Rest-Frame UV and Visible Properties of Early Type Galaxies at $1 < z < 2$.

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Summary. Massive early-type galaxies at intermediate redshift provide a unique perspective on star formation at early times. The rest-frame UV spectra of passively evolving systems provide constraints on the formation redshift and abundances for the oldest stars at a time when the universe was roughly 1/3 its present age. The passive galaxies have spectra characteristic of F stars with strong absorption from MgII, MgI and FeII. Best fitting ages are in the 1-3Gyr range and models with solar or super-solar abundances are preferred. These properties point towards an early formation epoch and rapid down-sizing in the star formation rate.

1 Introduction

The study of galaxies at intermediate and high redshift, and massive evolved galaxies in particular, is motived by our desire to understand the formation process. The evolution of stellar mass and stellar content provide a gauge of the key processes involved in building galaxies, particularly star formation and dissipationless mergers. It has long been recognized that today's massive early type galaxies bear the hallmarks of rapid formation: high metallicities, compact morphologies, low rotation velocities, and little or no on-going star formation. In their simplest form, UV studies of distant ellipticals and bulges aim to understand if the Eggen et al. (1962) picture of monolithic collapse is appropriate, or the Searle & Zinn (1978) view of gradual assembly provides a more accurate description of the formation process. In more contemporary terms, the goal of these studies is to reconcile the properties of massive elliptical galaxies with the successes of the hierarchical picture of structure formation.

2 Down-Sizing and the Evolution of Massive Galaxies

Recent spectroscopic surveys of large samples enable empirical studies of galaxy evolution over a broad range of parameter space for the first time.

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The Sloan Digital Sky Survey (SDSS) provides us with a local reference point and a clear division of the galaxy population in to a sequence of massive, and primarily passive, galaxies and a population of lower mass active star forming systems (Kauffmann et al. 2003). The transition occurs for stellar masses near $10^{10.5}M_{\odot}$. Several imaging and spectroscopic surveys now allow one to connect the present-day red sequence galaxies to their progenitors at intermediate redshifts. The COMBO-17 (Bell et al. 2004) and DEEP2 (Faber et al. 2007) surveys probe the red sequence to $z \sim 1.2$ for large samples, while deeper near-IR selected samples like the K20 (Cimatti et al. 2002) and Gemini Deep Deep Survey (GDDS; Abraham et al. 2004) probe massive and passively evolving galaxies to $z \sim 2$. Rest-frame UV spectra provide the most efficient redshift diagnostics for nearly all systems and these allow a clear discrimination between passively evolving and actively star forming systems, as exemplified in Figure 1.

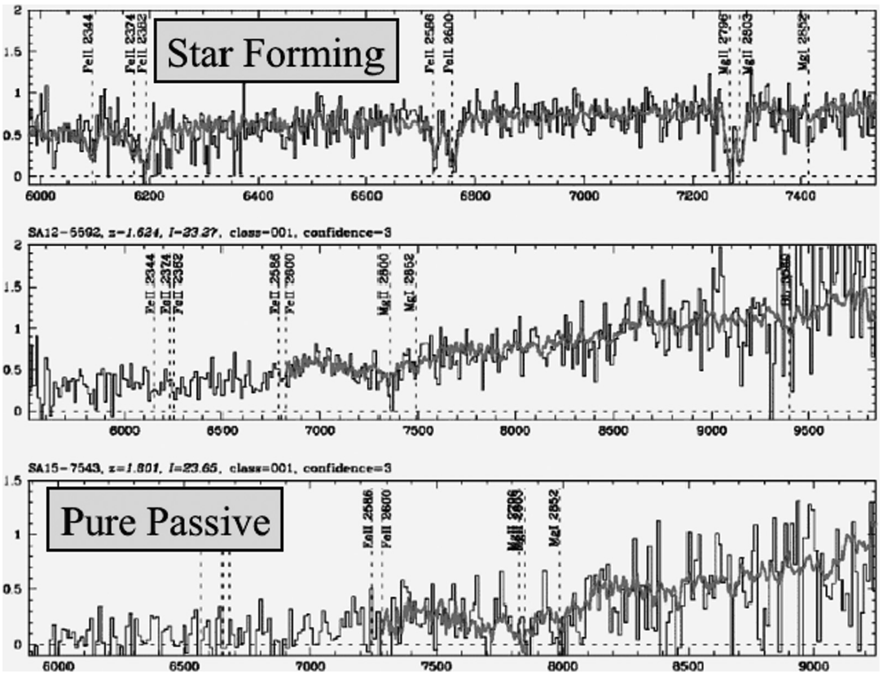

Fig. 1. Example spectra of actively star forming (top) and passively evolving galaxies (center and bottom) at $z \sim 1.5$. The redshifts are derived from template matching using local galaxy samples or composites constructed from spectra of bright galaxies at high redshift. The top panel shows a galaxy at $z = 1.60$ with strong interstellar absorption from MgII and FeII. The center and bottom panels show passive galaxies at $z = 1.62$ and 1.80, respectively, identified by matches with a composite of luminous red galaxies from the Sloan survey.

