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ENERGY DISTRIBUTIONS AND THE FORMATION TIMES OF SPHEROIDAL POPULATIONS

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Abstract

I review recent progress in exploring the formation times of spheroidal stellar populations (elliptical galaxies and large spiral bulges) using spectrophotometric techniques. A quickly growing body of evidence shows that although massive spheroids can form at early times, there are strong environmental dependencies, and major transitions in star formation histories and even morphologies are detectable to surprisingly small redshifts ($z \sim 0.2$). These features are consistent with neither the strict monolithic collapse nor hierarchical merging scenarios. Restframe UV observations are a promising means of improving our understanding of spheroid evolution.

1 Introduction

Unlike the highly varied stellar populations of spiral disks, the spheroidal populations found in elliptical galaxies and the bulges of large spiral galaxies are outwardly homogeneous. Over 80% of bright nearby spheroidal populations have similar, cool energy distributions and smooth spatial light distributions, suggesting that they are if not entirely quiescent at least in a phase of slow evolution. Since spheroids are dynamically hot systems, cool gas (from internal or external sources) cannot survive long within them. It will be quickly transformed either into stars or into a high temperature atmosphere which is resistant to further star formation. Spheroidal populations therefore reflect physical conditions in the distant past better than any other galaxy populations, and they have always been appealing as a means to test the early evolutionary history of galaxies.

Enough information on spheroidal populations at high redshifts is now becoming available to attempt to test scenarios for galaxy formation. Two extreme pictures have been under discussion for many years. In *monolithic collapse*, spheroids represent large initial perturbations and were the first massive stellar systems to form. This occurred at high redshift ($z \gtrsim$ 5-10) in roughly synchronized, intense, short-lived bursts of star formation. Spheroids evolved predominantly in isolation, and their masses did not change much after the initial collapse. A strong prediction of this picture is that evolution of the luminosities, luminosity functions, and spectra of spheroids should be strictly passive (i.e. without significant star formation) at lower redshifts.

In *hierarchical merging*, spheroids are less fundamental. They grow through stochastic assembly from small amplitude seed systems, often disks. Spheroid formation continued for an extended period to relatively low redshifts, involving strong environmental interactions between fragments and punctuated by star formation bursts if these contain any gas. Masses of spheroids increased with time. In this picture, the approach to a state of passive evolution will depend on the environment, happening earlier in denser regions. Models for regions typical of the present-day, low-density field tend to predict that strong evolution should be detectable at relatively low redshifts $z \sim 0.5$–1.

In this review I discuss recent progress made in exploring the formation times of spheroidal populations using their spectral energy distributions. Important questions include: what is the earliest verifiable formation time for a spheroidal population? what is the range of formation times? and what is a typical star formation history?

2 Spectrophotometric Tests of Formation Time

A comparison of the integrated spectral energy distributions (SEDs) of a young (30 Myr) and old (10 Gyr) population is shown in Figure 1. The SED of the younger system rises sharply to shorter wavelengths. It is relatively smooth, showing (at this resolution) mainly the stronger hydrogen absorption lines and continuum discontinuities. In the units plotted, the older SED is flat above 4500Å but exhibits a "blue precipice" with increasing slope at shorter wavelengths with very strong absorption features, mostly blends of metallic lines. The younger SED is produced almost entirely by main sequence stars at wavelengths below 8000 Å. In the older SED, red giant branch stars dominate for wavelengths > 5000 Å. Since the temperature and luminosity function of the RGB evolves only slowly, so does this part of the older SED. However, for $\lambda < 4000$ Å, over 75% of the light in the old SED comes from the main sequence (near 1 $M_\odot$), which evolves faster.

The characteristic flat spectrum with a blue dropoff is a readily identifiable signature of any population older than ~ 0.5 Gyr and has been widely used in searches for evolved systems at high redshifts. (Dropoffs in younger SEDs caused by the Lyman discontinuity at 912 Å or the Lyman forest below 1216 Å can look qualitatively similar in low S/N data but are usually distinguishable by the slope longward of the cutoff.) The pronounced structure of the blue precipice also permits good determinations of photometric redshifts from low resolution data.

