Morgan class. Luminosity changes due to evolution of the stellar population can be expressed in terms of $f_L \equiv \partial \ln L/\partial z$ (stellar evolution). Models predict $f_L \gtrsim +1$; in particular, $f_L > 1.2$ is predicted by models that are consistent with the observed slow color evolution (Tinsley 1977b, c). It can be shown that, to first order, departures of the Hubble diagram from a straight line ($m = 5\log z + \text{const.}$) measure the quantity

$$Q_H = q_o + \frac{2}{2-\alpha} f_L + \frac{2-2\alpha}{2-\alpha} f_a,$$

which is evidently the "apparent q_o" that one would get by ignoring evolution. For example, with $\alpha = 0.6$, $f_L = 1.2$, $f_a = -1$, one would find $Q_H = q_o + 1.1$. A similar analysis of the isophotal diameter-redshift relation shows that the "empirical" quantity determined is

$$Q_S = q_o + f_L + \frac{r-a}{r+a} f_a;$$

e.g. $Q_S = q_o + 0.4$ at $r/a = 10$ with the above parameters. Interestingly, the same quantity Q_S is determined by Spinrad's (1977) "metric surface brightness" (SB) test; the SB of a galaxy is measured at an angular radius that would correspond to a fixed metric radius if q_o had some chosen fiducial value (cf. Tinsley, 1976). Note that the three tests have similar relative sensitivities to q_o and the two types of evolution. In particular, the Hubble diagram is not especially favored as a test for q_o and metric SBs are not especially good cosmology-independent measures of evolution.

A hope for the future is to check theoretical predictions of the evolution of elliptical galaxies using lookback data. We need, first, accurate enough estimates of q_o from local data and well-determined relations between magnitude, SB, etc. and redshift. Scatter and selection biases in currently available data preclude any detailed comparisons yet, but the situation is promising.

Counts of galaxies to limiting magnitudes $> 18^m$ are sensitive to luminosity evolution of field galaxies and they are very insensitive to q_o; thus counts are a promising probe of evolution - as has long been clear in radio astronomy. K-dimming is predicted to reduce the counts at 24^m by a factor ~ 20 below the "static Euclidean" value $N_o \propto \text{dex}(.6m)$. It is therefore remarkable that Kron (1977) finds almost the Euclidean slope for the N-m relation at a blue limit $m_B = 24$. The exact interpretation is complicated by uncertainties in the ultraviolet spectra of galaxies (i.e. in the K terms), but these preliminary data almost certainly reflect luminosity evolution. An extensive study of the color-magnitude distribution of faint galaxies is in progress, by Kron and others, from which important information on evolution can be expected.

3. PRIMEVAL GALAXIES: ARE THEY VISIBLE YET?

The possibility of detecting very young galaxies undergoing a brilliant first flash of star formation was explored theoretically by Partridge and Peebles(1967a). Their models predicted objects with very high luminosities, because a large fraction of each galaxy's mass was supposedly made into stars in $\lesssim 10^8$ yr; they would be of uniform surface brightness, with angular diameters $\sim 10''$, and there would be thousands per square degree on the sky. Subsequently, Partridge (1974) and Davis and Wilkinson (1974) searched for primeval galaxies (PGs) with such properties. Their negative results set limits on possible redshifts and luminosities, and have been useful in testing later PG models.

Kaufman and Thuan (1977) constructed models for the formation of stars in massive galactic halos. The primeval halos would not have been detected unless q_o is $\gtrsim 0.5$. As yet, massive halos are no more visible in their formative stages than around nearby galaxies!

Models for giant elliptical PGs with a very different appearance have been developed by Meier (1976a, b). Based on Larson's (1974) collapse models for the formation of ellipticals, these PGs reach their brightest stage after they are already nearly as centrally condensed as an E galaxy, and their star formation takes longer than in Partridge and Peebles' models, so they would look smaller and fainter. If the bright stage occurred two free-fall times after the big bang, they would have been too faint for the foregoing searches to detect. But if the collapse occurred later, these PGs would be bright enough but with almost stellar images, so the searches would have rejected them. Meier suggests that some so-called quasars - with suitable thermal spectra and no variability - might in fact be PGs.

