THE STELLAR INITIAL MASS FUNCTION IN EARLY-TYPE GALAXIES FROM ABSORPTION LINE SPECTROSCOPY. III. RADIAL GRADIENTS

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ABSTRACT

There is good evidence that the centers of massive early-type galaxies have a bottom-heavy stellar initial mass function (IMF) compared to the IMF of the Milky Way. Here we study the radial variation of the IMF within such galaxies, using a combination of high quality Keck spectroscopy and a new suite of stellar population synthesis models that cover a wide range in metallicity. As in the previous studies in this series, the models are fitted directly to the spectra and treat all elemental abundance ratios as free parameters. Using newly obtained spectroscopy for six galaxies, including deep data extending to \( \sim 1R_e \) for the galaxies NGC 1407, NGC 1600, and NGC 2695, we find that the IMF varies strongly with galactocentric radius. For all six galaxies the IMF is bottom-heavy in the central regions, with average mass-to-light ratio “mismatch” parameter \( \alpha \equiv (M/L)/(M/L)_{\text{MW}} \approx 2.5 \) at \( R = 0 \). The IMF rapidly becomes more bottom-light with increasing radius, flattening off near the Milky Way value \((\alpha \approx 1.1)\) at \( R > 0.4R_e \). A consequence is that the luminosity-weighted average IMF depends on the measurement aperture: within \( R = R_e \) we find \( \langle \alpha \rangle_L = 1.3 \pm 1.5 \), consistent with recent lensing and dynamical results from SLACS and ATLAS. Our results are also consistent with several earlier studies that were based on analyses of radial gradients of line indices. The observed IMF gradients support galaxy formation models in which the central regions of massive galaxies had a different formation history than their outer parts. Finally, we make use of the high signal-to-noise central spectra of NGC 1407 and NGC 2695 to demonstrate how we can disentangle IMF effects and abundance effects.

Keywords: galaxies: structure — galaxies: stellar content — galaxies: evolution — galaxies: abundances — stars: luminosity function, mass function

1. INTRODUCTION

There is strong evidence that the stellar initial mass function (IMF) in the centers of massive early-type galaxies is bottom-heavy with respect to the IMF in the Milky Way disk. The evidence primarily comes from three distinct observations. First, recent stellar population synthesis (SPS) modeling consistently indicates a relatively large contribution of low mass stars to the integrated light (e.g., Cenarro et al. 2003; van Dokkum & Conroy 2010, 2011; Conroy & van Dokkum 2012b; Smith, Lucey, & Carter 2012; Spiniello et al. 2012; La Barbera et al. 2013; La Barbera, Ferreras, & Vazdekis 2015). Second, the dynamics of massive galaxies are better fitted when a Kroupa (2001) or Chabrier (2003) IMF is used, as a Kroupa IMF implies a total mass in stars that is higher by a factor of 1.6 (e.g., Thomas et al. 2011; Cappellari et al. 2012; Dutton, Mendel, & Simard 2012). Dutton et al. (2012) show that this also holds for very compact galaxies, which are thought to have only a minor contribution from dark matter within their effective radius. Third, gravitational lensing studies show a behavior similar to the dynamical studies, requiring a heavy, Salpeter-like IMF for the highest mass lenses (e.g., Treu et al. 2010; Spiniello et al. 2011; Sonnenfeld et al. 2015).

It is encouraging that all three methods are qualitatively consistent, and that comparisons of different techniques generally show the same trends. Conroy et al. (2013) show that dynamical and stellar population synthesis modeling of compact galaxies are consistent with each other, and Posacki et al. (2015) combine lensing with stellar population modeling. Lyubenova et al. (2016) find good agreement between dynamical and stellar population measurements of galaxies in the CALIFA survey, carefully controlling for systematic differences in the methodology. Taking these studies a step further, Spiniello et al. (2015a) combine lensing, dynamics, and SPS modeling to constrain both the slope and the cutoff of the IMF below 1 M\(_{\odot}\) for a sample of nine galaxies.

However, not all studies are in agreement, and the question whether the IMF varies between galaxies is not yet settled. As shown by Smith (2014) a direct comparison of published results of the same individual galaxies using different techniques shows very large scatter. In addition, a detailed study of several very nearby strong lenses suggests tension between the lensing masses and the SPS-inferred ones (Smith, Lucey, & Conroy 2015). Another example of possible tension is the lack of variation in the number of X-ray binaries with galaxy velocity dispersion (Peacock et al. 2014), although this constrains the IMF at high masses, not low masses.

It is likely that these disagreements, and the large differences between some independent measurements of the same galaxies (see Smith 2014), are due to a combination of factors. First, it seems that there is considerable galaxy-to-galaxy scatter in the IMF (e.g., Conroy & van Dokkum 2012b; Leier et al. 2016). Furthermore, it is certainly the case that the random errors in all methods underestimate the true uncertainty (see, e.g., Tang & Worthey 2015). A striking illustration of this is...
the SPS-derived IMF can vary between Milky Way-like and super-Salpeter for different model assumptions and spectral fitting regions. Also, different techniques are sensitive to different stellar mass ranges, as explored effectively in Spiniello et al. (2015a). Whereas lensing and dynamics measure the total mass, which includes stellar remnants, dark matter, and gas, SPS methods are sensitive to the light of stars in specific mass ranges (see Fig. 17 of Conroy & van Dokkum 2012a, and Conroy et al. 2017).

Another possible explanation for the variation between studies is that the IMF may not only vary between galaxies but also within galaxies. If this is the case, the use of different effective apertures will introduce scatter even if the same methodology is applied to the same objects. Also, for a given projected aperture, lensing is sensitive to the mass in a cylinder, dynamics to the mass in a sphere, and stellar population synthesis to the projected light. IMF gradients may be expected, because the velocity dispersion, surface mass density, metallicity, age, and \( \alpha \)-enhancement all change with radius (e.g., Mehlert et al. 2003; Kuntschner et al. 2010), and the IMF may correlate with these parameters (Conroy & van Dokkum 2012b; Hopkins 2013). There are also reasons to expect an IMF gradient from the formation history of massive galaxies. There is evidence that the centers of many massive galaxies were assembled in a short period of intense star formation at \( z \gtrsim 2 \) (Bezanson et al. 2009; Oser et al. 2010; Barro et al. 2013; Nelson et al. 2014) that is distinct from their later growth. The physical conditions inside these star forming cores were very different from those in the Milky Way disk today (e.g., Zolotov et al. 2015; van Dokkum et al. 2015; Barro et al. 2016).

In the previous papers in this series (van Dokkum & Conroy 2012; Conroy & van Dokkum 2012b) we used an effective aperture of \( R < R_e / 8 \), where \( R_e \) is the projected half-light radius. This small aperture was largely determined by the signal-to-noise ratio (S/N) that is required to measure the IMF-sensitive FeH \( \lambda 8195 \) Å band (Wing & Ford 1969). For comparison, dynamical studies typically quote results at \( \sim 0.5 - 1 R_e \). In this paper we extend this analysis to larger radii, using newly obtained data from the Keck I telescope in combination with an updated suite of stellar population synthesis models.

This is not a new topic: studies of gradients in IMF-sensitive spectral features go back at least to Boroson & Thompson (1991), who found that the Na \( \lambda \lambda 8183,8195 \) Å doublet increases toward the centers of early-type galaxies. The difficulty is that stellar abundances also change with radius; Boroson & Thompson (1991) could not clearly distinguish an IMF gradient from a gradient in the sodium abundance (see also Worthey, Ingermann, & Serven 2011). Recent studies have provided superficially somewhat conflicting results, although this may largely be due to differences in modeling techniques. Martín-Navarro et al. (2015a) find evidence for strong IMF gradients (from bottom-heavy in the center to Milky Way-like at large radii) in two massive early-type galaxies, and a constant IMF in a low mass galaxy. Similarly, La Barbera et al. (2016) derive a strong IMF gradient in a single massive elliptical galaxy using deep optical and near-IR spectroscopy with the Very Large Telescope. In parent contrast, McConnell, Lu, & Mann (2016) suggest that the observed line index gradients of two massive early-type galaxies can be fully explained by abundance variations, and Zelenewski et al. (2016) show that a Milky Way IMF is consistent with their two-dimensional spectroscopy of two of the three brightest galaxies in the Coma cluster. Both studies emphasize that IMF effects are subtle, and that even if IMF trends are present, abundance variations will likely dominate the observed radial changes in the strength of absorption lines. Adopting a different approach, Davis & McDermid (2017) find significant variation in the IMF gradients among seven galaxies using their molecular gas kinematics.

In this paper, we build on this previous work using optical spectroscopy extending to 1 \( \mu m \) obtained with the dual-beam Low Resolution Imaging Spectrograph (LRIS; Oke et al. 1995) on Keck. We obtained high quality spectra out to \( \gtrsim 1 R_e \), thanks to a custom long slit mask and the fact that we spent half of the observing time on empty sky fields. Following the methods we used in previous papers in this series, and in contrast to other studies of IMF gradients, we fit state of the art models directly to the spectra rather than to indices.

