Initial Mass Function Variation in Two Elliptical Galaxies Using Near-infrared Tracers

R. Elliot Meyer1, Suresh Sivanandam1,2, and Dae-Sik Moon1

1 Department of Astronomy & Astrophysics, University of Toronto, 50 St. George Street, Toronto, ON, M5S 3H4, Canada; meyer@astro.utoronto.ca
2 Dunlap Institute for Astronomy & Astrophysics, University of Toronto, 50 St. George Street, Toronto, ON, M5S 3H4, Canada

Received 2019 January 15; revised 2019 March 14; accepted 2019 March 19; published 2019 April 24

Abstract

Using integral field spectroscopy, we demonstrate that gravity-sensitive absorption features in the zJ band (0.9–1.35 μm) can constrain the low-mass stellar initial mass function (IMF) in the cores of two elliptical galaxies, M85 and M87. Compared to the visible bands, the near-infrared (NIR) is more sensitive to light from low-mass dwarf stars, whose relative importance is the primary subject of the debate over IMF variations in nearby galaxies. Our analysis compares the observed spectra to the latest stellar population synthesis models by employing two different methods: equivalent widths and spectral fitting. We find that the IMF slopes in M85 are similar to the canonical Milky Way IMF with a median IMF-mismatch parameter αK = 1.26. In contrast, we find that the IMF in M87 is steeper than a Salpeter IMF with αK = 2.77. The derived stellar population parameters, including the IMF slopes, are consistent with those from recent results in the visible bands based on spectroscopic and kinematic techniques. Certain elemental abundances, e.g., Na and Fe, have dramatic effects on the IMF-sensitive features and therefore the derived IMF slopes. We show evidence for a high [Na/H] ∼ 0.65 dex in the core of M85 from two independent Na1 absorption features. The high Na abundance may be the result of a recent galactic merger involving M85. This suggests that including [Na/H] in the stellar population model parameters is critical for constraining the IMF slopes in M85. These results confirm the viability of using NIR absorption features to investigate IMF variation in nearby galaxies.

Key words: galaxies: abundances – galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: stellar content – stars: luminosity function, mass function

1. Introduction

The functional form of the initial mass function (IMF) has far-reaching implications in our understanding of the stellar component of galaxies, galaxy formation, and evolution, as well as the interpretation of observed galactic properties. It has been traditionally assumed that the IMF of extragalactic stellar populations follows the same functional form as measured in the Milky Way (MW; Salpeter 1955; Kroupa 2001; Chabrier 2003; Bastian et al. 2010). Recently, measurements of the IMF in early-type galaxies (ETGs) have called this assumption into question (Treu et al. 2010; van Dokkum & Conroy 2010; Cappellari et al. 2012; Conroy & van Dokkum 2012b; Spiniello et al. 2012; La Barbera et al. 2013). These studies have suggested that the IMF becomes increasingly “bottom-heavy,” meaning a larger fraction of low-mass (<1 M⊙) stars, in ETGs with higher central velocity dispersions (σv), higher α-element abundances ([α/Fe]), or increasing metallicity ([Z/H]; Martín-Navarro et al. 2015). This variation has also been measured in the bulges of some massive spiral galaxies (Dutton et al. 2013; Parikh et al. 2018).

There are two general methods that have been adopted to constrain the IMF of unresolved stellar populations. The first method relies on either galactic dynamics (e.g., Cappellari et al. 2012; Li et al. 2018) or gravitational lensing (e.g., Treu et al. 2010; Smith et al. 2015; Collier et al. 2018) to constrain the galactic mass and therefore the stellar mass-to-light (M/L) ratio. These measured M/L ratios are then compared to those derived from stellar population models to infer a mass excess that would be indicative of a variable IMF. The second method uses several surface gravity-sensitive absorption features (e.g., NaI 0.84 μm, Ca II triplet 0.86 μm, Wing–Ford band (FeH) 0.99 μm) along with stellar population synthesis (SPS) to fit the IMF directly from the integrated galaxy spectrum (e.g., Spiniello et al. 2012; van Dokkum & Conroy 2012; La Barbera et al. 2013; Zieleniewski et al. 2016; Alton et al. 2017). Both of these methods have independently found evidence for IMF variations in galaxies, strengthening the overall argument for the existence of some effect. However, different studies have identified discrepancies in the IMFs measured for particular galaxies (Smith 2014), the existence of IMF variation (Smith & Lucey 2013; Smith et al. 2015), or the cause of the variation (La Barbera et al. 2015). Reconciling these discrepancies requires additional confirmation based on evidence from new or expanded methods.

Constraining the IMF using gravity-sensitive features is enticing, as it directly probes the galactic stellar populations. They help break the degeneracy arising over the relative contribution of dwarf and giant stars with similar effective temperatures to the integrated light. Absorption features, however, are highly sensitive to stellar population parameters such as age, star formation history, and elemental abundances (Conroy & van Dokkum 2012a, hereafter CvD12a). This requires either additional features, full spectral modeling, or broader spectral coverage to more reliably constrain these population parameters.

A majority of studies that have employed SPS have focused on using absorption features in the visible bands (up to 1.0 μm). Few studies have extended further into the near-infrared (NIR), with notable exceptions (e.g., Lagattuta et al. 2017; Alton et al. 2017, hereafter ASL17). There are advantages to exploring the NIR relative to the visible bands for use in constraining the IMF, including its increased sensitivity to light from faint, low-mass dwarfs. The spectral intensity of M dwarfs, which tend to dominate the stellar mass of galaxies regardless of the shape of the IMF, peaks in the
range of 0.8–1.2 μm (Rajpurohit et al. 2013). In addition, a significant percentage of the light emitted by late-type M dwarfs, i.e., $M \lesssim 0.3 M_\odot$, is emitted in the NIR. According to the CvD12a models, there are numerous gravity-sensitive absorption features in the $zJ$ band (0.9–1.35 μm) that vary by 1% or more between a Kroupa (MW-like) and bottom-heavy IMF. These features are the Wing–Ford band (FeH) at 0.99 μm, a Ca I line at 1.13 μm, an Na I line at 1.14 μm, a K I doublet at 1.17 μm, a K I line at 1.25 μm, and an Al I line at 1.31 μm.

In this paper, we present a pilot study on constraining the IMF of nearby ETGs using the above set of $zJ$-band gravity-sensitive features. For this, we observed the innermost cores of two nearby ETGs. Recent spatially resolved studies of nearby ETGs have found indications that the IMF slopes in these galaxies vary radially (Martín-Navarro et al. 2015; La Barbera et al. 2016; van Dokkum et al. 2016; Sarzi et al. 2017). These studies suggested that the bottom-heavy IMF may be localized in the cores of massive ETGs, while the IMF becomes more MW-like at larger radii. Galactic cores are, therefore, ideal locations for investigating variations in the IMF. We compare our observed spectra to the latest version of the Conroy & van Dokkum (2012a) models (Conroy et al. 2018, hereafter C18). Our analysis adopts two standard methods, equivalent width (EW) measurement and spectral fitting based on a Markov chain Monte Carlo (MCMC) technique, and we conduct a detailed comparison between the results from the two methods.

This paper is organized as follows. We provide the details of our observations and data reduction procedure, the measured EWs, the MCMC simulations, and discussion in Sections 2–5, respectively, followed by a summary and our conclusions in Section 6.

### 2. Observations and Data Reduction

We chose two galaxies, M85 and M87, from the van Dokkum & Conroy (2012, hereafter vDC12) target sample that were shown to have highly contrasting central IMFs. Selected parameters for the targets can be found in Table 1. Conroy & van Dokkum (2012b, hereafter CvD12b) concluded that M85 has an MW-like IMF, while M87 has a Salpeter type. Also, M87 has been the subject of IMF variation analysis using SPS in ASL17 and Sarzi et al. (2017) and dynamical modeling in Oldham & Auger (2018), all of which have found a Salpeter-like or steeper IMF. Furthermore, these two galaxies are on opposite ends of both the IMF–σ$_v$ and IMF–[α/Fe] distributions in CvD12b. They are therefore exemplary targets for observational analysis of stellar populations with contrasting IMFs.

| Galaxy | R.A. | Decl. | $T_{exp}$ (minutes) | $z$ | $\sigma$ (km s$^{-1}$) | [Mg/Fe] | [Fe/H] | $\alpha$ |
|--------|------|-------|---------------------|----|-----------------------|---------|--------|--------|
| M85 (NGC 4382) | 12:25:24.1 | +18:11:29 | 40 (Z), 40 (J) | 0.0024 | 170 | 0.11 | −0.02 | 0.63 |
| M87 (NGC 4486) | 12:30:49.4 | +12:23:28 | 30 (Z), 40 (J) | 0.0043 | 170 | 0.33 | −0.16 | 1.90 |

Note. (1) Target galaxy. (2) R.A. (3) Decl. (4) Total exposure time (5 minute exposures). (5) Redshift from Smith et al. (2000). (6) Velocity dispersion averaged in the central 3″ from Emsellem et al. (2004). (7)–(9) From CvD12b; $\alpha_K = (M/L)_K/(M/L)_{K, MW}$ is the “IMF-mismatch” parameter (see Section 4.4). This parameter measures the “bottom-heavyness” of the IMF.