The models suggest that only massive and late-forming galaxies may be visible as PGs. If many galaxies form at redshifts < 5 and make a large fraction of their stars in an early burst, they would show as pronounced excesses in galaxy counts at certain magnitude levels (Tinsley 1977a) - unless of course they were discounted as stars. But now I argue that maybe few young galaxies had very high star formation rates.

The UBV colors of typical Sc and later galaxies are consistent with a constant star formation rate (SFR), and any substantial past enhancement in the rate would lead to too red colors (Larson and Tinsley 1978) - unless of course only massive stars formed at early times. Similarly, earlier spirals can have had somewhat higher SFRs in the past than at present, and E/SOs have UBV colors consistent with negligible star formation for the last several Gyr. Thus if the first generations of stars had a normal mass spectrum, present colors indicate that only Es and SOs can have been very bright as PGs, and only for ellipticals do dynamical arguments strongly favor rapid formation. The formation of disc galaxies by gradual collapse and star formation is at least consistent with their general morphology (Larson 1976) and with various chemical

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and kinematic properties (Tinsley and Larson, in preparation); it is also relevant that the average age of disc stars in the solar vicinity appears to be less than 5 Gyr (Demarque and McClure, 1977).

The following picture is therefore suggested. Later types of spirals have had almost constant SFRs, so their luminosities have increased continuously (Fig. 1). Earlier spirals have had SFRs decreasing on time scales of several Gyr, leading to an increase in luminosity for much of the lifetime followed by a moderate recent decline (an example is shown in Fig. 1). SO galaxies are former spirals in which star formation has been cut off; their luminosities must drop rapidly thereafter, so they were brightest near the cutoff time. Only ellipticals made nearly all their stars during the initial collapse; their early luminosities were high, in inverse proportion to the time available for star formation. The cases illustrated in Figure 1 show that only SOs with early cutoffs and ellipticals would be bright enough when young to qualify as PGs. SOs with later cutoffs would appear as luminous blue objects at intermediate redshifts (see upper scale, for example); these are candidates for the excess blue galaxies found in clusters and in the field (§ 1).

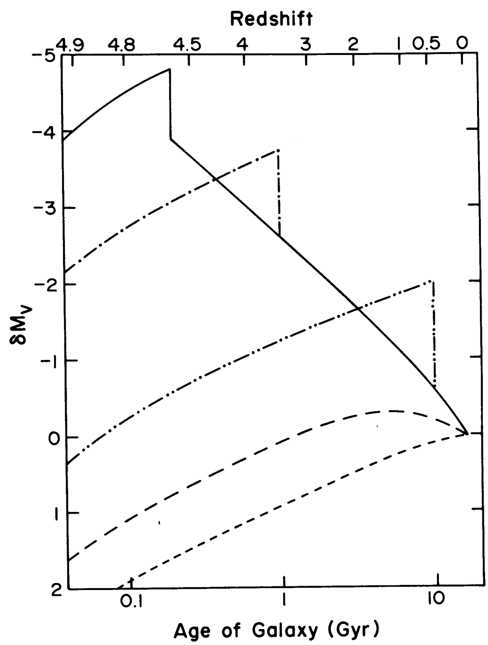

FIG. 1. Evolution of absolute magnitude, relative to its present value, in typical galaxy models consistent with observed colors. Upper scale: redshift for q_o=0.02, H_o=50, and formation at z_F=5. Short dashes: constant SFR (late spiral). Long dashes: SFR $\propto$ exp(-age/15 Gyr) (early spiral). Other lines: constant SFR to cutoff age τ_c = 0.2, 1, or 10 Gyr, dropping to a model with SFR = 0 thereafter (E/SO galaxies).

