RADIAL TRENDS IN IMF-SENSITIVE ABSORPTION FEATURES IN TWO EARLY-TYPE GALAXIES: EVIDENCE FOR ABUNDANCE-DRIVEN GRADIENTS

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ABSTRACT

Samples of early-type galaxies show a correlation between stellar velocity dispersion and the stellar initial mass function (IMF) as inferred from gravity-sensitive absorption lines in the galaxies’ central regions. To search for spatial variations in the IMF, we have observed two early-type galaxies with Keck/LRIS and measured radial gradients in the strengths of absorption features from 4000–5500 Å and 8000–10000 Å. We present spatially resolved measurements of the dwarf-sensitive spectral indices Na i (8190 Å) and Wing-Ford FeH (9915 Å), as well as indices for species of H, C2, CN, Mg, Ca, TiO, and Fe. Our measurements show a metallicity gradient in both objects, and Mg/Fe consistent with a shallow gradient in α-enhancement, matching widely observed trends for massive early-type galaxies. The Na i index and the CN1 index at 4160 Å exhibit significantly steeper gradients, with a break at \( r \approx 0.1 \, r_{\text{eff}} \) (\( r \approx 300 \, \text{pc} \)). Inside this radius, Na i strength increases sharply toward the galaxy center, consistent with a rapid central rise in [Na/Fe]. In contrast, the ratio of the FeH to Fe index strength decreases toward the galaxy center. This behavior cannot be reproduced by a steepening IMF inside of 0.1 \( r_{\text{eff}} \) if the IMF is a single power law. While gradients in the mass function above \( \sim 0.4 \, M_\odot \) may occur, exceptional care is required to disentangle these IMF variations from the extreme variations in individual element abundances near the galaxies’ centers.

Key words: galaxies: abundances – galaxies: elliptical and lenticular, cD – galaxies: star formation – stars: mass function

Supporting material: data behind figures

1. INTRODUCTION

Driven primarily by observations within our own Galaxy, the assumption of a universal stellar initial mass function (IMF) throughout space and time has been employed in numerous studies of galaxy evolution. The canonical IMFs have the form of a power law at high masses with \( \frac{dn}{dm} \propto m^{-\alpha} \) and \( \alpha = 2.3 \) above \( m > 0.5 \, M_\odot \) (Kroupa 2001) or \( m > 1 \, M_\odot \) (Chabrier 2003). These IMFs then flatten and turn over with a decreasing number of stars at masses below 0.5–1 \( M_\odot \). In an extragalactic context, key observables are influenced by the universal-IMF assumption, such as the galaxy mass function, mass–metallicity relation, and the correlation between total star formation rate and galaxy mass (e.g., Noeske et al. 2007; Wyys et al. 2011; Leauthaud et al. 2012; Smit et al. 2012; Behroozi et al. 2013; Zahid et al. 2014; Salmon et al. 2015). Spectral energy density fitting is the most prevalent method for determining the stellar masses of intermediate- and high-redshift galaxies, and requires an assumed form of the IMF (e.g., Conroy et al. 2009; Marchesini et al. 2009). Consequently, claims of IMF variations deserve intense scrutiny (Bastian et al. 2010; Krumholz 2014) since any systemic IMF variation has broad implications for the inferred properties of galaxies and galaxy evolution.

In the past five years, numerous studies have asserted that early-type galaxies with the largest velocity dispersions (σ) reveal a bottom-heavy IMF in their old stellar populations: an overabundance of stars with \( m < 1 \, M_\odot \) relative to the canonical IMFs of Kroupa (2001) or Chabrier (2003). Methodologies used to assess the IMF in these galaxies have included (1) examinations of stellar absorption features dominated by either giant or dwarf stars (e.g., Cenarro et al. 2003; van Dokkum & Conroy 2010, 2012; Conroy & van Dokkum 2012b; Ferreras et al. 2013; La Barbera et al. 2013; Spiniello et al. 2014), (2) comparisons of mass-to-light ratios from stellar population synthesis (SPS) and stellar dynamics (e.g., Cappellari et al. 2012, 2013; Dutton et al. 2013; McDermid et al. 2014), (3) and comparisons between SPS and gravitational lensing (e.g., Treu et al. 2010; Spiniello et al. 2011, 2012, 2015a; Barnabè et al. 2013; Posacki et al. 2015). Results with the most divergent IMFs show that the inferred slope of the IMF above 0.1 \( M_\odot \) steepens to \( \alpha \sim 3 \) for the most massive early-type galaxies (e.g., La Barbera et al. 2013). Other studies have found a deviation between the average IMF in early-type galaxy samples and the canonical IMF, without verifying a differential trend between different early-type galaxies (e.g., Auger et al. 2010; Dutton et al. 2012; Smith et al. 2012; Smith & Lucey 2013). Alternatively, a few investigations have identified massive early-type galaxies with an IMF similar to the Milky Way (e.g., Smith & Lucey 2013; Smith et al. 2015b). Using a different approach, Peacock et al. (2014) examined eight nearby galaxies for emission from X-ray binaries, and found that the fraction of massive stellar remnants across their sample was consistent with a uniform IMF slope above 8 \( M_\odot \). Thus, it is still debated whether the IMF varies, how much the functional form changes, and how these variations depend on galaxy properties.

A limitation of the majority of IMF investigations in early-type galaxies is the use of a single spatial aperture per galaxy. For instance, stacked spectra from the Sloan Digital Sky Survey (SDSS) have a fixed radius on the sky, blending data from less than and greater than one galaxy effective radius, \( r_{\text{eff}} \).
from different galaxies (e.g., Ferreras et al. 2013; La Barbera et al. 2013; Spiniello et al. 2014). In contrast, the absorption-line studies by van Dokkum & Conroy (2012) and Conroy & van Dokkum (2012b) focus on the innermost regions of nearby galaxies, with a long-slit aperture of $r_{\text{eff}}/8$. For lensing studies, the Einstein radius matches a different physical radius in each galaxy, typically between $\sim 0.3$ $r_{\text{eff}}$ and $\sim 1$ $r_{\text{eff}}$ (e.g., Koopmans et al. 2009; Smith et al. 2015b). Cappellari et al. (2012, 2013) and McDermid et al. (2014) use resolved two-dimensional stellar kinematics, extending to $1$ $r_{\text{eff}}$ for many of the galaxies in their ATLAS$^{3D}$ sample. However, the most massive galaxies in ATLAS$^{3D}$ are not covered out to $1$ $r_{\text{eff}}$. At best, studies with different spatial footprints offer leverage for interpreting the role of IMF gradients within individual galaxies, although there are numerous complications from synthesizing heterogeneous and sometimes contradictory results. At worst, these studies all fail to distinguish between an IMF that varies only from galaxy to galaxy and IMF gradients within single galaxies.

Theoretical motivation for the presence of IMF gradients within early-type galaxies comes from models of inside-out growth, wherein massive galaxies are built first as compact starbursts and then accrete numerous smaller systems at large radii (e.g., Naab et al. 2009, 2014; Hopkins et al. 2010; Oser et al. 2012; Shankar et al. 2013). This model coincides with observations of size growth in massive red galaxies from redshifts of $\sim 2$ to the present (e.g., Trujillo et al. 2006; van Dokkum et al. 2010; Patel et al. 2013; van der Wel et al. 2014; Vulcani et al. 2014) and with the metal-poor stellar halos of nearby early-type galaxies (e.g., Coccato et al. 2010; Greene et al. 2012, 2015; Pastorello et al. 2014). If the IMF differs between low- and high-$\sigma$ galaxies, then the most massive (and highest $\sigma$) early-type galaxies should naturally exhibit IMF gradients because their outer regions have been assembled from smaller systems.