2. OBSERVATIONS

We obtained spatially-resolved spectroscopy of six early-type galaxies on December 19–20 2014, using LRIS on the Keck I telescope. For three of the galaxies we obtained deep data with a special long slit, and interspersed the science images with blank sky exposures of equal integration time.

2.1. Sample

The three primary targets of our study are the giant elliptical galaxies NGC 1407 and NGC 1600 and the S0 galaxy NGC 2695. NGC 1407 is the dominant member of the eponymous NGC 1407 group at 24 Mpc, which also includes the elliptical galaxy NGC 1400 (Brough et al. 2006; Romanowsky et al. 2009). NGC 1600, at \( \sim 50 \) Mpc, is generally considered an isolated elliptical, with an extensive system of satellite galaxies (Smith et al. 2008). NGC 2695 is one of the brightest galaxies in a group that also contains the elliptical galaxy NGC 2699. Distances are averages taken from NED.

It should be emphasized that these uncertainties mostly affect the overall normalization of the IMF; in all panels of Fig. 12 in Conroy & van Dokkum (2012b) there is strong evidence for IMF variation between galaxies.

\[ \text{Table 1} \]

| Id   | \( D^a \) [Mpc] | \( R_e^b \) ['] | \( \sigma_0^c \) [km s\(^{-1}\)] | \( P_{\text{slit}} \) | \( t_{\text{exp}}^d \) [s] |
|------|----------------|----------------|-------------------------------|-----------------|-----------------|
| NGC 1407 | 23.3           | 1.26           | 292                           | maj             | 7800            |
| NGC 1600 | 45.8           | 1.12           | 340                           | maj             | 9000            |
| NGC 2695 | 35.3           | 0.42           | 229                           | maj             | 3000            |
| NGC 3414 | 23.5           | 0.49           | 240                           | min             | 1800            |
| NGC 4552 | 16.0           | 0.52           | 264                           | min             | 1800            |
| NGC 4564 | 17.0           | 0.24           | 163                           | min             | 1800            |

\(^a\) Averages from the NASA/IPAC Extragalactic Database.

\(^b\) Effective radii along the direction of the slit. For NGC 1407, NGC 1600, and NGC 2695 this is the major axis; for the other galaxies this is the minor axis.

\(^c\) Measured values, uncorrected for seeing, from the central spectra in this paper.

\(^d\) Total on-target exposure time. For the first three galaxies, an equal amount of time was spent off-target.

https://ned.ipac.caltech.edu/
the far red. The beams were split with the D680 dichroic, which has a 50% reflectance wavelength of 6640 Å and a 50% transmission wavelength of 6800 Å. In the blue arm, we used the 300 l mm\(^{-1}\) grism blazed at 5000 Å. This is a departure from the strategy of van Dokkum & Conroy (2012) and McConnell et al. (2016), who used the higher resolution 600 l mm\(^{-1}\) grism. The 300 l mm\(^{-1}\) grism covers the full spectral range from the atmospheric cutoff to the dichroic. The 600 l mm\(^{-1}\) grism covers wavelengths \(\lambda \lesssim 5600\) Å, missing the Na D \(\lambda\lambda 5892, 5898\) Å doublet. As shown in Fig. 12 of Conroy & van Dokkum (2012a) (and in §5.1), the Na D line is important for distinguishing IMF effects from variations in the sodium abundance. In the red arm the 6001 mm\(^{-1}\) gold-coated grating blazed at 10000 Å was used, as in previous work. The LRIS-red detector has fully depleted, high-resistivity CCDs (see Rockosi et al. 2010). These devices are sensitive to wavelengths > 1 µm, and have no appreciable fringing. This makes it possible to do accurate, sub-percent spectroscopy in the far red.

The standard long slit of LRIS covers only approximately half of the field of view. Furthermore, in both the blue and the red beams the middle of the slit falls in the gap between the two mosaiced detectors. As a result the usable contiguous length of the slit on a single chip is only \(\approx 90''\). We designed a custom slit mask, comprised of a 0''7 wide, \(\approx 290''\) long slit that is broken into four pieces to ensure mechanical stability. This slit is approximately twice as long as the standard long slit. It has three gaps; the central one coincides with the detector gap.

For the three primary targets we used the following observing strategy. We used the "special" long slit that we designed, aligned with the major axis of the galaxy. The red side data were binned on-chip by a factor of two to reduce the readout time, providing pixel scales of 0''27 in the red and 0''135 in the blue. We obtained a series of 600 s exposures, alter-
nating on-target exposures with off-target exposures. These off-target exposures are used in the reduction to enable very accurate sky subtraction over the entire spatial range of interest. They are \( \sim 15^\circ \) removed from the galaxies, and carefully chosen so that no stars or other contaminating objects fall in the slit. For each object an equal number of on-target and off-target exposures was obtained. This strategy is similar to that of Kelson et al. (2002), who used LRIS to study the kinematics of a brightest cluster galaxy to large radii. McConnell et al. (2016) also took off-target exposures but less frequently (one sky exposure for every 2–4 science exposures). The total on-target exposure times were 7800 s, 9000 s, and 3000 s for NGC 1407, NGC 1600, and NGC 2695 respectively.

The other three galaxies were observed in a classical way, dispensing with the off-target exposures. The slit was aligned with the minor axis, to facilitate standard sky subtraction techniques. Three 600 s exposures were obtained for each galaxy, moving the telescope along the slit by 30′′ in between exposures. The total exposure time was therefore 1800 s for each object. The slit positions are indicated on Fig. 1 for all six galaxies.

### 2.3. Data Reduction

#### 2.3.1. Two-dimensional Sky Subtraction

The data reduction was done with a custom pipeline written in the Python programming environment. We focus here on the reduction of the three primary targets, as the analysis of the other galaxies largely follows that described in van Dokkum & Conroy (2012). The first step in the reduction is to subtract a blank sky frame from each of the science exposures. The data were divided into sets of three exposures, consisting of a science exposure and the two adjacent blank sky exposures. For each science exposure, a two-dimensional sky frame was created by averaging the adjacent sky exposures. This produces a good match to the sky in the science exposure if changes in the sky line intensities were linear over the \( \sim 30 \) min that elapsed during the three exposures. To account for non-linearity, the averaged sky frame was scaled to match the science frame by measuring the fluxes of the brightest sky lines in both images. This scaling was typically \( \lesssim 1 \% \), and only important for data taken in the evening or morning when approaching 18 degree twilight.

#### 2.3.2. Wavelength Calibration and Instrumental Resolution

Next, the spectra were wavelength calibrated. The initial solution is based on arc line exposures of the custom long slit taken in the afternoon. We used all lamps. The cadmium, zinc, and mercury lamps are the main calibrators in the blue and the neon and argon lamps have many lines in the red. In the standard line list there is a rather large gap in wavelength coverage between the Ar lines at 9787 Å and 10473 Å, a wavelength regime that contains the FeH 0.9920 Å band. Fortunately there is a faint Ar line at 10054.81 Å, and we added this line to the list.

In both the blue and the red, the detector consists of two chips with two amplifiers each. The data from each of the four amplifiers (two chips, and two amplifiers per chip) were fitted separately. In the red, a polynomial of 6th order in the spatial direction and 5th order in the wavelength direction gives an rms scatter of \( \approx 0.08 \) Å for each of the segments.

The full observed wavelength range is approximately 7450 Å – 10750 Å. A check on the wavelength calibration in the far red we collapsed the 2D arc spectra in the spatial direction and measured the location of the very weak \( \lambda 10335.55 \) Ar line. The measured wavelength is 10335.5, which demonstrates that the polynomial fit accurately captures the transformation from pixel coordinates to wavelengths in this regime. In the blue, a polynomial of 6th order in both the spatial direction and the wavelength direction gives an rms scatter of \( \approx 0.15 \) Å. LRIS has considerable flexure, and the exact wavelength solution is a complex function of the pointing of the telescope and other factors. For each individual science exposure we applied a zero-order offset to the high order arc line solutions. The applied offsets are medians of the offsets calculated from multiple sky emission lines. The offsets are typically \( \sim 3 \) Å in the blue and \( \sim 1 \) Å in the red, with the exact effect dependent on the field and time of night, and with no obvious residual wavelength dependence.

For the stellar population fitting it is important to accurately measure the instrumental resolution. In the red \( \sigma_{\text{instr}} \approx 40 \text{ km s}^{-1} \), much smaller than the velocity dispersions of the galaxies, and it can be measured accurately from sky emission lines (see Fig. 2). The blue resolution as determined from arc lamps is shown by the dashed line, for reference.