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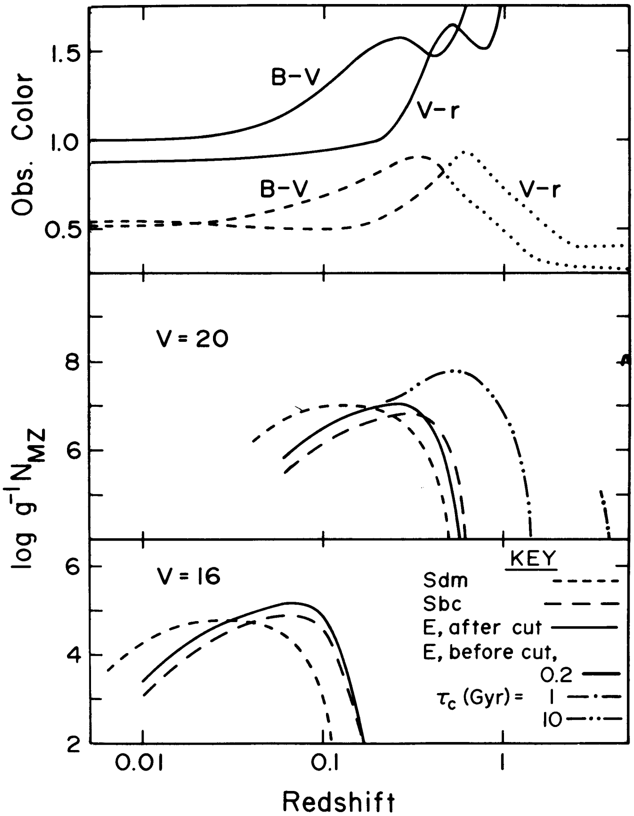

FIG. 2. Center and bottom panels: computed redshift distributions for galaxies at m_V = 16 and 20 respectively. Ordinate is no. per unit mag. and unit log z (with a fudge factor g $\stackrel{\sim}{<}$ 1, depending on the normalization to bright galaxy counts). Representative spirals and E/SOs are shown; see key. Each E/SO alternative is scaled as though all were cut simultaneously. Upper panel: colors, including K-corrections and evolution, for the reddest and bluest galaxy models. Solid lines: E/SOs after cutoff (no star formation); broken lines: constant SFR.

Figure 2 shows some consequences of this scenario for the redshift and color distributions of galaxies (Tinsley, in preparation). At m_V = 16, the z distribution of each type of galaxy is simply a smooth reflection of the width of its luminosity function, and the observed range of colors depends mostly on K-corrections, with evolutionary changes < 0.05 mag. At m_V = 20, the spirals (dashed lines) and E/SOs after cutoff (thin solid lines) are still well-behaved. But the latter types before cutoff contribute various features depending on the cutoff age τ_c

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(see key on figure). Note that the colors before cutoff could be as blue as those shown by the broken lines in the top panel, but after cutoff they would rapidly become as red as the solid lines. Rather than the sharp features illustrated, one might expect a range of cutoff ages; perhaps there would be some very bright primeval ellipticals near the formation redshift, and active proto-S0s at a great range of redshifts.

Redshift data for a sample of the faint blue galaxies seen by Kron (§1) would be very valuable for testing this type of picture. Another handle on the early luminosities of galaxies comes from the extragalactic background light (EBL), which is the last topic to be discussed.

4. THE EXTRAGALACTIC BACKGROUND LIGHT

Dube et al. (1977) have measured an intensity of $1.0 \pm 1.2\ S_{10}$ (10^m stars per square degree) for the EBL at 5100 Å. On comparison with published models, they found this low value to be consistent either with galaxy formation so early that almost all emission from PGs is redshifted beyond visible wavelengths (Partridge and Peebles, 1967b), or with a closed cosmological model in which the lives of galaxies are too short for later emission to contribute too much light (Tinsley 1977a). A third alternative, suggested by the discussion in § 3 above, is that only a small fraction of galaxies were bright when young. (Note that, in contrast to Figure 1, both sets of models considered by Dube et al. assumed that all galaxies were maximally bright near formation time.)