### 2.1. Observations

We carried out seeing-limited, integral field spectroscopic observations of M85 and M87 with the Near-Infrared Integral Field Spectrometer (NIFS; McGregor et al. 2003) on the 8 m Gemini North Telescope as part of the GN–2015A–Q–47 program. We observed M85 on 2015 May 8, 27, and 30, while M87 was observed on 2015 June 2 and 5. The observations were made using the $zJ$ filter and both the $z$-band (0.94–1.15 μm) and $J$-band (1.15–1.33 μm) gratings, respectively. This provided an effective spectral coverage of 0.94–1.33 μm. These bands have spectral resolving powers in the range of ~5000–6000. The NIFS integral field size was ~3″ × 3″ mapped by 29 image slices and a pixel scale of 0″.103 and 0″.04 across and along the slices, respectively.

The targets were observed with a repeated target–sky–target nodding sequence. The $z$ and $J$ bands for M85, as well as the $J$ band for M87, were observed for 8 × 300 s exposures and 4 × 300 s sky exposures. In the $z$ band, M87 was observed for 6 × 300 s exposures and 3 × 300 s sky exposures. During each observing night, we observed an A0V standard star at a similar air mass as the target galaxy for use in removing telluric features from the galaxy spectrum.

Our analysis relied on using NIFS as a spectrographic “light bucket” for obtaining an integrated spectrum with a high signal-to-noise ratio (S/N). It is critical to have a high-S/N spectrum so as to resolve the minute differences in flux (1%–2%) caused by IMF variation in each of the absorption features.

### 2.2. Data Reduction

The obtained NIFS data were primarily reduced using a suite of PYTHON/IRAF reduction scripts provided by the standard Gemini NIFS pipeline. The pipeline scripts perform flat-fielding, sky subtraction, spatial distortion correction, wavelength calibration, and spectral cube extraction. Additional data processing such as atmospheric absorption (telluric) correction and uncertainty estimation were accomplished with custom PYTHON routines.

Atmospheric absorption in the galaxy spectra was removed using the spectrum of an A0V telluric star observed at a similar air mass as the galaxy observations. Before being applied to the galaxy spectrum, the telluric star spectrum was first corrected for intrinsic A0V star absorption features, such as the strong Paschen series lines, following the method outlined in Vacca et al. (2003). This method employs a template Vega spectrum that is scaled to match the observed A0V star absorption features.

In order to remove the telluric features from the galaxy spectra, the telluric standard spectrum was aligned with the respective galaxy spectrum using seven telluric regions that appear in both spectra. This was necessary, as the wavelength
The measurement bands are shaded in magenta. The emission feature seen in the M87 spectrum at 9500 Å is an [S III] + Pa ε composite feature from the central AGN. This line was not removed from the spectrum, as it does not affect the measurement of any of the IMF-sensitive features.

The NaI 1.14 μm feature is located in a region of strong telluric absorption at the end of the NIFS z band. The above telluric correction method was repeated on this feature in isolation so as to further reduce the effects of atmospheric absorption on the feature profile.

The strong, central active galactic nucleus (AGN) of M87 likely contaminates the measured absorption features (Alton et al. 2017; Sarzi et al. 2017). Two strong emission features were identified in the final M87 spectrum: an [S III] + P ε feature at ~0.953 μm and a weaker [Fe II] feature at ~1.26 μm. The [Fe II] feature intersected with the K I 1.25 μm feature in the EW index measurement bands. It was removed from the M87 spectrum with a Gaussian profile fit; however, the residual effects significantly reduced our confidence in the measurement of the K I 1.25 μm feature. We therefore excluded this feature from our analysis of the observed M87 spectrum.

In addition to the line emission, continuum emission from the AGN also likely contaminated the observed M87 spectrum. To measure the level of AGN contamination to the spectrum continuum level, ASL17 used Hubble observations of M87. They estimated an approximately 15% contribution to the total M87 continuum level. Since the field of NIFS is almost identical to that of the KMOS field in their study, we consider the effect a 15% continuum correction would have on our IMF measurements in Section 5.3.

The final, telluric-corrected, integrated spectra for both galaxies are shown in Figure 1. We removed the background continuum level by fitting the spectra with seventh-order polynomials. The spectral bands that we use in the EW index analysis (see Section 3) are shaded: the blue shaded regions are the continuum bands, and the magenta regions are the measurement bands. The spectral resolution of the M87 spectra was halved (R ~ 3000) in order to improve the overall S/N. This was implemented by taking the mean spectral value for consecutive pairs of wavelength points. It was necessary to improve the S/N due to the lower integration time, as well as the high central velocity dispersion in M87. Higher velocity dispersions reduce the strength of the spectral indices by spreading the signal over a wider bandpass, thereby requiring higher-S/N measurements to accurately measure the effects of the IMF on the index strengths. The final, mean S/Ns per resolution element across the full z band (~0.95–1.35 μm) are 71 and 61 for M85 and M87, respectively.

3. EW Analysis

3.1. EW Measurements

In Section 1, we identified seven gravity-sensitive absorption features in the z/J band that vary by greater than 1% between stellar populations with a bottom-heavy IMF and those with an MW-like IMF. The EW index definitions for these features are identical to those given in CvD12a, ASL17, and Smith et al. (2012) and are listed in Table 2. All seven features increase in strength for stellar populations with a higher percentage of dwarf stars than giants. Any giant star sensitive features in the z/J band vary weakly with respect to the IMF, so they were not included in the following analysis due to the high S/N required to accurately measure the effects of the IMF.

We defined fiducial models from C18 for each galaxy in order to provide a standard comparison to the measured indices. The stellar ages and metallicities of the fiducial models closely match those measured within an R_e/8 radius for M85 (5.0 Gyr age, [Z/H] = 0.0) and M87 (13.5 Gyr age, [Z/H] = 0.2) in McDermid et al. (2015). The observed NIFS fields for both galaxies were fully contained within an R_e/8

![Figure 1. Fully collapsed and reduced spectra for both M85 (solid blue line) and M87 (solid red line). The spectra were normalized by dividing by a high-order polynomial for clarity. The absorption features that are measured in this paper are labeled and highlighted (Table 2). The EW continuum bands are shaded in blue, and the measurement bands are shaded in magenta. The emission feature seen in the M87 spectrum at 9500 Å is an [S III] + Pa ε composite feature from the central AGN. This line was not removed from the spectrum, as it does not affect the measurement of any of the IMF-sensitive features.](image-url)
radius and accounted for 18% and 32% of the $R_\text{s}/8$ radii for M85 and M87, respectively (Krajnović et al. 2013).

We show a close-up view of the seven observed absorption features in Figures 2 and 3. The observed spectra are represented by the solid blue lines, while fiducial models with a Kroupa and bottom-heavy IMF are shown in green and red dashed lines, respectively. The model spectra have been broadened to match the central velocity dispersion of M85. The blue and red shaded areas correspond to the EW bandpass regions, and the magenta shaded areas correspond to the feature index measurement region (see Table 2). The gray shaded regions correspond to a 68.3% confidence level in the spectral intensity.

Figure 2. Seven observed IMF-sensitive absorption features from the observed M85 spectrum (solid blue lines). The dashed lines are fiducial models with a stellar age of 5.0 Gyr and solar metallicity. Models with Kroupa and bottom-heavy IMFs are shown as green and red dashed lines, respectively. The model spectra have been broadened to match the central velocity dispersion of M85. The blue and red shaded areas correspond to the EW bandpass regions, and the magenta shaded areas correspond to the feature index measurement region (see Table 2). The gray shaded regions correspond to a 68.3% confidence level in the spectral intensity.

Figure 3. Same as Figure 2. The fiducial models for M87 have a stellar population age of 13.5 Gyr and $[Z/H] = 0.2$. The EW bandpass regions for the K I 1.25 feature are gray, as this feature was excluded from our analysis of the M87 spectrum.

We measured the EW indices of the IMF-sensitive absorption features following the method of Trager et al. (1998). Table 3 lists the measured index strengths with their estimated uncertainties and the mean S/N across the feature band for each index. The uncertainties were calculated based on the variance in the intensity at a given wavelength in the set of six to eight target exposures. The S/Ns for the z-band EW in M87 are lower due to the shorter total integration time in that filter relative to the surface brightness of the galaxy.
The Astrophysical Journal, 875:151 (15pp), 2019 April 20

Meyer, Sivanandam, & Moon

Table 3

| Line     | EW     | S/N°C  | EW     | S/N°C  |
|----------|--------|--------|--------|--------|
|          | M85    | M85    | M87    | M87    |
| FeH 0.99 | 0.39 ± 0.08 | 81  | 0.31 ± 0.11 | 67  |
| Ca I 1.03 | 0.20 ± 0.07 | 73  | 0.06 ± 0.15 | 50  |
| Na I 1.14 | 1.33 ± 0.24 | 53  | 0.05 ± 0.50 | 28  |
| K I 1.17  | 0.32 ± 0.07 | 84  | 0.17 ± 0.09 | 95  |
| K ii 1.17 | 0.56 ± 0.06 | 100 | 0.28 ± 0.14 | 64  |
| K I 1.25  | 0.21 ± 0.11 | 67  | ...        | ...  |
| Al I 1.31 | 1.11 ± 0.18 | 45  | 0.67 ± 0.25 | 59  |

Note.

