Directly Detecting the Evolution of Early-Type Galaxies

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Abstract. We describe observations focused on understanding the epochs and timescales of the formation and evolution of early-type galaxies, particularly those in clusters. We show that while early-type cluster galaxies are on average older and closer to coeval than their counterparts in the field, significant age spreads (a factor of two in massive ellipticals, more in low-mass galaxies, especially S0's) still exist in these objects. We then show that it is now possible to detect the evolution of early-type galaxies directly by comparing deep absorption-line spectroscopy of intermediate-redshift cluster galaxies with local cluster galaxies. We find that the stellar populations of early-type cluster galaxies do indeed evolve, at a rate that appears to be consistent with the cosmological lookback time.

1 Introduction

A fundamental question in modern astrophysics is understanding the epochs and timescales of galaxy formation and evolution. Spheroidal galaxies – elliptical and S0 galaxies and their close relatives, the bulges of spiral galaxies – constitute between 50% [25] and 75% [9] of the total *stellar* mass of the Universe. Observational evidence of when these galaxies form, how long this process takes, and how this process varies with different factors – specifically mass and environment – are crucial inputs for galaxy formation models.

Elliptical and S0 galaxies are predominantly found in high-density environments [1], with perhaps as many as 80% of ellipticals and 50% of S0's found in clusters [7]. Various lines of evidence suggest that cluster early-type galaxies formed the bulk of their stellar populations at high redshift, including the variation of the mass-to-light ratios [5,12,13,6] and optical and infrared colors [2,14,30] (just to name a few significant papers) of cluster galaxies with redshift. On the other hand, recent studies of the line strengths of early-type galaxies in the general field (primarily loose groups) [34,35] and the Fornax [15], Virgo [4], and possibly even Coma [22,17] clusters suggest that recent episodes of star formation are likely to have occurred, particularly in smaller galaxies. The resolution of this apparent disagreement requires a larger sample of local cluster galaxies with excellent line strength data, particularly in higher density regions like Coma, and line strengths of higher-redshift cluster galaxies.

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A closely related problem is the consistency of astrophysical clocks. In essence, do the timescales of the “concordance” cosmological model [29] and those of modern stellar population evolution models [31] match? If we look back to $z = 0.4$, do the spectra of the oldest galaxies appear to be four billion years younger than those of the oldest galaxies today?

In this contribution, we describe observations focused on understanding the epochs and timescales of the formation of giant early-type galaxies, ellipticals and S0’s, especially those found in clusters of galaxies. We begin a brief discussion of stellar population models, then discuss in turn the stellar populations of local and distant cluster galaxies. We conclude with some outstanding questions raised by this study and a hint of what is to come.

2 Models of Integrated Spectra: A Brief Overview

Unfortunately, we cannot study the vast majority of early-type galaxies star by star, and so we must be happy with the integrated spectra of these objects. In turn, the interpretation of integrated spectra requires stellar population models. This is an ancient subject [37] with a rich history and literature; a more complete description of stellar population models can be found in, e.g., [38,31,32].

The basic problem with interpreting the integrated spectra of galaxies (particularly those that are not currently forming stars) is that an increase in the stellar opacities of a stellar population by an increase in its metallicity is equivalent to a decreased mean temperature of that population [19]. In other words, a metal-rich population can be simulated by increasing the age – decreasing the mean temperature – of a more metal-poor population. This is the *age–metallicity* degeneracy.

Breaking the age–metallicity degeneracy requires finding a suitable tracer of temperature that is as independent of metallicity as possible. Two groups in the early 1980’s [11,23] discovered that the Balmer absorption lines of hydrogen, in particular Hβ, were mostly temperature sensitive. This was reinforced by the comprehensive stellar population models of Worthey [38], which included metallicity effects for the first time. He found that breaking the age–metallicity degeneracy required both a Balmer absorption line and a metal absorption line. A modern version of this approach is shown in the left panel of Fig. 1 [31].

Modern stellar population models require either three or four ingredients. First, a set of stellar evolutionary models is needed to provide the basic astrophysical input to the models, in the form of a set of isochrones – different mass stars of the same age and abundance. Next, an initial mass function is chosen to populate the isochrones at a given age (time). Finally, either an extensive catalog of spectrophotometric stellar spectra or a combination of theoretical stellar fluxes and parameterized absorption-line strengths are needed to produce the integrated spectra or absorption-line strengths of simple (single-age, single-metallicity) stellar populations. Different approaches for each of these ingredients can be seen in, e.g., [38,31,3]. Calibration of stellar population models has re-