Using galaxy models like those illustrated in Figure 1, with SFRs consistent with present colors, I have predicted the EBL for a variety of formation redshifts, cutoff ages for E/S0s, etc. In all cases, the visual EBL is at least 3 times fainter than predicted by the corresponding models in Tinsley (1977a). Normalizing the local luminosity density to reproduce counts of bright galaxies, I predict intensities of 0.6 – 1.5 S_{10}, <u>even</u> with an open cosmological model (q_o=0.02, galaxy ages $\gtrsim$ 13 Gyr) and with formation redshifts as low as 2 to 5.

The conclusion is that if E/S0 galaxies alone were much brighter in the past, a visual EBL $\sim 1\ S_{10}$ does not demand very short-lived galaxies and/or very high formation redshifts. This possibility gives a footnote to the solution of Olbers' Paradox mentioned in § 1: perhaps the sky is very dark because most stars are much younger than the oldest ones.

5. CONCLUSION

At last, lookback observations confirm that the stellar populations of galaxies change with time. Color changes in ellipticals correspond to the predicted evolution of the main-sequence turnoff point, and excess blue galaxies in distant clusters and faint field samples indicate that many S0s were actively forming stars in the visible past.

Information on the primeval stages of galaxy evolution is still in the form of upper limits to the numbers, formation times, and luminosities (or surface brightnesses) of galaxies that were extremely bright. Theoretical "predictions" for such stages will surely prove to be simply idealizations with which the real primeval chaos can be contrasted. It will be exciting to see what is discovered as observations probe further into the past.

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Note added by the author: In the printed version of my paper I inadvertently forgot to mention that Longair and Sunyaev (IAU Symposium No.74 *"Radio Astronomy and Cosmology"*, 353) developed models for primeval galaxies similar to Meier's models. Longair and Sunyaev also suggested that some "quasars" could be primeval galaxies.

DISCUSSION

Abell: In my paper I showed integral number-magnitude counts in different directions by George Rainey; my purpose was to show the isotropy of the counts. Rainey's counts are in excellent agreement with those of G. S. Brown, and in qualitative agreement with the data we have just seen from 6-m telescope counts. They are not compatible with Dr Tinsley's older strong evolution models, and certainly not with the Euclidean slope that Kron's counts are reported to suggest.

However, contrary to what I said in Paris in 1976, a careful inspection of Rainey's data does show evidence for some evolution. Rainey's counts are roughly halfway intermediate between the predictions of the no-evolution Friedmann models and the Euclidean model. In other words, Rainey's data suggest a conservative amount of galaxian evolution.

Tinsley: It sounds as though Rainey's data may give some support to the models I have discussed here, because they predict a rather small evolutionary enhancement in the counts at magnitudes fainter than 22^m in blue light or 20^m in red light. (Details will be published elsewhere.) The main uncertain parameters in the calculations are the UV spectra (K-corrections) of E/S0 galaxies, and the range of redshifts at which star formation takes place in E/S0 galaxies.

Bolton: I now understand the point of your question to me this morning! From the few redshifts we obtained of UVX galaxies between 19^m and 20^m the absolute luminosities of these objects are of the same order as strong radio galaxies.

Ostriker: Didn't Sargent and Searle draw the same conclusion that the rate of star formation was relatively constant from the colours of spiral galaxies?

Tinsley: Yes. I did a similar calculation in 1968 but I did not realise that it was a theorem!

Zeldovich: In your models do you take account of the evolution of the chemical composition of galaxies? What would be the result if galaxies consisted only of hydrogen and helium and no heavy elements?

Tinsley: If galaxies consisted only of hydrogen and helium they would be much bluer. However, since the stars in most of the galaxies we see have normal chemical compositions, they probably formed from material with the same element abundance. For any reasonable change in the

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chemical composition, the changes to the models would be small.

