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OBSERVED CORRELATIONS, EVOLUTION, AND ENVIRONMENTAL DEPENDENCE OF 9000 EARLY-TYPE GALAXIES IN THE SDSS

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RESUMEN

Utilizando criterios morfológicos y espectroscópicos se seleccionó una muestra de $\sim$ 9000 galaxias tempranas en las bandas g^*,r^*,i^* y z^* del Sloan Digital Sky Survey. La muestra comprende el intervalo $0 < z < 0.3$ y se usó para estudiar correlaciones entre observables como luminosidad, radio efectivo, brillo superficial, color, dispersión de velocidades y abundancias químicas, cómo evolucionan éstas, y si dependen del entorno. Las galaxias a $z's$ menores y mayores que $z \sim 0.1$ (la z mediana de la muestra) han evolucionado poco con relación a la población con esta z. Las luminosidades, los colores, el Plano Fundamental y las intensidades de las líneas de absorción sugieren que la población está evolucionando pasivamente después de haber formado la mayor parte de sus estrellas unos 9 Giga años antes. Si bien el Plano Fundamental sugiere que las galaxias en regiones densas son algo distintas que las galaxias en regiones menos densas, las abundancias químicas y la relación color-dispersión de velocidades no muestran una dependencia significativa con el entorno.

ABSTRACT

A sample of nearly 9000 early-type galaxies, observed in the g^*, r^*,i^*, and z^* bands, was selected from the Sloan Digital Sky Survey using morphological and spectral criteria. The sample spans the redshift range $0 < z < 0.3$, and was used to study how early-type galaxy observables, including luminosity, effective radius, surface brightness, color, velocity dispersion, and chemical abundances are correlated with one another, how they evolve, and whether they depend on environment. Relative to the population at $z \sim 0.1$, the median redshift of the sample, galaxies at lower and higher redshifts have evolved little. The luminosities and colors, the Fundamental Plane, and absorption-line strengths (obtained from co-added spectra of similar objects) suggest that the population is evolving passively, having formed the bulk of its stars about 9 Gyrs ago. While the Fundamental Plane suggests that galaxies in dense regions are slightly different from galaxies in less dense regions, the chemical abundances and color–velocity dispersion relations show no statistically significant environmental dependence.

Key Words: **GALAXIES: ELLIPTICAL — GALAXIES: EVOLUTION**

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1. INTRODUCTION

Although galaxies differ significantly in their observed properties (luminosities, colors, masses, sizes, surface brightnesses, morphologies, star formation histories and environments) they show several very precise relationships among these measured features. Among all galaxy families, early-type galaxies show the most precise regularities. Early-type galaxy colors, luminosities, half-light radii, velocity dispersions, and surface brightnesses are all correlated (e.g., Faber & Jackson 1976; Kormendy 1977); the sizes, surface brightnesses and velocity dispersions can be combined into a two-dimensional "Fundamental Plane" with very little scatter (e.g., Djorgovski & Davis 1987). The homogeneity of the early-type galaxy population is difficult to understand if early-type galaxies are assembled at late times by stochastic mergers of less-massive galaxies of, presumably, different ages, star formation histories, and gas contents, as many models postulate (e.g., Larson 1975). It is possible that the homogeneity of early-type galaxies points to early formation (e.g., Worthey 1994); certainly their stellar populations appear old (e.g., Bernardi et al. 1998).

It is essentially a stated goal of the Sloan Digital Sky Survey (SDSS; Stoughton et al. 2002) to revolutionize the study of galaxies. The SDSS is imaging π steradians of the sky (Northern Galactic Cap) in five bands and taking spectra of $\sim 10^6$ galaxies and $\sim 10^5$ QSOs. Among the 10^6 SDSS spectra there will be roughly 2×10^5 spectra taken of early-type galaxies. The high quality of the SDSS 5-band CCD imaging and spectra allows precise measurements of their photometric and spectroscopic properties. Furthermore, because the SDSS surveys a huge volume of the local Universe, the sample described below includes early-type galaxies in every environment from voids to groups to rich clusters.

