SALPETER NORMALIZATION OF THE STELLAR INITIAL MASS FUNCTION FOR MASSIVE GALAXIES AT $z \sim 1$

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Received 2013 October 4; accepted 2014 February 26; published 2014 April 15

ABSTRACT

The stellar initial mass function (IMF) is a key parameter for studying galaxy evolution. Here we measure the IMF mass normalization for a sample of 68 field galaxies in the redshift range 0.7–0.9 within the Extended Groth Strip. To do this we derive the total (stellar + dark matter) mass-to-light ($M/L$) ratio using axisymmetric dynamical models. Within the region where we have kinematics (about one half-light radius), the models assume (1) that mass follows light, implying negligible differences between the slope of the stellar and total density profiles, (2) constant velocity anisotropy ($\beta_c \equiv 1 - \sigma_r^2/\sigma_z^2 = 0.2$), and (3) that galaxies are seen at the average inclination for random orientations (i.e., $i = 60^\circ$, where $i = 90^\circ$ represents edge-on). The dynamical models are based on anisotropic Jeans equations, constrained by Hubble Space Telescope/Advanced Camera for Surveys imaging and the central velocity dispersion of the galaxies, extracted from good-quality spectra taken by the DEEP2 survey. The population ($M/L$) are derived from full-spectrum fitting of the same spectra with a grid of simple stellar population models. Recent dynamical modeling results from the ATLAS3D project and numerical simulations of galaxy evolution indicate that the dark matter fraction within the central regions of our galaxies should be small. This suggests that our derived total ($M/L$) should closely approximate the stellar $M/L$. Our comparison of the dynamical ($M/L$) and the population ($M/L$) then implies that for galaxies with stellar mass $M_\star \gtrsim 10^{11} M_\odot$ the average normalization of the IMF is consistent with a Salpeter slope, with a substantial scatter. This is similar to what is found within a similar mass range for nearby galaxies.

Key words: galaxies: evolution – galaxies: formation – galaxies: high-redshift – galaxies: kinematics and dynamics – galaxies: structure

Online-only material: machine-readable table

1. INTRODUCTION

Knowledge of the stellar mass of galaxies has long been pivotal to the study and testing of galaxy formation and evolution theories, but an economical method for its estimation has remained elusive to astronomers for decades (see Courteau et al. 2014, for a review). The main reason for this is the fact that the galaxy photometry does not sufficiently constrain the stellar mass, which is dependent on both the stellar populations of the galaxy and the stellar initial mass function (IMF) of those populations. The IMF represents the distribution of stellar masses at a single star formation event. The form of the IMF is critical for estimating the mass of the galaxies and in understanding the stellar feedback and the chemical enrichment processes taking place within them.

It is currently accepted, from direct star counts, that the IMF shape in our Milky Way can be approximated by a power law $dN/dm \propto m^x$ with the Salpeter (1955) slope $x \approx -2.35$, above a stellar mass $m \gtrsim 0.5 M_\odot$ and a more shallow slope below $m \lesssim 0.5 M_\odot$ (Kroupa 2001; Chabrier 2003). Though this IMF seems universal within the Milky Way, its applicability to external galaxies has been uncertain for decades (see Bastian et al. 2010 and Kroupa et al. 2013 for recent reviews).

Early attempts comparing the dynamical mass-to-light ratio ($M/L$) to the value inferred from stellar population synthesis concluded that at least some spiral galaxies (Bell & de Jong 2001; Kassin et al. 2006; Bershady et al. 2011; Dutton et al. 2011; Brewer et al. 2012) and early-type galaxies (ETGs; Cappellari et al. 2006; Ferreras et al. 2008; Thomas et al. 2011) require an overall Kroupa/Chabrier mass normalization of the IMF like the Milky Way. By studying the variation of the average $M/L$ of galaxies in clusters at different redshifts, Renzini (2006) concluded that a Salpeter IMF slope was required for the mass range of $1 < M < 1.4 M_\odot$.