The spectra in Fig. 1 are normalized at the V-band and do not reflect the difference in light-to-mass ratio for different ages. Because of the rapid decline in brightness as the main sequence burns down, the older spectrum would be 140 times fainter than the younger one for a given mass of stars with a normal initial mass function. By the same

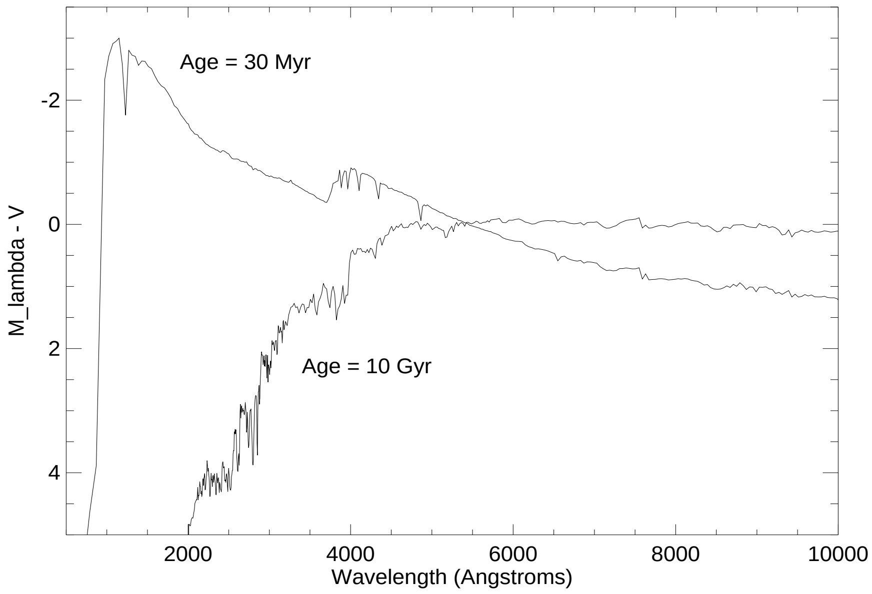

Figure 1: Comparison of energy distributions for a young and old stellar population. SED units are flux per unit wavelength converted to magnitudes. Normalized here at 5500 Å, but the young population is 140 times brighter per unit mass. Taken from the synthesis models of [7]. See text for further details.

token, however, the cool SEDs of older systems permit sensitive detection of tiny amounts of recent star formation at UV wavelengths. Referring to Fig. 1, we see that a 30 Myr-old SED would be easily detectable below 2000 Å in the spectrum of a predominantly old system even if it contributed only 1% of the V-band light. For a normal IMF, a young component of this amplitude would contain only 0.01% of the galaxy's mass.

The strengths and weaknesses of testing galaxy formation times using their SEDs are illustrated in Figure 2. This shows a hypothetical distribution of galaxy *light-weighted ages* (at an arbitrary wavelength) as a function of redshift. Two intrinsic limitations of SED methods are obvious: first, SED methods cannot probe the *mass*-weighted ages in which we are most interested. Second, time scales derived from SED analysis refer only to star formation, not to possible dissipationless assembly of systems at later times.

A less obvious difficulty is that younger stars dominate the light of a galaxy if there has been significant recent star formation, regardless of the actual age of the oldest populations. Because of this swamping of the older light, only poor constraints can be placed on earlier star formation in systems containing multiple generations of stars. Unfortunately, this limitation implies that most of the region inside the boundaries shown in Fig. 2 is not useful in constraining the early history of galaxies.

The best tests of formation times lie at the upper and lower envelopes in Figure 2. First, one can search directly for starbursting primordial systems at or near their formation

