When did the Large Elliptical Galaxies Form?

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Abstract. The simple reading of the evidence is that the large elliptical galaxies existed at about the present star mass and comoving number density at redshift \( z = 2 \). This is subject to the usual uncertainties of measurement and interpretation in astronomy, but should be taken seriously because it is indicated by quite a few lines of evidence. And it might be a guide to a more perfect theory of galaxy formation.

1. Issues

Current ideas about structure formation suggest roughly half the large elliptical galaxies were assembled at redshifts less than unity. The measurements do not rule this out, as noted in many observational papers, but a far simpler interpretation is that the large ellipticals formed well before \( z = 1 \).

The commonly discussed structure formation theory, \( \Lambda \)CDM\(^1\), certainly deserves careful attention because of its dramatic success in the interpretation of the temperature anisotropy of the 3K thermal cosmic background radiation. But the test is limited, and aspects of the theory seem problematic: small-scale structure (Moore et al. 1999 and references therein) and the void phenomenon (Peebles 2001). The case for early formation of the elliptical galaxies deserves careful attention too, because it is the simple interpretation of an impressively broad range of observations.

The main competing pictures of galaxy formation, at high redshift and low, often are termed monolithic and hierarchical. This makes historical sense\(^2\), but can be confusing, because one can imagine galaxies form by hierarchical growth of structure either at high redshift or low. I will take “formation” to be the assembly of more than half the material now in the luminous parts of a galaxy,

\(^1\)This assumes the mass of the universe is dominated by cold dark matter, with gravitational growth of structure out of primeval adiabatic, Gaussian, and near scale-invariant density fluctuations in a low density cosmologically flat universe. I adopt Hubble parameter \( H_o = 70 \) \( \text{km} \text{s}^{-1} \text{Mpc}^{-1} \), matter density parameter \( \Omega = 0.25 \), zero space curvature, and a cosmological constant that makes fractional contribution \( \Omega_{\Lambda} = 0.75 \) to \( H_o^2 \).

\(^2\)Thus the Partridge & Peebles (1967) fit of the Friedmann-Lemaître cosmology to the Eggen, Lynden-Bell & Sandage (1962) picture for formation of the Milky Way indicates galaxies formed at \( z \sim 20 \). Tinsley (1972) and Larson (1974) pioneered the modern picture for the properties of an elliptical that formed as a galaxy of stars at high redshift. At another extreme, Kauffmann, Charlot, & White (1996) discuss evidence that only about one third of present-day early-type galaxies were assembled at \( z = 1 \), roughly in line with what would be expected in \( \Lambda \)CDM.
gathered within a sphere of radius 30 kpc, let us say. The epoch at which half the present-day stars formed may precede or follow assembly. Either way, galaxy evolution may continue well after formation as defined here. This includes merging of satellite galaxies, as in the Ostriker-Tremaine (1975) “cannibalism” picture, and more major mergers of galaxies that formed in tight pairs, as might be seen in clusters at high redshift (van Dokkum et al. 2000) and low (Struble & Rood 1981). It also includes new generations of stars from gas from the outer parts of the galaxy, or recycled from evolved stars in the “frosting” picture of Trager et al. (2000).

I limit this discussion to the formation of large elliptical galaxies, or in some cases E plus S0 galaxies. There is a lot to be learned from late-type galaxies; of course, but the limitation helps focus the discussion on systems that present us with a fascinating pattern of regularities. The simplicity of the early-type galaxies allows close exploration of rich details of departures from the regularities. Both aspects, regularity and complexity, may prove to be important guides to how and when the galaxies formed and what that might teach us about the physics of our expanding universe.

Since I am more taken by the side of simplicity I should acknowledge here that this certainly is not the whole story: the departures from the patterns reflect significant differences among the histories of galaxies (Toomre 1977; Schweizer 2000). We see this in strongly disturbed late-type systems, whose remnants likely will qualify as new early-type galaxies, in more moderately disturbed ellipticals, that have gained mass by recent accretion or mergers, and in Butcher-Oemler (1984) galaxies, that show us morphological transformations. Aspects of this complexity are reviewed in §2.2.