More recently van Dokkum & Conroy (2010, 2011) studied near-infrared spectral features, where the contribution from dwarf stars is easier to measure. They concluded that massive elliptical galaxies have an IMF dominated by dwarfs, unlike the Milky Way. Auger et al. (2010) studied the IMF by comparing stellar masses from strong gravitational lensing to stellar masses from population synthesis. Their models assume that massive ETGs are spherical, satisfy a power-law dependence of IMF normalization with the galaxy mass, have dark halos following the mass–concentration relation predicted by simulation, and have total to stellar mass ratio derived from halo abundance matching. They concluded that massive ETGs as a class have a Salpeter-like mass normalization of the IMF.

Cappellari et al. (2012) used more general axisymmetric dynamical models that allow the IMF, the stellar profiles, the halo slope, and the stellar fraction to vary freely in different galaxies to reproduce the data. The models were constrained by integral-field stellar kinematics for a sample of 260 ETGs spanning a large range of masses and $\sigma$. They found a systematic trend in the IMF normalization. The average IMF varies from Kroupa/Chabrier to Salpeter and becomes heavier with increasing $\sigma$, which was shown to trace the bulge fraction (Cappellari et al. 2013a).

A number of recent works appear so far to be consistent with a systematic IMF variation. These used either spectral synthesis (e.g., Spiniello et al. 2012; Conroy & van Dokkum 2012; Smith et al. 2012; Ferreras et al. 2013; La Barbera et al. 2013), dynamical scaling relations (Dutton et al. 2013), or...
approximate spherical dynamical models (Tortora et al. 2013) to study absorption features. However, quantitative agreement between the different approaches has not yet been achieved and full consensus has not been reached (e.g., Maraston 2013).

The study of IMF in galaxies at high redshift has so far been dominated by dynamical mass derivations using the virial estimator (e.g., Renzini 2006; van de Sande et al. 2013). In this study, we constrain the IMF normalization at redshift $z \sim 1$ using axisymmetric dynamical models and compare the results with findings in the local universe. This is one of the few studies to attempt dynamical modeling at higher redshift (van der Marel & van Dokkum 2007; Cappellari et al. 2009) but is the first to place constraints on the IMF normalization of galaxies at high redshift.

In Section 2, we give a description of the data used for this study and a description of the galaxy set. We describe our methodology in Section 3, while we present our results in Section 4. In Section 5, we discuss the results. We used the following cosmological constants: $\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$.

2. DATA AND SAMPLE

2.1. Spectral Data

The one-dimensional (1D) spectrum of our galaxies was obtained from the DEEP2 spectrographic survey (Newman et al. 2013). It is a magnitude-limited, $R_{AB} \leq 24.1$, galaxy redshift survey. In this study, we use the Extended Groth Strip (EGS; Groth et al. 1994) field of the survey due to the availability of Hubble Space Telescope (HST) imaging (Davis et al. 2007). The data was taken by the DEIMOS multi-object spectrograph, mounted on the Keck-2 Telescope, with a observed wavelength range of 6500–9100 Å, in a spectral resolution of $R \sim 6000$ at 7800 Å. The typical total exposure time for each galaxy is 1 hr, with average seeing of $0.85$. The two-dimensional (2D) spectra of the galaxies were observed using slitlets of dimensions $1'' \times 7''$. 1D spectra of the galaxies were then derived using the boxcar technique, within extraction windows of $\sim 1'' \times 1''$. Due to the design of the survey, the spectra of the objects are divided into two halves. For our study, we use the blue half of the wavelength range so as to observe the CaK and G stellar lines for our given redshift range.

2.2. Photometric Data

A survey of the EGS was done, using the HST/Advanced Camera for Surveys, by the GO program 10134 (PI: M. Davis; Davis et al. 2007). The survey was done with the F606W (V) and F814W (I) filters, at 5σ magnitude limits of $V_{606W} = 26.23$(AB) and $I_{814W} = 25.61$(AB). The observations were done in a four-point dither pattern, which was processed by the STSDAS MultiDrizzle package to produce a final mosaic of the field with a pixel scale of $0.03''$.

2.3. Selection

The DEEP2 survey has observed $\sim 49,000$ galaxy spectra. For this study, our initial selection criteria are that galaxies have reliable redshift between $0.7 < z < 0.9$ and have high-resolution HST photometry. This meant selecting galaxies with “secure” and “very secure” redshifts in the DEEP2 catalog. These criteria reduced the sample to $\sim 1350$.