A second challenge for IMF investigations in early-type galaxies is the competing influence of elemental abundance ratios, which can drastically reshape stellar absorption features and subtly alter the mass-to-light ratio of stars. Some SPS models can vary the abundances of individual elements (e.g., Graves & Schiavon 2008; Conroy & van Dokkum 2012a). However, the impacts of these abundance variations are woefully entangled with one another, and with the effects of IMF variations and other systematics such as isochrone offsets in temperature-luminosity space (Graves & Schiavon 2008; Conroy & van Dokkum 2012a; Spiniello et al. 2015b). These same models have identified stellar absorption features that are especially sensitive to IMF variations, and targeted analyses of those features in observed galaxy spectra claim sufficient leverage to detect IMF variations robustly (e.g., Conroy & van Dokkum 2012b; La Barbera et al. 2013; Spiniello et al. 2014). However, abundance ratios are known to vary within individual galaxies (e.g., Strom et al. 1976; Tamura et al. 2000; Weijmans et al. 2009; Kuntschner et al. 2010; Greene et al. 2012, 2013, 2015), and the few investigations of IMF gradients in individual systems have offered scant analyses of single-element abundance variations (Martin-Navarro et al. 2015a, 2015b, 2015c).

Herein, we examine two early-type galaxies, NGC 1023 and NGC 2974, for IMF and abundance gradients. For each object, we use long-slit spectra to probe spatial scales from $\sim 100$ pc to a few kiloparsecs ($0.03 r_{\text{eff}}$ to $\sim 1$ $r_{\text{eff}}$). We present gradients in a selected set of stellar absorption-line indices and qualitatively interpret their connection to stellar population studies. We have paid special attention to the sodium doublet at 8190 Å (hereafter Na i) and the Wing-Ford iron hydride feature at 9915 Å (hereafter FeH), both of which are sensitive to the number density of cool dwarf stars. Our spectra also cover the giant-sensitive calcium triplet at 8500 Å (hereafter Ca ii), temperature-sensitive TiO features, numerous features of individual atomic species, and several Balmer lines.

Recently, Martin-Navarro et al. (2015a, 2015b) analyzed long-slit spectra of four nearby early-type galaxies and reported IMF gradients in two ellipticals with large central $\sigma$ ($270–300$ km s$^{-1}$) and a mild gradient in the compact, high-$\sigma$ galaxy NGC 1277. They inferred a uniform IMF slope in an elliptical galaxy with $\sigma \approx 100$ km s$^{-1}$. The two objects presented herein have central $\sigma \approx 210–250$ km s$^{-1}$, and our set of IMF-sensitive spectral indices has little overlap with those analyzed by Martin-Navarro et al. (2015a, 2015b). Although our spectral coverage excludes the TiO and TiO$_2$ features at 5960 and 6230 Å, we perform a much more rigorous analysis of Na i and we are among the first to present spatially resolved measurements of FeH.

We summarize the basic properties of NGC 1023 and NGC 2974 in Table 1. NGC 1023 is an SB0 galaxy, and NGC 2974 is an E4, as classified by the NASA/IPAC Extragalactic Database. Both galaxies are fast rotators (Emsellem et al. 2011). We selected both objects from the sample of van Dokkum & Conroy (2012), who observed the central $r_{\text{eff}}/8$ of $34$ early-type galaxies with identical spectral coverage to our investigation. Based on full-spectrum fitting to stellar population models, Conroy & van Dokkum (2012b) measured a stellar mass-to-light ratio, $\Upsilon_K$, of 1.53$\Upsilon_{K,\text{MW}}$ in NGC 1023, and 1.45$\Upsilon_{K,\text{MW}}$ in NGC 2974, where $\Upsilon_{K,\text{MW}}$ is the stellar mass-to-light ratio of the Milky Way disk. They infer that the central IMF in both galaxies is consistent with a Salpeter (1955) power law.

| Galaxy | $D$ (Mpc) | $M_K$ | $r_{\text{eff}}$ ($''$) | $\sigma_0$ (km s$^{-1}$) | $[\text{Fe/H}]_\text{f}$ | $[\text{Mg/Fe}]_\text{f}$ | $[\text{Z/H}]_\text{f}$ | $[\text{\alpha/Fe}]_\text{f}$ | Age, Gyr | Integration time (s) | Slit PA ($^\circ$) |
|--------|-----------|-------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-------|-----------------|-------------|
| NGC 1023 | 11.1 | $-24.01$ | 47.8 | 217 | $-0.01$ | +0.18 | +0.09 | +0.19 | 11.7 | $13 \times 600$ | 85 |
| NGC 2974 | 20.9 | $-23.62$ | 38.0 | 247 | $-0.06$ | +0.20 | +0.11 | +0.29 | 8.9 | $14 \times 600$ | 45 |

Note. We adopt distances, K-band absolute magnitudes, and effective radii (columns 2–4) from the ATLAS$^{3D}$ survey (Cappellari et al. 2011). Central velocity dispersions, $[\text{Fe/H}]$, and $[\text{Mg/Fe}]$ (columns 5–7) are from Conroy & van Dokkum (2012b) and we approximate a circular aperture with radius $r_{\text{eff}}/8$. Central $[\text{Z/H}]$, $[\text{\alpha/Fe}]$, and stellar ages (columns 8–10) are from Kuntschner et al. (2010), summing SAURON integral-field data over a circular aperture of $r_{\text{eff}}/8$. Using the new data herein and stellar population models from Conroy & van Dokkum (2012a), we estimate that both galaxies are $>10$ Gyr old at all radii.
law ($\alpha = 2.35$) extending down to 0.1 $M_\odot$ and is significantly more bottom-heavy than the Kroupa or Chabrier forms.

This paper is organized as follows. We summarize our long-slit observations in Section 2 and our data reduction methods in Section 3. In Section 4, we describe how absorption-line indices are determined from our spectra, including random and systematic errors. We present radial trends for 13 selected line indices in Section 5. In Section 7, we offer a qualitative interpretation of the underlying stellar population trends in NGC 1023 and NGC 2974, with rigorous stellar population modeling deferred for future work. Our conclusions are briefly summarized in Section 8. Our two appendices contain detailed examinations of systematic errors in line index measurements, with particular focus on the Na I feature.

2. OBSERVATIONS

We observed NGC 1023 and NGC 2974 in 2013 December using LRIS on the Keck I telescope (Oke et al. 1995; Rockosi et al. 2010), in long-slit mode. LRIS comprises a red arm and a blue arm. For the red side, we used the 600 line mm$^{-1}$ grating spanning 7500–10800 Å, sampled at $\approx 0.79$ Å per pixel. For the blue side, we used the 600 line mm$^{-1}$ grism spanning 3100–5560 Å, sampled at $\approx 0.62$ Å per pixel. For this instrumental setup, we measured a spectral resolution of $\approx 3.0$ Å full width at half-maximum (FWHM) for both the blue arm and the red arm. Our slit was 0"7 wide and spanned a length of 175". The LRIS field of view is sampled by two detectors on each spectrograph arm, resulting in a coverage gap near the center of the slit. For the data presented herein, the gap spans 35" on the red side and 14" on the blue side. On the LRIS detectors, we employed a pixel scale of 0"135 in the spatial direction. Seeing on the night of observations was between 1"70 and 1"5 FWHM.