° Mean S/N within the index feature band defined in Table 2.

3.2. Adopted Stellar Population Models

In the following analysis, we make use of two groups of synthetic single stellar population models from C18: one group that varies the IMF while holding other stellar population parameters (e.g., age, metallicity) constant, and another group of “response functions” for individual elemental abundances (e.g., [Na/H], [Fe/H], [Ca/H], [K/H], etc.). These models are computed by combining observed stellar spectra from the MIST (Choi et al. 2016) and Extended IRTF (Villaume et al. 2017) spectral libraries with the theoretical response functions. Both groups of models are subdivided into sets with fixed metallicities ranging from [Z/H] = −1.5 to +0.2 and stellar ages from 1.0 to 13.5 Gyr. The former group of models is used to characterize the IMFs of M85 and M87 and the latter to infer the effects of possible abundance variations.

The group of models with variable IMF slopes follows a broken power law for the IMF functional form. The power law is split into three mass intervals with exponents ($x_i$):

$$x_1: 0.08 \leq \frac{M}{M_\odot} < 0.5$$

$$x_2: 0.5 \leq \frac{M}{M_\odot} < 1.0$$

$$x_3: 1.0 \leq \frac{M}{M_\odot}$$

The $x_1$ and $x_2$ exponent values range from 0.5 to 3.5 in steps of 0.2. The IMF slope for stellar masses above 1.0 $M_\odot$ is static and identical to the Kroupa IMF value of 2.3. We refer to “X” as a single-slope IMF exponent, equivalent to an IMF where $x_1$ and $x_2$ are equal; i.e., a Salpeter IMF is defined as $X = 2.3$ and a bottom-heavy IMF as $X \geq 3.0$.

3.3. Constraints on the IMF from Individual Line Indices

We compare the observed EW indices for both M85 and M87 to those measured from the broadened fiducial models in Figures 4 and 5. The indices are plotted as a function of the two low-mass IMF exponents, $x_1$ and $x_2$, with the black and red contours marking lines of constant model index and the observed index, respectively. Also included for reference are Kroupa, Salpeter, and bottom-heavy ($X = 3.0$) IMFs shown as blue, magenta, and green stars, respectively.

In Figures 4 and 5, the observed index strength of some of the features, e.g., FeH and Na I 1.14 μm, show discrepancies in their favored IMF slopes, making it difficult to draw consistent conclusions regarding the IMF slopes in either galaxy. A likely explanation for these discrepancies is the strong degeneracy between the effects of the IMF and other stellar population parameters, such as elemental abundances and stellar ages, on the measured index strengths (Conroy & van Dokkum 2012a).

This indicates that a simple analysis based on general stellar population parameters available in the literature is inadequate for constraining the IMF; consequently, we need a more rigorous analysis that takes the effect of the varying abundance ratios into account to more effectively constrain the IMF. Below, we conduct an investigation into the effects of varying elemental abundances on the measured index strengths for each observed feature. This investigation is used to interpret the results of a more thorough study of the IMFs of the observed galaxies in Section 4.

3.3.1. Wing–Ford Band (FeH 0.99 μm)

The FeH 0.99 μm feature is widely included in IMF variation studies (e.g., van Dokkum & Conroy 2012; Alton et al. 2017; Vaughan et al. 2018) due to its low sensitivity to a stellar population’s age and α-element abundance (Conroy & van Dokkum 2012a). It is the only molecular feature in the measured set of seven features. According to the C18 models, the strength of this index is primarily sensitive to [Fe/H] and has a negative relationship with [Na/H]. The latter relationship originates from the role of Na as a major electron donor in cool stars. A high Na abundance encourages the dissociation of the FeH molecule in stellar atmospheres (CvD12a; ASL17; Smith et al. 2012; Vaughan et al. 2018).

The observed index strength of the FeH 0.99 μm feature is 0.39 ± 0.08 Å in M85 and 0.31 ± 0.11 Å in M87. For M85, this index strength is consistent (within a 68.3% confidence level) with IMF slopes similar to a Kroupa-like IMF, as predicted in CvD12b. In M87, the FeH index is very weak relative to what is expected for a stellar population with a bottom-heavy IMF, as suggested by CvD12b and others.

One possible cause for the low FeH index strength in M87 is an underlying low [Fe/H] and/or high [Na/H]. CvD12b measured [Fe/H] = −0.16 dex in the core of M87, and Sarzi et al. (2017) measured a high central [Na/H] = +0.7 dex. If we find that the C18 models predict that the FeH index is reduced by approximately 13% at [Fe/H] = −0.16 dex and by 25% at [Na/H] = +0.7 dex. Correcting the index strength for these abundance effects increases the measured index to 0.43 ± 0.15 Å, which would instead be marginally consistent with a Salpeter-like IMF. Other possible factors influencing the strength of the FeH index include increased uncertainties arising from measuring this index for a galaxy with high α$_v$ (McConnell et al. 2016) or spectral contamination from the central AGN.

3.3.2. Calcium Feature (Ca I 1.03 μm)

The Ca I 1.03 μm feature is the weakest IMF-sensitive feature in our set. The strength of the Ca I 1.03 μm index is strongly sensitive to [Ca/H], but it is not affected by variations in [Na/H], unlike other IMF indicators in both the visible and NIR bands (Smith et al. 2012). We measured a Ca I index strength of 0.20 ± 0.07 Å in M85 and 0.06 ± 0.15 Å in M87. These indices are very weak in both galaxies, particularly in M87, relative to the expected index strengths in the fiducial models (Figures 4 and 5). The low Ca I index strength in M87 may be the result of a low Ca abundance, as found in ASL17 for a set of similarly massive ETGs.
Salpeter, and bottom-heavy IMFs are marked as blue, magenta, and green stars, respectively. The gray regions represent the index space covered by 68.3% measured from the strong, negative relationship with addition, the models indicate that the index strength has a Figure 4. The Astrophysical Journal, zJ feature in the relationship between FeH and observed galaxies, 1.33 lines for low-redshift galaxies.

The NaI 1.14 μm feature is the most dwarf star sensitive feature in the zJ band, according to the C18 models. In addition, the models indicate that the index strength has a strong, negative relationship with [Fe/H], similar to the relationship between FeH and [Na/H].

> The measurement of this index is complicated by its location within a densely populated band of telluric water absorption lines for low-redshift galaxies.

We measured a very strong NaI 1.14 μm index in both observed galaxies, 1.33 ± 0.24 Å in M85 and 0.95 ± 0.50 Å in M87, relative to the expected index strengths from the fiducial models. In M85 and M87, the index strength is consistent with a “bottom-heavy” IMF and/or a stellar population with a significantly enhanced Na abundance.

In M85, the measured NaI 1.14 μm index strength is greater than expected for an MW-like IMF as measured in CvD12b. Reconciling this index strength with the fiducial model strength for a Kroupa IMF (0.72 Å) would require either a significantly enhanced [Na/H], a higher [Z/H], a more bottom-heavy IMF, or a combination of these effects. If we compare the measured index strength with a stellar population model with [Z/H] = +0.2 dex instead of solar metallicity, the index strength is instead marginally consistent with a Kroupa IMF.

Our measured NaI 1.14 μm index in M87 is consistent with a Salpeter-like IMF, albeit with very high uncertainties (Figure 5). As previously mentioned, the central [Na/H] in M87 has been measured to be significantly greater ([Na/H] > 0.7 dex) than the abundance assumed in our fiducial model ([Z/H] = 0.2 dex). Our measurements are similar to the results of Smith et al. (2015), who found this index to be extremely strong in M87 relative to stellar population models in massive ETGs. Smith et al. (2015) also found that the CvD12a models still underpredict the NaI 1.14 μm index despite a close fit to the overall spectrum and a predicted Salpeter-like IMF.

3.3.3. Sodium Feature (NaI 1.14 μm)

The NaI 1.14 μm feature is the most dwarf star sensitive feature in the zJ band, according to the C18 models. In addition, the models indicate that the index strength has a strong, negative relationship with [Fe/H], similar to the relationship between FeH and [Na/H].

The measurement of this index is complicated by its location within a densely populated band of telluric water absorption lines for low-redshift galaxies.

We measured a very strong NaI 1.14 μm index in both observed galaxies, 1.33 ± 0.24 Å in M85 and 0.95 ± 0.50 Å in M87, relative to the expected index strengths from the fiducial models. In M85 and M87, the index strength is consistent with a “bottom-heavy” IMF and/or a stellar population with a significantly enhanced Na abundance.

In M85, the measured NaI 1.14 μm index strength is greater than expected for an MW-like IMF as measured in CvD12b. Reconciling this index strength with the fiducial model strength for a Kroupa IMF (0.72 Å) would require either a significantly enhanced [Na/H], a higher [Z/H], a more bottom-heavy IMF, or a combination of these effects. If we compare the measured index strength with a stellar population model with [Z/H] = +0.2 dex instead of solar metallicity, the index strength is instead marginally consistent with a Kroupa IMF.