The galaxy spectra were then logarithmically rebinned to $60$ km s$^{-1}$ per spectral pixel and a signal-to-noise ratio (S/N) > 3 cut-off was applied. We visually inspected the spectra after their initial spectral fits (Section 3.1) and retained galaxies showing clear and well-fitted stellar absorption lines. This reduced the sample to $\sim 200$.

After the photometric parameterization (Section 3.2), a visual inspection of the contour fits of the galaxy photometry and the model was done to ensure that the models accurately reproduce the galaxy photometry, removing galaxies with non-axisymmetric features, e.g., disturbed morphology or strong dust. This reduced our sample to 87.

Another selection criterion implemented on our galaxy sample was that of the luminosity-weighted age of the galaxies, derived by identifying the best-fitting single stellar population model with solar metallicity via full-spectrum fitting. Galaxies with best-fitting template age $< 1.2$ Gyr were removed. A similar selection was made by Cappellari et al. (2012, 2013a) who found that young galaxies have strong stellar population gradients, hence breaking the assumption of constant stellar $M/L$.

Finally, we removed galaxies with strong evidence for multiple populations using full-spectrum fitting (Section 3.3), leading to a final sample of 68 galaxies.

These galaxies consists of massive ETGs (stellar masses $10^{11} \lesssim M_*/M_\odot \lesssim 10^{12}$), except for seven galaxies at lower masses. More information on these galaxies will be given in a follow-up paper.

3. METHODS

3.1. Velocity Dispersion Measurements

To create dynamical models for our galaxies, we first extracted reliable velocity dispersions for the galaxies using the pPXF code1 (Cappellari & Emsellem 2004). The spectrum fitting was done with a subset of 53 stellar spectra taken from the Indo-US Library of Coudé Feed Stellar Spectra Library (Valdes et al. 2004). These spectra were selected so that (1) each spectrum is gap-free and (2) the subset is a good representation of the library’s atmospheric parameter range ($T_{\text{eff}}$ versus [Fe/H]). During the fitting process, the telluric features in the galaxy spectra were masked, along with any significant gas emission feature. Examples of spectral fits are given in Figure 1.

A bootstrapping technique was used to estimate the real errors on the derived single aperture velocity dispersions. The technique involved re-sampling the residuals between the observed spectrum and an initial best fit. The bootstrapped spectra are then fitted with an “optimal” template which is the summation of the templates used for the initial fit of the spectrum, multiplied with their respective weights. The process was iterated 500 times, and the distribution of the stellar kinematic values was used to estimate the velocity dispersion and its error.

We compare our derived velocity dispersion with that of Fernández Lorenzo et al. (2011) for our 40 common galaxies using the LTS_LINEFIT routine (see footnote 1), after modification to fix the slope of the comparison at 1. We find that our velocity dispersions are consistent with those of Fernández Lorenzo et al. (2011) with a negligible offset of 0.013 ± 0.013 dex and an observed rms scatter of 0.094 dex.

3.2. Calculating Dynamical $M/L$

The multi-Gaussian expansion (MGE; Emsellem et al. 1994) parameterization of our galaxy photometry was done using the MGE_FIT_SECTORS (see footnote 1) code of Cappellari

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1 Available at http://purl.org/cappellari/software.
Figure 1. Summary plots of spectrum fitting for nine galaxies. The galaxy spectrum is shown in black, while the best fit is in red. The galaxy spectrum has been rebinned to 60 km s$^{-1}$ spectral pixel resolution and Gauss-smoothed to make the absorption features clearer to the eye. The green dots below the galaxy spectrum are OII CaK and the blue features are the masked pixels. The portion of the spectrum around $\sim$3800 Å and $\sim$4100 Å are the telluric features that have been masked.

(2002). To ensure that our MGE fits reflect the underlying mass distribution of galaxies, we adopt the technique used by Scott et al. (2013; Section 3.2.1). We also force the surface brightness distribution of galaxies, we adopt the technique used by Scott (2002). To ensure that our MGE fits reflect the underlying mass distribution of galaxies, we adopt the technique used by Scott et al. (2013; Section 3.2.1). We also force the surface brightness profile at the largest observed radius to have an outer slope of $R^{-4}$. Examples of MGE fits are shown in Figure 2.