We placed our slit along the major axis of each galaxy with the galaxy center slightly offset from the chip gap. For a single exposure our spatial coverage extended from $\approx 60"$ on one side of the galaxy to $\approx 115"$ on the opposite side. Images were dithered between two positions that straddled the gap to achieve symmetric coverage of each galaxy. Additionally, a sky field of 4" away was observed after every two to four science exposures. Total integration times for each target are included in Table 1. We completed more than two hours of integration time on each galaxy in order to obtain signal-to-noise ratios (S/N) $\sim 100$ per pixelin spatial bins near $r_{\text{eff}}$. The final spectra for NGC 1023 meet this criterion out to 1.6 $r_{\text{eff}}$, for all features except the faint FeH band near 1 $\mu$m. For NGC 2974, the outermost bin with sufficient S/N spans 0.5–0.8 $r_{\text{eff}}$.

Although our instrument setup matched that of van Dokkum & Conroy (2012), our observing pattern was selected to maximize spatial coverage and measure gradients in absorption-line depths. In contrast, observations by van Dokkum & Conroy (2012) aligned the slit along the minor axis of each galaxy and used the far edges for in-frame sky subtraction. As a result, their previous analysis was restricted to the central few arcseconds of each galaxy, corresponding to an aperture of $r_{\text{eff}}/8$.

3. DATA PROCESSING AND ANALYSIS

Our data reduction procedures largely follow the template described in van Dokkum & Conroy (2012). The notable exception is sky subtraction. Whereas van Dokkum & Conroy (2012) aligned the slit with the minor axis of each galaxy and used the far edges of the slit for sky subtraction, we wish to extract spectral features over the entire slit. To this end, we recorded separate, non-concurrent sky exposures. On the red side, our sky subtraction requires careful wavelength calibration for each science frame, and a scaled subtraction procedure that adjusts the relative strengths of telluric emission-line families, which vary on timescales of a few minutes. Details of these various calibration steps are described below, and representative cleaned spectra are illustrated in Figures 1 and 2.

3.1. Instrumental Calibrations

We use the lpipe software package (D. Perley 2016, private communication) for bias subtraction, flatfield correction, and cosmic-ray cleaning. This package first determines and subtracts bias levels from the overscan region of each frame. Next it performs flatfielding using halogen lamp exposures taken at the end of the observing night, with the slit and disperser in place. The lpipe package coadds individual flatfield exposures, computes a boxcar-smoothed response spectrum for each row of the coadded flatfield, and divides each row by its matching response spectrum to produce a pixel-to-pixel flat. This flatfielding correction retains response variations along the spatial axis of the CCD, which are calibrated during the sky subtraction step (Section 3.2). After flatfielding, we split the raw frames into the separate CCD chips for each arm and process each chip independently.

On the red side, we use telluric OH emission lines to define a wavelength solution for each frame, using the IRAF routines identify, fitcoords, and transform. We divide each frame into blocks of 40 rows ($5''4$) and extract a one-dimensional spectrum for each block. We fit a fifth-order polynomial to the peaks of the OH lines, converting pixels to Å. To calibrate for wavelength variation across each chip, we then fit a two-dimensional polynomial solution to the set of peak locations from all blocks. The 40-row extraction window permits reliable sky line fitting except for one or two blocks near the center of each galaxy; these blocks are masked from the two-dimensional fit.

The blue side includes a faint telluric line from N I at 5199 Å, but is otherwise devoid of telluric emission features. We therefore derive a two-dimensional wavelength solution from daytime arc lamp frames, and assume that temporal variation in the wavelength solution can be described by a constant offset term at all wavelengths, along the entire slit. In some frames, the N I line is too faint to perform a useful fit. We therefore use the Fe5270 absorption feature at the galaxy center to measure the relative wavelength offsets across a sequence of frames. We anchor the frame-to-frame offsets to a single exposure for each galaxy, where the N I 5199 feature is strong enough to establish the absolute wavelength scale. In order to avoid substantial velocity structure when measuring the wavelength shifts in Fe5270, we only extract a 1''5 region at the galaxy center. We account for each galaxy’s rotation curve once we have extracted final one-dimensional spectra for all spatial bins, and before we measure line indices (see Section 4).

The lpipe IDL routines are available at http://www.astro.caltech.edu/~dperley/programs/lpipe.html.
Figure 1. LRIS blue-arm spectra extracted from the central and outer regions of NGC 1023 (top, green) and NGC 2974 (bottom, blue), and shifted to rest-frame wavelengths. Each spectrum has been sky-subtracted and flux-calibrated. Emission lines have been removed, as described in Appendix A.2. The spectra are normalized to the same median value, and constant offsets have been added for clarity. Stellar absorption features analyzed herein are labeled.

Figure 2. LRIS red arm spectra extracted from the central and outer regions of NGC 1023 (top, green) and NGC 2974 (bottom, blue), and shifted to rest-frame wavelengths. Each spectrum has been background-subtracted with a scaled sky spectrum, corrected for telluric absorption, and flux-calibrated. The spectra are normalized to the same median value, and constant offsets have been added for clarity. Stellar absorption features analyzed herein are labeled. The increased noise at 9200–9700 Å corresponds to strong telluric absorption bands.
3.2. Sky Subtraction and Telluric Correction

The background spectrum at red wavelengths is dominated by telluric emission lines, whose relative strengths vary on timescales comparable to our exposure times. Our goal of extracting galaxy light over the full length of the LRIS slit prohibits in-frame sky subtraction, and our sky frames must be corrected for variation in the line strengths. We extract a high-S/N sky spectrum from each science frame by applying a large aperture, offset from the galaxy center by at least 30",. We collapse the entire sky frame into a one-dimensional spectrum and use the \textit{Skycorr} routine (Noll et al. 2014\textsuperscript{5}) to perform scaled sky subtraction on the spectrum extracted from our science frame. \textit{Skycorr} adjusts the relative amplitudes of OH and O\textsubscript{2} emission groups in the input sky spectrum to best match the input science-frame spectrum, and subtracts the rescaled sky spectrum to output a clean science spectrum.

Subtracting the \textit{Skycorr} output spectrum from the initial science-frame spectrum yields a one-dimensional “master” sky spectrum for that particular frame. Next we use the halogen flats to compute the average response function of the CCD chip in the spatial dimension. We expand the master sky spectrum as a two-dimensional array, scaled by the spatial response function, and subtract this array from the science frame. Figure 3 illustrates the improvement in sky subtraction after performing this scaled sky procedure, relative to direct sky subtraction.

Residuals from telluric emission lines are our dominant source of noise near the FeH, Mg\textsubscript{0.88}, and TiO0.89 features (see Table 2 for definitions). These residuals are likely a combination of high shot noise from the bright lines, and wavelength calibration errors with magnitudes <0.1 Å. We have experimented with multiple variants of our sky subtraction procedure, including zoomed-in wavelength calibration over a narrow wavelength interval near the FeH band, fitting the wavelength solution with different polynomial orders, and applying \textit{Skycorr} over narrower chunks of wavelength space. None of these attempts yielded clear improvements.

In addition to their native pixels, residuals from bright sky lines may contaminate adjacent pixels during smoothing, which we employ to bring spectra to a common \(\sigma\) (Section 4). To mitigate this, we perform a version of the iterative masking procedure described by van Dokkum & Conroy (2012). We first construct a mean sky spectrum for our observing night and flag the pixels corresponding to the brightest sky lines. We then mask these pixels at the corresponding wavelengths in each galaxy spectrum, such that their values are interpolated from nearby good pixels before smoothing. Because the smoothing introduces undesired correlations between good pixels and masked pixels, we return to the un-smoothed spectrum and replace only the masked pixels with the smoothed output. We then perform the smoothing again, and iterate the substituting and smoothing steps five times. Although pixels near the edges of our masked regions are still over-weighted in our final spectrum, the iterations serve to distribute the excess weights more broadly.