Our measured NaI 1.14 μm index in M87 is consistent with a Salpeter-like IMF, albeit with very high uncertainties (Figure 5). As previously mentioned, the central [Na/H] in M87 has been measured to be significantly greater ([Na/H] > 0.7 dex) than the abundance assumed in our fiducial model ([Z/H] = 0.2 dex). Our measurements are similar to the results of Smith et al. (2015), who found this index to be extremely strong in M87 relative to stellar population models in massive ETGs. Smith et al. (2015) also found that the CvD12a models still underpredict the NaI 1.14 μm index despite a close fit to the overall spectrum and a predicted Salpeter-like IMF.

3.3.4. Potassium KI Features

We use two KI features in our NIFS data for constraining the IMF of M85: a doublet feature (KIa and KIb) at 1.17 μm and a feature at 1.25 μm. The index strengths of the doublet feature are strong in M85, suggesting that the IMF slopes of M85 are similar to a Salpeter IMF. The strength of the 1.25 μm index, on the other hand, favors a more MW-like IMF than Salpeter. Note that in the doublet, the KIb index provides tighter constraints on the IMF than the KIa index, as the former is more sensitive the changes in the IMF slope than the latter.

This discrepancy in the favored IMF slopes of the two KI features is seen to a lesser degree in ASL17, where the measured central index strengths of the doublet are consistent with steeper IMFs than the 1.25 μm index. This effect may be related to the high sensitivity of the 1.25 μm feature to variations in [α/Fe], as the strength of this feature can be dramatically weakened as [α/Fe] increases due to changes in the local continuum behavior (ASL17). We find that the discrepancy in the favored IMF slopes of the two KI features is reduced if we instead adopt a [Z/H] = +0.2 dex model. This is suggestive that an increased metallicity or K abundance may also be responsible for the discrepancies (see ASL17).

For M87, the strengths of the KI doublet indices both favor Salpeter-like IMFs, which is consistent with the IMFs observed in the center of the galaxy by CvD12b. As mentioned in Section 2.2, we excluded the K I 1.25 μm line in our analysis of M87 due to AGN effects.
3.3.5. Aluminum Feature (1.31 μm)

We measure an Al I feature at 1.31 μm that has not been well explored for use in constraining the IMF slopes of integrated stellar populations. This feature was first identified as IMF-sensitive in CvD12a, and ASL17 included measurements of the index strength in their study of the IMF of massive ETGs. We measure an Al I index strength of 1.11 ± 0.18 and 0.67 ± 0.25 Å in M85 and M87, respectively. Neither of these index strengths favor a particular IMF due to the large uncertainties that cover the entire \( x_1-x_2 \) index space for this feature.

3.4. Comparison to Reported Index Strengths

For M87 measured the index strengths of all seven features listed in Table 2. In order to compare our index strengths to those measured in ASL17, we scale our measurements to a common \( \sigma_v = 230 \text{ km s}^{-1} \). Because ASL17 did not report central index strengths for FeH and Ca I 1.03 μm, we instead compare to their measurements at \( R_e/3 \). We find that our index strengths are generally consistent with those in ASL17, with the exception of the Na I 1.14 μm index. We measure a scaled index of 1.24 ± 0.65 Å compared to their index strength of 2.65 ± 0.26 Å. This discrepancy is likely a result of the lower S/N of our z-band spectrum for M87, as well as complications with the index measurement due to the dense telluric absorption around this feature.

Smith et al. (2012) measured the Ca I 1.03 μm index strength in a sample of Coma cluster ETGs with similar \( \sigma_v \) to M85 (>100 km s\(^{-1}\)). Our measured strength in M85 is consistent with their mean measurement of 0.279 ± 0.024 Å. Baldwin et al. (2018) measured an Na I 1.14 μm index strength of approximately 1.0 in low-\( \sigma_v \) ETGs, which is also consistent with the strength of our measured index in M85.

4. Spectral Fitting Analysis

We now describe our method for fitting the observed spectra of M85 and M87 to the C18 models. We construct a set of adjusted models to account for abundance ratio variations in Na, Fe, Ca, and K by scaling the C18 models with fixed ages and [Z/H] by the theoretical elemental response functions. Specifically, we fit these adjusted C18 models to the observed feature spectral bands defined in Table 2 while allowing for variable stellar population parameters: the age, [Z/H], IMF slopes, and aforementioned elemental abundances. We fit the feature spectral bands to the models, in contrast to fitting broader spectral bandpasses as in CvD12b, in order to characterize the effectiveness of this particular set of features for constraining the IMF. In addition, fitting the feature bands allows for a comparison with the similar extragalactic IMF analysis in the NIR presented in ASL17.

4.1. Additional Features

The seven features discussed in this paper are weakly sensitive to stellar population ages in the range of 7–13.5 Gyr (Kin17). The index strengths vary by a much greater amount (<20%) for younger stellar populations in the range of 3–5 Gyr. As a consequence of this stronger age–index strength sensitivity for younger stellar ages, in addition to previous measurements of a young ~4 Gyr stellar population in the core of M85 (McDermid et al. 2015; Ko et al. 2018), we find it necessary to include the stellar population age in our model parameters. In order to provide better constraints on the stellar age, we define a new EW index for the Paschen \( \beta \) (Pa \( \beta \))
feature at 1.28 μm. The Pa β feature is highly sensitive to the stellar population age, similar to the classical Lick H β feature employed to constrain stellar ages in stellar population studies in the visible bands (e.g., McDermid et al. 2015). Furthermore, many of the features in Table 2 are sensitive to variations in the Na abundance (see Section 3.3). The Na abundance is primarily constrained by the Na I 1.14 μm feature, which is the most IMF-sensitive of the seven features. Due to the importance of [Na/H] in constraining the IMF slopes in this analysis, we define a new EW index for the Na I feature at 1.27 μm. The Na I 1.27 μm feature provides an independent constraint on the Na abundance that is not sensitive to variations in the IMF slopes (Smith et al. 2015).

The EW index measurement bands for both features are defined in Table 4. The spectral bands are designed to have similar bandwidths (20–30 Å) and total widths (~100 Å) as the seven features in Table 2. Profiles of the observed Pa β and Na I 1.27 μm features for both galaxies can be seen in Figure 6 alongside stellar population models with ages of 3 and 13.5 Gyr and [Na/H] = 0.6 for illustration purposes. The models in the figure assume either Kroupa or bottom-heavy (X = 3.0) IMFs for the M85 and M87 spectra, respectively, although neither feature is significantly sensitive to the IMF slopes. The Pa β feature, in the left panels, is clearly sensitive to the stellar population age, with the observed M85 and M87 spectra being better described by models with younger and older stellar populations, respectively. In the right panels, the Na I 1.27 μm feature is highly sensitive to the Na abundance, with the observed feature profiles for both galaxies more closely aligned with the Na-enhanced models. Furthermore, Pa β has a minor sensitivity to [Ca/H], while both features have minor sensitivities to [Fe/H].

### 4.2. MCMC Model Overview

The model parameters are estimated with the publicly available emcee routine (Foreman-Mackey et al. 2013), an MCMC ensemble sampler that characterizes the posterior probability distributions of a particular model provided observed data and uncertainties. Our implementation of this routine maximizes a log-likelihood function,

$$\ln p(D|\theta, \sigma) = -\frac{1}{2} \sum_i \left[ \frac{D_i - M_i(\theta)}{\sigma_i} \right]^2, \tag{2}$$

where $D_i$ is the observed spectrum at the $i$th wavelength element, $\theta$ is the input model parameters value listed in Table 5, $M_i(\theta)$ is the adjusted C18 model, and $\sigma_i$ is the measured uncertainty in the spectral intensity.

Each MCMC simulation consists of 512 “walkers,” each of which explores the posterior distributions, $p(\theta|D, \sigma)$, of the model input parameters over 4000 steps or a total of 2.048 × 10⁶ samples. The final 1000 samples of each walker are kept for the following analysis, while the preceding 3000 samples are discarded as a standard parameter “burn-in” phase.

### Table 4

**Additional Line Index Bandpass Definitions**

| Index | Feature (Å) | Blue Continuum (Å) | Red Continuum (Å) |
|-------|-------------|--------------------|-------------------|
| Na I 1.27 | 12670–12690 | 12648–12660 | 12700–12720 |
| Pa β | 12810–12840 | 12780–12800 | 12855–12880 |

### Figure 6

The Pa β and Na I 1.27 μm features from the observed M85 (top panels) and M87 (bottom panels) spectra. The observed spectrum (solid blue line) is compared to model spectra for a stellar population with 3 and 13.5 Gyr ages (dotted lines) and one with an enhanced [Na/H] = 0.6 dex (black line). The [Na/H] enhanced model has a stellar age of 3 Gyr for M85 and 13.5 Gyr for M87. The model M85 spectra assume a Kroupa IMF, while the model M87 spectra assume a bottom-heavy IMF. The model spectra have been broadened to match the velocity dispersion of each galaxy. The gray shaded regions correspond to a 68.3% confidence level in the spectral intensity. The vertical shaded regions correspond to the EW index measurement bands, as in Figure 2.