In this study, we use the Jeans Anisotropic MGE (JAM) method (see footnote 1; Cappellari 2008). These models solve the anisotropic Jeans equations for a given light and mass profile of axisymmetric galaxies while allowing for orbital anisotropy. The modeling code also allows for the rigorous application of seeing and aperture effects.

We adopt this method over the more commonly used virial estimates based on Sésic spherical Jeans models since spherical models cannot reproduce the variety in the stellar kinematics of galaxies (Cappellari et al. 2013b, Figure 1). In addition, Cappellari et al. (2013b, Figure 14) show that virial estimates suffer from large scatter and potential biases in the absolute $M/L$ normalization, which is critical for our work.

We assume for all galaxies the average inclination ($i \approx 60^\circ$) for random orientations ($i \approx 90^\circ$ being edge-on). For a few galaxies for which this inclination is not allowed by the deprojection of the MGE model, we assign the lowest allowed inclination. We adopt an anisotropy $\beta_z \equiv 1 - \sigma^2_z / \sigma^2_R = 0.2$ which is the typical value, within one half-light radius $R_e$, for ETGs in the local universe (Cappellari et al. 2007; Gerhard et al. 2001). Previous studies have shown the $M/L$ to be very weakly sensitive to the adopted inclination (Cappellari et al. 2006, Figure 4). However, our quoted errors do not include the effect of our constant anisotropy assumption.

Given our lack of spatially resolved spectral data, we are unable to separate luminous and dark matter in our galaxies. Hence, we use mass-follow-light models, which were shown to robustly recover the total $M/L$ within $1R_e$, even when dark matter is present (Cappellari et al. 2013b), when the data extend out to the same radius. The dynamical $M/L$ of our galaxies is given by $(M/L)_{JAM} = (\sigma/V_{\text{rms}})^2$ (Table 1), where $\sigma$ is measured within the DEEP2 1'' slit (Table 1) and $V_{\text{rms}}$ is the value predicted by the JAM model within the same aperture for $M/L = 1$.

The extensive modeling study of Cappellari et al. (2013b) measures a low dark matter fraction (<30%), within $1R_e$, for nearby galaxies of similar mass to ours. Numerical simulations by Hilz et al. (2013) provide a general argument as to why dark matter should further decrease with increasing redshift. These results indicate that the dark matter fraction in the central regions
Figure 2. Summary plots of the MGE fits for nine galaxies. The black contour lines represent the observed light distribution of the galaxies, while the red represents the model. Since we calculate the \((M/L)_{\text{JAM}}\) for the inner regions of the galaxies, it is important to reproduce the inner light profile accurately.

of our galaxies should be negligible, hence indicating that our \((M/L)_{\text{JAM}}\) should closely approximate the stellar \(M/L\). Without this assumption, our \(M/L\) would only provide an upper limit to the IMF mass normalization.

We use the parameterization of the photometry and the redshift of the galaxies to derive their absolute magnitude. Since the F814W filter observes the rest frame \(B\) band for galaxies at redshift \(\sim 0.8\), all magnitudes and \((M/L)\)s presented in this study are in the \(B\) (Vega) system.

3.3. Calculating Stellar Population \(M/L\)

We derive the population \(M/L\) of the galaxies using the MILES stellar evolutionary models (Vazdekis et al. 2010). These models use the MILES empirical stellar spectral library (Sánchez-Blázquez et al. 2006) to derive single age and metallicity models for the entire optical wavelength range. We use the Salpeter IMF as the reference IMF for this study.

The full-spectrum fittings were done using pPXF with a template grid of 40 logarithmically spaced ages, between 0.089 to 7.9 Gyr, for metallicities \([M/H]\) of \(-0.4, 0.00,\) and \(0.22\). The upper limit of the ages was constrained to the age of the universe at the adopted redshift while the metallicity range is justified by the results of Schiavon et al. (2006) who find that galaxies at \(0.7 < z < 0.9\) have nearly solar metallicities. The \((M/L)_{\text{Salpeter}}\) in the \(B\) (Vega) band was calculated as

\[
(M/L)_{\text{Salpeter}} = \sum_j w_j \frac{M_{\text{no gas}}^j}{w_j L^j_B},
\]
where \( w_j \) is the weight of each template, \( M_*^{\text{Pop}} \) is the mass of stars and stellar remnants, and \( L_B \) is the \( B \) (Vega) band luminosity of the model.