In Figure 3(b), it is evident that the sky masking removes a substantial fraction of the FeH line region at 9902–9932 Å. In Appendix B, we examine additional variants of the FeH index that extend the line region to 9962 Å. These variants contain a larger fraction of unmasked pixels and yield similar radial trends in the FeH index for \(r < 0.5 \, r_{\text{eff}}\). As a second test, we have smoothed our spectra and measured line indices without any masking. The resulting index values do not differ significantly from the measurements we present below. Only the masked data exhibit a marginal upturn in Mg\textsubscript{0.88} at large radii in NGC 1023 (Figure 5(j)). Otherwise, the radial trends in Mg\textsubscript{0.88} and FeH are qualitatively similar for masked and unmasked measurements.

After subtracting the sky emission spectrum, we correct each red arm frame for telluric absorption. We start with three transmission spectra from the \textit{SkyCalc} sky model (Noll et al. 2012; Jones et al. 2013; see footnote 4) a baseline spectrum (\(T_{\text{BL}}\)) for low airmass and low water vapor, a high-airspace spectrum (\(T_{\text{HR}}\)), and a high-water vapor spectrum (\(T_{\text{WH}}\)). After convolving each model spectrum to the instrumental resolution of the LRIS red arm, we form a grid of linear

\textsuperscript{5} \textit{Skycorr} and \textit{SkyCalc} are available from the European Southern Observatory at http://www.eso.org/sci/software/pipelines/skytools.
For each exposure, we extract a spectrum from the central region of the galaxy, flatten it over the range of 9250–9650 Å by dividing out a fourth-order polynomial, and determine the values of \((h, w, z)\) that best reproduce the observed telluric absorption over the wavelength range 9310–9370 Å. We then divide the frames on both CCD chips by the corresponding model \(T_C\). At small radii, noise from our transmission correction dominates the galaxy spectra over the range \(\approx 9200–9700\) Å, where there are no stellar absorption features of interest. More importantly, a band of telluric H\(_2\)O overlaps the redshifted Na\(^{+}\) feature in both galaxies, with a particularly strong transmission dip at 8230 Å observed wavelength. In Appendix A.3, we assess a plausible error range for the transmission spectra used to correct the Na\(^{+}\) feature, and the corresponding error \(\epsilon_{\text{tel}}\) in our measurements of the Na\(^{+}\) line index. We find that variations of 10\% in our adopted transmission spectrum lead to errors as high as 13\% and 4\% in the Na\(^{+}\) index for NGC 1023 and NGC 2974, respectively. These errors are incorporated along with other systematic terms in the line index measurements presented below (e.g., in Figures 5 and 6). We note that our empirically derived errors are much larger than the estimate of 0.1\%–0.2\% by van Dokkum & Conroy (2012).

For our wavelength coverage on the blue side, the sky background is dominated by a continuum spectrum, and the background level was very stable during our observing night in 2013 December. For the corresponding blue-arm data, we directly subtract a calibrated sky frame from each calibrated science frame. Telluric absorption is negligible on the blue side.

3.3. Position Registration

For each science exposure, we trace the position of the galaxy center by fitting a two-component Gaussian profile to the central \(\approx5''\) of each galaxy, in each of the 10 wavelength blocks. The resulting trace is interpolated to all wavelengths, and one-dimensional spectra are extracted with sub-pixel spatial precision at each wavelength, approximating the flux in each pixel to be evenly distributed in the spatial dimension. Each science exposure also includes one chip per arm that is offset from the galaxy center. We measure the spatial gap between the on-center and off-center chip by comparing the RA and decl. header keywords for alternating dither positions to the location of the galaxy center on the corresponding chips. For NGC 1023 and NGC 2974, the gap spans 35'' on the red arm and 14'' on the blue arm. This includes a small buffer region where the data frames are trimmed during initial
Table 2
Line Index Definitions

| Index  | Ref. | Line | Blue Pseudo (Å) | Red Pseudo (Å) | Units | Dependence |
|--------|------|------|-----------------|----------------|-------|------------|
| Ca II  |      |      |                 |                |       |            |
| Ca2    |      |      |                 |                |       |            |
| C      |      |      |                 |                |       |            |
| Mg     |      |      |                 |                |       |            |
| TiO    |      |      |                 |                |       |            |
| FeH    |      |      |                 |                |       |            |

Note. The index definitions above use air wavelengths, as do all figures in this paper. The TiO0.89 index is defined as the flux ratio for the blue pseudo-continuum divided by the red pseudo-continuum. The last column lists some of the main atomic species and stellar atmosphere properties that influence the depth of each feature.

4. MEASURING LINE INDICES

While some investigations of stellar populations employ full spectral fitting (e.g., Cid Fernandes et al. 2005; Koleva et al. 2009; Kuntschner et al. 2010; Conroy & van Dokkum 2012b; Podorvanyuk et al. 2013; Conroy et al. 2014; McDermid et al. 2015; Posacki et al. 2015; Wilkinson et al. 2015), line indices or equivalent widths of specific absorption features are useful for qualitative interpretation and can be readily applied to a number of SPS models (e.g., Trager et al. 2000a, 2000b; Thomas et al. 2005; Schiavon 2007; Graves & Schiavon 2008; La Barbera et al. 2013; Spiniello et al. 2014). In Table 2, we list the definitions of 13 line indices discussed herein. On the blue side, we track prominent indices from the Lick/IDS system, introduced by Faber et al. (1985) and updated by Worthey et al. (1994) and Trager et al. (1998), as well as the bTiO index from Spiniello et al. (2014). Our wavelength coverage with the LIRIS blue arm cuts off in the middle of their aTiO feature. At near-infrared wavelengths, we adopt line index definitions for Na I, Ca II, FeH, TiO, and Mg from Conroy & van Dokkum (2012a, hereafter CvD12).

La Barbera et al. (2013) introduced an alternative definition for the Na I index, whose pseudo-continuum regions traced smaller residuals between stellar population models and galaxy spectra from SDSS. We describe this feature, Na I$_{gSSS}$, in Table 2. In Appendix B, we examine the radial behavior of Na I$_{gSSS}$ and three new variants of the FeH index, to test for biases that might arise from overlapping absorption features or contamination by sky lines. In brief, we find that the choice of the Na I or FeH definitions does not change the essential radial trends we observe (Section 5), or our interpretation (Section 7).
Figure 5. Selected line index strengths vs. radius in NGC 1023, corresponding to $\sigma = 230$ km s$^{-1}$. Vertical errors include systematic effects discussed in Appendix A, and horizontal error bars indicate the radial bin sizes. Panels are ordered by wavelength and color-coded according to each index’s primary use as a diagnostic: gray (panels (a), (c), and (g)) for indicators of C, N, and Fe abundance; blue (panels (b), (f), and (j)) for α-element indicators; purple (panels (d), (e), and (k)) for stellar age and effective temperature indicators; and red (panels (h), (i), and (l)) for IMF indicators. However, we stress that simultaneous modeling of multiple indices is necessary to quantitatively assess the contributions of star formation history, IMF, and abundances of individual elements. Most panels have units of Å for equivalent width, except for CN1 and bTiO (magnitudes), and TiO0.89 (ratio of blue to red pseudo-continuum). The y-axis in each panel scales from 0 to 1.3 times the maximum line depth. Magenta diamonds in panel (e) represent H$\beta$ measurements extracted without any correction for emission lines. The last data point in panel (l) (FeH, dashed error bar) is severely compromised by sky emission. Tabulated index values are available as supplementary materials. (The data used to create this figure are available).
Figure 6. Selected line index strengths vs. radius in NGC 2974, corresponding to $\sigma = 245$ km s$^{-1}$. Color codings and equivalent width units are the same as in Figure 5. The y-axis in each panel scales from 0 to 1.3 times the maximum line depth. The last two data points in panel (l) (FeH, dashed error bar) are severely compromised by sky emission. Tabulated index values are available as supplementary materials. (The data used to create this figure are available).
To assess spatial gradients in line indices, we must compare spectra with the same velocity dispersion σ in a common rest frame. To this end, we measure one-dimensional spectra of blue to red pseudo-continuum levels as defined by Cappellari & Emsellem (2004) for each galaxy into two subsets, with frames from each dither position evenly distributed. We extract one-dimensional spectra from each frame, matching the spatial apertures in Section 5, and coadd all of the spectra within a subset. After pairing data of data, particularly at radii \( r > 5'' \), once our spectra have been extracted from individual science frames, they are coadded via direct summation.

