

HOW MASSIVE ARE MASSIVE COMPACT GALAXIES?

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ABSTRACT

Using a sample of nine massive compact galaxies at $z \sim 2.3$ with rest-frame optical spectroscopy and comprehensive $U \rightarrow 8 \mu\text{m}$ photometry, we investigate how assumptions in spectral energy distribution (SED) modeling change the stellar mass estimates of these galaxies, and how this affects our interpretation of their size evolution. The SEDs are fitted to τ -models with a range of metallicities, dust laws, and different stellar population synthesis codes. These models indicate masses equal to, or slightly smaller than, our default masses. The maximum difference is 0.16 dex for each parameter considered, and only 0.18 dex for the most extreme combination of parameters. Two-component populations with a maximally old stellar population superposed with a young component provide reasonable fits to these SEDs using the models of Bruzual & Charlot; however, when using models with updated treatment of TP-AGB stars, the fits are poorer. The two-component models predict masses that are 0.08–0.22 dex larger than the τ -models. We also test the effect of a bottom-light initial mass function (IMF) and find that it would reduce the masses of these galaxies by 0.3 dex. Considering the range of allowable masses from the τ -models, two-component fits, and IMF, we conclude that on average these galaxies lie below the mass–size relation of galaxies in the local universe by a factor of 3–9, depending on the SED models used.

Key words: galaxies: evolution – galaxies: fundamental parameters – galaxies: high-redshift – galaxies: stellar content – infrared: galaxies

1. INTRODUCTION

Numerous observational studies have shown that the population of massive galaxies at $z \sim 1.5$ – 2.5 is significantly more compact than local galaxies of similar mass (e.g., Daddi et al. 2005; Trujillo et al. 2006; Zirm et al. 2007; Toft et al. 2007; Longhetti et al. 2007; Cimatti et al. 2008; Damjanov et al. 2008; van Dokkum et al. 2008; Franx et al. 2008; Buitrago et al. 2008; van der Wel et al. 2008; Saracco et al. 2009; Taylor et al. 2009). Simple arguments based on the light profiles of these compact galaxies (e.g., Bezanson et al. 2009; Hopkins et al. 2009), as well as the evolution of their space density (e.g., van der Wel et al. 2009; Saracco et al. 2009), suggest that these galaxies may be the progenitors of local early-type galaxies being assembled from the inside out, and these arguments are supported by recent numerical simulations (e.g., Naab et al. 2009).

Thus far, little effort has been focused on how well determined the stellar masses (M_{star}) of these galaxies are. Indeed, claims about the total size growth of the galaxies, as well as explanations for the method of size growth based on their space density, require us to associate these galaxies to local galaxies of a particular mass. It is well known that there can be serious systematic effects in photometrically determined M_{star} 's caused by assumptions about metallicity, the galactic extinction law, or the method of stellar population synthesis (e.g., Maraston et al. 2006; Conroy et al. 2009a, 2009b; Marchesini et al. 2009; Longhetti & Saracco 2009; Muzzin et al. 2009). Furthermore, most models of high- z galaxies assume only simple star formation histories (SFHs; usually parameterized by an exponentially decreasing SFR with timescale τ). As suggested by earlier authors (e.g., van Dokkum et al. 2008; Hopkins et al. 2009;

La Barbera & De Carvalho 2009), if the compact galaxies have multi-age stellar populations with different spatial distributions, this may complicate our interpretation of their evolution. In this Letter we investigate how robust the M_{star} of $z \sim 2.3$ compact galaxies are, and how the uncertainties on these masses affect our interpretation of their size evolution.

2. DATA AND SED FITTING METHOD

Our sample of galaxies consists of the nine compact galaxies with strongly suppressed star formation presented in Kriek et al. (2006, 2008). The relatively low star formation rates of these galaxies have been recently reconfirmed both by ultradeep spectroscopy (Kriek et al. 2009), and spectral energy distribution (SED) modeling that includes the rest-frame NIR (Muzzin et al. 2009). These galaxies have effective radii (R_e) of ~ 1 kpc as measured from NICMOS H_{F160W} -band imaging by van Dokkum et al. (2008). The combination of accurate R_e 's from space-based imaging as well as the spectroscopic redshifts and well-sampled SEDs make this the best sample for testing the effect of assumptions in SED modeling of M_{star} on the inferred size evolution of massive galaxies.