2. OBSERVED CORRELATIONS

A sample of $\sim$ 9000 early-type galaxies were selected from the SDSS database (data observed be-

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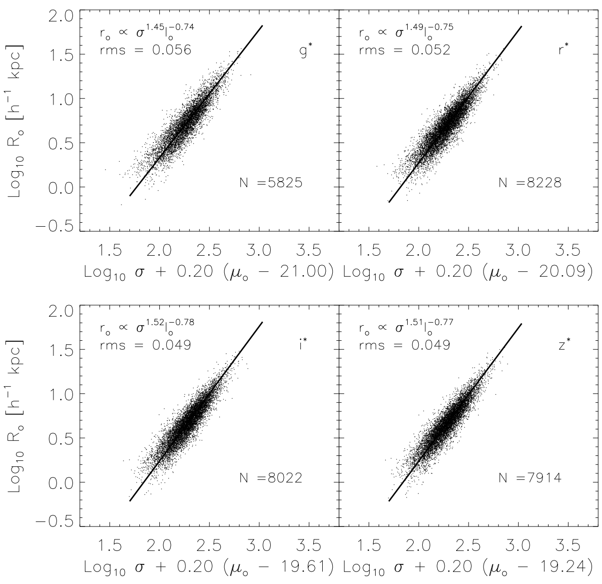

Fig. 1. The Fundamental Plane in the four SDSS bands. Coefficients shown are those which minimize the scatter orthogonal to the plane, as determined by the maximum-likelihood method (Bernardi et al. 2002). Surface-brightnesses have been corrected for passive evolution.

tween March 1999 and October 2000) using objective morphological and spectroscopic criteria. A detailed description of the selection criteria and of the photometric and spectroscopic parameters used here below is given in Bernardi et al. (2002). The SDSS sample is magnitude limited at both the bright and faint ends. This complicates studies of how the population as a whole is evolving, and, if not accounted for, can lead to incorrect estimates of how various observables correlate with each other. Bernardi et al. (2002) describe a number of techniques which were used to account for evolution and selection effects when estimating the correlations presented below.

In any given band, each galaxy in our sample is characterized by three numbers: its luminosity, L, its size, R_o, and its velocity dispersion, σ. Correlations between these three observables are expected if early-type galaxies are in virial equilibrium. Among the various possible pairwise relations we find that $\langle\sigma|L\rangle \propto L^{1/4}$, $\langle R_o|L\rangle \propto L^{5/8}$, and $\langle R_o|I_o\rangle \propto I_o^{-0.76}$ approximately independent of waveband ($I_o = (L/2)/R_o^2$ is a surface brightness).

Following Djorgovski & Davis (1987), correlations involving all three variables are often called the Fundamental Plane (FP). Figure 1 shows how the surface brightnesses I_o, sizes R_o, and velocity dispersions σ are correlated. Because both $\mu_o \propto -2.5\log_{10}[I_o]$ and σ are distance independent quantities, it is in these variables that studies of early-type galaxies are usually presented. Thus, the FP is defined by: $\log_{10} R_o = a\log_{10}\sigma + b\log_{10} I_o + c$, where the coefficients a, b, and c are determined by minimizing the residuals from the plane. There are a number of ways in which this is usually done. See Bernardi et al. (2002) for a detailed discussion of the techniques used to find the best-fitting plane (which account for selection and evolution effects).

The coefficients a and b given by the "orthogonal" fit are very similar in all four bands ($a = 1.5 \pm 0.05$ and $b = -0.77 \pm 0.01$). The scatter around the mean relation decreases slightly from the bluer band ($rms_{orth} = 0.056$) to the redder band ($rms_{orth} = 0.049$). Although b is approximately the same both for the 'orthogonal' and the 'direct' fits, a from the direct fit is always about 25% smaller than from the orthogonal fit. If the direct fit is used as a distance indicator, then the thickness of the FP translates into an uncertainty in derived distances of about 20%. The similarity of the coefficients, and the fact that the thickness of the FP decreases slightly with increasing wavelength, can be used to constrain models of how different stellar populations (which may contribute more or less to the different bands) are distributed in early-type galaxies.

The fact that $a \neq 2$ means that the FP is tilted relative to the simplest virial theorem prediction $R_o \propto \sigma^2/I_o$. One of the assumptions of this simplest prediction is that the kinetic energy which enters the virial theorem is proportional to the square of the observed central velocity dispersion. Busarello et al. (1997) argue that, in fact, the kinetic energy is proportional to $\sigma^{1.6}$ rather than to σ^2. Since this is close to the $\sigma^{1.5}$ scaling we see, it would be interesting to see if the kinetic energy scales with σ for the galaxies in our sample similarly to how it does in Busarello et al.'s sample. This requires measurements of the velocity dispersion profiles of (a subsample of) the galaxies in our sample, and has yet to be done.