One of the key results from recent deep surveys was the recognition that star formation in the most massive systems has evolved dramatically from $z \sim 2$ to the present. In the mass down-sizing (Cowie et al. 1996) picture, the most massive galaxies form early and rapidly, while less massive systems experience later and more extended star formation histories. The stellar populations of present-day massive galaxies provide strong evidence for this (Heavens et al. 2004), while faint galaxies surveys reveal it directly, at least at the high mass end (e.g. Juneau et al. 2005). The star formation rate density evolution (Madau et al. 1996) provides a metric for one component of galaxy formation. Juneau et al. showed that the evolution in the star formation rate could be broken down by mass and suggested that there is a cascade in the site of active star formation from high to low mass systems with time, as shown in Figure 2. Juneau et al. (2005) and Dickinson et al. (2007) also cast this in the form of the specific star formation rate - the instantaneous star formation rate divided by the integral of the past rate - and show that high mass systems were primarily in a quiescent state at redshifts below ~ 2, but were forming stars at a faster than average rate at earlier epochs.

A significant fraction of the star formation in the most massive systems at $z \sim 2-3$ appears to be obscured (e.g. Houck et al. 2005; Yan et al. 2007), in addition to the classical Lyman break galaxies that have modest

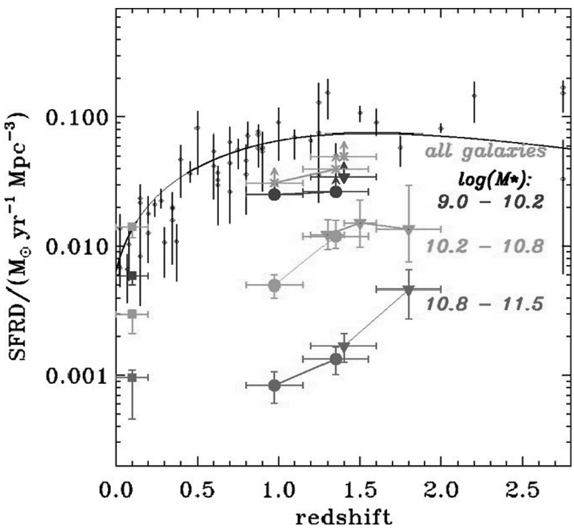

Fig. 2. Evolution of the star formation rate density as a function of stellar mass. The SFR density for all galaxies as compiled by Hopkins (2004) is shown as open black symbols. The rates for galaxies in three mass bins are shown as colored symbols. The most massive galaxies, shown in red, have negligible star formation at $z \sim 1.5$, just as they do today. At $z \sim 2$ their star formation rates were quite a bit higher. Similarly, galaxies with M$\sim$M* have their peak star formation rate at $z \sim 1.5$ and decline to the present day value by $z \sim 0.5$. From Juneau et al. (2005).

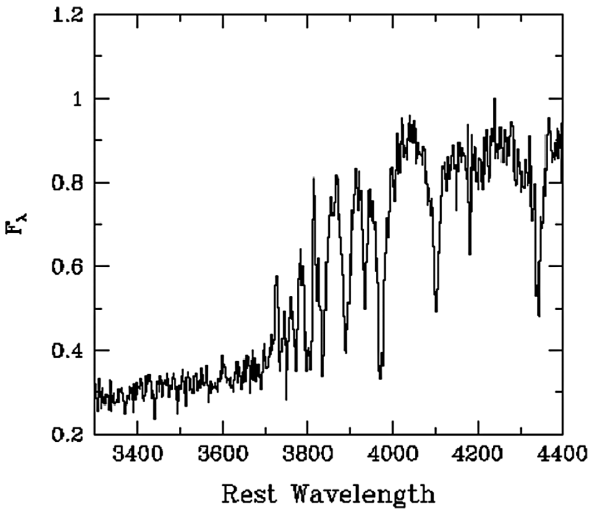

Fig. 3. An example of an extreme post starburst galaxy. This object underwent a recent burst involving roughly 50% of its present stellar mass. The strong nearly pure A star spectrum is the signature of a rapidly truncated star forming event.

UV extinction (e.g. Pettini et al. 2001). The immediate aftermath of intense star formation activities are often easier to observe than the burst phase. At $z \sim 1$ approximately 50% of M^* galaxies show signs of recently truncated star formation (Le Borgne et al. 2006). These include strong Hδ absorption, weak 4000 Å breaks and, in some cases, nearly pure A-star spectra. These post-starburst signatures are evidence of vigorous episodes of star formation in galaxies representative of today's red-sequence galaxies. An example of a particularly strong post-starburst galaxy is shown in Figure 3.