The issue for the present discussion is whether the examples of late formation show us the main way galaxies formed, or amount to a perturbative effect on physical properties that were established much earlier. Arguments of some years’ standing for the latter are that one sees large elliptical galaxies of old stars at high redshifts (Oke 1971, 1984), and that subsequent formation might be expected to erase the correlations of color and heavy element abundance with luminosity (Faber 1973; Visvanathan & Sandage 1977; Ostriker 1980). The known patterns of regularities among early-type galaxies are much richer now. I devote most of this contribution to a review of the literature of these patterns, because I find them fascinating and surely educational. Just what we might be learning is briefly considered in §3.

2. The Observational Situation

2.1. Patterns at Modest Redshifts

Bower, Lucey, & Ellis (1992), and Terlevich, Caldwell, & Bower (2001) discuss the color-magnitude relation for early-type galaxies in the Coma cluster:

\[ U - V = \text{constant} - 0.08M_V \pm 0.05. \]  (1)

I have taken the slope from Bower et al. and the rms scatter to be intermediate between that observed for E and for E+S0 galaxies. The color-magnitude relation at redshift \( 0.5 \lesssim z \lesssim 1 \) in clusters is analyzed by Ellis et al. (1997) and
van Dokkum et al. (2000; 2001b), and in the Hubble Deep Field, that might be representative of ellipticals in groups, by Kodama, Bower, & Bell (1999). These results offer three constraints on when the ellipticals formed: the scatter of colors is a measure of the scatter of mean ages of the stars in different galaxies, and hence of the typical age; the evolution of the color with redshift is a measure of the epoch of formation of the stars; and the scatter of colors constrains the typical number of generations of random mergers.

The relation between the color and age of a population of old stars is $d(U - V)/dt \simeq -0.025 \text{ mag Gyr}^{-1}$ (from Fig. 33 of Worthey 1994). The scatter in equation (1) thus translates to an rms scatter of mean star ages, $\sigma_t \sim 2 \text{ Gyr}$, if galaxies with the same luminosity have the same metallicity. It is easy to imagine the scatter $\sigma_t$ in ages is larger than the mean galaxy age, $t(z_f)$, as a result of galaxy formation spread over several factors of two expansion, but difficult to imagine the synchronization that would make $\sigma_t$ appreciably smaller than $t(z_f)$ (Bower et al. 1992). In the cosmologically flat model with the parameters adopted here the condition $\sigma_t \gtrsim t(z_f)$ says $z_f \gtrsim 3$. A similar bound follows from the scatter of colors in cluster and group ellipticals at $0.5 \lesssim z \lesssim 1$. This is an underestimate of the bound on $z_f$ if the scatter in color has a contribution from metallicity that is uncorrelated with age, an overestimate if correlated fluctuations in age and metallicity cancel the effect on color.

The second measure is the variation of the zero point of the color-magnitude relation with redshift. The measurements at $z < 1$ match what would be expected if the redshift of formation of the majority of field and cluster ellipticals satisfied $z_f \gtrsim 2$ (Kodama et al. 1999). Van Dokkum & Franx (2001) make the very good point that this measure may be biased by morphological transformations that remove the bluer galaxies from the accepted sample of early types. Arguing against the bias is the consistency with the limit from the scatter of colors. The bias also is tested by the evolution of the luminosity function: if a significant fraction of present-day early-type galaxies entered the ranks at $z < 1$ then counts of early-type galaxies would show a deficit at $z = 1$. Kauffmann, Charlot, & White (1996) find evidence for this deficit. But in the deeper and perhaps more secure Groth HST Strip, Im et al. (2000) find little evidence for evolution in the numbers of early-type galaxies back to $z = 1$, after allowance for the luminosity evolution expected for old star populations.