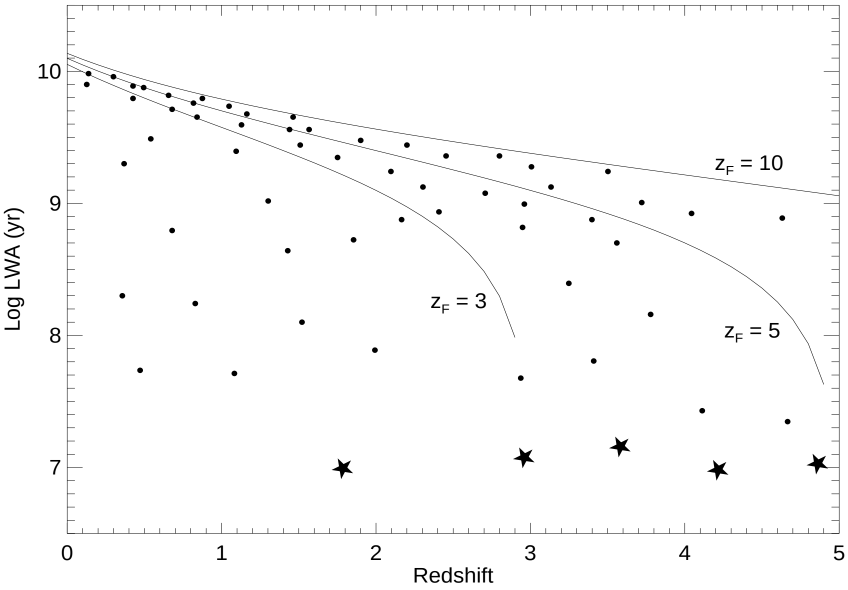

Figure 2: Schematic distribution of galaxy light-weighted ages (LWA) with redshift in a hypothetical field sample. Trajectories for single-burst systems with 3 different formation redshifts (z_F) are shown. Stars represent initial burst systems, and dots represent evolved objects. Most objects fall between the upper (red) and lower (blue) envelopes because they contain multiple generations. Ages assume $H_0 = 65$, $q_0 = 0$.

redshifts ($z_{\rm F}$) in the lower "blue envelope." This is challenging because of the (possible) large distance moduli ($\gtrsim 50$) involved and the shift of the stellar spectrum to the near-infrared, where the ground-based sky is bright and one requires cooled telescopes in space. Heavy internal extinction by dust is also expected to be common. Deep IR observations of starlight or IR/sub-mm observations of the ISM, now becoming feasible, can identify distant starbursts, though determining the duration of the burst or whether there were earlier bursts is difficult.

Alternatively, one can study the least active systems near the upper "red envelope" and *infer* $z_{\rm F}$ from their SEDs. The advantages are that this can done at lower redshifts, so much better S/N is possible, and that infrared telescopes are not required. Dust is also likely to be less of a problem. One can probe formation times by analyzing SEDs of individual galaxies or statistical samples in various slices through (magnitude, color, redshift) space.

The main difficulty with the age-dating of older SEDs is that they evolve *slowly.* This is because the luminosity and temperature of main sequence stars are power laws in mass (or age) and therefore change more slowly as age increases. Models show that spectrophotometric properties such as continuum colors (expressed in magnitudes) change logarithmically: Color $\sim a + b \log t$, where t is the age. (Hence, SED changes are proportional to the ordinate in Fig. 2.) The coefficient b, which determines the evolutionary rate, is given in the following table for several restframe colors:

Color	b
B-V	0.3
U-V	0.8
U-J	1.4
2500-V	2.0

b increases at shorter wavelengths and as the wavelength baseline increases. The logarithmic color dependence means that age resolution is given by $t/\delta t \sim b/2.3\,\delta{\rm C}$ and is directly proportional to b for a given observational precision. This relation translates to stiff demands on data quality. For instance, the "3-σ" age interval derived from restframe U–V data with an unusually good precision of $\sigma_{\rm obs} = 0.05$ mag is ±43%.

There have been some attempts to estimate absolute ages from color scatter (δC), but we see that color scatter constrains only the fractional range in age, not age itself (unless we have independent information on δt).

3 Spheroids in Rich Clusters

Recent studies have shown that spheroids can form at $z > 1$ in the dense environment of rich clusters of galaxies. The red envelope is in place in clusters at redshifts at least up to