Gott: Spiral galaxies consist of both spheroidal and disk components. The spheroidal bulge components look just like elliptical galaxies (i.e. colours,velocity dispersions, light distributions as a function of luminosity are the same). If primeval elliptical galaxies are 100 times brighter than at present, wouldn't one expect that the bulge components of spiral galaxies would be similarly brighter in the past and dominate the total light of the spirals? Wouldn't this make all galaxies brighter in the past?

Tinsley: This is an interesting question and the answer is a bit surprising. The light of the bulge is included in the integrated colours of a spiral galaxy, so the limit that we get from colours of the past star formation rate includes early, rapid formation of the bulge. For example, I showed the luminosity evolution of an early (Sb) spiral with an exponential star formation rate; a very similar result would be obtained if star formation was an initial burst followed by a constant rate, scaled to give the same present colours. The system would get brighter during most of its life and never be much brighter than at present. Pushing as much star formation as possible into rapid bulge formation, I still get only 50% more EBL than in the cases illustrated here.

Chernomordik: How can you explain in your model the deficiency of G-dwarfs with low metal abundance in the disk of the Galaxy?

Tinsley: There are several ways of explaining the paucity of metal-poor stars in the solar neighbourhood. The idea suggested by Schmidt (1963) was an initial burst of massive stars; Dr Chernomordik's question refers to the fact that my current models for disk galaxies do not have such a burst. An alternative explanation of the G-dwarf metallicities involves infall of metal-poor gas (Larson, *Nature Phys. Sci.* 1972). The models I discussed here for slow disk formation, although not explicitly dependent on any gas flows, could be associated with dynamical models of disk formation by infall, which would be consistent with the metallicity distribution. Larson and I have calculated some detailed models (preprint) that illustrate this statement. To summarize, there is no inconsistency between the models I use here of disk galaxies and the empirical metallicities of stars in the solar neighbourhood.

Silk: One may have difficulties in appealing to ram pressure stripping to account for the colour evolution at redshifts as low as 0.4, because a considerable number of characteristic galaxy crossing times (the relevant time-scale for stripping) have already occurred in a cluster at this redshift. Another possibility may be due to the effects of enhanced star formation that follows the accretion of intracluster gas.

Would you comment on the effect of assuming different forms for the initial mass function of your models?

Tinsley: This is another way of saying the same thing. The blue galaxies are seen at a redshift z = 0.39 and these must turn into systems like Coma by the present day. We have considered models similar to the one you describe. In answer to the question, the only drastic effect of changing the initial mass function is that you can make young galaxies as bright as you like and not affect the present colours.

Jaakkola: A difference in the colour distribution between the Coma cluster and some distant clusters was your empirical argument in favour of evolution of galaxies over cosmological distances. Now there must be serious selection effects present, making a cluster at z = 0.95 - which is the only one observed out of the thousands at that distance - uncomparable with Coma which is our nearest cluster. I remind you in passing that Zwicky mentions in *Morphological Astronomy* ten parameters of galaxies and of clusters which are similar at large and at small distances.

Tinsley: I believe that the clusters studied by Butcher and Oemler were selected for study because of the radio or optical luminosity of their first-ranked galaxies, not because of the blueness of other cluster members. Possibly some such selection effect is present, however, and equivalent data for many more clusters would be welcome.

Suchkov: I would like to make a comment on the IMF which is important for some points discussed by Dr Tinsley. We now have some evidence from the distributions of old population stars in metallicity and in eccentricity, that the IMF in the early Galaxy favours large-mass stars, as was first suggested by Dr M. Schmidt in 1963. This means that a major part of the metal content of the Galaxy was produced during the period of formation and evolution of halo stars, no matter what fraction of the mass of the Galaxy they constitute. This is important for the luminosity evolution of the Galaxy.

Tinsley: Unfortunately I have not had a chance to study Dr Suchkov's data. The models that I have discussed, with a constant IMF, do give stellar metallicities in accord with earlier data on galactic stars (Tinsley & Larson, 1978 preprint).