3 The Oldest Stars

A subset of the massive galaxies at $z > 1$ show no evidence of ongoing or recent star formation. These passive galaxies are the oldest systems at high redshift and provide a powerful probe of star formation and galaxy building at early epochs. In Figure 4 we show composite spectra of passive galaxies from the GDDS covering the wavelength range from 2300 - 3400 Å. The upper left panel is a composite of galaxies with $1.3 < z < 1.6$, while the upper right panel contains objects at higher redshifts, $1.6 < z < 1.9$. These galaxies have spectral features characteristic of stars in the mid to late F spectral classes. The strongest features are the MgII2796/2803 resonance lines, MgI2582 and a series of blended FeII lines, particularly near 2600 Å. A number of attempts have been made to determine the ages of passive galaxies by modeling their spectra features and determining the temperature of the main sequence

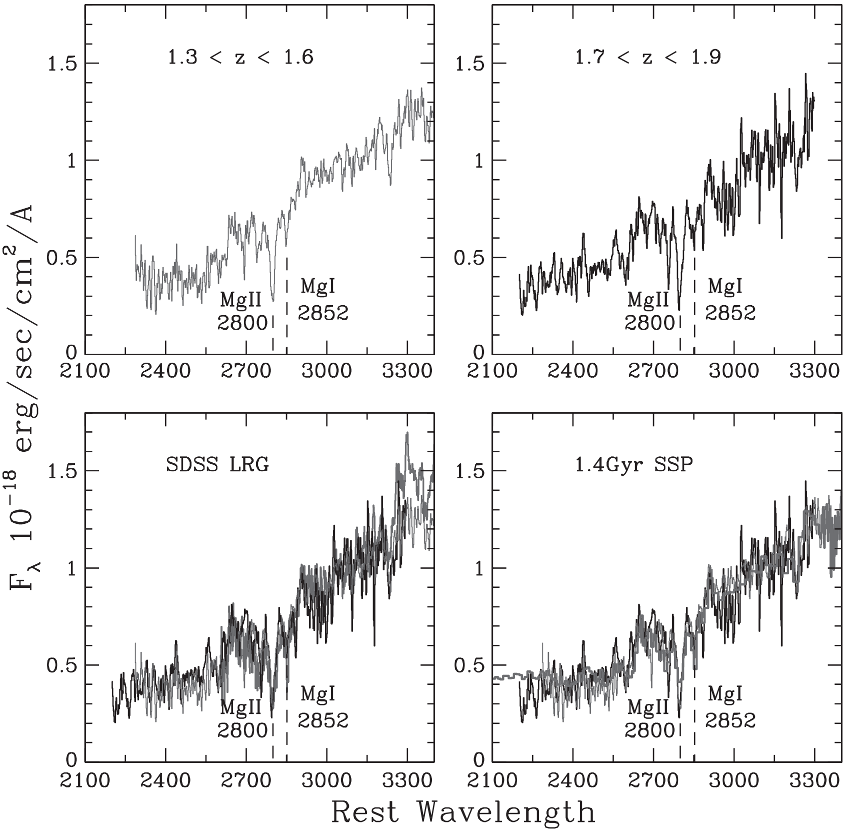

Fig. 4. Composite spectra of passively evolving galaxies at $1 < z < 2$. The upper panels show composite spectra of passive galaxies with $1.3 < z < 1.7$ (left) and $1.7 < z < 1.9$ (right). The lower panels show these same composite compared with a local luminous red galaxy template (left) and a simple stellar population model with an age of 1.5Gyr (right). The good agreement between the continuum shapes and spectral features between the two high redshift composites, the local LRG composite and the 1.5Gyr model all suggest an early formation redshift for the stars in these massive galaxies.

turn-off (e.g. Dunlop et al. 1996). A useful empirical benchmark is again provided by the SDSS through composite spectra of luminous red galaxies (LRGs) at modest redshifts. In the lower left panel of Figure 4 we compare the SDSS LRG composite from Eisentein et al. (2003) with the GDDS composites at $z = 1.3$ and 1.9. The basic spectral features and overall continuum shape are nearly indistinguishable in the spectra showing that there has been little evolution in the ensuing $\sim$ 8 Gyr from $z \sim 1.8$ to $z \sim 0.2$. This lack of evolution alone suggests that the formation epoch for the stars in the $z \sim 1.3$ passive systems is quite high.