To assess spatial gradients in line indices, we must compare spectra with the same velocity dispersion \( \sigma \) in a common rest frame. To this end, we measure \( \sigma \) and the radial velocity \( v \) for each spatially binned spectrum (Section 5), and apply a Gaussian smoothing kernel in order to artificially raise \( \sigma \) to a common value. The kernel width is chosen such that each binned spectrum has a final dispersion of 230 km s\(^{-1}\) for NGC 1023 and 245 km s\(^{-1}\) for NGC 2974, matching our highest measurement of \( \sigma \) in each galaxy. We also shift the wavelength grid for each spectrum to rest-frame wavelengths, based on our measurement of \( v \). Figure 4 illustrates spectra near the Na i, Ca ii, and FeH features, after performing kinematic calibrations. Our measurements of \( v \) and \( \sigma \) employ the \texttt{pPXF} procedure by Cappellari & Emsellem (2004). In Appendix A.1, we discuss possible systematic errors in measuring kinematics, and the resulting impact on our measurements of line indices.

The blue-arm spectra of NGC 2974 include strong emission lines, which must be removed before measuring the depths of nearby absorption features. We fit and subtract an emission-line component for each blue-arm spectrum by including Gaussian emission-line profiles for H, N i, O i, and O iii in our list of kinematic templates for \texttt{pPXF}. We explore uncertainties and alternative methods for the emission-line fitting in Appendix A.2. NGC 1023 shows much subtler traces of emission, which we also discuss in Appendix A.2.

### Table 3: Systematic Errors in Line Indices

| Index | Error from \( v_0 \) | Error from \( \sigma_0 \) | Telluric Absorption Error NGC 1023/NGC 2974 | Error from Emission Lines NGC 1023/NGC 2974 | Adopted Systematic Error NGC 1023/NGC 2974 |
|-------|----------------------|----------------------|-----------------------------------|-----------------------------------|-----------------------------------|
| CN_i  | 0.4%                 | 0.9%                 | ...                               | 0.9%/1.4%                         | 1.3%/1.7%                         |
| Ca ii | 1.3%                 | 1.9%                 | ...                               | ...                               | 2.3%                             |
| C4668 | 0.4%                 | 0.4%                 | ...                               | ...                               | 0.6%/0.7%                         |
| bTiO | 4.1%                 | 1.4%                 | ...                               | ...                               | 4.3%/6.8%                         |
| H\(_{\beta}\) | 1.4% | 0.2% | ... | 6.0%/6.0% | 6.2%/6.2% |
| Mg b  | 0.4%                 | 0.9%                 | ...                               | 0.7%/1.0%                         | 1.2%/1.4%                         |
| Fe5270| 0.3%                 | 1.4%                 | ...                               | ...                               | 1.4%                             |
| Fe5335| 0.7%                 | 2.7%                 | ...                               | ...                               | 2.8%                             |
| Na i  | 0.025 Å              | 5.5%                 | 8.8%–13.4%/1.2%–3.8%              | ...                               | [0.025\(^2\) + \(\epsilon_{\text{tel}}^2\) + \(\epsilon_{\text{sys}}^2\)]\(^{1/2}\) Å |
| Ca ii | 1.1%                 | 0.7%                 | ...                               | ...                               | 1.3%                             |
| Mg 0.88| 2.1%                 | 5.6%                 | ...                               | ...                               | 6.0%                             |
| TiO0.89| 0.03%                | 0.06%                | ...                               | ...                               | 0.07%                            |
| FeH  | 2.6%                 | 2.3%                 | ...                               | ...                               | 3.5%                             |

Note. In most cases, the adopted systematic error is \( \epsilon_{\text{sys}} = (\epsilon_{\text{S/N}}^2 + \epsilon_{\text{tel}}^2 + \epsilon_{\text{sys}}^2 + \epsilon_{\text{gas}}^2)^{1/2} \), where \( \epsilon_{\text{S/N}} \) and \( \epsilon_{\text{tel}} \) are the error terms from \( v_0 \) and \( \sigma_0 \). For indices impacted by telluric absorption or galaxy emission lines, the adopted systematic error is \( \epsilon_{\text{sys}} = (\epsilon_{\text{S/N}}^2 + \epsilon_{\text{tel}}^2 + \epsilon_{\text{gas}}^2)^{1/2} \), where \( \epsilon_{\text{tel}} \) is the error resulting from uncertainties in the atmospheric transmission spectrum, and \( \epsilon_{\text{gas}} \) is the error derived from different settings for emission-line removal. For Na i, the adopted systematic error ranges from 11% of the equivalent width near the galaxy center to 16% of the equivalent width at large radii.

Once our spectra are cleaned and calibrated for kinematics, we compute equivalent widths using the formulae of Worthey et al. (1994, Equations (1)–(3)), whereby the continuum level is modeled as a straight line connecting the midpoints of the red and blue pseudo-continuum bands in Table 2. Our only exception is the TiO0.89 index, which is expressed as the ratio of blue to red pseudo-continuum levels as defined by CvD12.

### 4.1. Random and Systematic Errors

In principle, noise in a galaxy spectrum can be propagated analytically to compute formal statistical errors in an ensuing equivalent width measurement. However, noise from sky subtraction and telluric absorption is not random and uncorrelated in our spectra. Instead of formal error propagation, we perform a simpler and more empirical estimate of line index measurement errors, as follows. We split the science frames for each galaxy into two subsets, with frames from each dither position evenly distributed. We extract one-dimensional spectra from each frame, matching the spatial apertures in Section 5, and coadd all of the spectra within a subset. After pairing data from opposite sides of the galaxy and measuring indices as described above, we have four index measurements for each interval in \( r \). We adopt the mean and standard deviation of these measurements as our final equivalent width and \( 1\sigma \) random error. We then add the random errors in quadrature to the total systematic error \( \epsilon_{\text{sys}} \) from kinematic uncertainties, emission-line removal, and telluric absorption. We derive \( \epsilon_{\text{sys}} \) in Appendix A and summarize its value for each index in Table 3.