$z = 0.9$, or about 50% of the age of the universe [2], [16], [34]. The envelope is composed largely of E or S0 systems at HST resolution. The slope of the color-magnitude relation (driven by the metallicity-luminosity correlation) is preserved, and the envelope shows impressively small scatter in the photometric-dynamical correlations of the fundamental plane, e.g. [37], and also in color ($\sigma[U - V]_{\rm rest} \lesssim 0.1$). However, mean colors are offset to bluer values with respect to nearby clusters such as Coma, with $\Delta(U - J)_{\rm rest} \sim -0.5$. The color trend is consistent with passive evolution. The age of these least active systems at the observed epoch is $\sim 3-5$ Gyr, implying $z_{\rm F} \gtrsim 1.5-3$ and present-day ages for their descendents of $\gtrsim 9$ Gyr ($\rm H_0 = 65$). Even though the limits on color scatter are small, they imply a significant range in age at the observed epoch ($z \sim 0.7$) of $\sigma(t)/t \sim 0.3$, which means that the max/min age ratio for the most homogeneous 68% of the sample is a factor of 1.7. The available data therefore permit a formation epoch extended over several Gyrs within and among rich clusters. Whether this involved mergers or simple collapse cannot be determined yet, nor can continuous production of some fraction ($\lesssim 25\%$) of the E galaxies through interactions be excluded.

The populations of most E galaxies in clusters therefore probably form early and typically suffer only minor pollution from star forming events at $z < 1$. However, the situation is very different regarding the spheroids of cluster S0 galaxies. HST observations show the *mixture* of morphological types appears to differ substantially from that in local clusters even at redshifts as low as $z \sim 0.3$. There are many more spirals (Sa-Sdm/Irr) and many fewer S0's (factors of 2-4) than in nearby rich clusters [12] [14]. It is the higher incidence of spirals which produces the "Butcher-Oemler effect" [9] on color statistics. A dominant evolutionary process in clusters during the past 5 Gyr has therefore apparently been the transformation of star-forming spirals into quiescent S0's. Good evidence of rapid spiral/S0 evolution is present in radial gradients of S0 colors within clusters [38] and in the spectra of cluster members, roughly 30% of which have suffered major changes in their star formation rates (bursts or quenching) within the preceding 2 Gyr [3] [12]. Careful spectral surveys have shown that similar activity continues at a low level to the present epoch in some clusters [10]. The data suggest that several processes, including infall, galaxy mergers, subcluster mergers, small accretion events, and ram-pressure stripping, are important in morphological transformations. One implication is that S0 spheroids in nearby clusters are considerably younger on average than their E neighbors. This interpretation must be reconciled with the well-known result that nearby cluster E's and S0's have very similar photometric properties; one possibility is that the photometric tests made so far are insensitive to age differentials of 30-50% for old populations.

4 Spheroids in the Field

It is somewhat misleading to contrast rich clusters with *the field*, since the latter comprises a very wide range of environments, and these can differ substantially from the local region which we define as "normal." Large fluctuations mean that pencil-beam surveys are always statistically insufficient. Strong selection effects operate to bias samples as regards depth, luminosity, star formation histories, morphology, and other properties [23] [24].

The most conspicuous evolutionary feature in the field is the "blue excess" in the faint galaxy counts, reviewed in [15] and [23]. Although it was initially thought this might be associated with the formation of massive spheroids at high redshifts, instead it appears to be produced by moderate luminosity, moderate redshift, irregular systems, which disappear at lower redshifts. These may evolve into spheroidal systems, but probably not luminous ones.

There is no doubt that old spheroidal systems exist in the field at high redshifts. The best example is the radio galaxy LBDS 53W091, which appears to be a bona-fide quiescent elliptical at a redshift $z = 1.55$. From restframe UV spectra, Spinrad et al. [33] obtained an age of $\gtrsim 3.5$ Gyr, implying $z_{\rm F} > 3 - 5$. This age is large enough that it significantly constrains cosmology, here requiring $\Omega < 0.4$ if $\rm H_0 > 65$. This demonstrates the potential power of "red envelope" analysis (even if there is debate over the appropriate limiting age value [20]). Other examples of $z > 1$ red spheroids have recently been found in radio samples [28] and deep HST NICMOS observations, e.g. [5] and [35].

However, the global history of spheroids in the field has yet to be established. Considering the selection effects and variety of environments, it is not surprising that there is considerably more controversy here than for clusters. Mutually contradictory claims are the rule. Samples of putative spheroids in the field can be selected on the basis of (red) color or, since the 1993 repair of HST, high resolution morphologies and light profiles. Although morphology is generally considered a stronger criterion, nonetheless there are good nearby examples of systems whose apparent E/S0 morphology is a product of low resolution [11], and such limitations on classification must affect the higher redshift samples.