A rough idea of the range of appropriate ages is provided by fitting a single burst model to the composite spectra. In the lower right panel of Figure 4 we show a simple stellar population model with solar abundances and an age of 1.5 Gyr overlaid on the composite spectra. The strength of the features and continuum shape are well matched at this age. Older models (e.g. $\sim 3-4$ Gyr) fit equally well, while models younger than about 1 Gyr are too blue and have weaker features. This gives a rough indication that $1-3$ Gyr is the relevant age range.

We have modeled the spectra of the individual galaxies that went into the composite with a wide range of simple stellar populations, as described in McCarthy et al. (2005). These include a range of star formation histories, abundances up to twice solar, and range of reddening and ages anywhere from zero to the age of the universe at the time of observations. Not unexpectedly, we find that it is difficult to separate age and metalicity effects. Solar metalicity models yield best fit ages up to 3-4 Gyr in extreme cases, implying formation redshifts well above five. Allowing super solar abundances lowers the best fitting ages, but we still find that the median formation redshift is near 3, and roughly 1/3 of the objects are still best fit with formation redshifts > 4. The basic conclusion of our modeling procedure is that high metallicities and fairly early formation redshifts are required to understand the spectra of these massive galaxies. At this time we are limited by the models as much as the data. A better understanding of the features in the 2600-2900 Å region of the spectrum for F- and G-type stars would improve the precision of our fits. Higher signal-to-noise observations are certainly desirable, but these are not likely to be available until a new generation of extremely large telescopes come on line.

4 Old Stars in Young Galaxies

One of the crucial challenges in understanding the formation of the red sequence is separating the dynamical ages of galaxies, the time since more than 50% of their final mass was assembled, from the ages of their constituent stars. In the hierarchical model of structure formation galaxies in dense regions are assembled from smaller stellar systems, many of which will contain old stars. It is quite possible that the old passive galaxies discussed above have dynamical ages that are quite a bit younger than their stellar ages. Any merging process that produces passive galaxies at modest redshifts, below $z \sim 1.5$, should not produce bursts of star formation that will mask the signature of the oldest stars. Such "dry mergers" are expected in dense regions such as the cores of rich clusters or compact groups. A number of groups have been identified in the DEEP2 and other redshift surveys and wide-area mid-IR surveys with the Spitzer Space Telescope have discovered a number of rich clusters of red galaxies at $z \sim 1.5$ (e.g. Stanford et al. 2006). In Figure 5 we present an example of a small cluster or group of massive red galaxies that appears to be on the verge or merging to form a single massive red galaxy. This system has

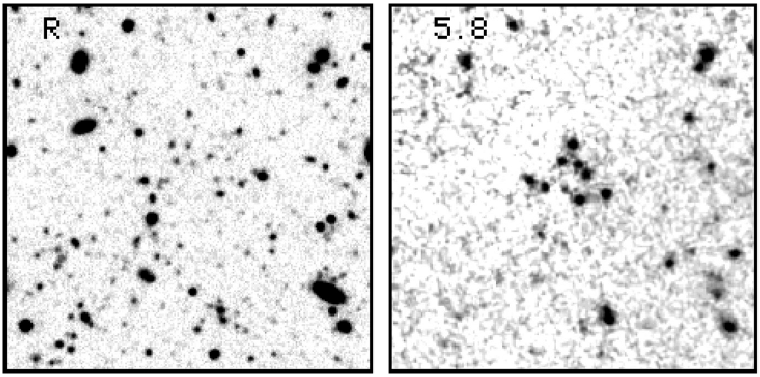

Fig. 5. R-band and 5.8μm images of the environment of a massive passive galaxy at $z = 1.52$ from the Gemini Deep Deep Survey. The 3.8μm image reveals a compact group of massive red galaxies associated with the GDDS galaxy. Our 12-band photometry suggest that these galaxies all lie at $z \sim 1.5$. We speculate that this system will merge by $z \sim 0.7$ to form a single large, passive, elliptical galaxy. These compact groups and cluster cores may be the locations where much of the red sequence is built up.

a high stellar density, roughly $10^{12}\mathrm{M}_\odot$ is contained within a sphere 120kpc in radius. In McCarthy et al. (2007) we speculate that some of the galaxies in this system will merge by $z \sim 0.5 - 0.7$ to form a single large elliptical galaxy with a stellar age much larger than its dynamical age. This process of dry merging in dense groups and cluster cores is likely to be an important part of the process that forms the massive red sequence galaxies.

5 Conclusion

Large redshift surveys and deep near-IR imaging surveys are producing large samples of massive galaxies at high redshifts. A subset of these are nearly purely passive galaxies that provide a window on early star formation. The near-UV region of the spectrum contains the key diagnostics for understanding star formation and enrichment histories. Large telescopes and improved empirical and theoretical spectral libraries are needed before we can realize the full potential of this region of the spectrum as a probe of galaxy formation and assembly.

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