The third measure is less constraining but worth considering. If three identical elliptical galaxies on the mean color-magnitude relation merged to form an elliptical with three times the luminosity (and the stars where the colors are measured, at projected radius $\sim 4 \text{ kpc}$ in Bower et al. 1992, fairly sampled the progenitors), it would produce an elliptical that is two standard deviations off the mean relation for galaxies that had avoided this round of merging. In the Kauffmann & Charlot (1998a) selective merging picture the color-magnitude and other correlations can survive a considerable number of generations of mergers because large galaxies tend to merge with large galaxies and small with small, with limited scatter in the numbers of generations of mergers. This is suggested by the CDM theory for structure formation, and certainly could happen at high redshift. But it is hard to see how merging could be selective at the present epoch because maps of the nearby galaxies show large and small are intermingled. Pending more detailed observations of the situation at $z = 1$,
and analyses of models for random merging, I would guess the tightness of the color-magnitude relation says fewer than half the ellipticals can have undergone three major mergers since formation.

Similar considerations apply to the fundamental plane and luminosity-size relations. For early-type galaxies in clusters Jørgensen, Franx, & Kjærgaard (1996) find

\[ L \propto M^{0.76} r_e^{0.02} e^{0.23}, \]

where \( L \) is the \( r \)-band luminosity, the mass is \( M \propto r_e \sigma^2 \), the half-light radius is \( r_e \), the velocity dispersion is \( \sigma \), and the last factor in equation (2) is the rms scatter of individual galaxies from the mean relation. This scatter is thought to be dominated by intrinsic differences among galaxies. If the difference is a scatter in ages then the relation between luminosity and age in an old star population, \( d\ln L/d\ln t \simeq 0.8 \) (Tinsley 1972; Worthey 1994), translates to scatter \( \sigma_t = 4 \) Gyr in ages. If \( \sigma_t \gtrsim t(z_f) \) this says \( z_f \gtrsim 1.8 \), comparable to the constraint from the evolution of zero point of the color-magnitude relation.

From the fit of the fundamental plane relation to cluster galaxies at redshifts \( z < 0.6 \), Jørgensen et al. (1999) find that the mass-to-light ratio varies with redshift about as expected for the evolution of a star population that formed at redshift \( z_f \gtrsim 2.5 \). The fundamental plane relation for ellipticals in groups is observed to be quite similar to that of cluster ellipticals (Kochanek et al. 2000; de la Rosa, de Carvalho, & Zepf 2001; van Dokkum et al. 2001a), and yields a similar bound on the redshift of formation of the stars.

The luminosities and radii of elliptical galaxies, in clusters and the field, are correlated as

\[ L_B \propto r^{1.33}. \]

The evolution of the luminosity zero point with redshift again agrees with the evolution of a star population that formed at redshift well above unity (Barger et al. 1998; Ziegler et al. 1999; Schade et al. 1999).

As for the color-magnitude relation, we can consider the effect of merging on the fundamental plane and luminosity-size relations. The constraint based on equation (2) is not demanding but worth recording. If three identical ellipticals with radii \( r_i \), all on the fundamental plane, merged to form an elliptical with radius \( r_f \), the resulting galaxy would be off the fundamental plane by the factor

\[ L/L_{FP} = 1.30(r_i/r_f)^{0.02}. \]

This is only 1.3 standard deviations, and not very sensitive to the ratio of initial to final radii. If three identical galaxies on the size-luminosity relation merged to form a galaxy on the relation, the final radius would be \( 3^{0.75} \) times the initial radius. One can imagine this is the natural value for the effect merging has on radii, but one might imagine the kinetic energy of relative motions of the galaxies is a random variable, that perturbs the final radius and adds scatter to the luminosity-radius relation. Veeraraghavan & White (1985) show that mergers of spirals can produce a reasonable approximation to the elliptical luminosity-velocity dispersion relation, and Hibbard & Yun (1999) show examples of galaxies in the late stages of mergers that are likely to end up with the light profiles characteristic of elliptical galaxies. Advances in the theory of radii of merger remnants will be useful.