To test the robustness of our results to model selection, the \((M/L)_{\text{Salpeter}}\) was calculated using two different template sets: (1) unregularized fitting with solar metallicity templates and (2) a regularized fitting with the entire single stellar population model grid. The \( M/L \) derived from these template sets are offset by only 0.07 dex and have an intrinsic scatter of 0.08 dex. We find that our results are robust to variations of this scale and so we present our results here using the latter set.

4. RESULT

In this study, we derive accurate total dynamical \((M/L)_{\text{JAM}}\) and stellar population \((M/L)_{\text{Salpeter}}\) for 68 galaxies. In Table 1, the reader will find the list of physical parameters derived in this study.

Our results allow us to compare the \( M/L \) from detailed models with the virial estimate:

\[
(M/L)_{\text{virial}} = 5.0 \times \frac{R_e \sigma_e^2}{G L}, \tag{2}
\]

where \( \sigma_e \) is the measured velocity dispersion within \( R_e \) (Cappellari et al. 2006). In our study, we have measured the \( R_e \) using MGE and use the aperture correction for the velocity dispersion as given in Equation (1) of Cappellari et al. (2006). We use a virial coefficient of 5.0 since Cappellari et al. (2013b, Figure 13) shows that it is applicable to virial mass estimations of the \( R_e \), specifically due to shallow observations of galaxy photometry and our non-extrapolated radii.

In Figure 3, we show the mass plane (\( R_e \) vs. stellar mass) of our final galaxy set, with \( R_e \) rescaled using the offset observed between \((M/L)_{\text{JAM}}\) and the virial estimate. The thick red line represents the zone of exclusion from Cappellari et al. (2013a), which approximates the 99% boundary for the nearby galaxy population. The colored diagonal dashed lines are the predicted lines of constant velocity dispersion according to the scalar virial equation. Part of the trend in mass normalization with mass must be due to the correlation between \( M_{\text{JAM}} \) and \((M/L)_{\text{JAM}}/(M/L)_{\text{Salpeter}}\).

![Figure 3](image-url)

\( \Delta \sigma \) of the model.

Table 1

| DEEP2 ID No. | Redshift | \( M_B \) | \( R_e \) (\( \circ \)) | \( \sigma \) (km s\(^{-1}\)) | \( \Delta \sigma \) (km s\(^{-1}\)) | \( (M/L)_{\text{JAM}} \) (\( M_\odot/L_B \)) | \( (M/L)_{\text{Salpeter}} \) (\( M_\odot/L_B \)) |
|-------------|----------|----------|----------------|----------------|----------------|-----------------|----------------|
| 11050845    | 0.840    | -21.76   | 0.40           | 298            | 28             | 6.10            | 3.55            |
| 12004136    | 0.812    | -21.62   | 0.50           | 202            | 21             | 3.09            | 2.92            |
| 12004516    | 0.820    | -21.44   | 0.44           | 176            | 28             | 2.85            | 1.97            |
| 12008254    | 0.745    | -21.51   | 0.41           | 250            | 33             | 4.92            | 4.32            |
| 12008360    | 0.828    | -20.97   | 0.18           | 185            | 31             | 2.63            | 2.39            |
| 12008441    | 0.832    | -21.34   | 0.53           | 257            | 64             | 9.26            | 1.79            |
| 12011900    | 0.719    | -20.88   | 0.23           | 318            | 57             | 9.75            | 4.46            |

