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The Rest-Frame Near-Infrared Colors and M/L of Early-Type Galaxies at z = 1

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Abstract. We present the results of a study of the evolution of the optical and near-IR colors and mass-to-light ratios (M/L) of early-type galaxies from $z \sim 1$ to the present. This exercise is relevant for studies that use photometry of galaxies to infer properties such as stellar masses and star formation histories through comparison with stellar population models. We have dynamical M/L for a sample of 20 early types at $z \sim 1$ with velocity dispersions from deep optical spectroscopy and structural parameters (size and surface brightness) from high-resolution HST imaging. We compare those with 23 early-type galaxies in the Coma Cluster at $z = 0.02$. For both samples rest-frame optical/near-IR photometry is available, from HST and Spitzer in the case of the $z \sim 1$ sample. We find that the M/L evolves faster in the near-IR than expected from most stellar population models, and also that predictions from different models can differ significantly in the near-IR. As a consequence, there is a systematic uncertainty of a factor of two in stellar mass estimates from near-IR photometry for evolved, high-z galaxies. Optical colors provide a less biased indicator of the M/L. Agreement among the models is required before near-IR photometry can be used as a robust tool to estimate galaxy masses without systematic uncertainties.

Keywords. galaxies: elliptical and lenticular, galaxies: evolution, galaxies: fundamental parameters galaxies: photometry, infrared: galaxies

1. Introduction

Recent studies are beginning to study high-redshift galaxy populations in terms of their stellar mass function (e.g., Bundy, Ellis & Conselice 2005; Borch *et al.* 2006; Holden *et al.* 2006; Wuyts *et al.* 2006). The mass estimates rely on the accuracy and robustness of the conversion from photometric properties via stellar population models (e.g., Worthey 1994; Vazdekis *et al.* 1996; Bruzual & Charlot 2003; Maraston 2005). This correspondence between photometric properties and mass has been quantified and tested for nearby galaxies (first by Bell & de Jong 2001), but, until recently, not at higher redshifts. Meaningful comparisons of galaxy masses at different redshifts require that the models reproduce the correct evolution of color and luminosity simultaneously. This needs to be tested. It is particularly interesting to include the near-IR in such an analysis, as with instruments such as IRAC on the Spitzer space telescope it is now very efficient to obtain photometry of large samples of galaxies at wavelengths that have the advantage that stellar light is not strongly attenuated by dust. In this contribution we present the results of an analysis of the evolution of the optical/near-IR luminosities and colors of early-type galaxies between $z = 1$ and the present, which provides a calibration of stellar mass estimates of such galaxies at high redshift.

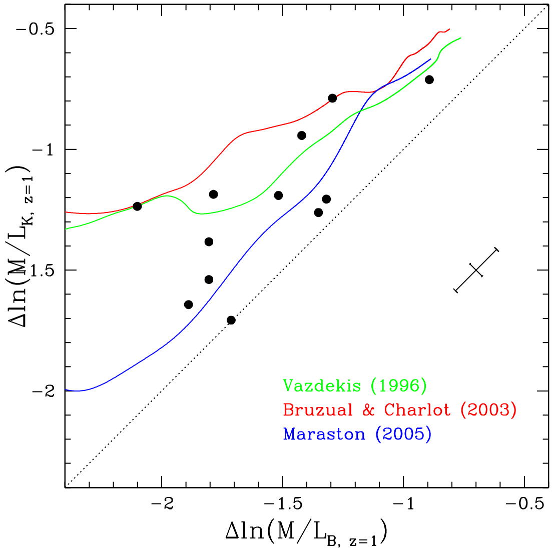

Figure 1. The evolution of M/L_B compared with the evolution in M/L_K for the 12 (out of 20) early-type galaxies at $0.9 < z < 1.2$. Model tracks from various stellar populations are shown. The models are for single stellar populations with solar metallicity and a Salpeter IMF.

2. The evolution of M/L_B and M/L_K

In van der Wel *et al.* (2004) and van der Wel *et al.* (2005) we measured the evolution of the rest-frame B-band M/L from $z \sim 1$ to the present. Masses and M/L were inferred from deep optical spectroscopy obtained at the VLT/FORS2 and high-resolution HST/ACS imaging from GOODS (Giavalisco *et al.* 2004). With Spitzer/IRAC imaging we determined the rest-frame K-band luminosities and M/L for the same sample (van der Wel *et al.* 2006a). As a local comparison sample we use 23 early types in the Coma Cluster with optical and near-IR M/L and colors (Faber *et al.* 1989; Jørgensen, Franx & Kjærgaard 1996; Pahre, Djorgovski & de Carvalho 1998).