![Figure 2.](https://www2.keck.hawaii.edu/inst/lris/txt/all_line_list.txt) Instrumental resolution (in km s\(^{-1}\)) as a function of wavelength, as determined from sky emission lines (blue) and fits to the spectra (red, see text). Solid curves are fits to the data. We use the same functional form for all galaxies in the red, but due to focus variations we use a custom fit for each of the six galaxies in the blue. The blue resolution as determined from arc lamps is shown by the dashed line, for reference.

For the stellar population fitting it is important to accurately measure the instrumental resolution. In the red \( \sigma_{\text{instr}} \approx 40 \text{ km s}^{-1} \), much smaller than the velocity dispersions of the galaxies, and it can be measured accurately from sky emission lines (see Fig. 2). In the blue the situation is more complex, and requires careful treatment. First, due to our choice of a low resolution grism that covers Na D, \( \sigma_{\text{instr}} \approx 150 – 250 \text{ km s}^{-1} \), comparable to the velocity dispersions of the galaxies. Second, there are no sky emission lines that can
be used blueward of the $\lambda 5578$ [O I] line. Third, we find that there are significant focus variations in the blue, particularly redward of 5500 Å. The variations seem random and may be caused by temperature changes during the nights.

We measured the instrumental resolution in the blue in the following way. All six galaxies were previously observed with the higher resolution 6001-mm$^{-1}$ grism (in 2012; see Conroy et al., in preparation). The instrumental resolution of these data varies between $\sigma_{\text{instr,2012}} \approx 100$ km s$^{-1}$ at 3700 Å to $\sigma_{\text{instr,2012}} \approx 70$ km s$^{-1}$ at 5500 Å. Using the same extraction aperture, we fit the new spectra with the high-resolution 2012 data in six wavelength intervals between 3700 Å and 5500 Å, with the velocity dispersion $\sigma_{\text{fit}}$ as the only free parameter. The instrumental resolution of the new data is then $\sigma_{\text{instr,2014}} = (\sigma_{\text{instr,2012}}^2 + \sigma_{\text{fit}}^2)^{1/2}$ in each wavelength interval. The results are shown by the red points in Fig. 6. For each galaxy the red points connect smoothly to the $\lambda > 5500$ Å blue points, demonstrating that our methodology is consistent with direct measurements from sky emission lines. Solid lines show the third-order polynomials that are used in the stellar population modeling.

2.3.3. Residual Sky Subtraction, Image Combination, and $s$–Distortion Correction

The wavelength-calibrated individual amplifiers of each science exposure were placed in a common 2D image, taking the detector gap into account. Next, a zero-order residual sky subtraction was performed to account for small differences in wavelength calibration and sky line intensity between the science exposures and the adjacent sky frames. This is particularly important for the broad O$_2$ (0–1) band at $\approx 8650$ Å, which is independent of the OH lines and varies on short time scales. To do this, a small region at the bottom of the frame was used to measure the residual sky spectrum in each science exposure. As the center of the galaxy was placed on the top detector away from the chip gap (the standard slit pointing origin), this region is at a radius of approximately 3′ from the center. We verified that the galaxy flux at this radius is sufficiently low that its subtraction has a negligible effect on the analysis in this paper.

The individual science frames were combined, scaling by the collapsed galaxy flux and rejecting high and low pixels. The distortion in the spatial direction (the $s$–distortion) was determined by measuring the central position of the galaxy as a function of wavelength and fitting these positions with a 3rd order polynomial. The spectra were shifted, ensuring that the center of the galaxy falls on the center of a pixel in the corrected frame.

2.4. Atmospheric Transmission and Response Function

The corrections for telluric absorption and the instrument response function follow the same procedures as described in detail in van Dokkum & Conroy (2012). Briefly, a theoretical atmospheric transmission spectrum was fitted to the observed central spectrum of the galaxy in the wavelength interval 9300 Å – 9700 Å, where there are many strong H$_2$O lines. The fit also includes a polynomial to account for the variation in the galaxy spectrum in this spectral range. The fits converge quickly and provide a near-perfect removal of the telluric absorption lines. We note that for the galaxies in this paper there is no ambiguity, as the telluric lines are a factor of $\approx 6$ narrower than the galaxy absorption lines. The spectra were corrected for the instrument response using observations of the white dwarf Feige 110. Special care was taken to correct for the broad hydrogen Paschen lines in the observed white dwarf spectrum.

A graphic illustration of the reduction in the outermost spectral bins is shown in Fig. 3. Accurate modeling of the sky is critical, as the galaxy flux is only 1% – 10% of the sky emission in the far red. The reduced 2D spectra of the three primary galaxies are shown in Fig. 4. The spectra were divided by a polynomial in the wavelength direction to reduce the dynamic range and highlight the absorption lines at all radii. With a few isolated exceptions (such as the strong $\lambda 5578$ [O I] line) the spectra are very clean with no obvious systematic issues.

3. Fitting

3.1. Extracted Spectra as a Function of Radius

For all six galaxies we extracted one-dimensional (1D) spectra from the two-dimensional (2D) reduced spectra. The apertures are defined in units of binned (0′′/27) pixels. With the exception of the inner apertures they are spaced quadratically, following the relation $r_a = 3 \times i^2$, with $i$ an integer and $r_a$ the aperture radius in pixels. This scaling is a compromise between having a sufficiently fine sampling of the full radial range and maximizing the S/N ratio in each bin. The central aperture is 3 pixels (0′′/81), corresponding to the approximate seeing. The galaxy spectrum at each radius is defined as the sum of all image rows between $r_a(i-1)$ and $r_a(i)$, not including rows that were masked because of missing data (due to the chip gap) or because of contaminating objects.

For each aperture in each galaxy we calculated the luminosity-weighted mean radius $R$, properly taking masked rows into account. Except for the central aperture ($r = 0$) each
Figure 4. Two-dimensional major axis spectra for the three galaxies that were obtained with our on/off observing strategy. The spectra were divided by a polynomial in the wavelength direction to highlight the absorption features. Grey horizontal bars indicate masked regions; these are contaminating objects as well as the chip gap. The blue spectra have a resolution that ranges from $\sigma_{\text{inst}} \approx 250 \text{ km s}^{-1}$ to $\approx 150 \text{ km s}^{-1}$. The red spectra have a much higher resolution of $\sigma_{\text{inst}} \approx 40 \text{ km s}^{-1}$, and velocity and velocity dispersion gradients can be seen by eye. Prominent spectral features are marked, as well as two strong night sky emission lines.

radius occurs twice, as spectra are independently extracted from each side of the galaxy. Because the weighting and masking are not the same on each side of the galaxy, the positive and negative distances from the center are not identical. These luminosity-weighted radii are the ones that are used in the remainder of this paper.

Extracted spectra at $R = 0$ and $R \sim R_e/2$ are shown in Figs. 5–7 for the three primary galaxies. The $R \sim R_e/2$ spectrum is the average of the three radial bins that are closest to $R = \pm R_e/2$. As we show later, this is the approximate radius where the IMF is no longer bottom-heavy but consistent with that of the Milky Way. The spectra were de-redshifted and smoothed to a common resolution of $450 \text{ km s}^{-1}$, so they can be compared directly. The chosen wavelength ranges do not cover the full extent of the spectra but correspond approximately to the regions that were used in the stellar population modeling (see Conroy et al. 2017). There are several obvious differences between the inner spectra and outer spectra. The Na lines, and particularly Na D $\lambda\lambda 5892, 5898$ Å, are stronger in the center than at $R = R_e/2$. For NGC 1407 and NGC 1600 the FeH $\lambda 9920$ Å band is also more prominent in the central aperture. In this study we do not analyze the
Figure 5. Observed spectra (black) and best-fitting stellar population synthesis models (red) for NGC 1407, at $R = 0$ (top) and $R = R_e/2$ (bottom). Note that the Na I $\lambda\lambda 8183, 8195$ Å feature appears offset to the red because it is blended with a TiO bandhead at 8205 Å.

Figure 6. Observed spectra (black) and best-fitting stellar population synthesis models (red) for NGC 1600, at $R = 0$ (top) and $R = R_e/2$ (bottom).
Figure 7. Observed spectra (black) and best-fitting stellar population synthesis models (red) for NGC 2695, at $R = 0$ (top) and $R = R_e/2$ (bottom).

Figure 8. Residuals from the fits, for all radial bins and all six galaxies. Spectra of higher S/N ratio are displayed darker. The green line in the upper panels is the median residual. The residuals are nearly identical for all spectra, and likely represent systematic errors in the models that are independent of age, metallicity, and the IMF. The lower panels show the residual after subtracting the green line.
Figure 9. Ratio of central spectrum to the spectrum at $R \sim R_e/2$, for the three primary galaxies. The data are shown in black and the best-fitting models in red. The spectra of NGC 1600 and NGC 2695 were vertically offset for clarity. The ratio spectra show significant features throughout the spectral range, and these features are very similar for the three galaxies. The sodium lines show strong trends with radius, whereas Mg and the calcium triplet are nearly constant with radius.

strength of individual absorption features, as their interpretation is not straightforward (see, e.g., Conroy & van Dokkum 2012a). Nevertheless, given its well-known IMF sensitivity we discuss measurements of FeH in Appendix C.