The merger rate is constrained also by the chemistry of large ellipticals. This elegant application of astrophysics uses the difference of time scales for
production of the iron group elements by thermonuclear burning in Type Ia supernovae, on the order of 1 Gyr, and the considerably more rapid production of $\alpha$-elements in massive Type II supernovae (Thomas, Greggio, & Bender 1999; Pagel 2001). It is reckoned that about two thirds of the iron group elements in the Sun came from Type Ia supernovae. This suggests the material now in the thin disk of the Milky Way galaxy experienced 1 Gyr or more of star formation and element enrichment before large-scale star formation in the thin disk. In ellipticals, the abundance of magnesium and the abundance ratio $\text{[Mg/Fe]}$ are correlated with the velocity dispersion, $\sigma$, and at large $\sigma$ is larger than solar (Jørgensen 1999; Colless et al. 1999). This is consistent with formation of large ellipticals on time scales less than 1 Gyr, as would happen if the ellipticals formed at $z_f \gtrsim 6$. The $\text{[Mg/Fe]}$ relation is not so easy to reconcile with the idea that ellipticals form by merging of spirals of stars with systematically lower $\text{[Mg/Fe]}$ (Thomas et al. 1999).

Finally, in early-type galaxies and the bulges of spirals the star velocity dispersion correlates with the black hole (or very compact) mass in the nucleus (Ferrarese & Merritt 2000; Gebhardt et al. 2000). As we have noted, at $z < 1$ large and small galaxies are intermingled, so merging would broaden the relation. That is avoided if merging is followed by significant black hole growth by accretion, at a rate that might be controlled by the velocity dispersion. But arguing against late growth is the existence of radio galaxies and quasars at high redshift, that presumably operate with black holes similar to those in radio galaxies at lower redshifts.

### 2.2. Observations of Galaxy Formation at Low Redshift

Interactions among galaxies, and of galaxies with extragalactic gas and plasma, certainly have affected the population of ellipticals at $z < 1$; some aspects are reviewed here.

Arp’s (1966) Atlas of Peculiar Galaxies shows examples of strongly disturbed late-type systems that surely will merge. What else could that produce but elliptical galaxies (Toomre 1977; Schweizer 2000)? The nearby large elliptical galaxy NGC 5128, or Centaurus A, has a prominent disk of dust and gas, a clear example of a recent merger that added about 10% to the star mass (Israel 1998). Centaurus A may eventually merge with the other five spiral members of the group, plus an S0 and some 20 dwarf and generally gas-rich irregulars (Côté et al. 1997). That seems likely to have a deleterious effect on the fit of Centaurus A to the patterns discussed in §2.1. Silva & Bothun (1998) show elegant examples of field ellipticals that may have gained small central disks by merger-driven starbursts a few Gyr ago, but they note that this applies to a minority of ellipticals, and may qualify as frosting. I have not found an estimate of the fraction of large galaxies at low redshift that show distinctive signatures of a substantial gain of mass — on the order of a factor of two — from recent mergers. The commonly encountered list of prime candidates is not long.

There are young stars in ellipticals. The fits of line strength indices to single-age star population models yield a considerable scatter of ages of nearby early-type galaxies (Jørgensen 1999; Trager et al. 2000). The indices are sensitive to young stars, and show there has been significant recent star formation. In the frosting model of Trager et al. (2000) about 20% of the stars in the central
parts of nearby early-type galaxies are \( \sim 5 \) Gyr old, forming at \( z \sim 0.5 \), the rest substantially older. Menanteau, Abraham, & Ellis (2001) find that the central parts of about half the field ellipticals at redshifts \( 0.4 \lesssim z \lesssim 0.8 \) are relatively blue, indicating recent star formation, again in the amount of a few tens of percent of the star mass. The effect is not seen in ellipticals in clusters, in line with the idea that field ellipticals are better able to retain gas shed from evolving stars, that can make new generations of heavy element-rich stars. Zepf (1997) made the excellent point that if large ellipticals existed at \( z > 1 \) in numbers comparable to today their colors would have to have been affected by ongoing star formation, in clusters and the field, because galaxies with the red colors of a pure old population are rare at \( z > 1 \). This ongoing star formation is a not unreasonable extrapolation of what is observed at lower redshift, of course. I have not seen an observationally based estimate of the redshift at which this ongoing star formation might integrate to half the star mass in a typical elliptical.