For these galaxies we adopt two methods for fitting the SEDs. In order to test the effects of metallicity, dust law, and SPS code on the M_{star} we fit the galaxies to models with exponentially declining SFHs, hereafter “ τ -models.” In these models τ , age, and A_v are fitted as free parameters. The SED fitting is performed using a $\langle \chi^2 \rangle$ -minimization routine and the errors in M_{star} are determined using Monte Carlo simulations. Details of the SED fitting procedure and parameter error estimation are described in Muzzin et al. (2009). In an attempt to isolate variables we adopt the models of Bruzual & Charlot (2003; BC03) with solar metallicity, the Calzetti et al. (2000) dust law, and a Chabrier (2003) initial mass function (IMF) as the control

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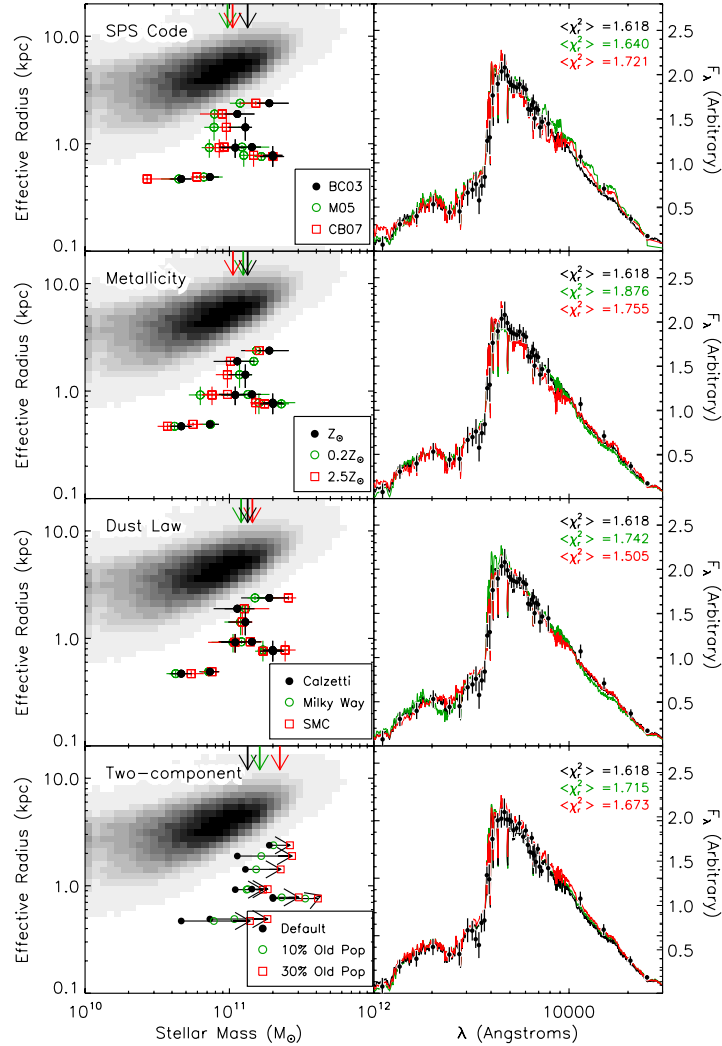


Figure 1. Left panels: plots of effective radius (R_e) vs. stellar mass (M_{star}) for various assumptions in the SED modeling. Local galaxies from the SDSS are plotted as contours ranging between 5 galaxies (lightest) to 1000 galaxies (darkest). The default models for the compact galaxies are plotted as large black circles, with variations denoted in the legend. The average mass for each model is shown as an arrow at the top of the panel. The effects of SED modeling assumptions on the M_{star} of the galaxies is less than 0.30 dex for all tested assumptions showing that size growth at fixed mass of a factor of 3–9 is a robust result from these data. Right panels: mean SEDs for the galaxies with the best fits overplotted. The $\langle \chi_r^2 \rangle$ are similar for all fits, which shows that assumptions in the SED modeling such as SPS code, metallicity, dust law, or two-components cannot be fitted as free parameters, even with these well-constrained SEDs.