3.2. Modeling

The spectra were fitted with stellar population synthesis models, following the procedures described in Conroy & van Dokkum (2012b). Only spectra with a median S/N ratio $> 30 \, \text{Å}^{-1}$ in the red were used. The S/N is 200–500 in the center (depending on the galaxy) and falls off to values near the limit in the outermost bins. For the three primary galaxies there are typically 20 radial bins that satisfy this criterion; for the other three galaxies there are typically 10. In total, 92 spectra were used.

Almost every aspect of the models has been updated since the analysis in Conroy & van Dokkum (2012b). The changes are briefly summarized here, and described in more detail in Conroy et al. (2017). The most important difference is that the models cover a large range of metallicity and age, owing to the use of a greatly expanded stellar library (Villaume et al. 2016). This is important as we aim to separate abundance gradients from IMF gradients. The model ages range from 1 Gyr to 13.5 Gyr and $[Z/H]$ ranges from $-1.5$ to $+0.25$. Furthermore, the MIST stellar isochrones are used (Choi et al. 2016), which cover a wide range of ages, masses, and metallicities. The expanded stellar library uses the M dwarf library of Mann et al. (2015) and newly obtained near-IR spectroscopy of 283 stars (which already had optical spectra from the MILES library Sánchez-Blázquez et al. 2006). A spectral interpolator is used to provide spectra on a continuous grid of $T_{\text{eff}}$, $\log g$, and metallicity. The library and interpolator are presented in Villaume et al. (2016). Finally, the elemental response functions have been revised, using updated atomic and molecular line data.

The models have 36 free parameters, including 17 individual elemental abundances and several nuisance parameters. A list of all parameters is given in Appendix A, and details are given in Conroy et al. (2017). Two of the nuisance parameters are the weight and temperature of a hypothetical hot star component; we verified that the fit results are nearly identical if this component is turned off. Among several “data” parameters is a multiplicative factor that is applied to all the errors and a scaling factor that is applied to a residual telluric absorption spectrum. Following our previous papers the IMF has two free parameters, $x_1$ and $x_2$, which are the logarithmic slopes of the IMF in the mass ranges $0.08 < M/M_\odot < 0.5$ and $0.5 < M/M_\odot < 1.0$ respectively. The IMF is assumed to have the Salpeter (1955) slope of 2.35 at $M > 1.0 M_\odot$. In Conroy et al. (2017) we analyze more complex forms of the IMF. The models are fit using a Markov chain Monte Carlo algorithm (Foreman-Mackey et al. 2013), after broadening them to the (wavelength-dependent) instrumental resolution (see § 2.3.2).

The best-fitting models are shown in red in Figs. 5–7 after shifting them to the rest-frame and smoothing to a resolution $\sigma = 450 \, \text{km} \, \text{s}^{-1}$. Note that the fits were performed on the original spectra, not on the smoothed spectra. The fits are generally excellent, but there are systematic differences between the models and the data that exceed the expected photon noise. This is demonstrated in Fig. 8 which shows the
ratio between the data and the best-fitting model, for all six galaxies and all radial bins. The residuals are not consistent with random noise but are highly correlated, with the residuals from each of the 92 spectra showing the same rest-frame wavelength dependence. The green line shows the median as a function of wavelength. The rms of these systematic residuals at a resolution of $\sigma = 450 \text{ km s}^{-1}$ is 0.50% from 4000 Å – 5000 Å, 0.23% from 5000 Å – 6300 Å, 0.22% from 8000 Å – 8900 Å, and 0.20% from 9650 Å – 10070 Å. We also show the residual after subtracting the green line. There are virtually no features in these “residuals of the residuals”, which means that we model the variation of the spectra (from galaxy to galaxy and as a function of radius) extremely well.

Qualitatively similar behavior was seen in Conroy & van Dokkum (2012b) for individual early-type galaxies and in Conroy, Graves, & van Dokkum (2014) for SDSS stacks. The residuals are probably not due to problems in the data, as the six galaxies have different radial velocities: if the systematic residuals were related to the sky subtraction, the telluric absorption correction, or the response function they would line up in the observed frame, not the rest-frame. It is also unlikely that they are caused by errors in the line profiles. Although the assumption of Gaussian profiles is a simplification (see, e.g., van der Marel & Franx 1993), there is no correlation between the strength of absorption features and the amplitude of the residuals.

The most likely cause is deficiencies in the stellar population synthesis models at the ~0.2% level. The strongest residuals are at $\approx 8200$ Å and $\approx 8450$ Å. These are probably related to TiO; note that the feature at $\approx 8200$ Å is redward of the Na I $\lambda\lambda 8183, 8195$ Å doublet and coincides with a TiO band head at $\lambda 8205$ Å. The interplay between this TiO feature and Na i is demonstrated explicitly in the inset of Fig. 9 in van Dokkum & Conroy (2012). In Appendix B we show that these residuals correlate only weakly with metallicity, radius, and the IMF mismatch parameter. In particular, we show that the variation in the residuals is significantly weaker than the signal from IMF variations. The residuals in the present study do not correlate very well with those in Conroy & van Dokkum (2012b) or Conroy et al. (2014). For example, the main deficiency in the red in Conroy & van Dokkum (2012b) was that the models underpredicted the strength of the calcium triplet lines, whereas in the present study the main residuals are at the locations of TiO bandheads. This is perhaps not surprising given the many changes to the stellar population synthesis models since our previous papers.

3.3. Radial Variation in the Spectra

In this paper we are primarily concerned with the variation in the spectra as a function of radius. In Fig. 3 we show the ratio of the central spectrum to that at $r \sim 0.5 R_e$, that is, the ratio of the two spectra shown for each galaxy in Figs. 5–7. These ratio spectra show which spectral features have strong radial gradients and which are approximately constant. Expressed as a ratio, Na D $\lambda\lambda 5892, 5898$ Å shows the largest variation of all individual spectral features. Its equivalent width in the ratio spectrum ranges from 0.8 Å for NGC 1600 to 2.3 Å for NGC 2695. Na D is a well-known interstellar medium (ISM) line, but its increase toward small radii is almost certainly stellar in origin. In HST images NGC 1600 has no visible dust absorption in its central regions (van Dokkum & Franx 1995), and neither has NGC 1407. Furthermore, the decrease of Na D with radius is gradual rather than abrupt, and there is no obvious kinematic difference between this line and the other absorption lines (see Schwartz & Martin 2004).

The Na I $\lambda\lambda 8183, 8195$ Å doublet also varies strongly with radius, as do many other spectral features, particularly in the blue. The Mg $\lambda 5177$ Å feature and the calcium triplet lines do not show much variation. It is striking how complex the ratio spectra are, and how different from the actual spectra. This illustrates the difficulty of interpreting spectral index measurements and the power of full spectrum fitting. For each galaxy, the red line shows the ratio of the best-fitting models. The models generally fit the variation in the spectral features within the (correlated) errors, as shown explicitly for the FeH band in Appendix C. Furthermore, they not only reproduce the changes (and lack of changes) in strong features such as Mg and Na, but also the behavior of the spectra on all scales.

4. RADIAL GRADIENTS IN STELLAR POPULATIONS AND THE IMF

4.1. Stellar Population Parameters

We now turn to the measured values for the kinematics, stellar abundance ratios, ages, and mass-to-light ($M/L$) ratios of the galaxies, as a function of radius. The model has 36 free parameters; 11 of these are shown in Fig. 10. From left to right and top to bottom, the panels show the velocity dispersion (taking instrumental broadening and the model resolution into account); the degree of rotational support; the age; the iron abundance; the abundances of Mg, O, C, Ca, and Na with respect to iron; the $M/L_r$ ratio for a Kroupa (2001) IMF; the $M/L_r$ ratio for the best-fit IMF; and the ratio of these $M/L$ ratios $\alpha$. Errorbars indicate the $16^{\text{th}}$ and $84^{\text{th}}$ percentiles of the posterior probabilities.

The galaxies span a range of a factor of two in central dispersion, from 163 km s$^{-1}$ to 340 km s$^{-1}$. Five of the six galaxies are slow rotators; the exception is NGC 2695, which is an S0 galaxy with a prominent disk. The ages are uniformly high: all galaxies are older than 10 Gyr at all measured radii.

A full analysis of the metal line gradients is beyond the scope of the present paper. Briefly, the gradients are very similar from one galaxy to the next, and broadly consistent with previous work (e.g., Trager et al. 2000; Kuntschner et al. 2010; Greene et al. 2015). The iron abundance decreases with radius, from [Fe/H] $\approx 0.1$ in the center to [Fe/H] $\approx -0.3$ at $R = R_e/2$. The [Mg/Fe] and [O/Fe] ratios increase with radius. The increase with radius in the $\alpha$-elements is somewhat more pronounced than previously found for NGC 1407 (Spolaor et al. 2008b), but we note that these gradients depend sensitively on the assumed relation between [X/Fe] and [Fe/H] in the stellar population synthesis model. We use the measured Mg abundances for MILES stars by Milone et al. (2011) to derive the [Mg/Fe] vs. [Fe/H] relation in our model using the

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11 Compared to the 2012 work we also improved the treatment of instrumental broadening in the present study. This may be relevant for the residuals near the calcium triplet.