For most of the line indices we have investigated, \( \epsilon_{\text{sys}} \) is comparable to the random deviations between our four subsets of data, particularly at radii \( \lesssim 10'' \) where our spectra have very high S/Ns. Exceptions where random variance dominates systematic errors at all radii are the bTiO index in NGC 1023, the Ca ii index in NGC 2974, and the TiO0.89 and FeH indices in both galaxies. For the FeH feature in particular, the noise including sky lines exceeds the 3.5% total systematic error by at least a factor of two. Our error bars in Figures 5 and 6 below include both random and systematic terms.
The largest systematic effects occur for Na\textsc{i} and are discussed extensively in Appendix A. In particular, we note that the sizable error bars for Na\textsc{i} in NGC 1023 (Figure 5(h)) are largely driven by the $\sim 10\%$ error term for possible errors in telluric correction. Biases introduced by imperfect telluric correction vary gradually with radius because rotation in each galaxy’s rotation curve shifts the Na\textsc{i} feature across the overlapping telluric band (Appendix A.3). While this term is important for considering the absolute strength of the Na\textsc{i} index, the hypothetical telluric bias may be approximated as a uniform offset near the center of each galaxy. Therefore, radial trends in Na\textsc{i} are more significant than suggested by Figure 5. In NGC 2974, $c_{	ext{tel}}$ is $<4\%$ and is outweighed by other terms in the total error budget. When $c_{	ext{tel}}$ is excluded, the remaining systematic error in Na\textsc{i} ranges from 7% to 12%.

Moreover, van Dokkum & Conroy (2012) have suggested that the scatter in the relation between Na\textsc{i} strength and the center of the Na\textsc{i}+TiO blend provides a heuristic upper limit for the total error in the measured Na\textsc{i} index. In essence, if the only varying quantity is the Na\textsc{i} component of the Na\textsc{i}+TiO blend, this will drive a tight anti-correlation between the blend center and the Na\textsc{i} index strength. Additional scatter in the relation reflects a combination of measurement errors in the Na\textsc{i} index and blend center, and independent variation of the TiO component. We have performed a linear fit to this relation for each galaxy, estimating the blend center as the wavelength of minimum flux between 8180 and 8230 Å. With respect to our best fit, we find a scatter in Na\textsc{i} of 0.08 Å for NGC 1023 and 0.06 Å for NGC 2974. These values are indeed comparable to our combined random and systematic errors in Na\textsc{i}, which range from 0.05 to 0.08 Å for NGC 1023 and 0.04–0.07 Å for NGC 2974. If anything, this test indicates that we have assessed our systematic errors conservatively.

5. RESULTS: SPATIAL VARIATION IN LINE DEPTHS

The radial variations in the Na\textsc{i}, Ca\textsc{ii}, and FeH spectral features are illustrated in Figure 4, after convolving binned spectra to the same rest frame and velocity dispersion. In both galaxies, the Na\textsc{i} and Ca\textsc{ii} features become visibly shallower toward larger radii. At $\sigma \sim 200$ km s$^{-1}$, the Na\textsc{i} doublet (8183 and 8195 Å) is unresolved, and blended with a TiO band at 8205 Å. In the left panels of Figure 4, it is apparent that as the Na\textsc{i} blend becomes shallower toward large radii, its center shifts toward redder wavelengths, an indication that the Na\textsc{i} feature is weakening more rapidly than TiO. This trend is qualitatively consistent with variations in sodium abundance or the stellar IMF; we discuss both possibilities in Section 7.2.

From Figure 4, it is evident that the trend toward shallower FeH at large $r$ is present in both the line region and the red pseudo-continuum region defined by CvD12. While the CvD12 definition highlights the deepest part of the FeH bandhead, their red pseud-continuum still includes contributions from FeH and possibly TiO. To ensure that radial variations in the pseudo-continuum near FeH are not dominating our index measurements, we have tested three alternative variants of the FeH index, including two that extend the line region to 9962 Å. Details are provided in Appendix B. All variants yield similar trends in FeH with respect to $r$ near the centers of NGC 1023 and NGC 2974.

Radial trends in measured line indices are shown in Figure 5 for NGC 1023 and Figure 6 for NGC 2974. We group the H$\beta$, bTiO, and TiO0.89 indices as indicators of age and temperature; the CN$_1$, C$_2$4668, and (Fe) indices as indicators of C, N, or Fe abundance; the Mg b, Mg0.88, and Ca4227 indices as indicators of $\alpha$-process elements; and the Na\textsc{i}, Ca\textsc{ii}, and FeH indices as IMF-sensitive indicators. Nonetheless, we stress that variations in the underlying stellar population have degenerate effects on multiple indices, and no single index or set of indices maps directly to a single stellar population property. In particular, we will inspect the meaning of Na\textsc{i}, Ca\textsc{ii}, and FeH more carefully in Section 7.2.

All of the absorption features (except FeH in NGC 2974) weaken toward large radii, as expected for galaxies harboring metallicity gradients. However, there are noteworthy differences between the rate of decline for different indices. The Na\textsc{i} and CN$_1$ features exhibit steep gradients that appear nearly constant in log($r$), while other features decline less steeply on average, and/or turn over toward a flat profile in the central kiloparsec. Interestingly, the Wing-Ford FeH band does not mirror the steep radial trend in Na\textsc{i}, although both are dwarf-sensitive features. In both galaxies, our measurements of FeH are consistent with uniform strength out to 0.2 $r_{\text{eff}}$. Beyond this radius, NGC 1023 shows a gradual decline in FeH strength. NGC 2974 shows subtle evidence for increasing FeH strength toward large radii, but our outermost points for this galaxy are badly contaminated by telluric emission. The Ca4227, Mg b, and (Fe) indices all exhibit similar radial behavior, with a decline of 15%–25% per dex in $r$. Our trends in H$\beta$, Mg b, and (Fe) are broadly similar to those measured by Kuntschner et al. (2006) with SAURON integral-field data out to $r \approx 20\arcsec$. One exception is our measurement of increasing H$\beta$ toward the center of NGC 1023. The absence of an H$\beta$ gradient in the SAURON map may reflect differences in our respective methods for removing emission lines of ionized gas. Also, our measured Mg b values in both NGC 1023 and NGC 2974 vary more steeply than the average trends displayed by Kuntschner et al. (2006), though noise in their two-dimensional maps hinders a direct comparison.

We display ratios of selected line indices in Figures 7 and 8. For these figures, we have switched to a linear scale in radius so as to emphasize rapid changes within the central region of each galaxy. We have also removed the telluric absorption term from our error bars in Na\textsc{i}, as justified in Section 4.1. In Figure 7, we compare the Na\textsc{i} index to six other species. In every case except for CN$_1$, the relative strength of Na\textsc{i} increases toward the galaxy center, with a particularly steep rise in the innermost 0.1 $r_{\text{eff}}$. This region turns out to be very similar to the $r_{\text{eff}}/8$ aperture size used by van Dokkum & Conroy (2012).

In Figure 8, we compare the radial variation of IMF-sensitive and $\alpha$-element indices, relative to (Fe). Remarkably, the Na\textsc{i} and FeH indices show opposite trends with respect to (Fe) in the central 0.1 $r_{\text{eff}}$. As in Figure 7(e), Na\textsc{i}/(Fe) rises dramatically in the central 0.1 $r_{\text{eff}}$ of each galaxy. On the other hand, FeH/(Fe) decreases by $\sim$10%–20%. Even considering the large uncertainties in our measurements, the deviation between Na\textsc{i} strength and FeH strength appears to be significant (Figure 7(f)). As discussed further in Section 7.2, this behavior can arise from a strong gradient in sodium abundance, whereas gradients in the low-mass IMF slope would cause Na\textsc{i} and FeH to simultaneously increase or decrease. Although IMF variations still may be possible within

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6 We define (Fe) $\equiv 0.5(\text{Fe5270} + \text{Fe5335})$, following Trager et al. (2000a).
these galaxies, the opposing behavior of Na I and FeH constrains the magnitude and functional form of the IMF variations relative to abundance variations.