### Table 5

**Model Parameter Priors for the MCMC Ensemble Sampler**

| Parameter | Prior Limits |
|-----------|--------------|
| Age | 1.0–13.5 |
| [Z/H] | −0.25–0.2 |
| $x_1$ | 0.5–3.5⁹ |
| $x_2$ | 0.5–3.5⁹ |
| [Na/H] | −0.5–0.9 |
| [K/H] | −0.5–0.5 |
| [Ca/H] | −0.5–0.5 |
| [Fe/H] | −0.5–0.5 |

**Note.**

⁹ The IMF slope exponents are limited to increments of 0.2 as in the C18 models.

The MCMC model input parameters and their priors are listed in Table 5. We impose uniform, “top-hat” distributions for the priors of the input parameters in order to avoid any potential bias to the ensemble sampler. The initial model parameters for each walker are chosen at random from within these distributions. We split the input parameters into two groups: a base set and an extended set. The base set of parameters consists of the stellar population age and metallicity ([Z/H]) and the two IMF slopes, $x_1$ and $x_2$. In contrast, the extended set adds four elemental abundance ratios to the base set: [Na/H], [Fe/H], [Ca/H], and [K/H]. We fit the observed feature bands (Tables 2 and 4) of M85 and M87 to both sets of model parameters in order to assess the effects of fitting abundance variations on the IMF slope constraints.

In order to calculate the log-likelihood (Equation (2)), we first create “adjusted models” by scaling and broadening the
models from C18 as a function of the input abundance ratios and the known velocity dispersion of M85 and M87 (Table 1), respectively. The log-likelihood is then calculated by comparing the feature bands between the observed spectra and the adjusted model. The feature bands are normalized with the same method detailed in Section 3.1 for calculating the EW index strengths.

We account for variable abundance ratios in our adjusted models by linearly interpolating the elemental response functions along the spectral and abundance ratio (X/H) axes. This method is a standard assumption when modeling near-solar abundance variations (Conroy & van Dokkum 2012b; Alton et al. 2017). Here C18 provided spectral response functions at ±0.3 dex for [Fe/H], [Ca/H], and [K/H] and for [Na/H] in the range of −0.3 to +0.9 dex with an increment of 0.3 dex. The extended abundance ratio coverage for Na is due to its critical role in determining the depth of many of the IMF-sensitive absorption features (see Section 3.3.3). We increase the MCMC prior limits for the abundance ratios from ±0.3 to ±0.5 dex to conduct a more thorough investigation into the effect of the abundance ratios on the IMF slopes.

The stellar population age and metallicity parameters are accounted for in a similar way as the abundance ratios by linearly interpolating between models with fixed ages and metallicities.

### 4.3. Results: MCMC Spectral Fitting

Table 6 presents the “best-fit” model parameters for M85 and M87 as constrained by the final 1000 likelihood samples of the MCMC walkers, including the stellar population ages, metallicities, IMF slopes, abundance ratios, and “IMF-mismatch” parameters (α_k). The latter is a common measure that relates the constrained (M/L) in the K band to the (M/L) measured from the models assuming an MW-like IMF. This parameter is described in more detail in Section 4.4. The “best-fit” values are defined as the median (50th percentile level) of the posterior distributions, and the 16th and 84th percentile levels are given as the uncertainties in the median. Table 6 provides the best-fit results for both the extended and base set of model parameters and demonstrates that the exclusion of the individual abundance ratios has a significant effect on the measured IMF slopes in M85. This discrepancy is further discussed in Section 5.2.

Figures 7 and 8 show the posterior distribution plots (diagonals) and covariance plots (contours) for the extended set of model parameters derived from the observed M85 and M87 spectral features, respectively. The two IMF slopes, x_1 and x_2, have very broad distributions in both figures, indicating that it is difficult to constrain the exact power-law shape of the IMF with our data. These broad distributions may also be due to the high degree of covariance between the individual IMF slopes, which results in an unusual best-fit IMF functional form in M85, x_1 = 1.98^{±0.92}_{−0.97} and x_2 = 1.47^{±0.98}_{−0.69}, where the IMF slope is shallower in the range of 0.5 ≤ M/M_⊙ < 1.0 than below 0.5 M/M_⊙. The best-fit IMF slopes in M87, x_1 = 2.74^{±0.54}_{−0.10} and x_2 = 2.70^{±0.59}_{−1.01}, are consistent with a super-Salpeter IMF. Despite the broad distributions of the IMF slopes, we find contrasting IMFs in M85 and M87, with the former favoring a more MW-like IMF and the latter more bottom-heavy IMFs.

We measure best-fit ages for M85 and M87 of 3.65^{±1.25}_{−0.72} and 11.59^{±1.40}_{−2.39} Gyr, respectively. The measured ages agree with previous measurements of 3.84 ± 0.78 and 17.7 ± 2.04 Gyr for M85 and M87 in McDermid et al. (2015). McDermid et al. (2015) argued that their unphysical age measurement for M87 is consistent with the fiducial age of the universe, i.e., ≥13.798 ± 0.037 Gyr (Planck Collaboration et al. 2014), when measurement and systematic uncertainties are taken into account. Furthermore, we note that the stellar population age distribution in Figure 8 peaks at the maximum age supplied in the C18 models (13.5 Gyr), which suggests that the stellar age is older than the median age. Including the Pa β line in the MCMC model analysis has a dramatic effect on the measured best-fit ages. This effect is discussed in more detail in Section 5.1.

The best-fit metallicities ([Z/H]) are 0.17^{±0.02}_{−0.04} and 0.02^{±0.12}_{−0.16} dex for M85 and M87, respectively. For M85, the measured metallicity is close to the recent measurement of [Z/H] ~ 0.32 in the galactic core (Ko et al. 2018). Similar to the measured age of M87, the metallicity posterior distribution for M85 peaks strongly at the C18 model maximum of [Z/H] = 0.2 dex, which suggests that the metallicity is greater than the median value. The measured metallicity in M87 is consistent with the previous measurement within R_e/8 from McDermid et al. (2015).

In addition to the IMF slopes, stellar population age, and metallicity, we measure four abundance ratios, [Na/H], [Fe/H], [Ca/H], and [K/H], in M85 and M87. We find evidence for a very high [Na/H] = 0.67^{±0.13}_{−0.13} dex and a reduced [Ca/H] of −0.13^{±0.19}_{−0.15} dex in M85. In addition, we measure [Fe/H] = −0.03^{±0.10}_{−0.04} and [K/H] = 0.09^{±0.21}_{−0.22} dex, which are consistent with solar metallicity. We note that the measured [Ca/H] and [Fe/H] are primarily constrained by a single absorption feature. Their best-fit values are therefore susceptible to degeneracies with other stellar population parameters (e.g., age and IMF slopes). The observed M87 spectrum is unable to provide strong constraints on the individual abundance ratios; however, including the abundance ratios does not have a significant effect on the best-fit base parameters in M87.

### Table 6

| Galaxy     | Age (Gyr) | [Z/H] | x_1    | x_2    | [Na/H] | [Fe/H] | [Ca/H] | [K/H] | α_k   |
|------------|-----------|-------|--------|--------|--------|--------|--------|--------|-------|
| M85 (extended) | 3.65^{±1.25}_{−0.72} | 0.17^{±0.02}_{−0.04} | 1.98^{±0.92}_{−0.97} | 1.47^{±0.98}_{−0.69} | 0.67^{±1.11}_{−0.13} | −0.03^{±0.10}_{−0.15} | −0.13^{±0.19}_{−0.15} | 0.09^{±0.21}_{−0.22} | 1.26^{±0.31}_{−0.46} |
| M85 (base)  | 3.25^{±0.94}_{−0.51} | 0.16^{±0.03}_{−0.51} | 2.72^{±0.67}_{−0.67} | 2.93^{±0.42}_{−0.69} | Fixed to [Z/H] | 3.1^{±1.49}_{−0.20} |
| M87 (extended) | 11.59^{±2.39}_{−0.51} | 0.02^{±0.12}_{−0.16} | 2.74^{±1.04}_{−1.10} | 2.70^{±0.59}_{−1.01} | 0.34^{±0.37}_{−0.50} | −0.19^{±0.22}_{−0.50} | −0.24^{±0.34}_{−0.50} | 0.05^{±0.31}_{−0.35} | 2.77^{±0.49}_{−2.09} |
| M87 (base)  | 11.60^{±2.39}_{−0.51} | −0.03^{±0.14}_{−0.14} | 2.83^{±1.02}_{−1.02} | 2.75^{±1.01}_{−1.01} | Fixed to [Z/H] | 3.0^{±2.05}_{−1.61} |

Note.

* Best-fit IMF-mismatch parameter; see Section 4.4.
The addition of the Na I 1.27 μm feature does not significantly affect the constrained Na abundance in either galaxy (see Section 5.2). If the Na abundance is instead constrained with the Na I 1.27 μm feature exclusively (i.e., without the Na I 1.14 μm feature), the best-fit stellar population parameters, including [Na/H], remain unaffected. The consistency between the Na abundances constrained with either Na I feature supports the conclusion that the stellar population in the core of M85 has a significantly enhanced Na abundance.