Sunyaev: There are many observers of quasars here. Therefore I would like to amplify the problem mentioned by Dr Tinsley in her report. We heard how bright elliptical galaxies might be in the early stages of their evolution when they were young and had a lot of bright hot stars. Their luminosity during this stage might exceed their present luminosity by 100 or 1000 times. If our Universe is open ($\Omega << 1$), the angular dimensions of the central part of giant galaxies ($\sim$ 10 kpc) may be very small $\lesssim$ 1". Therefore they may appear as quasistellar sources. The next step is: they may be hidden among optically selected quasars. Hence the problem is how we can distinguish "real" quasars from young galaxies. In the case of young galaxies (1) the range of variability must be very small, (2) light must be unpolarized, (3) there may be spectral features common to very hot stars. Young galaxies might be rather bright in the CO line λ 2.6 mm. In the case of young galaxies with $z \approx 3$-5 the line must be redshifted to the waveband 2.6(1+z) mm $\approx$ 1 cm. Observations of this line in the most distant quasars might help to prove if there is a galaxy with stars and gas around them. The line might be rather bright because the galaxy has finite angular dimensions and they must be saturated even in the case of a low abundance of heavy elements.

Huchra: A comment on the Butcher-Oemler result - the clusters were chosen to have similar morphological properties (density, etc.) So the comparison made is not between a Virgo type cluster at z = 0.4 and Coma now - but rather a Coma then.

A complaint I have with your models, however, is that good evidence exists for star formation with an IMF (initial mass function) other than the Salpeter function. People should not blithely use a single value. Your results for the luminosity evolution change drastically with other IMF's, in particular, with a flatter IMF there can be almost no luminosity evolution!

Tinsley: I am fully aware of the sensitivity of my models to the IMF, and of evidence for variations of the IMF from place to place (e.g. see my review in IAU Symposium No. 77). In a 30-minute talk, one has to sound blithe about complicated issues! There are several reasons for showing here models with an invariant IMF. (1) The colours of "normal" galaxies are consistent with the local (solar-neighbourhood) function holding in typical cases (as I showed in 1968 and has been emphasized by others since). Therefore this seems a useful first approximation.
(2) I cannot predict or derive from observations the incidence or nature of departures from the local IMF in the population of galaxies.
(3) Models do not pretend to be exact representations - they are examples of possibilities, and here I have chosen to see what happens with the most economical set of hypotheses. I wanted to discuss the significance of star formation rates, and it would confuse the issue to vary the IMF too. Of course, you are right that one would get different results with different IMFs. (Incidentally, the models discussed here use not the Salpeter power-law IMF, but a more detailed function based on recent stellar statistics.)

Gursky: It is my understanding that a limit on the background light at a particular frequency simply puts the burst of star formation back to an earlier epoch. What is the limiting epoch in this instance?

Tinsley: As described in my paper (and more fully in a current preprint), the EBL in this picture is insensitive to the turn-on redshift. This is because only a small fraction of galaxies have a burst of star formation. A redshift of 2 for the time of first star formation (in all galaxies) does not give too high a background intensity.

Komberg: Do you believe that quasars are the whole galaxies or the nuclei of E galaxies?

Tinsley: The idea that I mentioned, due to Meier and to Sunyaev and Longair, is that the integrated starlight of a young massive E galaxy would look like a quasar. The angular radius of these models of young galaxies would be $\lesssim 1$ arc sec. The authors do not propose that all quasars are young ellipticals, but that some so-called quasars are in fact primeval galaxies. Dr Sunyaev's comment during this discussion amplified these points.

Jones: Given your explanation of the Butcher and Oemaler effect, do we have to come to terms with the idea that galaxy clusters formed as recently as $z \approx 0.5$? The point is that those galaxies have not had their first trip through the central regions of the cluster or are accreting a lot of material.

Tinsley: I think I described approximately Butcher and Oemler's interpretation of their data. None of us has thought of a less surprising explanation.

Jones: Astonishing.

Tinsley: I agree.

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