Measurements of the fraction of S0 galaxies in clusters show a distinct decrease from \( z = 1 \) to the present (Dressler et al. 1997; van Dokkum et al. 2001b). Following Dressler et al., one can imagine some cluster spirals, particularly those that already have colors similar to early-type galaxies, transform morphology to S0 as a result of disturbances by galaxies and the intracluster medium, preserving the color-magnitude relation and modestly disturbing counts of early-type galaxies. This is a clear demonstration of the effect of environment on morphology, but not necessarily an example of galaxy formation at \( z < 1 \).

### 2.3. The Situation at Redshift Three

This topic is left to last, as most speculative. But the striking regularity of the \( K \)-band apparent magnitude-redshift relation for radio galaxies beyond \( z = 3 \) surely is telling something of value about galaxy formation.

The relation was discovered by Lilly & Longair (1984) for 3CR radio galaxies. The colors of these objects at \( z < 0.5 \) are consistent with large present-day ellipticals, and at \( z \sim 1 \) the \( r - K \) colors are consistent with Bruzual’s (1981) models for luminosity evolution with modest ongoing star formation. Van Breugel et al. (1998), Willott, Rawlings, & Blundell (2001), and Jarvis et al. (2001) show the \( K \)-band magnitude-redshift relation extends beyond \( z = 3 \), without much increase in scatter at higher redshift. At high redshift the optical and radio images tend to be aligned, a sign of significant star formation or non-stellar light associated with the radio activity. But the colors and \( K \)-band magnitude-redshift relation to \( z = 3 \) are consistent with the evolution of star populations that mostly formed at higher redshift, in giant galaxies of stars. Consistent with this, a close examination of the spectra of two radio galaxies at redshift \( z \simeq 1.5 \), by Nolan et al. (2001), indicates “star formation in at least these particular elliptical galaxies was completed somewhere in the redshift range \( z = 3 - 5 \).” The Nolan et al. constraint from spectra would allow the galaxies to be in pieces at \( z = 3 \), provided the subsequent assembly respected the patterns reviewed in §2.1, but this is not consistent with the redshift-magnitude relation.

Since the star masses in high redshift radio galaxies seem to be close to the largest present-day ellipticals, it is reasonable to assume these galaxies and their central black holes generally have not grown much by merging or accretion since \( z = 3 \). It seems reasonable also to suppose quasars at \( z = 6 \) are associated
with massive black holes, but more a matter of speculation whether at \( z = 6 \) the black holes are already clothed with the present complements of stars at the present velocity dispersion.

We have a measure of the numbers of radio-quiet ellipticals at \( z \sim 3 \) from the deep rest-frame optical counts of Rudnick et al. (2001). They conclude that if galaxies were conserved and their \( B \)-band luminosities a factor of about three larger at \( z = 3 \) than now it would about match the observed counts. The factor of three would bring the the \( B \)-band luminosity of the group elliptical Centaurus A to \( 10^{10.7} L_\odot \), and the cluster elliptical M 87 to \( 10^{11.3} L_\odot \). These are within the limit of the Rudnick et al. survey. Thus the assumption that giant ellipticals are as abundant at \( z = 3 \) as now would be consistent with the Rudnick et al. counts if the factor of three evolution of luminosity were astrophysically reasonable and the counts were not dominated by something else. In the cosmology adopted here the ages of stars that formed at very high redshift are \( t_3 = 2.3 \) Gyr at \( z = 3 \) and \( t_o = 14 \) Gyr now. Following Tinsley (1972), the evolution of luminosity is \( L_3/L_o \approx (t_o/t_3)^{0.8} = 4 \). Worthey (1994) gives a similar factor for \( L_B \). Within the uncertainties, this seems consistent with the Rudnick et al. (2001) factor of three. That is, by this simple argument the counts are consistent with the assumption that large ellipticals are conserved back to \( z = 3 \). On the other hand, the passive evolution model of Kauffmann & Charlot (1998b) predicts the galaxy counts at \( z = 3 \) are well in excess of the observation. I await instruction on whether parameters might be tuned to fit the passive evolution model to the Rudnick et al. counts, as the simple estimate of luminosity evolution suggests might be possible.