model. This combination of models and parameters has been used extensively in previous studies of compact galaxies, and was the default model for the van Dokkum et al. (2008) study, making it the obvious choice for a control model. We compare the M_{star} from the control model to those determined with the dust law from the SMC (Prevot et al. 1984) and Milky Way (Fitzpatrick 1986), a subsolar ($0.2 Z_{\odot}$) and supersolar ($2.5 Z_{\odot}$) metallicity, as well as M_{star} from the SPS codes of Maraston (2005; hereafter M05), and S. Charlot & G. Bruzual (2009 in preparation, hereafter CB09).

We also test the effects of a two-component stellar population on the M_{star} of the galaxies. The SEDs are fit with a linear combination of a “young” and “old” component. The young component has τ , age, and A_v as free parameters, but age restricted to < 0.5 Gyr. The old component is a maximally old stellar population with no dust, and therefore has no free parameters. We perform the fitting three times, varying the amplitude of the old component between 10%, 20%, or 30% of the total observed H_{F160W} -band light. We note that this does not define the full range of M_{star} that could be allowed from two-component models; however, the primary purpose of fitting

these models is to explore the possibility of components with very different M/L ratios that could plausibly explain the sizes of the compact galaxies using age gradients.

3. EFFECTS OF ASSUMPTIONS IN SED MODELING

In the left panels of Figure 1 we show the effects of the different assumptions in the SED modeling on the M_{star} of the compact galaxies by comparing their location in the R_e versus M_{star} plane to galaxies from the SDSS (adapted from Kauffmann et al. 2003; Franx et al. 2008). In the right panels we show the mean observed SED of the entire sample as well as the mean fit. The $\langle \chi_r^2 \rangle$ of all fits are similar, demonstrating that even with these high quality SEDs it is not possible to fit SPS code, metallicity, dust law, or multiple components as free parameters.

Compared to the BC03 control model, the masses from the SPS codes of M05 and CB07 are systematically lower by 0.13 dex. Assuming a subsolar or supersolar metallicity systematically reduces the (M_{star}) by 0.10 and 0.16 dex compared to their control values, respectively. The Milky Way dust law reduces the (M_{star}) by 0.03 dex, whereas the SMC dust law increases it by 0.06 dex. Figure 1 shows that although all the

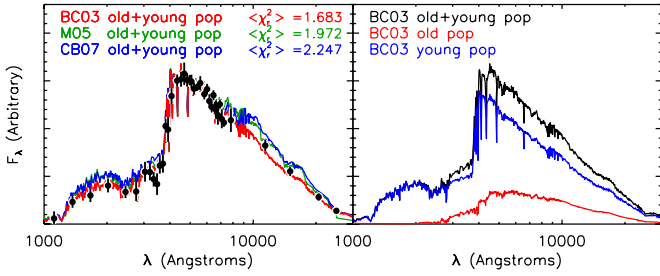


Figure 2. Left panel: mean SED for the compact galaxies with the best-fit two-component model from the various SPS codes superposed. The two-component model has 20% of the observed H_{160W} -band light in an old component. The BC03 model provides a good fit to the data, but the fits with the M05 and CB07 models are poorer, suggesting that they are less compatible with a two-component stellar population for these galaxies. Right panel: breakdown of the BC03 SED in the left panel into the old and young components.

SED modeling assumptions cause systematic differences in the M_{star} of the galaxies, none of them are large enough to change the fact that the galaxies are significantly more compact than local galaxies of similar mass. In fact, even if we combine the most extreme assumptions in the SED modeling, e.g., the M05 models with supersolar metallicity, and the Milky Way dust law, the mean M_{star} is only 0.18 dex lower than the default modeling assumptions.