12 We visually inspected Advanced Camera for Surveys images of NGC 1407. NGC 2695 has not been observed with HST.

13 For [O/Fe] we adopt the relation from Schiavon (2007). For [Ca/Fe] we fit a relation based on the Bensby et al. (2014) data. We assume that Ca, Ti, and Si all trace one another, and apply the same correction factor to Ti and Si as we apply to Ca. We assume no corrections are necessary for the iron-peak elements (Cr, Ni, Cu, V, Mn, and Co) and that no corrections are necessary for C, N, and Na. This approach is supported by known trends in the literature; see, e.g., Bensby et al. (2014) for Na, Cr, and Ni, and the
Figure 10. Stellar population gradients, as derived from full spectrum fitting. Data points at $R = 0$ were placed at $\log R/R_e = -2$. The six galaxies have similar gradients, showing the same qualitative behavior.

Figure 11. Radial gradients in the IMF parameter $\alpha$, for all six galaxies. Squares and circles indicate the two different sides of the galaxies. All galaxies have a bottom-heavy IMF in their centers, compared to the IMF of the Milky Way. The IMF becomes less bottom-heavy with increasing radius, and is consistent with that of the Milky Way at the last-measured point.
Figure 12. Average radial gradient in the IMF parameter for the six galaxies, with a logarithmic (left) and linear (right) x-axis. Data points at $R = 0$ were placed at $\log R/R_e = -2$. The line has the form $\alpha = 2.5 - 3.6(R/R_e)$ at $R < 0.4R_e$ and $\alpha = 1.1$ at $R > 0.4R_e$. Grey bands indicate 100 random MCMC samples. The bottom panels are binned versions of the top panels. Thin grey errorbars indicate the rms in each bin.
sample of stars of Bensby et al. (2014) instead would change the radial gradient by \( \sim 0.1 \) dex. These issues will be discussed further in a future paper; here we note that the errors do not include the contribution of these calibration uncertainties. We also note that the model fits, and the IMF constraints, are completely independent of this calibration: the fits measure relative abundances with respect to the stellar library, and the conversion to absolute abundances takes place after the fit.

The Ca abundance tracks Fe, as was also seen in previous studies (e.g., Saglia et al. 2002; Graves et al. 2007; Conroy et al. 2014). The [Na/Fe] ratio shows a steep negative gradient, again consistent with previous work (Boroson & Thompson 1991, and many other studies). As [Fe/H] also decreases with radius, the gradient in the sodium abundance [Na/H] is even steeper; it decreases from \( \sim 0.6 \) in the center to \( \sim -0.1 \) at \( R \gtrsim R_e/2 \). This is important as the Na I \( \lambda \lambda 8183, 8195 \) Å doublet is a key IMF diagnostic. We will return to this in \( \S 5.1 \).

4.2. IMF Gradients

The last three panels of Fig. 10 show the key result of this study. The second panel of the bottom row shows the \( M/L \) ratio as a function of radius when assuming a Kroupa (2001) IMF. The \( M/L \) ratio gradually decreases with radius, from \( M/L_e \approx 4 M_\odot/L_\odot \) in the center to \( M/L_e \approx 3 M_\odot/L_\odot \) at \( R = 0.5 R_e \), again consistent with many previous studies (e.g., Tortora et al. 2011). The next panel shows the \( M/L \) ratio when allowing the IMF to vary. For all six galaxies, the central \( M/L \) ratio is much higher for a varying IMF than for a Kroupa (2001) IMF. That is, all galaxies prefer a bottom-heavy IMF that is steeper than that of the Milky Way at low masses. The final panel shows the IMF “mismatch” parameter \( \alpha \), defined as \( \alpha \equiv (M/L)/(M/L)_\text{MW} \). The IMF parameter falls off steeply, from \( \alpha = 2-3 \) at \( R = 0 \) to \( \alpha \sim 1 \) at \( R \gtrsim 0.3 R_e \).

The \( \alpha \) gradients for the individual galaxies are shown in Fig. 11. Only measurements with average uncertainties \( \Delta \alpha = (\alpha_{44} - \alpha_{16})/2 < 1 \) are shown. The \( x \)-axis is logarithmic, to show the individual points more clearly. For the purpose of this Figure the central aperture (\( R = 0 \)) was placed at \( R = 0.01 R_e \). At most radii there are two measurements, one for each side of the galaxy. It is reassuring that the measurements on each side of the galaxy are generally consistent within the uncertainties\(^{14} \). The six galaxies show the same trends: the IMF is bottom-heavy in the center, and gradually becomes more bottom-light. The last-measured point is consistent with the IMF of the Milky Way for all galaxies.

We parameterize the IMF variation in the following way. We fit a model of the form \( \alpha = a(R/R_e) + b \) at small radii, reaching a plateau of \( c \) when \( a(R/R_e) + b < c \). Gradients in early-type galaxies are usually expressed in \( \log R \) rather than \( R \), but the advantage of a simple linear function is that it does not diverge at \( R = 0 \). Using all data points for the six galaxies we find

\[
\alpha \left( \frac{R}{R_e} \right) = \max \left\{ 2.48^{+0.05}_{-0.05} - 3.6^{+0.1}_{-0.2} \left( \frac{R}{R_e} \right), 1.10^{+0.05}_{-0.06} \right\}.
\]

This fit is shown in Fig. 12. It is remarkable that the best-fitting value for \( c \) is only \( \sim 10 \% \) larger than the Milky Way IMF; there is no known aspect of our modeling that prefers the Kroupa (2001) or Chabrier (2003) IMF over other forms. The rms of the residuals of the fit is 0.41, a factor of 1.3 higher than the expected scatter from the formal errors. This is probably due to a combination of systematic errors in the models and galaxy-to-galaxy variation in the IMF (see \( \S 5.1 \)). The transition to the plateau value of \( \alpha = 1.1 \) occurs at \( R \approx 0.4 R_e \). Based on these six galaxies, we conclude that bottom-heavy IMFs are a phenomenon that is unique to the centers of massive galaxies, on physical scales of \( \lesssim 1 \) kpc.

We express these results in a different way in Fig. 13, which shows the form of the IMF in three radial bins: \( R \leq 0.1 R_e \), \( 0.1 R_e < R \leq 0.5 R_e \), and \( R > 0.5 R_e \). In each radial bin we determined the averages of the fit parameters \( x_1 \) and \( x_2 \), the logarithmic slopes of the IMF in the mass ranges \( 0.05 M_\odot < m < 0.5 M_\odot \) and \( 0.5 M_\odot < m < 1.0 M_\odot \) respectively (see Appendix A). The average IMF is steep in the center, with \( x_1 = 2.97 \pm 0.05 \) and \( x_2 = 2.13 \pm 0.04 \). At intermediate radii the form of the IMF is close to Salpeter (which has \( x = 2.3 \) at all masses): we find \( x_1 = 2.35 \pm 0.13 \) and \( x_2 = 2.07 \pm 0.11 \). Beyond \( R = 0.5 R_e \) the average IMF has \( x_1 = 1.54 \pm 0.06 \) and \( x_2 = 2.43 \pm 0.12 \). This is close to the IMF of the Milky Way: the Kroupa (2001) form has \( x_1 = 1.3 \) and \( x_2 = 2.3 \), and the Chabrier (2003) IMF is shown in Fig. 13. An in-depth discussion of the form of the IMF in the center of NGC 1407 is given in paper IV in this series (Conroy et al. 2017).

\[ \text{Figure 13. Average form of the IMF in three radial bins, as determined from the best-fitting logarithmic slopes in the stellar mass ranges 0.08 M}_\odot < m < 0.5 M_\odot \text{ and } 0.5 M_\odot < m < 1.0 M_\odot \text{ respectively. The IMF s were normalized so they all have the same number of stars at } m = 1 M_\odot. \text{ The IMF is steeper than the Salpeter form in the center (see Conroy et al. 2017) and similar to the Milky Way IMF at large radii.} \]

5. DISCUSSION

5.1. Disentangling IMF Effects and Abundance Effects

In this paper we find strong gradients in the IMF of massive early-type galaxies. These results are qualitatively consistent with several other recent studies (e.g., Martín-Navarro et al. 2015a; La Barbera et al. 2016). However, others have stressed the difficulty of disentangling the effects of abundance variations and the effects of the IMF (McConnell et al. 2016; Zierleniewski et al. 2016). Our modeling allows for independent

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\(^{14}\) A possible exception is NGC 2695, where three adjacent bins show one side to be higher than the other by 2–3\( \sigma \).
variations in all the relevant elements and optimally uses the information content of the full optical spectra. Nevertheless, it is a valid question whether the subtle effects of a changing initial mass function can really be reliably detected given the (sometimes dramatic) changes in the stellar abundances.