4.4. IMF-mismatch Parameter

The individual IMF slopes, $x_1$ and $x_2$, show a high degree of correlation regardless of the set of features included in our spectral model fitting. This can be seen in Figures 7 and 8 in the consistently broad distributions for the IMF slopes. To better
quantify the IMFs of M85 and M87, we calculate the IMF-mismatch parameter \( \alpha_K \), defined as

\[
\alpha_K = \frac{(M/L)_K}{(M/L)_{K,MW}},
\]

where \((M/L)_K\) is a mass-to-light ratio measured in the \(K\) band, i.e., 2.03–2.37 \(\mu\)m, and \((M/L)_{K,MW}\) is the \(K\)-band mass-to-light ratio assuming an underlying MW-like IMF. Note that a Kroupa IMF is adopted for the MW-like IMF here. The \((M/L)\) values are corrected for the remaining stellar mass at the best-fit age, including remnants, following the MIST isochrones (Choi et al. 2016).

The IMF-mismatch parameter is a common measure used to describe the “bottom-heaviness” of IMFs derived from integrated stellar populations (e.g., La Barbera et al. 2016; van Dokkum et al. 2016; Sarzi et al. 2017). Here \(\alpha_K = 1.0\) is representative of an MW-like IMF, while \(\alpha_K \sim 1.8\) is equivalent to a Salpeter IMF due to the presence of a higher percentage of low-mass stars that do not contribute significantly to the measured luminosity. For IMFs steeper than
Kroupa IMF. are clearly contrasting, with M85 favoring a Kroupa IMF and M87 a super-Salpeter ages. Here we discuss some effects resulting from in the MCMC analysis had a dramatic effect on the constrained Ko et al. (2018) feature from the MCMC simulation of the M85 spectra The IMF-mismatch parameter \( \alpha_K \) calculated from models constructed with the best-fit IMF slopes, which was expected due to the low IMF sensitivity of these features outlined in Section 4.1.

Figure 9 shows distributions of \( \alpha_K \) for both galaxies calculated from models constructed with the best-fit ages and metallicities (Table 6) and the posterior distributions of the two IMF slopes. The medians of the \( \alpha_K \) distributions for M85 and M87 are marked with green and blue dashed lines, respectively. The median \( \alpha_K \) values are presented in Table 6 for each set of stellar population parameters. We find median \( \alpha_K \) values of 1.26 \( ^{+0.41}_{-0.46} \) and 2.77 \( ^{+1.09}_{-1.49} \) with the best-fit stellar population parameters in Table 6 for M85 and M87, respectively, indicating that the underlying IMFs are likely similar to a Kroupa and super-Salpeter IMF in those galaxies.

5. Discussion

5.1. Effect of the Stellar Age on the Measured Parameters

In Section 4.3, we noted that the addition of the Pa \( \beta \) feature in the MCMC analysis had a dramatic effect on the constrained stellar ages. Here we discuss some effects resulting from constraining the model parameters without the Pa \( \beta \) and Na I 1.27 \( \mu m \) features described in Section 4.1. Removing the Pa \( \beta \) feature from the MCMC simulation of the M85 spectra significantly increased the median age from 3.65 \( ^{+1.25}_{-0.72} \) to 7.88 \( ^{+2.46}_{-3.44} \) Gyr. In contrast to the former, a stellar age of 7.88 \( ^{+2.46}_{-3.44} \) Gyr is inconsistent with recent measurements of the stellar age in the core of M85 from McDermid et al. (2015) and Ko et al. (2018). For M87, the median stellar age increased from 10.23 \( ^{+2.36}_{-3.44} \) to 11.59 \( ^{+1.40}_{-2.39} \) Gyr. This small adjustment was likely a consequence of the stellar age posterior distribution peaking at the maximum 13.5 Gyr regardless of the inclusion of the Pa \( \beta \) feature.

Another important effect of excluding the Pa \( \beta \) and Na I 1.27 \( \mu m \) features from the MCMC simulations was a significant decrease in the best-fit metallicity for M85. The decrease in the best-fit [Z/H] in M85, from [Z/H] = 0.17 \( ^{+0.07}_{-0.04} \) in Table 6 to [Z/H] = 0.08 \( ^{+0.07}_{-0.12} \) without the additional features, was likely a consequence of the formerly more tightly constrained, younger stellar population age. Younger stellar populations are dominated by hotter stars that have intrinsically weaker absorption lines, thereby requiring a higher metallicity to account for the same feature strengths. As mentioned in Section 4.3, the best-fit [Z/H] measured with the additional features was closer to the recent measurement of [Z/H] \( \sim 0.32 \) dex in the nucleus of M85 (Ko et al. 2018).

We find that the best-fit [Z/H] = 0.06 \( ^{+0.10}_{-0.16} \) derived for M87 without the two additional features was increased by approximately 0.04 dex relative to the [Z/H] in Table 6. This slight increase was likely also a consequence of the tighter constraints on the stellar population age \( \sim 11.59 \pm 1.00 \) Gyr in M87, as an older stellar population reduces the best-fit metallicity given constant index strengths.

Excluding the Pa \( \beta \) and Na I 1.27 \( \mu m \) features from the MCMC simulations did not result in a significant change in the best-fit IMF slopes.

5.2. Impact of Elemental Abundances on the IMF

In Table 6, we presented the best-fit stellar population parameters for M85 and M87 when including (extended) and excluding (base set) the elemental abundances from the MCMC simulations. There was a significant discrepancy between the best-fit IMF slopes for M85 when constrained by the base and extended sets of model parameters. The former is best fit by a very bottom-heavy IMF, while the latter is best fit by a more MW-like IMF. We investigated two possible origins for this inconsistency: the exclusion of individual abundance ratios, i.e., [Fe/H], [Na/H], [Ca/H], and [K/H], from the MCMC model parameters and the removal of individual features (Table 2) from the fitting procedure. When the individual elemental abundances are excluded, their values are fixed to the metallicity ([Z/H]), which does not account for the large deviations of certain elemental abundances, such as the high best-fit [Na/H] in M85. Fixing the abundance ratios to [Z/H] may result in the inconsistency between the IMF slopes when derived with or without the elemental abundance ratios.

Further MCMC simulations that excluded each of the four line abundance ratios from the model parameters and/or individual IMF-sensitive features from the fitting procedure were therefore conducted to investigate this inconsistency.

Excluding [Ca/H] and [K/H] from the model parameters did not result in any meaningful differences in the resulting best-fit IMF slopes. In addition, excluding [Fe/H] resulted in only slightly shallower best-fit IMF slopes in M85. Individually excluding the FeH, Ca I, K I, and Al I features from the fitting procedure also had no effect on the best-fit IMF slopes.

The best-fit IMF slopes for M85 were significantly steepened when [Na/H] was excluded from the model parameters (i.e., fixing [Na/H] to [Z/H]). In this case, the best-fit [Fe/H] was dramatically reduced in order to fit the strong Na I 1.14 \( \mu m \) feature, as this feature strengthens for lower Fe abundances (see Section 3.3.3). If [Fe/H] was excluded in addition to [Na/H], the resulting IMF became bottom-heavy, similar to the IMF derived with the base set of model parameters for M85 in Table 6. Furthermore, excluding both [Na/H] and the Na I 1.14 \( \mu m \) feature from the fitting procedure did not impact the
derived IMF slopes. In summary, we found that including [Na/H] in our model parameters was critical to the interpretation of the strong Na I 1.14 μm feature in the observed M85 spectrum.

The best-fit IMF slopes for M87 did not exhibit the same sensitivity to the Na abundance and the Na I 1.14 μm feature. This was likely a result of both the lower overall S/N in the M87 spectrum and the weaker influence of abundance variations on the spectra of high-σ galaxies.

We note here that the strength of the Na I 1.14 μm feature is known to be difficult to accurately predict with current stellar population models. According to Smith et al. (2015), the strength of this feature was often underestimated despite a strong overall fit to the rest of their observed spectra. We obtained consistent results, however, when [Na/H] was constrained by either or both of the Na I 1.14 and 1.27 μm features (see Section 4.3). This consistency, along with the assertion in Smith et al. (2015) that the Na I 1.27 μm feature is only visible at high [Na/H], increased our confidence in the high [Na/H] reported in Table 6 for M85.

5.3. M87 AGN Correction

It is known that M87 has a strong, central AGN that contaminates the observed spectral continuum (see Section 2.2). The K I 1.25 μm line was excluded from our analysis of the stellar population properties in M87 due to an [Fe II] emission line from this AGN. We considered two possible effects of accounting for the M87 AGN on the best-fit IMF slopes: excluding the K I 1.25 μm feature in our analysis of M85 and correcting the M87 spectrum for estimated AGN continuum emission. For the former, we repeated the MCMC analysis of M85 and correcting the M87 spectrum for estimated AGN IMF slopes: excluding the K I 1.25 μm feature in our analysis of M85 may be a result of this metallicity-dependent Na yield.

To measure the effect of removing the AGN continuum, we repeated our analysis of M87 after subtracting a percentage of the linear continuum defined for each spectral feature in Table 2. We adopted the estimation from ASL17 that the AGN in M87 contributes approximately 15% of the observed continuum level within the central 3″. As expected, this correction resulted in a steepening of the best-fit IMF slopes in M87 from a Salpeter-like (X ∼ 2.3) to a bottom-heavy (X ∼ 3.0) IMF. This did not affect our overall conclusion that the best-fit IMF in M87 is consistent with a Salpeter or steeper IMF.