The bottom panel of Figure 1 shows the effect of the two-component models on M_{star} . Adding an old stellar component to the modeling increases the overall M_{star} by 0.08 to 0.22 dex. Interestingly, two-component fits from the models of BC03 have a better $\langle \chi_r^2 \rangle$ than from the M05 and CB07 models. In the left panel of Figure 2 we plot two-component fits using all three SPS codes. In the right panel we plot the average old and young components of the fits using the BC03 models. Two-component fits from M05 and CB07 models are probably poorer descriptions of the data because of the increased contributions from the TP-AGB stars in those models. These stars contribute significantly to the rest-frame NIR flux in young populations (0.2–2 Gyr), and therefore, in these models the SED of both the young and old component have significant flux in the rest-frame NIR, and their linear combination cannot reproduce the overall SED shape. This suggests that models that explain the dramatic size evolution of these galaxies using age gradients in local galaxies (e.g., La Barbera & De Carvalho 2009) are unlikely to be compatible with our observed SEDs if interpreted with the M05 and CB07 models.

4. IMPLICATIONS FOR THE SIZE GROWTH OF MASSIVE GALAXIES

For the single-component τ -models, it is clear that changes in the SED modeling assumptions produce M_{star} values that are typically smaller on average than the default model. In particular, if we believe that the newer SPS models of M05 and CB07 provide more accurate masses than the BC03 models, then it has two implications for the method of size growth for these galaxies.

First, assuming our sample of galaxies increase in M_{star} by a factor of $\gtrsim 2$ from $z \sim 2.3$ to $z = 0$, then to match the sizes of local galaxies they would have to increase in size by a factor of $\gtrsim 5$ using the default model, and a factor of $\gtrsim 4$ for the newer SPS models. Recent numerical simulations show size growth of a factor of ~ 3 , with an M_{star} increase of a factor of ~ 2 since $z = 2$ (e.g., Naab et al. 2009), and therefore are in modestly better agreement with the size-mass relation from the

newer SPS models. Second, the lower M_{star} from the M05 and CB07 models also allow for more simultaneous mass and size growth in the galaxies. Bezanson et al. (2009) argued that given the M_{star} and number density of the $z \sim 2.3$ galaxies, minor mergers are the best candidate for increasing the size of these galaxies because they increase the size faster than the M_{star} . If the compact galaxies have an $\langle M_{\text{star}} \rangle$ that is 0.13 dex lower, the mass and number density argument still favors minor merging as the best candidate for size growth; however, it would permit some fraction of the population to grow in size from major mergers.

Recently, Mancini et al. (2009) claimed that using the newer SPS models would reduce the offset of our galaxies from the local relation by a factor of ~ 3 , and inferred that this could significantly alter our interpretation of their size evolution. Our modeling shows that this offset is only a factor of ~ 1.2 , and hence does not significantly alter the compact galaxy “problem.” Mancini et al. (2009) also claimed that with the newer masses and a 25% systematic underestimate in sizes, some of the galaxies in our sample may follow the local relation; however, Figure 1 shows that this is not the case, and that even the galaxies that lie closest to the local relation are still a factor of $\gtrsim 2$ off the relation.

If the two-component models provide the correct masses, they suggest very different scenarios for size growth. Assuming that the spatial distribution of the old and young components is identical, then the size growth at fixed mass would be significantly larger than previous estimates, a factor of ~ 9 . Furthermore, these galaxies would be roughly as massive as the most massive galaxies in the local sample, which means that the size growth would have to be extremely efficient, resembling a pure expansion model.

Such efficient size growth may not be required if the old component is significantly more extended than the young component. If so, the mass-weighted size of the galaxies could be much larger than its light-weighted size. In our SED fits the old component of these galaxies contain 10%–30% of the total light (by construction), yet it contains 50%–80% of the total stellar mass. Indeed, we cannot rule out the possibility that if the old component has an R_e of ~ 10 kpc and 50%–80% of the mass, that we may be looking at fully formed early-type galaxies with compact, centrally concentrated post-starburst component in the center. However, local early-type galaxies tend to have only modest color gradients, most of which can be attributed to metallicity (see, e.g., Franx & Illingworth 1990; Sanchez-Blazquez et al. 2007; Kormendy et al. 2009). These color gradients imply that galaxies have decreasing mass-to-light ratios with radius, and are therefore more compact in mass than in light, not the converse. It is possible that a combination of mergers and low-level star formation could mix the composite populations and create the locally observed color gradients; however, with the two-component SED modeling the $z \sim 2.3$ galaxies are already as massive as the most massive local galaxies, leaving little room for structural changes caused by processes that require additional mass growth.