The high S/N spectra presented in this paper offer the opportunity for a “semi-empirical” demonstration how IMF effects and abundance effects can be distinguished. We compared the derived stellar population parameters for all 92 spectra and looked for pairs of spectra where the abundance pattern and age are a close match but the IMF is very different. This analysis is similar in spirit to the comparison between massive elliptical galaxies in Virgo and M31 globular clusters that we did in 2011 (van Dokkum & Conroy 2011). Using the criteria $\Delta$age $<$ 2 Gyr, $\Delta$[Fe/H] $<$ 0.1, $\Delta$[Na/Fe] $<$ 0.1, $\Delta$[Ca/Fe] $<$ 0.1, $\Delta$[O/Fe] $<$ 0.1, $\Delta$[Ti/Fe] $<$ 0.1, and $\Delta$α $>$ 1 we found a single match: the central 3-pixel aperture of NGC 1407 and a slightly larger central aperture (of 5 pixels) of NGC 2695. The age is 13.3 Gyr for the NGC 1407 spectrum and 13.7 Gyr for the NGC 2695 spectrum. The abundance ratios of eight elements are shown in Fig. 14. They are very similar, although it should be noted that the differences in [X/Fe] are somewhat smaller than the differences in [X/H], given the 0.05 dex offset in [Fe/H].

The best-fitting IMF parameters are (by selection) quite different, with $\alpha = 3.20^{+0.23}_{-0.25}$ for NGC 1407 and $\alpha = 1.93^{+0.22}_{-0.16}$ for NGC 2695.

The two spectra are shown in the top panels of Fig. 15 (black and grey). They are, as expected, very similar. The best-fitting models are overplotted in red and blue. Rows 2, 3, 4 and 5 of Fig. 15 all show the ratio of the two spectra in black, with the errors in grey. The ratio spectrum is flat to $\approx 0.5\%$ over most of the wavelength range. The two most prominent exceptions are the Na D $\lambda\lambda$5892, 5898 Å doublet and the Na i $\lambda\lambda$8183, 8195 Å doublet, which are both stronger in NGC 1407 than in NGC 2695. There are also systematic differences at the 0.5% level at the location of the $\lambda 8665$ Å Ca triplet line, near the FeH $\lambda 9920$ Å band, and in the blue near 4600 Å.

We created ad hoc models for NGC 1407 and NGC 2695 to investigate whether we can isolate the IMF features in the ratio spectrum. First, we made two models that differ only in their IMF. That is, the model for NGC 1407 has $\alpha = 3.3$ and the model for NGC 2695 has $\alpha = 1.9$ but in all other respects they are identical, with all model parameters except the IMF set to the averages of the two galaxies. The red line in the second row of Fig. 15 shows the ratio of these two models. These IMF-only models do well in the red, fitting the Na i doublet, the Ca triplet region, and the FeH band reasonably well. The residuals in the blue are not well matched by this model; this is expected as the blue spectrum is not very sensitive to variation in the contribution from low mass stars. More importantly, IMF-only models fail to account for the large difference in Na D between the two galaxies: only $\sim 1/3$ of its depth in the ratio spectrum can be accounted for by the IMF.

Although the spectra were selected to have similar abundance ratios, they are of course not identical. Of particular relevance is that the sodium abundance of NGC 1407 is slightly higher than that of NGC 2695. NGC 1407 has [Na/Fe] = 0.47 and NGC 2695 has [Na/Fe] = 0.44. Taking the Fe/H ratios into account, we have [Na/H] = 0.57 for NGC 1407 and [Na/H] = 0.49 for NGC 2695, a difference of 0.07 dex. In the third row of panels of Fig. 15 we show the ratio of two models that only differ in their sodium abundance. The model for NGC 1407 has [Na/H] = 0.57 and the model for NGC 2695 has [Na/H] = 0.49, and all other model parameters, including the IMF, are identical and set to the average of the best-fitting models of the two galaxies. The red line fits the Na D doublet well, but underpredicts the dwarf-sensitive Na i doublet by a factor of $\sim 3$. This sodium-only model also fails to fit the FeH region of the ratio spectrum.

The blue line in these panels reflects an attempt to fit the Na i doublet by artificially increasing the Na abundance. The response is approximately linear, and we fit a model ratio spectrum of the form $S' = 1 + f(S - 1)$, with $S$ the ratio spectrum for the actual Na abundances of the two galaxies and $f$ a free parameter. The blue line has $f = 4$, and it provides a good fit to Na i $\lambda\lambda$8183, 8195 Å, by construction. However, the fit to Na D $\lambda 5892$, 5898 Å is catastrophic; unsurprisingly, given that the red line provided a good fit to this feature, it overpredicts Na D by a factor of $f$. We conclude that the difference in the observed strength of the Na i line between the two galaxies cannot be attributed to a difference in sodium abundance. Spectral coverage of the Na D doublet is critical: both Na D and Na i are sensitive to the IMF and the Na abundance, but Na D is mainly sensitive to the Na abundance and Na i is mainly sensitive to the IMF (as shown in the second and third row of Fig. 15). We note that any ISM contribution to Na D would imply that the IMF is even more bottom-heavy than what we infer in this paper: it would mean that the Na abundance is lower, which in turn implies that more low mass stars are needed to reproduce the observed strength of Na i $\lambda\lambda$8183, 8195 Å.

The models in the fourth row of panels show explicitly that the combination of a varying IMF and a small difference in the Na abundance can reproduce both Na i and Na D, as well as the FeH region. We now created a model for each galaxy that has the best-fit IMF and the best-fit Na abundance for that galaxy, with all other model parameters set to the averages for the two galaxies. The ratio of these models fits both Na lines, as well as the overall shape of the spectrum in the red.

![Figure 14. Key stellar abundances of the central spectra of NGC 1407 and NGC 2695. They are very similar, with $\Delta[X/Fe] < 0.1$ for all measured elements. The age difference is also very small at $\Delta$age $\approx 0.2$ Gyr. However, the derived IMFs are quite different: $\alpha = 3.3$ for the NGC 1407 spectrum and $\alpha = 1.9$ for the NGC 2695 spectrum.](image-url)
Figure 15. Top row: central spectra of NGC 1407 and NGC 2695, smoothed to the same resolution. The galaxies have nearly identical ages and abundances, but NGC 1407 has a more bottom-heavy IMF than NGC 2695. The spectra are nearly identical. All other panels show the ratio between these two spectra, and various model permutations. Second row: model that only has IMF variation. The fit to Na I is reasonable, but Na D is underpredicted. Third row: model with only Na variation. This model fits Na D well but underpredicts Na I. The blue model fits Na I but overpredicts Na D by a large factor. Fourth row: a combination of Na variation and IMF variation is needed to reproduce both Na I and Na D. Bottom row: full model, which also includes the small differences in all other elements. The blue model is the full model but with the IMF held fixed to the average IMF of the two galaxies. Only the full model with a varying IMF (red) fits the data.

In the bottom row of panels we show the ratio of the full models, with the parameters for each galaxy set to the best fitting values for that galaxy. The model ratio spectrum is an excellent fit throughout the spectral range. It is now clear that the residuals in the blue are not noise but due to the small differences between the galaxies in [Fe/H], [Ti/Fe], and the other model parameters. The rms residuals are 0.19 % from 4500 Å – 6200 Å, 0.13 % from 8000 Å – 8900 Å, and 0.11 % from 9650 Å – 10070 Å. As a final test we allow all parameters to vary for both galaxies except the IMF, which we fix to the best-fitting value for NGC 2695. We then take the ratio of this constrained full model fit to NGC 1407 to the full model fit for NGC 2695. The result is the blue line in the bottom panels. The model ratio spectrum fits the blue reasonably well, but underpredicts Na I by a factor ~ 3. It also fails to fit the FeH region, and is a poorer fit to the CaT lines than the red line. We conclude that our models cannot fit the ratio spectrum unless the IMF is allowed to vary.

5.2. What Parameter Best Predicts the Local IMF?

Throughout this paper we have analyzed the IMF as a function of $|R/R_e|$, the absolute distance from the center of the galaxy in units of the half-light radius. This is the most straightforward choice given that we extract spectra as a function of radius and the galaxies all have different sizes. However, as we have not only measured the local IMF but also the local velocity dispersion, age, and elemental abundances we can ask whether any of these parameters correlates better with the IMF mismatch parameter than $R/R_e$ does (see also, e.g., La Barbera et al. 2016).