5.4. Comparison to Previous IMF Results

The results presented in Section 4 represent the first measurement of contrasting IMFs in extragalactic stellar populations with this set of NIR, IMF-sensitive absorption features. In general, the best-fit IMFs for M85 and M87 presented in this paper are consistent with previous measurements of the IMFs in those galaxies. This is important, as it shows that constraints on the IMF are robust against the specific set of IMF-sensitive features or spectral bandpass. The work in this paper also provides a method for investigating the IMF of stellar populations with NIR spectroscopy. In this section, we compare our results to previous measurements of stellar population parameters in M85 and M87, e.g., vDC12 and Cappellari et al. (2013).

The IMF slopes obtained for both of the galaxies are generally consistent with the IMFs derived from long-slit spectroscopy in the visible bands in CvD12b and galactic kinematics in Cappellari et al. (2013). In M85, CvD12b measured a “bottom-light” IMF with αK = 0.63, which is shallower than the MW-like αK = 1.26±0.06 reported in Table 6. We note, however, that the αK distribution for M85 in Figure 9 peaks strongly at the lowest αK, suggesting that the αK for M85 is lower than the median. In M87, CvD12b found a super-Salpeter IMF with αK = 1.90 that is similar to our median αK = 2.77±0.09. Cappellari et al. (2013) measured the IMFs in M85 and M87 to be slightly steeper than a Kroupa IMF and slightly shallower than a Salpeter IMF, respectively, which is qualitatively consistent with our measurements.

Our measurement of a super-Salpeter IMF in the center of M87 is similar to the results of Sarzi et al. (2017) and Oldham & Auger (2018). Using spectroscopy in the visible bands, Sarzi et al. (2017) measured an IMF slope of approximately 2.9 in the core of M87, which is consistent with both IMF slopes for M87 in Table 6 of ∼2.7. Oldham & Auger (2018) inferred a single power-law slope below 1.0 M⊙ of approximately 2.5 in the core of M87 with a sophisticated dynamical model constructed from observations of M87 satellites.

A novel result of this paper is the measurement of four abundance ratios in M85, [Na/H], [Fe/H], [Ca/H], and [K/H], of which only [Fe/H] has prior reported measurements. In M85, vDC12 measured [Fe/H] = −0.02 dex, which is consistent with our [Fe/H] measurement of −0.03±0.10 dex in Table 6.

We measured an exceptionally enhanced [Na/H] = 0.67±0.13 dex in M85, which is typical of the cores of old, massive ETGs (Spinelli et al. 2012). However, M85 is known to have a young, counterrotating, kinematically decoupled core within the central 1″ that may have formed from a recent wet galaxy merger (Terlevich & Forbes 2002; Mcdermid et al. 2004). This burst of star formation in the core of M85 may be the cause of the enhanced Na abundance. The Na is injected into the interstellar medium (ISM) by both the stellar winds of massive stars and Type II supernovae, the latter having a strong, metallicity-dependent yield. Assuming that our best-fit [Z/H] = 0.09 dex is accurate, the high Na abundance in M85 may be a result of this metallicity-dependent Na yield (Kobayashi et al. 2006). The Na-enriched gas ejected into the ISM from recently formed massive stars may be accreted onto existing or still-forming stars, due to the high stellar density in the core of M85 (McConnell et al. 2016).

Furthermore, we measured a strong A11 1.31 μm index in M85. Both AI and Na are produced in a similar fashion during the carbon-burning phase of massive stars (Lecureur et al. 2007). AI exhibits the same strong metallicity-dependent yield in Type II supernovae as Na. It is therefore possible that both the strong [Na/H] and the high A11 index strength are a consequence of the recent star formation in M85.

The Na is also produced as a product of hot bottom burning in intermediate-mass (3–8 M⊙) AGB stars (Vaughan et al. 2018). There is evidence that the Na yield from this process also increases with metallicity (Ventura et al. 2013). At ∼3.5 Gyr, these stars have already enriched the ISM and may have further contributed to the high [Na/H] measured in M85.

Due to the lower S/N of the M87 spectra, we are not able to place strong constraints on the individual abundance ratios; however, we note that the best-fit [Na/H] = 0.34±0.37 dex for M87 (Table 6) is marginally consistent with recent
measurements of a high \([\text{Na/H}]\) \(\approx -0.7\) dex in the central regions of the galaxy (Sarzi et al. 2017).

A key question is, if the IMF is varying in ETGs as described by the stellar population models, what is the astrophysical driver for this variation? The main parameters proposed as the origin for the observed IMF variation in ETGs are \(\sigma_v\) and metallicity (see Section 1). The IMFs measured in this paper give further support to the observed trend of increasingly bottom-heavy IMFs in ETGs with higher central \(\sigma_v\) (CvD12b). Recently, Parikh et al. (2018) measured correlations of varying degrees between the low-mass \((<0.5\,M_\odot)\) IMF slope and galactic properties such as \(\sigma_v\), \([Z/H]\), \([\text{Na/Fe}]\), galactic radius, and stellar age in a sample of \(\sim 400\) ETGs. Our best-fit \(x_1\) slope for M85 and M87 is consistent with their IMF–\(\sigma_v\) correlation. The Parikh et al. (2018) sample, however, only includes galaxies with \(\sigma_v < 200\,\text{km}\,\text{s}^{-1}\), so the comparison to our measured IMF slopes in M87 is only qualitative. Parikh et al. (2018) also found that the IMFs in galaxies with high \([Z/H]\) and \([\text{Na/Fe}]\) are consistent with a Salpeter IMF, which is only marginally consistent with the \(x_1\) slope measured for M85 in this paper. In particular, they measured a very tight correlation between the IMF slope and \([Z/H]\), which is inconsistent with our IMF slope in M85. A possible explanation for this inconsistency is the lack of galaxies younger than 5 Gyr in the sample studied by Parikh et al. (2018).

The measurements of bottom-heavy IMFs in the core of massive galaxies, as measured for M87 in this paper, and more MW-like IMFs in less massive galaxies like M85 imply that the conditions during the formation of these stellar systems were fundamentally different. The cores of the brightest cluster galaxies, such as M87, were likely formed in massive dark matter potential wells and experienced an exceptionally dense star formation environment (Oldham & Auger 2018). The stellar populations in the cores of these galaxies would therefore be extremely old, as measured for M87 in Table 6. In contrast, M85 is a much less massive galaxy with a younger stellar population, comparable to those in the MW. The stars in the core of M85 likely formed in a significantly different environment than those in the core of M87. Chabrier et al. (2014) examined the physical basis for this type of IMF variation and determined that the compressive turbulent motions found in extreme star formation environments can shift the characteristic mass of the IMF to a lower mass, resulting in a bottom-heavy IMF. This provides a consistent picture for the origin of the observed IMF variation for M85 and M87 in this paper as a function of their contrasting formation histories.

6. Summary and Future Work

In this paper, we have presented a study of the IMFs for two ETGs, M85 and M87, with highly contrasting central velocity dispersions and \([\alpha/\text{Fe}]\) using a set of seven NIR, gravity-sensitive absorption features. This set of features has been relatively unexplored for the purpose of measuring variations in the IMF from the integrated light of extragalactic stellar populations. To that end, we compared the observed spectral regions for these features for both galaxies to stellar population models described in C18.

Our key conclusions are as follows.

1. Our measured feature indices and median \(\alpha_x\) for M85 and M87 are consistent with those found in previous studies using both spectroscopic and kinematic techniques (e.g., Cappellari et al. 2013; Sarzi et al. 2017; vDC12; ASL17).

2. The EW index strengths of the seven IMF-sensitive features give inconsistent constraints for the IMF slopes in both galaxies relative to fiducial models defined with previously measured stellar population ages and metallicities. These inconsistencies between the predicted IMF slopes and the measured index strengths can be reconciled by assuming particular elemental abundance ratios, thereby underlining the necessity of considering abundance variations when investigating the IMF.

3. The best-fit IMF slopes in M85, derived with the MCMC model fitting, are consistent with an MW-like IMF. However, the best-fit \(x_1\) slope is steeper than the \(x_2\) slope, which describes an unusual IMF functional form. This unusual IMF is likely a consequence of the high covariance between the individual IMF slopes. The median IMF-mismatch parameter, \(\alpha_{x}\), allows for a more definitive interpretation of an MW-like IMF in M85.

4. The best-fit IMF slopes in M87 are consistent with a super-Salpeter IMF. The median \(\alpha_{x}\) = 2.77 supports our conclusion that the IMF in M87 is likely between a Salpeter and a bottom-heavy IMF. The MCMC simulations were unable to constrain the individual abundance ratios in M87 due to the lower S/N of the M87 spectrum than the M85 spectrum. If the M87 spectral continuum is corrected for an estimated 15% additional continuum from the central AGN, the best-fit IMF slopes steepen to a bottom-heavy IMF.