Notes. Column 1: DEEP2 galaxy identifier. Column 2: DEEP2 estimated redshift. Column 3: absolute \( B \) (Vega) band magnitude derived using MGE. Column 4: effective radius as derived from MGE (without re-scaling). Column 5: aperture velocity dispersion. Column 6: error on aperture velocity dispersion. Column 7: dynamical \( B \)-band (Vega) mass-to-light ratio with a median error of 0.11 dex. Column 8: population \( B \)-band (Vega) mass-to-light-ratio with a scatter of 0.08 dex.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)
between the velocity dispersion of galaxies, part of which must be due to the correlation and population by a nearly complete lack of correlation between the dynamical qualitatively similar, and in both cases they are characterized $\sigma$ driven by systematics in our it must be intrinsic. However, the extreme cases must be dark matter in the central regions of the galaxies is valid. The consistent with a Salpeter-like, rather than a Milky Way-like, depth of the photometry as well as on the adopted extrapolation (1979)2 to provide easy comparison with the results of the local dispersions is smoothed using the LOESS method of Cleveland (1979). Though there is an indication of a trend of the mass normalization with the velocity dispersion of galaxies, part of which must be due to the correlation between $\sigma$ and $(M/L)_{\text{JAM}}$. A representative error bar is shown at the top left. The histogram on the bottom-right shows the log((M/L)$_{\text{JAM}}$)/(M/L)$_{\text{Salpeter}}$). The best-fitting Gaussian peaks at 0.00 and has a dispersion of 0.29.

Figure 4. $B$-band $(M/L)_{\text{JAM}}$ vs. $(M/L)_{\text{Salpeter}}$. The thick magenta line represents the Salpeter IMF. The dashed red line represents the Chabrier IMF, while the dashed blue line represents a single power law with a slope of $-2.8$ (dwarf-dominated) or $-1.5$ (stellar remnant dominated). The points are color coded to the velocity dispersion smoothed using the LOESS method of Cleveland (1979). The heavy gray line represents the local galaxy sample, can be directly compared to Figure 11 of Cappellari et al. (2013a). The two plots look qualitatively similar, and in both cases they are characterized by a nearly complete lack of correlation between the dynamical and population $M/L$ for galaxies with the largest $\sigma$.

5. SUMMARY

We used the JAM models to derive dynamical $(M/L)_{\text{JAM}}$ for 68 massive galaxies ($M_*/M_\odot \approx 10^{11}$) at redshifts $z = 0.7$ to 0.9. Our results show that using the virial equation at high redshifts can lead to a severe underestimation of the dynamical masses of galaxies, which is likely due to the underestimation of $R_e$. The underestimation must depend on the depth of the photometry as well as on the adopted extrapolation of the profiles, making the virial estimates dependent on the assumption (see also Cappellari et al. 2013b). The $(M/L)_{\text{JAM}}$ does not suffer from this problem as it only requires the knowledge of the light and mass distribution within a region comparable to where the stellar kinematics are available. Our result suggests that stellar population estimates of stellar masses of massive galaxies at high redshifts should assume a Salpeter IMF normalization for more accurate results instead of the Kroupa/Chabrier IMFs that are often adopted. This IMF normalization is the same inferred for nearby galaxies of similar masses.

