Formation of the Most Massive Galaxies: Insights from Passive Galaxies at $z \sim 1.5$

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Abstract

While fossil studies of massive cluster ellipticals suggest the majority of their stars were formed over a very short period of time early in the history of the universe, the mechanism by which they assemble their stars remains highly contested. I present results from a multi-wavelength study of several galaxies at $z \sim 1.5$ which may be the direct progenitors of the massive cluster population found at lower redshifts. These galaxies have baryonic masses $\sim 10^{12} M_\odot$ and stellar populations that already appear to be $\gtrsim 1$ Gyr old at $z \sim 1.5$. An overdensity of red sources is observed in these fields, suggesting these galaxies may lie in the centers of emerging clusters. Using a long photometric baseline, we have constrained the mass and age of their dominant stellar populations and find formation epochs only $\sim 1$-2 Gyr after the Big Bang. Furthermore, rest-frame near-UV spectroscopy indicates that these galaxies are remarkably quiescent, with any current star formation constrained to be $< 1 M_\odot$ yr$^{-1}$. Finally, by exploiting a unique feature in the rest-frame near-IR spectral energy distribution of $\sim$Gyr-old stellar populations, we are able to use Spitzer IRAC data to break the age-metallicity degeneracy that plagues shorter wavelength observations. We use these improved age and metallicity estimates in conjunction with high-resolution morphological data from HST to place these galaxies in context with current models of galaxy formation. Unlike their descendants in the local universe, we find a range in size and morphology, including extremely compact spheroids as well as massive disks of old stars, indicating that several different mechanisms could be important in building up the massive cluster population.

Method

Galaxies were selected in the fields of radio-loud quasars. The reason for using quasar fields is threefold:

1. The presence of the quasar ensures that there will be at least one object bright enough in a single short exposure typical of IR imaging, to use to register each frame in the dither pattern.
2. We know that quasars (as opposed to radio-quiet QSOs) exist preferentially in higher density environments. Since we expect star formation to proceed most rapidly in the highest density environments, this gives us a good place to start looking for the earliest massive galaxies.
3. Finally, and most importantly, looking for companions to radio sources at a specific redshift allows us to choose redshifts for which the photometric diagnostics from standard broadband filters gives the cleanest separation between old galaxy populations and highly reddened star-forming galaxies or other possible contaminants.

In all cases, photometric observations were taken to select galaxies that had strong 4000-Å breaks, the tell-tale signature of old stellar populations. Of special importance were deep IR surveys which enabled us to pin down the blue portion of the SED and determine the contribution (if any) from younger stellar populations. Once we had good candidates, we then obtained either AO imaging and/or HST imaging for all the sources, as well as high resolution spectroscopy using DEIMOS and ESI on Keck II. Deep Spitzer IRAC observations were taken to place further constraints on the stellar populations.

Disks of Old Stars at $z \sim 1.5$

4C 15.55 ER2 is a peculiar galaxy. It appears clearly elongated and follows an exponential surface brightness profile at both rest-frame NUV and optical. The SED fit to the photometry for 4C 15.55 ER2 is shown in Figure 3. The addition of Spitzer IRAC data constrains the age of the dominant stellar population to be $\sim 1$ Gyr, even when extreme metallicity models are used. The stellar mass derived from this SED fit is $1.75 \times 10^{11} M_\odot$.

Compact Spheroids at $z \sim 1.5$

TXS 1211+334 ER1 is similar to a number of other passively evolving spheroids found at high-redshift (e.g., Daddi et al. 2005; Trujillo et al. 2007; Thomas et al. 2000; Tacconi et al. 2008). Unlike their descendants in the local universe, we find a range in size and morphology, including extremely compact spheroids as well as massive disks of old stars, indicating that several different mechanisms could be important in building up the massive cluster population.