The hypothesis of conserved ellipticals also is challenged by the star masses in Lyman-break galaxies at \( z \sim 3 \). Estimates of star masses in the two nearby large ellipticals are

\[
M_{\text{star}}(\text{CenA}) \approx 10^{11.0} M_\odot, \quad M_{\text{star}}(\text{M87}) \approx 10^{11.5} M_\odot.
\]

The former is from Mathieu, Dejonghe, & Hui (1996); the latter assumes the same ratio of star mass to luminosity. Papovich, Dickinson, & Ferguson (2001) find the spectral energy distributions of Lyman-break galaxies at \( z \sim 3 \) are consistent with star masses in the range \( 10^9 M_\odot \lesssim M_{\text{star}} \lesssim 10^{11} M_\odot \). This reaches the mass of Centaurus A but not M 87. The straightforward interpretation is that the large ellipticals were assembled as galaxies of stars at \( z < 3 \). The evidence is that radio elliptical galaxies formed earlier, however, and Papovich et al. (2001) caution that estimates of the masses of old stars are subtle. Further exploration of this approach to an upper bound on the redshift of assembly of ellipticals as large as M 87 will be followed with interest.

## 3. So When did the Large Ellipticals Form?

What does the ΛCDM theory predict? Application of the theory on the scale of galaxies is difficult because the behavior is complex. Here are three aspects of analyses of the behavior.

First, in the ΛCDM simulations of Nagamine et al. (2001) the mean galaxy mass-to-light ratio in the \( B \)-band has changed by about one magnitude from \( z = 1 \) to the present, close to pure passive evolution of an old star population.
Second, Thomas & Kauffmann (1999) find that the abundance of ellipticals at \( z = 2 \) is predicted to be less than about one third of what it is now. Third, Baugh et al. (1998) find that the predicted comoving number density of galaxies with star mass \( \sim 10^{11} M_\odot \) has increased by a factor of about 50 since redshift \( z = 2 \), and because evolution is expected to be more rapid at larger mass this would say the number of elliptical galaxies with masses in the range of equation (4) is down by at least two orders of magnitude at \( z = 2 \). The Nagamine et al. (2001) result is in quite satisfactory agreement with the measurements of the fundamental plane as a function of redshift; it shows us the tests for early formation must be considered with caution. The Baugh et al. (1998) result suggests that if it were established that more than half the large ellipticals, at the range of star masses in equation (4), are present at \( z = 2 \), it would mean ΛCDM has to be adjusted. But impressions can change, and we will be following developments.

What do the observations say? The straightforward interpretation of the measured variations with redshift of the color-magnitude, fundamental plane, size-magnitude, and \( K \)-band magnitude-redshift relations is that the large ellipticals in groups and clusters had already formed by redshift \( z = 2 \). This relatively early formation is consistent with the straightforward interpretation of the tightness of the relations between color and magnitude, [\( \alpha/Fe \)] and luminosity, and velocity dispersion and central black hole mass. As we have noted, Kauffmann-Charlot (1998a) correlated merging can keep these relations tight, but the predicted segregation of large and small galaxies is not seen at low redshift. Exploration of the situation at \( z \sim 1 \) will be useful for analyses of the effects of mergers and to test the ΛCDM prediction that large and small galaxies are segregated at formation.

Within the still substantial uncertainties of interpretation of the observations and the theory ΛCDM is viable. But it certainly seems to have problems with the epoch of galaxy formation, as well as the formation of structure on smaller scales and the void phenomenon on larger scales. One might also wonder about its application to the cosmological tests, for it suggests a value of the mean mass density that seems high compared to the measurement from weak gravitational lensing (Wilson, Kaiser, & Luppino 2001). We have to straighten all this out before we can claim to have arrived at a new era in cosmology, where we can be reasonably sure we know what we’re talking about.

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When did the Large Ellipticals Form?

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