5. IMF OR AGN?

Another effect that could account for the extreme R_e – M_{star} relation of the distant galaxies is an IMF that becomes increasingly bottom-light at higher redshift. Such an IMF has been suggested for high-redshift early-type galaxies (van Dokkum 2008). If we fit our galaxies using the M05 models and the van Dokkum (2008) bottom-light IMF, we find that the $\langle M_{\text{star}} \rangle$ is

lower by 0.30 dex. However, even with masses this low, these galaxies would still be a factor of ~ 3 smaller in size than local galaxies of similar mass.

It is also worth noting that none of the compact galaxies show an observed $8\ \mu\text{m}$ excess (rest-frame $\sim 3\ \mu\text{m}$) above the best-fit SED template. These excesses are not uncommon in high-redshift galaxies (e.g., Labbé et al. 2005; Donley et al. 2008; Mentuch et al. 2009; Muzzin et al. 2009) and could be caused by an active galactic nucleus. Combined with the fact that none of the galaxies show emission lines, it suggests that the size measurements of these galaxies are not contaminated by an unresolved point source (see also Kriek et al. 2009).

6. DISCUSSION

Overall, our modeling shows that despite the numerous systematic uncertainties involved in determining photometric M_{star} 's, the most extreme masses of the $z \sim 2.3$ compact galaxies are 0.18 dex different from our nominal estimates using a normal IMF, and 0.30 dex different using a bottom-light IMF. From this, we conclude that on average these galaxies lie a factor of ~ 3 – 9 below this size–mass relation of local galaxies, depending on the SED models used. This range could be slightly larger because our comparisons have been made to the default SDSS model. Although using different SPS models is unlikely to affect the M_{star} of the SDSS galaxies because at old ages the BC03 and M05 models produce similar masses (e.g., M05), and the dust content of the massive SDSS galaxies should be negligible, there could be small systematic offsets between the SDSS M_{star} and our M_{star} because of technical issues such as fiber aperture corrections, or the method of measuring total magnitudes. We note that other systematic effects may play a role. In particular, there may be systematic differences in the measurement of effective radii between the high- and low-redshift samples. van Dokkum et al. (2008), van der Wel et al. (2008), and Hopkins et al. (2009) show that biases due to surface brightness effects are probably small, but deeper data at high redshift would obviously be helpful. The low-redshift data also have significant uncertainties: interestingly, Guo et al. (2009) find that the sizes of the most luminous galaxies in the SDSS NYU-VAGC (Blanton et al. 2005) are likely underestimated, which would imply somewhat stronger evolution than the factor 3–9 that we find here.

With our data we still cannot rule out age (and hence M/L) gradients in these galaxies, which could bias the size measurements of these galaxies; however, such two-component models are disfavored by our data using the most recent SPS codes. A two-component model is still compatible with our SEDs when using the BC03 models; therefore measuring color gradients in these galaxies out to large radii will be valuable for understanding if the luminosity-weighted sizes of these galaxies are comparable to their mass-weighted sizes.

Although the range of allowed photometric- M_{star} is only a few tenths of a dex, it is large enough that we advise caution when using the number density of galaxies larger than a given mass to identify the descendants of these galaxies at various redshifts. These galaxies sit on the exponential tail of the mass function (e.g., Marchesini et al. 2009) and therefore small, systematic differences in their photometric- M_{star} like those shown here could result in significant errors in their space density. Ultimately, dynamical measurements are needed to calibrate photometric- M_{star} 's at high redshift. Early results suggest the agreement between the two is reasonable (e.g., van Dokkum et al. 2009; Cappellari et al. 2009); however, it will be

very important to extend these to large samples with a range of properties.

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