In Fig. 1 we show that the change in M/L between $z = 1$ and the present is less in the K-band than in the B-band, which is qualitatively consistent with the generic model prediction that old, passively evolving stellar populations become redder with time. A quantitative comparison is more ambiguous, mainly because the different models differ from each other, which is also clear from Fig. 1. The observed evolution of M/L_K is faster than what most models predict, with the exception of the Maraston (2005) model. Are the other models (Bruzual & Charlot 2003; Vazdekis *et al.* 1996) not correct, or is the assumption of passive evolution wrong? We verified that adjusting the star formation history or metallicity generally does not help to reach agreement with the Bruzual & Charlot model, unless a young, heavily obscured population of young stars or an AGN affects the K-band luminosity of many of these galaxies (van der Wel *et al.* 2006b). However, in van der Wel *et al.* (2006c) we demonstrate, with the GOODS† 24 μm imaging that only $\sim 10 \pm 5\%$ of the early-type galaxy population at $z \sim 1$ have an obscured source (either young stars or AGN) that could affect their optical/near-IR spectral energy distributions (SEDs). Another possibility is that the stellar initial mass function (IMF) deviates considerably from the Salpeter IMF at masses higher than

† http://www.stsci.edu/science/goods/

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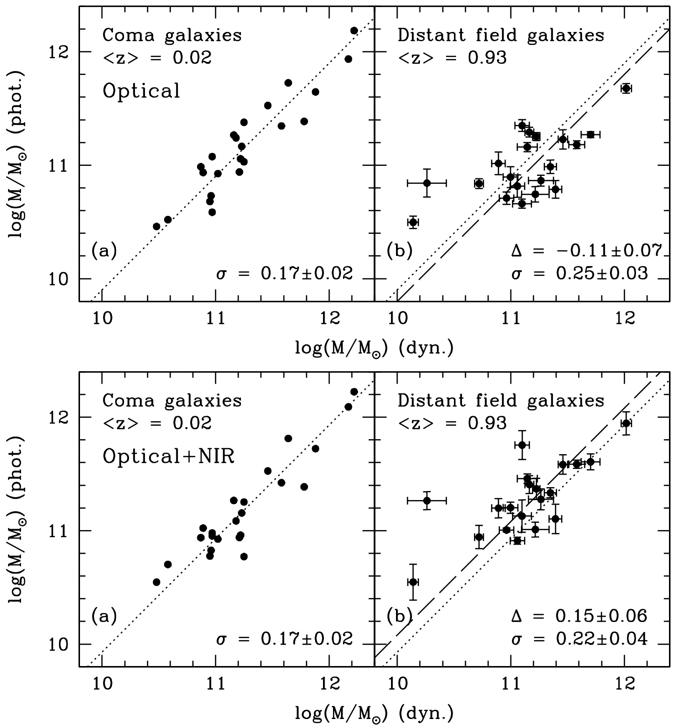

Figure 2. Photometric mass compared with dynamical mass for the low- and high-redshift early-type galaxy samples. The photometric masses are obtained from the Bruzual & Charlot SSP model with solar metallicity and a Salpeter IMF. In the top panels the photometric masses are inferred from rest-frame optical SED fits, and in the bottom panels the rest-frame near-IR is included as well.

$\sim 1\ M_\odot$. However, this leads to a discrepancy between the optical color and M/L (see van der Wel *et al.* 2006b). Therefore, it is most likely that the optical and near-IR light is entirely due to the evolved stellar populations of the galaxies, and that simple, one-component stellar populations should be sufficiently accurate to model their colors and luminosities. The demonstrated discrepancies seem to originate from problems with the models.

3. Biases in photometric mass estimates of $z \sim 1$ early-type galaxies

In this section we investigate to what extent the differences between the models and the data shown in the previous section affect photometric mass measurements. We fit the SEDs of the 23 low- and 20 high-redshift early-type galaxies with known M/L (from velocity dispersions), in different wavelength regimes and with different models. For details concerning the fitting technique and use of the models, see van der Wel *et al.* (2006b). First, we fit the rest-frame optical SEDs with the SSP model from Bruzual & Charlot. We show the results for both the low- and the high-redshift sample in Fig. 2 (top panels). In both samples we find an absolute difference between the photometric and the dynamical masses. This might be caused by low-mass stars (i.e., the low-mass end of the IMF is unconstrained) or dark matter. Our data do not allow to constrain and distinguish these contributions. It is more important that the difference is roughly the same for the

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samples at low and high redshift. This means that we can directly compare galaxies with similar photometric masses at different redshifts (i.e., with different ages).

The next step is to include the rest-frame near-IR in the fits (see Fig. 2, bottom panels). The photometric masses of the Coma Cluster early types do not change by much. The masses of the high-z early types, on the other hand, increase by a factor of ~ 2. Therefore, the masses of low- and high-redshift galaxies cannot be directly compared: an artificial and systematic difference is introduced. This is a direct consequence of the problem highlighted in the previous section: the Bruzual & Charlot model under-predicts the evolution of M/L_{K} between $z = 1$ and the present and therefore overestimates high-redshift stellar masses relative to low-redshift stellar masses.

The Maraston model provides an entirely different picture. A good feature of this model is that the estimated high-z galaxy masses, relative to the local galaxy masses, do not depend on whether the near-IR is used in the SED fits or not. However, we find that the high-z galaxy masses are systematically too low, by a factor of $\sim 1.5 - 2$. For more details and quantitative results, see van der Wel *et al.* (2006b), where we also explore a larger range in model parameters such as star formation history, dust content and IMF variations.

4. The Future

At the moment it seems best to rely on rest-frame optical colors to estimate the M/L of high-z galaxies if kinematic measurements are not available. This technique is very useful to construct large, mass-selected samples of galaxies at high redshifts. Convergence of the different stellar population models, and consistency of the models with tests such as described here, would be an important step forward, as it will remove systematic uncertainties in estimates of the high-z stellar mass budget relative to local measurements. Finally, for unambiguous application at redshifts higher than unity, it is essential that kinematic mass measurements are pushed to higher redshifts.

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