REFERENCES

Auger, M. W., Treu, T., Gavazzi, R., et al. 2010, ApJL, 721, L163
Bastian, N., Covey, K. R., & Meyer, M. R. 2010, ARA&A, 48, 339
Bell, E. F., & de Jong, R. S. 2001, ApJ, 550, 212
Bershady, M. A., Martinsson, T. P. K., Verheijen, M. A. W., et al. 2011, ApJL, 739, L47
Brewer, B. J., Dutton, A. A., Treu, T., et al. 2012, MNRAS, 422, 3574
Cappellari, M. 2002, MNRAS, 333, 400
Cappellari, M. 2008, MNRAS, 390, 71
Cappellari, M., Bacon, R., Bureau, M., et al. 2006, MNRAS, 366, 1126
Cappellari, M., di Serego Alighieri, S., Cimatti, A., et al. 2009, ApJ, 704, L34
Cappellari, M., & Emsellem, E. 2004, PASP, 116, 138
Cappellari, M., Emsellem, E., Bacon, R., et al. 2007, MNRAS, 379, 418
Cappellari, M., McDermid, R. M., Alatalo, K., et al. 2012, Natur, 484, 485
Cappellari, M., McDermid, R. M., Alatalo, K., et al. 2013a, MNRAS, 432, 1862
Cappellari, M., Scott, N., Alatalo, K., et al. 2013b, MNRAS, 432, 1709
Chabrier, G. 2003, PASP, 115, 763
Cleveland, W. S. 1979, J. Am. Stat. Assoc., 74, 829
Conroy, C., & van Dokkum, P. G. 2012, ApJL, 760, 71
Courteau, S., Cappellari, M., de Jong, R. S., et al. 2014, RvMP, 86, 47
Davis, M., Guhathakurta, P., Konidaris, N. P., et al. 2007, ApJL, 660, L1
Dutton, A. A., Conroy, C., van den Bosch, F. C., et al. 2011, MNRAS, 416, 322
Dutton, A. A., Macciò, A. V., Mendel, J. T., & Simard, L. 2013, MNRAS, 432, 2496
Emsellem, E., Monnet, G., & Bacon, R. 1994, A&A, 285, 723
Fernández Lorenzo, M., Cepa, J., Bongiovanni, A., et al. 2013, A&A, 562, A72
Ferreras, I., La Barbera, F., de la Rosa, I. G., et al. 2013, MNRAS, 429, L15
Ferreras, I., Saha, P., & Burles, S. 2008, MNRAS, 383, 857
Gerhard, O., Kronawitter, A., Saglia, R. P., & Bender, R. 2001, AJ, 121, 1936
Groth, E. J., Kristian, J. A., Lynds, R., et al. 1994, BAAS, 26, 1403
Hilz, M., Naab, T., & Ostriker, J. P. 2013, MNRAS, 429, 2924
Kassin, S. A., de Jong, R. S., & Weiner, B. J. 2006, ApJL, 643, 804
Kroupa, P. 2001, MNRAS, 322, 231
Kroupa, P., Weidner, C., Pfamm-Altenburg, J., et al. 2013, in Planets, Stars and Stellar Systems, The Stellar and Sub-Stellar Initial Mass Function of Simple and Composite Populations, ed. T. D. Oswalt & G. Gilmore (Dordrecht: Springer), 115
La Barbera, F., Ferreras, I., Vazdekis, A., et al. 2013, MNRAS, 433, 3017
Maraston, C. 2013, in IAU Symp. 295, The Intriguing Life of Massive Galaxies, ed. D. Thomas, A. Pasquali, & I. Ferreras (Cambridge: Cambridge Univ. Press), 272
Newman, J. A., Cooper, M. C., Davis, M., et al. 2013, ApJS, 208, 5
Renzini, A. 2006, ARA&A, 44, 141
Salpeter, E. E. 1955, ApJ, 121, 161
Sánchez-Blázquez, P., Peletier, R. F., Jiménez-Vicente, J., et al. 2006, MNRAS, 371, 703
Schiavon, R. P., Faber, S. M., Konidaris, N., et al. 2006, ApJL, 651, L93
Scott, N., Cappellari, M., Davies, R. L., et al. 2013, MNRAS, 432, 1894
Smith, R. J., Lucey, J. R., & Carter, D. 2012, MNRAS, 426, 2994
Spiniello, C., Trager, S. C., Koopmans, L. V. E., & Chen, Y. P. 2012, ApJL, 753, L32
Thomas, J., Saglia, R. P., Bender, R., et al. 2011, MNRAS, 415, 545
Tortora, C., Romanowsky, A. J., & Napolitano, N. R. 2013, ApJL, 765, 8
Valdes, F., Gupta, R., Rose, J. A., Singh, H. P., & Bell, D. J. 2004, ApJS, 152, 251
van de Sande, J., Kriek, M., Franx, M., et al. 2013, ApJ, 771, 85
van der Marel, R. P., & van Dokkum, P. G. 2007, ApJ, 668, 756
van Dokkum, P. G., & Conroy, C. 2010, Natur, 468, 940
van Dokkum, P. G., & Conroy, C. 2011, ApJL, 735, L13
Vazdekis, A., Sánchez-Blázquez, P., Falcón-Barroso, J., et al. 2010, MNRAS, 404, 1639

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5 As implemented in the CAP_LOESS_2D routine of Cappellari et al. (2013b), available from http://purl.org/cappellari/software.