The near constancy of Mg b/(Fe) at all radii suggests that $[\alpha/Fe]$ is uniform or varies mildly with radius. The Mg b index is modestly sensitive to carbon, and our inferred gradients in [C/Fe] (Section 7.3) ultimately allow for a shallow decrease in $[\alpha/Fe]$ toward large radii in each galaxy. In contrast to Mg b or Ca4227, Figure 8 shows an abrupt downturn in Ca II/(Fe) interior to $\sim$0.1 $r_{eff}$. This steep central trend could arise from a lower fraction of giant stars in the very center of the galaxy, or from an increase in sodium abundance (e.g., CvD12). Both effects predict a simultaneous increase in Na I strength. In Section 7.2, we argue that sodium abundance drives the radial variations in Na I and Ca II.

While the Na I gradients in NGC 1023 and NGC 2974 are largely consistent, the CN1 index shows mild discrepancies between the two galaxies. The overall gradient in CN1 is approximately $-0.06$ mag dex$^{-1}$ in $r$ for NGC 1023, versus $-0.04$ mag dex$^{-1}$ for NGC 2974. This difference corresponds to a shallow decrease in Na I/CN1 toward the center of NGC 1023, versus a shallow increase for NGC 2974 (Figure 7(b)).

### 6. COMPARISON WITH SPS MODELS

To complement our qualitative interpretation of the line index gradients in NGC 1023 and NGC 2974, we compare our measurements to model spectra by CvD12. Though rigorous fitting is reserved for future work, our comparison serves to highlight cases where strong radial variations in absorption-line indices reveal underlying changes in abundance ratios or the stellar IMF.

In Figure 9, we illustrate the radial variation of NGC 1023 in index–index space, for Hβ, Na I, Ca II, and FeH versus $\langle$Fe$\rangle$. For comparison, each panel includes vectors indicating the isolated effects of age, total metallicity $[Z/H]$, $[\alpha/Fe]$, and $[C/Fe]$ on model spectra. Figure 10 presents the same comparisons for NGC 2974. In each panel of Figures 9 and...
10, we display two “families” of models extrapolated from publicly available model spectra by CvD12. In our construction, a family of models sample [Na/Fe] values of 0, +0.5, and +1.0, and four IMF variants: Chabrier, Salpeter ($\alpha = 2.35$), and single (unimodal) power laws with $\alpha = 3.0$ and $\alpha = 3.5$. Each IMF in the CvD12 models is integrated down to 0.1 $M_\odot$. All parameters except for [Na/Fe] and the IMF are the same for a given family. For each galaxy, we construct one family to approximate the line indices in our central bin, and a second family at lower metallicity to approximate the line indices at large radii. Instead of adjusting [Fe/H] in isolation, we find better overall agreement by varying $[Z/H]$, a parameter available in more recent models (C. Conroy 2016, private communication).

In order to test an appropriate range of ages, $[Z/H]$, and other abundances, we construct a large number of model spectra based on extrapolations from the baseline grid of models by CvD12. Starting from a given age and IMF, the abundances are applied as multiplicative response functions, originally modeled for a Chabrier IMF at 13.5 Gyr.\footnote{The response function for $[Z/H]$ in the more recent models is based on a Kroupa IMF.} We extrapolate response functions from the following baseline parameters supplied by CvD12: $[Z/H] \in \{-0.3, 0, +0.3\}; [\alpha/Fe] \in \{0, +0.2\}; [C/Fe] \in \{-0.15, 0, +0.15\}; [N/Fe] \in \{-0.3, 0, +0.3\}; [Na/Fe] \in \{-0.3, 0, +0.3\};$ and $[Ca/Fe] \in \{-0.15, 0, +0.15\}$. We then convolve each extrapolated spectrum from the native resolution of the models to 230 or 245 km s$^{-1}$, for comparison to data from NGC 1023 or NGC 2974, respectively. We compute line indices for each model spectrum using the same procedure as for the galaxy spectra.

To estimate the stellar population parameters corresponding to a particular galaxy spectrum, we compare the indices H$\beta$, Mg b, CN$_1$, C$_{24668}$, and Ca$_{4227}$ to our set of extrapolated models. These indices are relatively insensitive to variations in [Na/Fe] or the IMF. We first find an age and total metallicity that approximately matches H$\beta$ and (Fe) and then iteratively adjust the age and all abundance parameters above (except [Na/Fe]) until the resulting model spectra nearly match the values of all six indices. We emphasize that our method is not designed to produce a statistically rigorous fit, but rather to select families of models approximating the galaxy at small and large radii, so that we may visualize the effects of [Na/Fe] and the IMF on the near-infrared gravity-sensitive features. In the following section, we examine the inferred abundances and possible IMF variations.

7. DISCUSSION

Variations in stellar masses, ages, and abundance ratios impose degenerate effects upon individual line indices. Inferring these physical properties demands an intricate comparison between observed data and stellar population and stellar evolution models. Herein we have attempted to present our measurements with sufficient transparency to support future analyses employing a wide range of modeling assumptions. With the caveat that rigorous interpretation requires careful modeling, we shall discuss some qualitative trends in the relative strengths of different line indices as a function of radius, in light of previously established connections to physical stellar properties. We discuss gradients in age and metallicity in Section 7.1 and then examine possible origins of the steep variations in Na i (Section 7.2) and CN$_1$ (Section 7.3), particularly in the context of star-forming progenitors of early-type galaxies like NGC 1023 and NGC 2974 (Section 7.4). In Section 7.5, we examine each galaxy for photometric or kinematic signposts near 0.1 $r_{\text{eff}}$, where the line indices and inferred stellar populations exhibit a sharp transition. Finally, in Section 7.6, we compare our findings to other recent investigations of radial IMF variations in early-type galaxies.
7.1. Age and Metallicity Gradients

Radial variations in Hβ suggest age gradients in both galaxies, although the Hβ index is sensitive to abundance variations as well as age (Figure 9(a)). Based on the process outlined in Section 6, we infer that NGC 1023 and NGC 2974 both have old stellar populations at large radii, matching 13.5 Gyr models. Their centers are slightly younger: »10.5 Gyr for NGC 1023 and »11 Gyr for NGC 2974. As illustrated by the vectors in Figures 9–12, age variations in this range have a weaker impact than [Z/H] or [Na/Fe] for all indices except Hβ. We note that our ages are derived after removing emission lines from the galaxy spectra. The presence of spatially extended emission lines alongside an old stellar population is consistent with photoionization from post-AGB stars, with smaller contributions from extreme horizontal branch stars and low-mass X-ray binaries (Binette et al. 1994; Sarzi et al. 2010).

Both galaxies exhibit strong gradients in total metallicity. In NGC 1023, [Z/H] declines from »+0.05 in the central bin to »–0.5 at r = r_eff. In NGC 2974, we measure [Z/H] »–0.1 at the center and [Z/H] »–0.6 at r » r_eff. The variations in [α/Fe] are shallower, from central values of »+0.3 to outer values of »+0.1 in both galaxies. We find that [Ca/Fe] is slightly less enhanced than other α-elements, similar to trends reported in other systems (e.g., Thomas et al. 2003; Graves et al. 2007; Worthey et al. 2011). Examination of the CN1 and C24668 index strengths suggests gradients in [C/Fe] from »+0.1 at large radii to »+0.4 and »+0.3 at the centers of NGC 1023 and NGC 2974, respectively. In contrast, we infer...
[N/Fe] ≈ +0.2 at all radii. Abundances of carbon and nitrogen are discussed further in Section 7.3.