In Fig. [16] we show the IMF mismatch parameter $\alpha$ as a function of six different parameters. The first is $R/R_e$, for ref-
ference. The red curve is Eq. 1, the residuals from this fit have an rms scatter of $s = 0.41$. The grey line is a fit of the form $\alpha = a \log(R/R_0) + b$. This fit has a higher scatter of 0.49, but it enables us to compare the predictive power of $R/R_0$ to the other parameters. The uncertainty in $s$ is $\approx 0.04$ for all panels, as derived from the formal error bars combined with the sample size. The top right panel shows the relation between $\alpha$ and physical radius. The scatter is identical to the relation between $\alpha$ and $R/R_0$.

The second row of Fig. 16 shows correlations with velocity dispersion and [Fe/H]. The central velocity dispersion has often been found to correlate with the central IMF; examples are Treu et al. (2010), Conroy & van Dokkum (2012b), Capellari et al. (2013), and La Barbera et al. (2015). Here we find, somewhat surprisingly, that the local dispersion is not a predictor of the local IMF: the correlation coefficient is only $r = 0.23$. The correlation with [Fe/H], on the other hand, is tight, with a correlation coefficient of 0.78 and a scatter of 0.44.

In the bottom panels we show relations with [Mg/Fe] and [Na/Fe]. In Conroy & van Dokkum (2012b) it was found that the [Mg/Fe] ratio correlates with $\alpha$, and we suggested that the star formation time scale might be a key driver of the form of the IMF. Here we do not find a strong correlation between $\alpha$ and [Mg/Fe]. There is, in fact, a weak anti-correlation, reflecting the mild increase of [Mg/Fe] with radius in Fig. 10. We note that the existence of a strong positive correlation between $\alpha$ and [Mg/Fe] had been called into question by Smith (2014) and by La Barbera et al. (2015). The last parameter that we consider is [Na/Fe], which shows a positive relation with $\alpha$ but with significant scatter ($s = 0.52$). All relations between $\alpha$ and [X/Fe] show larger scatter than the relations between $\alpha$ and [X/H]. This suggests that the overall metallicity, rather than a specific element, is coupled with the form of the IMF (see also Martin-Navarro et al. 2015c). However, we cannot determine this conclusively from our data: the correlation coefficient and scatter for the relation between $\alpha$ and [Z/H] are not significantly different from the relation between $\alpha$ and [Fe/H].

Finally, we caution that these results may partially be driven by scatter between the six galaxies in our small sample; as an example, the variation in velocity dispersion between the galaxies is larger than the typical variation within each individual galaxy. Larger samples are needed to explore these issues further.

5.3. The Luminosity-Weighted IMF in an Aperture

An implication of the existence of IMF gradients is that the measured IMF depends on the aperture that is used in the analysis. As noted in § 1 this complicates comparisons between different techniques, such as gravitational lensing and stellar population synthesis modeling. Using the form of the gradient given in Eq. 1 we calculate the average luminosity-weighted IMF within apertures of different radii. The galaxies span a range in Sersic index (Spolaor et al. 2008a; Krajnovic et al. 2013), and we calculate the average IMF for $n = 2$, $n = 4$, and $n = 6$. The results are shown in Fig. 17.

The average luminosity-weighted IMF parameter is $> 1.6$ (i.e., heavier than the Salpeter form) only for apertures $R < 0.6 R_e$. Within $R < R_e$ we find $\langle \alpha \rangle \sim 1.3 - 1.5$, depending on the form of the surface brightness profile. Our results are consistent with those of La Barbera et al. (2016), who analyzed a single massive galaxy in a similar way (small circles in Fig. 17). We conclude that the IMF in apertures that contain most of the light is lighter than the Salpeter form, and only mildly heavier than a Kroupa (2001) or Chabrier (2003) IMF.

This aperture-dependence may explain some of the discrepancies in IMF studies of massive galaxies in the literature. In particular, dynamical and lensing studies typically find values for $\alpha$ that are in between the Kroupa (2001) and the Salpeter (1955) forms (1.0 $\lesssim \alpha \lesssim 1.6$), whereas stellar population studies in much smaller apertures have found $\alpha \sim 2$ and even higher (e.g., Conroy & van Dokkum 2012b; Conroy et al. 2017). We can test whether our results are consistent with dynamical and lensing studies. First, we determine the luminosity-weighted velocity dispersion as a function of aperture radius. For each galaxy the observed relation between log $\sigma$ and log$(R/R_e)$ is fitted with a powerlaw and extrapo-

15 Note that this does not rule out the existence of a correlation between the central [Mg/Fe] and the central value of $\alpha$. 

Figure 16. IMF mismatch parameter $\alpha$ as a function of $R/R_e$, radius in kpc, velocity dispersion, [Mg/Fe], [Fe/H], and [Na/H]. The red line is Eq. 1. Grey lines are simple powerlaw fits, for all parameters that have a correlation coefficient $|r| > 0.5$. The scatter in the residuals from these fits is indicated in each panel; the uncertainty in the scatter is $\approx 0.04$. The metallicity predicts the local IMF as well as the radius does. We do not find strong correlations between $\alpha$ and the local velocity dispersion or [Mg/Fe] ratio.
Figure 17. Luminosity-weighted average IMF parameter \( \langle \alpha \rangle \) within an aperture of radius \( R \), calculated from Eq. 1. The solid red curve is for a Sersic (1968) index \( n = 4 \) and the broken curves are for \( n = 2 \) (dotted) and \( n = 6 \) (dashed). Large open symbols are determined from published relations between \( \langle \alpha \rangle \) and \( \sigma \), using the average dispersion of the six galaxies in our sample. The square is derived from strong gravitational lenses (Treu et al. 2013). The circle is from dynamical modeling of nearby early-type galaxies (Cappellari et al. 2013). The triangle is from Posacki et al. (2015), who combined ATLAS3D and SLACS data. Small open symbols are for a single massive galaxy, and are taken from La Barbera et al. (2016). Overlapping points are offset slightly in \( R \) for clarity. All results are in reasonable agreement, given the differences in methods.

6. SUMMARY AND CONCLUSIONS

Using a new suite of stellar population synthesis models and high quality data for six galaxies we find that the stellar IMF in massive galaxies is a strong function of radius. The IMF is bottom-heavy in the centers of the galaxies and reaches the approximate Milky Way form at \( R \gtrsim 0.4R_e \). This result is consistent with several recent studies that used different models and were based on index measurements rather than on full spectrum fitting (see Martín-Nabarros et al. 2015a; La Barbera et al. 2016). It is also consistent with earlier work on the centers of the most massive galaxies (van Dokkum & Conroy 2010; Conroy & van Dokkum 2012b). Given all the changes in our models and the vast improvements in data quality it is remarkable that we reached similar conclusions in 2010 as we do today. The reason is probably that we began by targeting galaxies with very large velocity dispersions and (as it turned out) very bottom-heavy IMFs, which are least sensitive to the details of the modeling. The agreement is not universal, however. McConnell et al. (2016) use very similar data, but conclude that the observed radial trends in two early-type galaxies can be explained entirely by abundance gradients. It may be that those two galaxies happen to have Milky Way IMFs throughout, but that is not a very satisfying explanation. Modeling of the McConnell et al. (2016) data using similar techniques as employed here may shed more light on this.

Abundance gradients are certainly a concern in all these studies, as they can mimic IMF effects. It is well known that the Na I \( \lambda \lambda 8183, 8195 \) Å doublet is sensitive to the Na abundance, and as discussed by Conroy & van Dokkum (2012a) and La Barbera et al. (2016) the FeH 9920 Å band depends on [Fe/H] and, in certain regimes, on age and [\( \alpha / \text{Fe} \)]. The upshot is that the two strongest gravity-sensitive features in the optical window are both difficult, or even impossible, to interpret in isolation. Allowing non-solar abundance ratios is critical, particularly for Na. Furthermore, only full spectrum fitting, or a carefully chosen combination of different indices (see Conroy & van Dokkum 2012a), can isolate IMF effects.

As the modeling gets more complex it becomes more difficult to identify the key data that produce a particular result; the high degree of sophistication in this field carries the risk that the modeling begins to resemble a black box. Some of these issues are addressed in Conroy et al. (2017), where we use the exquisite NGC 1407 data to analyze what specific stellar mass ranges are constrained by the data. In the somewhat stand-alone § 5.1 we address this issue in a different way, analyzing the ratio of two spectra with similar elemental abundances but a different IMF. This “semi-empirical” approach follows earlier work on M31 globular clusters and massive ellipticals (van Dokkum & Conroy 2011), although in the present case we do not have an independent constraint on the IMF that serves as a “hard” limit on the results. In the case of NGC 1407 and NGC 2695 we can point to specific features that drive the outcome, and the analysis also provides understanding of what spectral features constrain the IMF in the rest of the sample. It is fortuitous that we have two such spectra in our small sample; future studies could specifically single out such matched pairs for deep follow-up spectroscopy to increase the sample.

In § 5.3 we show that the luminosity weighted IMF within an aperture depends strongly on the aperture size. Lensing and dynamical studies typically have an effective aperture of 0.5 – 1\( R_e \), and we demonstrate in Fig. 17 that the gradients we measure are entirely consistent with the SLACS and ATLAS3D constraints for galaxies with similar velocity dispersions. These results are consistent with the recent study of Lyubenova et al. (2016), who found that there is good agree-
Text.
Ba[7–23].