5. We find a significantly enhanced Na abundance \(([\text{Na/H}]) \sim 0.65\) dex) in M85. The measured abundance ratio is consistent when constrained with either of the considered Na I features. This high \([\text{Na/H}]\) may be a consequence of both the high metallicity and the recent burst of star formation in the core of M85. We conclude that, due to the high Na abundance, including \([\text{Na/H}]\) in the model parameters is critical to the interpretation of the IMF slopes in M85.

This work adds to the growing body of evidence that the IMFs of ETGs vary as a function of fundamental galactic properties (e.g., \(\sigma_v\), \([\alpha/\text{Fe}]\), \([Z/H]\)) while also illustrating the viability of using NIR IMF-sensitive features as possible tools for investigating IMF variation. We are currently conducting a survey of nearby ETGs and the bulges of spiral galaxies using the recently commissioned Wide Integral Field Infrared Spectrograph (WIFIS; Meyer et al. 2016; Sivanandam et al. 2018). Similar to the NIFS spectrograph used in this work, WIFIS operates in the \(\sim J\) band and will be able to perform a spatially resolved investigation of the IMF slopes out to large radii using this set of IMF-sensitive features. This survey will serve as an NIR companion to integral field IMF variation studies in the visible bands, such as the MANGA (Bundy et al. 2015), CALIFA (Sánchez et al. 2012), and ATLAS3D (Cappellari et al. 2011) surveys. We anticipate that our analysis of the observed galaxies in the WIFIS extragalactic survey will significantly contribute to our broader understanding of IMF variation in nearby extragalactic objects.

We thank C. Conroy and his group for the use of their recent stellar population models in this paper. D.S.M. was supported
in part by a Leading Edge Fund from the Canadian Foundation for Innovation (project No. 30951). Both D.S.M. and S.S. were supported by Discovery Grants from the Natural Sciences and Engineering Research Council of Canada (NSERC). We thank the anonymous referee for helpful comments that improved the paper.

This paper is based on observations obtained at the Gemini Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the NSF on behalf of the Gemini partnership: the National Science Foundation (United States), the National Research Council (Canada), CONICYT (Chile), Ministerio de Ciencia, Tecnología e Innovación Productiva (Argentina), and Ministério da Ciência, Tecnologia e Inovação (Brazil).

The analysis in this publication made extensive use of the PYTHON modules NumPy (Van Der Walt et al. 2011), AstroPy (Astropy Collaboration et al. 2013), SciPy (Jones et al. 2001), and Matplotlib (Hunter 2007).

ORCID iDs

R. Elliot Meyer © https://orcid.org/0000-0002-2083-9941
Suresh Sivanandam © https://orcid.org/0000-0002-0767-8135
Dae-Sik Moon © https://orcid.org/0000-0003-4200-5064

References

Alton, P. D., Smith, R. J., & Lucey, J. R. 2017, MNRAS, 468, 1594
Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, A&A, 558, A33
Baldwin, C., McDermid, R. M., Kuntschner, H., Maraston, C., & Conroy, C. 2018, MNRAS, 473, 4698
Bastian, N., Covey, K. R., & Meyer, M. R. 2010, ARA&A, 48, 339
Bundy, K., Bershady, M., Law, D., et al. 2015, ApJ, 798, 7
Cappellari, M., Emsellem, E., Krajnović, D., et al. 2011, MNRAS, 413, 813
Cappellari, M., McDermid, R. M., Alatalo, K., et al. 2012, Natur, 484, 485
Cappellari, M., McDermid, R. M., Alatalo, K., et al. 2013, MNRAS, 432, 1862
Chabrier, G. 2003, PASP, 115, 763
Chabrier, G., Hennebelle, P., & Charlot, S. 2014, ApJ, 796, 75
Choi, J., Dotter, A., Conroy, C., et al. 2016, ApJ, 823, 102
Collier, W. P., Smith, R. J., & Lucey, J. R. 2018, MNRAS, 478, 1595
Conroy, C., & van Dokkum, P. 2012a, ApJ, 747, 69
Conroy, C., & van Dokkum, P. 2012b, ApJ, 760, 71
Conroy, C., Villaume, A., van Dokkum, P., & Lind, K. 2018, ApJ, 854, 139
Dutton, A. A., Treu, T., Brewer, B. J., et al. 2013, MNRAS, 428, 3183
Emsellem, E., Cappellari, M., Peletier, R. F., et al. 2004, MNRAS, 352, 721
Foreman-Mackey, D., Hogg, D. W., Lang, D., & Goodman, J. 2013, PASP, 125, 306
Hunter, J. D. 2007, CSE, 9, 90
Jones, E., Oliphant, T., Peterson, P., et al. 2001, SciPy: Open Source Scientific Tools for Python. http://www.scipy.org/
Ko, Y., Lee, M. G., Park, H. S., et al. 2018, ApJ, 859, 108
Kobyashi, C., Umeda, H., Nomoto, K., et al. 2006, ApJ, 653, 1145
Krajnović, D., Alatalo, K., Blitz, L., et al. 2013, MNRAS, 432, 1768
Kroupa, P. 2001, MNRAS, 322, 231
La Barbera, F., Ferreras, I., Vazdekis, A., et al. 2013, MNRAS, 433, 3017
La Barbera, F., Ferreras, I., & Vazdekis, A. 2015, MNRAS, 449, L137
La Barbera, F., Ferreras, I., Vazdekis, A., et al. 2016, MNRAS, 457, 1468
 Lagattuta, D. J., Mould, J. R., Forbes, D. A., et al. 2017, ApJ, 846, 116
Lecercue, A., Hill, V., Zoccali, M., et al. 2007, A&A, 465, 799
Li, H., Ge, J., Mao, S., et al. 2018, ApJ, 838, 77
Martin Navarro, I., La Barbera, F., Vazdekis, A., et al. 2015, MNRAS, 447, 1033
Martin Navarro, I., Vazdekis, A., La Barbera, F., et al. 2015, ApJL, 806, L31
McConnell, N. J., Lu, J. R., & Mann, A. W. 2016, ApJ, 821, 39
McDermid, R., Emsellem, E., Cappellari, M., et al. 2004, AN, 325, 100
McDermid, R. M., Alatalo, K., Blitz, L., et al. 2015, MNRAS, 448, 3484
McGregor, P. J., Hart, J., Conroy, P. G., et al. 2003, Proc. SPIE, 4841, 1581
Meyer, R. E., Moon, D.-S., Sivanandam, S., et al. 2016, Proc. SPIE, 9908, 99080Q
Oldham, L., & Auger, M. 2018, MNRAS, 474, 4169
Parikh, T., Thomas, D., Maraston, C., Westfall, K. B., et al. 2018, MNRAS, 477, 3954
Planck Collaboration, Ade, P. A. R., Aghanim, N., et al. 2014, A&A, 571, A16
Rajpurohit, A. S., Reyel, C., Allard, F., et al. 2013, A&A, 2013, A15
Salpeter, E. E. 1955, ApJ, 121, 161
Sánchez, S. F., Kennicutt, R. C., Gil de Paz, A., et al. 2012, A&A, 538, A8
Sarzi, M., Spiniello, C., La Barbera, F., et al. 2017, MNRAS, 478, 4084
Sivanandam, S., Moon, D.-S., Elliot Meyer, R., et al. 2018, Proc. SPIE, 10702, 1070218
Smith, R. J. 2014, MNRAS, 443, L69
Smith, R. J., Alton, P., Lucey, J., et al. 2015, MNRAS, 454, L71
Smith, R. J., & Lucey, J. R. 2013, MNRAS, 434, 1964
Smith, R. J., Lucey, J. R., & Carter, D. 2012, MNRAS, 426, 2994
Smith, R. J., Lucey, J. R., & Conroy, C. 2015, MNRAS, 449, 3441
Smith, R. J., Lucey, J. R., Hudson, M. J., Schlegel, D. J., & Davies, R. L. 2000, MNRAS, 313, 469
Spiniello, C., Trager, S. C., Koopmans, L. V. E., et al. 2012, ApJL, 753, L32
Terlevich, A. I., & Forbes, D. A. 2002, MNRAS, 330, 547
Trager, S. C., Worthey, G., Faber, S. M., et al. 1998, ApJS, 116, 1
Treu, T., Auger, M. W., Koopmans, L. V. E., et al. 2010, ApJ, 709, 1195
Vacca, W., Cushing, M., & Rayner, J. 2003, PASP, 115, 389
Van Der Walt, S., Colbert, S. C., & Varoquaux, G. 2011, CSE, 13, 22
van Dokkum, P., & Conroy, C. 2010, Natur, 468, 940
van Dokkum, P., & Conroy, C. 2012, ApJ, 760, 70
van Dokkum, P., Conroy, C., Villaume, A., et al. 2016, ApJ, 841, 68
Vaughan, S. P., Davies, R. L., Zienleniewski, S., & Houghton, R. C. W. 2018, MNRAS, 479, 2443
Ventura, P., Di Criscienzo, M., Carini, R., et al. 2013, MNRAS, 431, 3642
Villause, A., Brodie, J., Conroy, C., et al. 2017, ApJL, 850, L14
Zienleniewski, S., Houghton, R. C. W., Thatte, N., et al. 2016, MNRAS, 465, 192