It is known that the colors of early-type galaxies correlate with their luminosities, with small scatter around the mean relation. However, the SDSS sample shows clearly that, in fact, the primary correlation is color with velocity dispersion: the color–magnitude relation arises simply because both color and magnitude correlate with velocity dispersion. Figure 2 (in which the maximum likelihood estimates of the evolution in color and magnitude have been removed) shows this explicitly. This is also true for the color–size relation, although we have not included a figure showing this. One consequence of this is that residuals from the Faber–Jackson relation correlate

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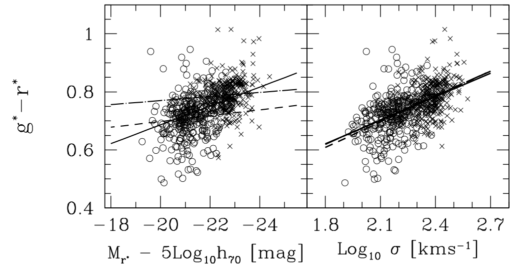

Fig. 2. Color–magnitude (left) and color$-\sigma$ (right) relations. Solid lines show $\langle g^* - r^*|M\rangle \propto -0.025M$, and $\langle g^* - r^*|\sigma\rangle \propto \sigma^{0.26}$. The two types of symbols in each panel show the color–magnitude relation for two bins in velocity dispersion (left), and the color$-\sigma$ relation for two bins in absolute magnitude (right). Dashed lines show fits to each subsample; they show that at fixed velocity dispersion, there is no color–magnitude relation (left), whereas at fixed magnitude, the color$-\sigma$ relation is the same as in the whole sample. Thus, the primary correlation is color$-\sigma$.

with color, whereas residuals from the luminosity–size relation do not.

Most chemical abundances, e.g., Mgb, $\langle$Fe$\rangle$ (an average over Fe5270 and Fe5335), and H_β (measured in Å), correlate with σ. These line indices depend both on the age and the metallicity of the stellar population (e.g., Worthey 1994), although Mg and Fe are more closely related to the metallicity, whereas the equivalent width of H_β is an indicator of recent star formation. Mgb is an alpha element; roughly speaking, it reflects the occurence of Type II supernovae. On the other hand, Fe is produced in SN Ia. The galaxies in our sample have nonsolar metallicities and alpha abundance ratios.

To measure spectral features reliably requires a spectrum with a higher signal-to-noise ratio than we have for any individual galaxy in the SDSS sample. So we co-added the spectra of all the galaxies with similar properties (redshift, luminosity, velocity dispersion, and effective radius) to increase the signal-to-noise ratio, and then estimated the line-indices in the higher signal-to-noise composite spectra. The estimated indices were aperture-corrected and corrected for broadening effects. Figure 3 shows the results. Solid line and text at top left in each panel show the relation which is obtained by performing simple linear fits at each redshift, and then averaging the slopes, zero-points, and rms scatter around the fit at each redshift. Notice that, at fixed redshift, Mgb and $\langle$Fe$\rangle$ increase with increasing σ, whereas H_β decreases.

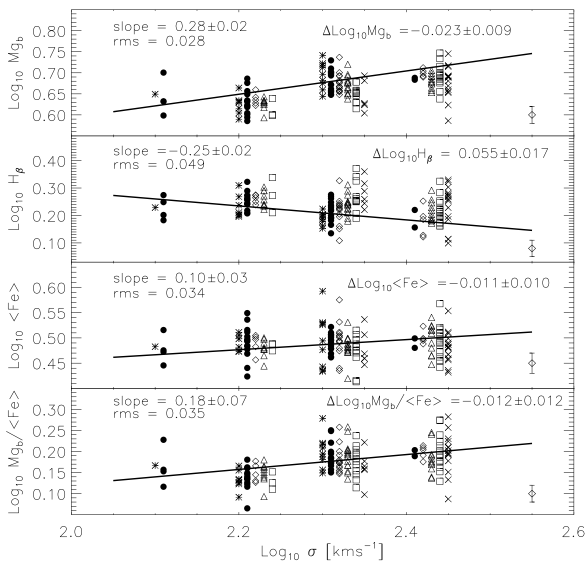

Fig. 3. Spectral line-indices Mgb, H_β, $\langle$Fe$\rangle$, and the ratio [Mgb/Fe] (top to bottom) as functions of σ. Stars, filled circles, diamonds, triangles, squares and crosses show results from coadded spectra of similar galaxies in successively higher redshift bins ($z < 0.075$, $0.075 < z \leq 0.1$, $0.1 < z \leq 0.12$, $0.12 < z \leq 0.14$, $0.14 < z \leq 0.18$, and $z > 0.18$). For clarity, at each bin in velocity dispersion, symbols for successive redshift bins have been offset slightly to the right from each other. This helps to separate out the effects of evolution from those which are due to the correlation with σ. Symbol with bar in bottom corner shows the typical uncertainty on the measurements.

3. EVOLUTION

A number of lines of evidence suggest that our early-type sample is a passively evolving population which formed the bulk of its stars about 9 Gyrs ago; here we show two (see Bernardi et al. 2002 for others).