**Initial mass function:** logarithmic slopes in the mass ranges $0.08 < M/M_{\odot} < 0.5$ ($x_1$) and $0.5 < M/M_{\odot} < 1.0$ ($x_2$) [24,25].

**Hot star component:** temperature ($T_{\text{eff, hot}}$) and weight of the component [26,27].

**Emission lines:** velocity dispersion of emission lines $\sigma_{\text{emi}}$ [26], line fluxes of H, [O III], [S II], [N I], and [N II] [28–33].

**Atmospheric transmission:** normalization of atmospheric transmission function (to allow for residual telluric absorption) [34].

**Error normalization:** correction applied to the observational uncertainties, of the form $(\Delta f)_{\text{corr}} = \text{jitter}_{\text{all}} \times (\Delta f)_{\text{org}} + \text{jitter}_{\text{sky}} \times f_{\text{sky}}$, with $\Delta f$ the uncertainties in the galaxy spectrum and $f_{\text{sky}}$ a template of the sky spectrum [35,36].

### B. ANALYSIS OF SYSTEMATIC RESIDUALS

In § 3.2 we showed that the residuals from the model fits are strongly correlated, in the sense that the residuals for different galaxies (and for different radial bins within galaxies) are very similar. The green line in the top panels of Fig. 8 shows the median residual for all radial bins in all six galaxies, and the bottom panels of that Figure show the remaining systematic variation after subtracting this green line. Here we quantify this variation, and compare the amplitude of the residuals for subsets of the spectra to the strength of the IMF signal that we are aiming to measure.

We split the 92 spectra (six galaxies, and an average of $\sim 15$ radial bins per galaxy) into two approximately equal-sized samples, based on three criteria. First, we divide the spectra according to their metallicity, separately considering spectra with $[\text{Fe/H}] < -0.1$ and those with $[\text{Fe/H}] \geq -0.1$. The median systematic residuals for these two samples are shown with red lines in Fig. B1 with dark red for the low metallicity sample and light red for the high metallicity sample. In Fig. B2 we show the same curves after subtracting the median residual for the full sample (the green line in Fig. 8 in the main text). We find that the systematic residuals depend weakly on metallicity. The rms of the systematic residual is $\approx 0.0023$ (0.23 %) in the region $5000 \text{Å} < \lambda < 6300 \text{Å}$ for both metallicity bins, and after subtracting the median residual of the full sample the remaining rms is only 0.0007 and 0.0006 for the two bins. The results are similar for the other spectral regions. We also split the sample by radius (blue curves; dark blue is for $R < 0.2 R_\text{e}$ and light blue is for $R \geq 0.2 R_\text{e}$) and by the IMF mismatch parameter (green; dark green is $\alpha \geq 2$ and light green is $\alpha < 2$). These binnings produce very similar curves as the metallicity bins, which is not surprising given the strong correlations between radius, [Fe/H], and $\alpha$.

![Figure B1](image.png)

**Figure B1.** Systematic median residuals from the fits, split by spectral properties. Dark and light red curves show the residuals for $[\text{Fe/H}] \geq -0.1$ and $[\text{Fe/H}] < -0.1$ respectively. Dark and light blue curves are for $R < 0.2R_\text{e}$ and $R \geq 0.2R_\text{e}$. Dark and light green curves are for IMF mismatch parameter $\alpha \geq 2$ and $\alpha < 2$. The residuals are very similar for all these subsamples. The black curve shows the signal of variation in the IMF, for $\Delta \alpha \sim 2.5$.

Importantly, these remaining residuals are weaker than the amplitude of IMF variations. The black lines in Figs. B1 and Fig. B2 show the spectral response due to a change in the IMF (see also, e.g., Conroy & van Dokkum 2012a). The curves were created...
by dividing a model spectrum for a stellar population with an $x = 3.0$ IMF by a model with an $x = 2.3$ IMF, and subtracting the continuum.\textsuperscript{16} The difference in IMF mismatch parameter between the two models is $\Delta \alpha \approx 2.5$. Even though the systematic residuals have a similar amplitude as the IMF effect (see Fig. [B1]), the variation in the systematic residuals is a factor of $\sim 4$ smaller than the IMF effect (Fig. [B2]). Moreover, with the exception of a feature near the FeH $\lambda 9920$ Å band, there is no evidence for systematic variation in the residuals at the locations of the “classic” IMF features (Na D $\lambda\lambda 5892, 5898$ Å, Na I $\lambda\lambda 8183, 8195$ Å, and the Calcium triplet). The feature near FeH may be caused by imperfect modeling of a strong TiO band, or simply caused by noise: the remaining variations in the red part of the spectrum are only a factor of $\sim 1.5$ higher than the expectation from photon noise.

We end by reiterating that the $\pm 0.2\%$ systematic residuals shown in Fig. [B1] are likely due to deficiencies in the stellar population synthesis models (see § 3.2). Although it is desirable to improve the models and reduce these residuals, we note that they do not adversely influence the formal errors on the derived parameters: one of the parameters in the fit (see Appendix A) multiplies the formal errors to ensure that the $\chi^2$ is acceptable.

C. THE WING-FORD BAND

In the main text we do not measure or analyze the strength of individual absorption features. Instead, the spectra are fit in their entirety (“full spectrum fitting”; see, e.g., Conroy & van Dokkum 2012b). For completeness, and for comparison to other studies, we here discuss the strength of the FeH $\lambda 9920$ Å Wing-Ford band for the extracted spectra. The FeH molecular band is very strong in low mass stars and absent in giants (Wing & Ford 1969; Schiavon 1997), and of all individual absorption features in the optical it may be expected to show the strongest correlation with the IMF. However, as with all individual features, the interpretation is not straightforward. As discussed in Conroy & van Dokkum (2012a) and La Barbera et al. (2016) FeH may not show an IMF-dependence if there are counter-acting variations in metallicity or other parameters. Furthermore, there is a contaminating TiO band head at 9900 Å ($\delta R_1(23)/2 - 3$; Valenti et al. 1998).

With these caveats in mind we measure the strength of FeH at all radii for all six galaxies, using the definition of van Dokkum & Conroy (2010).\textsuperscript{17} The measurements are performed on the de-redshifted spectra, smoothed to a common resolution of $\sigma = 450$ km s\(^{-1}\). We also measure FeH in the best-fitting models, at the same resolution. In Fig. [C1] the observed FeH index is compared to that in the best-fitting model. The units are A; they can be converted to the average absorbed continuum fraction within the band (as shown in van Dokkum & Conroy 2012b) by dividing them by the width of the band (20 Å). Only points with

\textsuperscript{16} Both models have an age of 13.5 Gyr and Solar metallicity.

\textsuperscript{17} Note that the van Dokkum & Conroy (2010) index definition is different from that of Conroy & van Dokkum (2012a); the latter is appropriate for spectra at high resolution, whereas the former was chosen for spectra at low resolution.
errors < 0.08 Å are shown. The rms scatter around the line of equality is 0.044 Å, and consistent with the measurement errors.

Figure C1. (a) Strength of the observed FeH λ9920 Å absorption versus that in the best-fitting model, only showing points with errors < 0.08 Å. The solid line is the line of equality. The models reproduce the observed line strengths within the errors. (b) Relation between the FeH index and the IMF. There is no strong correlation in this sample of high quality spectra. This is not just true for the data but also for the model spectra, reflecting the fact that there are other parameters that influence the FeH absorption. (c) Relation between FeH index and radius, now showing points with errors < 0.02 Å. There is a strong relation, likely driven by a combination of the IMF and metallicity.

The FeH index is compared to the IMF “mismatch” parameter $\alpha$ in Fig. C1b. There is no correlation, even though $\alpha$ varies from 1.5 to 3.5 in this sample. Crucially, there is no strong correlation between the model FeH index and the IMF either in this subsample of high quality spectra. The rms of the model points (red) is 0.040 Å, and it is barely reduced (to 0.036 Å) after subtracting the best-fitting linear relation. Some of the weakest FeH bands are found among models that have $\alpha > 3$, i.e., very bottom-heavy IMFs. This result reflects the fact that the Wing-Ford band alone is not sufficient for measuring the IMF, as discussed above.

Finally, we show the relation between FeH and radius in Fig. C1c. Here we also show points with larger errorbars (up to 0.2 Å), to extend the radial range. There is a strong anti-correlation, with the FeH band decreasing with radius in both the models and the data. This trend is likely due to a combination of the IMF and metallicity, as [Fe/H] decreases with radius. These panels highlight the importance of techniques that take all available information in the spectrum into account.

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18 We do find $\alpha < 1.5$ for some galaxies and radial ranges, as shown in the main text, but for those spectra the errors in FeH exceed the 0.08 Å threshold (as these tend to be at large radii where the S/N ratio is lower).