Several recent studies of morphologically-selected (by HST) E/S0 galaxies conclude that there is no strong evolution in the number density of such objects to $z \sim 1$ [21] [25] [32]. These results are still statistically marginal, and a much larger sample with confirmed redshifts is desirable, but they appear to exclude mergers at $z < 1$ as the main channel for production of field ellipticals.

Interestingly, however, these and other studies also appear to exclude the monolithic collapse picture for spheroid production, at least in the strict form which requires quiescent post-burst behavior. The evidence is of two kinds. First, several studies find a deficit in color-selected samples in the number of "ultrared" (e.g. $\rm I{-}K > 4$) objects which would correspond to old, quiescent populations at redshifts $z > 1$ [4] [22] [39]. It is not clear whether these results are statistically inconsistent with the (as yet) small sample of red spheroids known at higher z.

Second, many of the morphologically-selected E/S0's and spiral bulges at redshifts up to $z \sim 1$ show evidence of significant star formation in the preceding 2 Gyr [1] [19] [25] [32]. Schade et al. [32] find that 30% of the E's have strong [O II] emission, unlike local samples, and Abraham et al. [1] find color evidence of recent activity in a comparable percentage of HDF spheroids. Mananteau et al. [25] find that their spheroidal sample mixes in color with spiral and irregular galaxies and that only a small fraction has properties consistent with single bursts and $z_F \gtrsim 3$. Most studies argue that the bluer colors are associated with late, small-amplitude (5-25% of the mass) bursts of star formation rather than the decay of the initial burst. However, the relatively brief lifetime of color disturbances from bursts coupled with the large fraction of objects showing them implies that, statistically, most local field spheroids should have had significant star forming activity in the last 3-10 Gyr. This is consistent with evidence for a wide range of star-forming histories among local spheroids [17] [26] [30].

5 UV Probes of Spheroidal Populations

Most of the studies discussed here are based on observations of older populations at wavelengths longer than 3300 Å in the restframe. There will be considerable advantages in pushing to shorter wavelengths. As a glance at Fig. 1 shows, most of the information in the SED of a stellar population is to be found at rest wavelengths below 4000 Å. This is true both of age indicators (for which the b parameter rapidly increases below 3500 Å) and metal abundance indicators (by virtue of strong absorption features of Ca, CN, NH, Mg, and Fe and general background blanketing). Empirical mid-UV (2000-3200 Å) spectra of globular clusters and spheroidal galaxies demonstrate great sensitivity to population parameters [29] [31]. Increasingly realistic UV spectral synthesis models relevant for galaxy SED analysis are appearing [8] [13] [20] [18] [33]. The highest potential sensitivity is found in the "UV upturn" component, present at wavelengths below 2000 Å in all local spheroids observed to date [27]. This is produced by small-envelope, low-mass, extreme horizontal branch stars and their descendents. Simple models predict a sudden appearance of the upturn component as the population's turnoff mass drops below a critical threshold at an age of $\sim$ 4-8 Gyr. A recent detection of far-UV radiation in 4 E galaxies in the cluster A370 at $z = 0.38$ has been made by Brown et al. [6]. If this is the upturn component, it implies a high formation redshift ($z_F > 4$) in the context of existing models. However, serious uncertainties in modeling giant branch mass loss and helium enrichment, as well as the possibility of contamination from young populations, render any conclusion premature.

6 Conclusion

The remarkable profusion of new information on distant galaxies, especially "red envelope" systems, offers tantalizing if not conclusive insights into the basic processes of galaxy formation. The monolithic collapse model is an easier target because of its definite predictions. In its extended form, in which star formation in all galaxies begins intensely and synchronously at high redshift and then declines in smooth exponentials depending only on galaxy type (e.g. [36]), it has been the traditional foundation for interpreting galaxy populations for 40 years. This model is almost certainly wrong. There is no evidence for a unique, well-defined epoch of galaxy formation. Instead, galaxy evolution is accelerated in denser environments, and major transitions in star formation histories and even morphologies are detectable to surprisingly small redshifts ($z \sim 0.2$). These features are consistent with the hierarchical models. However, there is also good evidence, both in rich clusters and the field, that massive spheroidal systems can form at rather early times ($z_{\rm F} \gtrsim$ 3–5), which was not anticipated in the standard hierarchical models. Improvements in understanding and modeling UV spectra of old populations promise much better sensitivity to age and abundance.

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