Figure 4 shows estimates of the luminosity function $\phi(M)$ from several adjacent volume limited subsamples. Each subsample contains more than five hundred galaxies, except for the two most distant, which each contain about one hundred. As one would expect, the nearby volumes provide the faint end of $\phi(M)$, and the more distant volumes show the bright end. The bottom panels in Figure 4 show evidence that, at fixed comoving density, the higher redshift population is slightly brighter than that at lower redshifts. The small trends we see are statistically significant, and argue for a relatively high formation redshift: Bruzual & Charlot (2002, in preparation) models indicate that $t_{\rm form} \sim 9$ Gyrs.

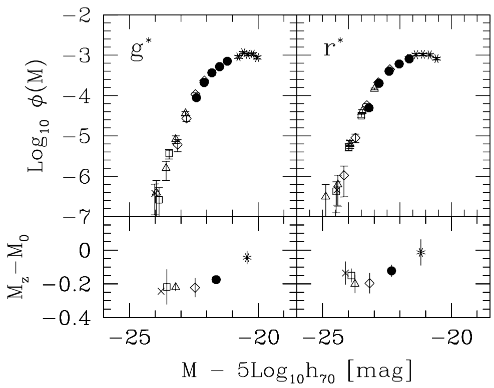

Fig. 4. Luminosity functions in the g^* and r^* bands. Stars, circles, diamonds, triangles, squares and crosses show measurements in volume limited catalogs which are adjacent in redshift of width $\Delta z = 0.04$, starting from a minimum of $z_{\min} = 0.04$. Top panels show that the higher redshift catalogs contribute at the bright end only. At the same comoving density, the symbols which represent the higher redshift catalogs tend to be displaced slightly to the left of the those which represent the lower redshift catalogs. Bottom panels show this small mean shift towards increasing luminosity with increasing z.

Figure 3 clearly shows that at fixed σ, the spectra from higher redshift galaxies are weaker in both Mg and $\langle$Fe$\rangle$, but stronger in H$_\beta$. Large values of Mg and $\langle$Fe$\rangle$ are expected to indicate either that the stellar population is metal rich, or old, or both. Thus, in a passively evolving population, the relation should be weaker at high redshift. This is consistent with the trend we see. The same is true for H$_\beta$: an increase of star formation activity with increasing redshift is consistent with a passively evolving population. Text at top right of each panel shows the shift between the lowest and highest redshift bins, averaged over the values at $\log_{10}\sigma = 2.2$, $\log_{10}\sigma = 2.3$ and $\log_{10}\sigma = 2.4$. Roughly speaking, this means that the shifts occur over a range of about $0.2 - 0.06 = 0.14$ in redshift, which for a flat ΛCDM model with $\Omega_0 = 0.3$ and $H_0 = 70$km s^{-1}Mpc^{-1} corresponds to a time interval of 1.63 Gyr. Comparison of our measurements with the stellar population models of Worthey (1994) suggests that the mean age in our lowest redshift bin (stars, median redshift 0.06) is 8 Gyrs, whereas it is 6 Gyrs in the highest redshift bin (crosses). If the population has evolved passively, and we have chosen the correct cosmological model, then this should equal the 1.63 Gyr of the redshift difference. A formation time of 8 or 9 Gyrs ago, as suggested by the chemical evolution, is close to what is required to explain the evolution in the luminosities (evolution in color and in the Fundamental Plane, which is consistent with this, is also seen; see Bernardi et al. 2002).

4. ENVIRONMENT

An efficient way to see if the properties of galaxies depend on environment is to show the residuals from the FP. We found that, in all redshift bins, the residuals (differences between galaxy surface brightnesses and those predicted by the FP given their sizes and velocity dispersions) tend to increase as local density increases. This suggests that the scatter from the FP depends on environment. If the offset in surface brightness is interpreted as evidence that galaxies in denser regions are slightly less luminous than their counterparts in less dense regions, then this might be evidence that they formed at higher redshift. While this is a reasonable conclusion, we should be cautious because it is difficult to decide if the correlation is due to changes in luminosity, size or velocity dispersion.

Although we have evidence from the FP that early-type galaxies in dense regions are slightly different from their counterparts in less dense regions, the colors and the strengths of spectral features show little if any dependence on environment. We are cautious on our finding of environment effects because: 1) our definition of environment is limited, since it is defined by early-type galaxies only; 2) our total sample was divided into bins in luminosity, size, radius, and redshift, and then by environment, so the statistical significance of these results would be greatly improved by increasing the sample size (see Bernardi et al. 2002 for a detailed discussion).

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