We caution that comparing our inferred [Z/H] values for NGC 1023 and NGC 2974 to other measurements relies on a consistent definition of total metallicity. In the models we have employed, [Z/H] and other abundances are adjusted as independent variables, whereas in other cases [Z/H] may be a secondary quantity estimated from abundances such as [Fe/H] and [Mg/Fe]. In particular, secondary estimates of [Z/H] and [α/Fe] depend heavily upon oxygen abundance, which is difficult to infer directly from stellar absorption features (e.g., Schiavon 2007).

Having approximated the ages and abundances of our inner and outer bins for NGC 1023 and NGC 2974, we can select appropriate families of models to isolate the effects of [Na/Fe] and IMF variation on various absorption indices. In spite of the weak trends in age, [α/Fe], [C/Fe], and [Ca/Fe] reported above, we choose in Figures 9–12 to illustrate grids that differ only in [Z/H]. The impacts of other abundance patterns are smaller in magnitude and are instead represented by the vectors in each figure panel. For both grids, the adopted age, [α/Fe], [C/Fe], [Ca/Fe], and [N/Fe] between the gray and red model grids. The labeled vectors represent the effects of varying age from 11.0 to 13.5 Gyr, [Z/H] by +0.5 dex, [α/Fe] by +0.2 dex, and [C/Fe] by +0.2 dex.

Figure 10. Index–index trends in NGC 2974 and in SPS models, comparing different indices to (Fe). The thick colored line in each panel traces the radial variations in NGC 2974, with symbols marking our measurements for each radial bin. Overplotted are two model grids from CvD12. In each grid, we vary the IMF (symbol size; solid line) and [Na/Fe] (symbol shape; dashed line). Closed gray symbols represent models at 11.0 Gyr, [Z/H] = −0.1, [α/Fe] = +0.3, [Ca/Fe] = +0.1, [C/Fe] = +0.3, and [N/Fe] = +0.2. The CvD12 models with these parameters have similar Lick index values to our central bin for NGC 2974. Open red symbols represent models with [Z/H] = −0.6, corresponding to our outermost bins for NGC 2974. For simplicity, we have not varied age, [α/Fe], [Ca/Fe], [C/Fe], or [N/Fe] between the gray and red model grids. The labeled vectors represent the effects of varying age from 11.0 to 13.5 Gyr, [Z/H] by +0.5 dex, [α/Fe] by +0.2 dex, and [C/Fe] by +0.2 dex.
behavior of Na I for the central three to four bins in each galaxy, relative to the trends in Ca II and FeH. As discussed further in Section 7.2, this break appears consistent with an abrupt rise in sodium abundance interior to \( \sim 0.1 \ r_{\text{eff}} \), and limits radial IMF variations to stellar masses above \( \sim 0.4 \ M_\odot \). Surprisingly, CN I is the only feature showing similar radial variation to Na I (Figure 7(b)). We have considered both carbon and nitrogen abundance variations as a possible explanation for the steep gradient in CN I and discuss these possibilities in Section 7.3.

### 7.2. IMF versus Sodium Abundance Variations

The Na I feature is primarily sensitive to surface temperature, surface gravity, and sodium abundance. The second effect makes it a strongly dwarf-sensitive feature in uniformly old stellar populations. Thus it is tempting to interpret our observations as a steep gradient from a bottom-heavy IMF at the galaxy center to a shallower IMF slope at \( r \gtrsim 0.1 \ r_{\text{eff}} \) (\( \sim 300 \) pc). However, this interpretation must be reconciled with the relatively mild decline in FeH and the opposing behavior of Na I/Fe and FeH/Fe. While the Na I and FeH features both peak in sensitivity for stellar masses \( m < 0.2 \ M_\odot \), the sensitivity of FeH declines much faster toward higher masses, such that Na I is more than twice as sensitive to the number of stars with \( m \gtrsim 0.4 \ M_\odot \) (see Figure 17 of CvD12). Thus a strong radial trend in Na I, but not FeH, could reflect an IMF gradient whose “bottom-heavy” nature is only expressed above \( \sim 0.4 \ M_\odot \). A bimodal IMF whose slope only varies above \( \sim 0.5 \ M_\odot \) has been shown to agree with the dynamical masses of early-type galaxies (e.g., La Barbera et al. 2013, 2016; Spiniello et al. 2014). However, the magnitude of the variation in Na I would demand drastic IMF variation on sub-kiloparsec scales if the IMF slope above \( \sim 0.4 \ M_\odot \) were the sole driver. The bTiO index also varies less steeply than Na I, although its strong temperature-sensitivity and the overlapping Mg4780 line leave some doubt regarding whether it is a valid IMF indicator (e.g., Serven et al. 2005; La Barbera et al. 2013; Spiniello et al. 2014).

Varying sodium abundance offers an alternative explanation for the steep variation of the Na I feature inside \( \sim 0.1 \ r_{\text{eff}} \). Indeed, the outer regions of both galaxies align with nearly solar [Na/Fe] in Figures 11 and 12, while the central index strengths indicate [Na/Fe] between +0.5 and +1.0. Due to its prominent role as an electron donor, sodium impacts other features via the atmospheric electron pressure. In particular, an increase in [Na/Fe] will drive a mild decrease in ionized calcium CvD12. This is qualitatively consistent with the flattening we observe in the Ca II index near the center of NGC 1023 and NGC 2974, and the corresponding decline in Ca II/Fe.

Comparing Na I and FeH in Figures 11(b) and 12(b), we find that both galaxy centers occupy the same locus on the central model grid: [Na/Fe] is just below +1.0 and the unimodal IMF slope lies between 2.35 and 3.0. The trends in Na I versus Ca II are more difficult to interpret because IMF and [Na/Fe] variations are more degenerate for this pair of indices. Furthermore, the Ca II predictions from the SPS models are sensitive to our estimate of [Ca/Fe]. Allowing for an error of \( \sim 0.5 \) A in the horizontal placement of the model grids in Figures 11(a) and 12(a), we again find that both galaxy centers are consistent with a sodium enhancement of approximately 1.0 dex and an IMF slope between 2.35 and 3.0. At large radii, the Na I and Ca II strengths of both galaxies (as well as FeH in NGC 1023) are roughly consistent with a Chabrier IMF. We note that while the Chabrier form is directly employed in the models by CvD12, it is not a unimodal power law, and the apparent transition from \( \alpha > 2.3 \) to Chabrier may not fully reflect the unimodal or bimodal form of the IMF at different radii.

Spatially resolved measurements of the Na D feature near 5890 Å would provide additional evidence for or against gradients in [Na/Fe]. Unfortunately, our settings for LRIS did...

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**Figure 11.** Index–index trends in NGC 1023 and in SPS models, comparing IMF-sensitive indices. Data, model grids, and vectors for individual parameter variations are defined as in Figure 9.
not cover Na D in NGC 1023 or NGC 2974. Jeong et al. (2013) constructed a stacked SDSS spectrum of early-type galaxies with strong Na D absorption and reported that the Na D line strength requires super-solar [Na/Fe] as well as [Z/H], with IMF slope having a relatively minor effect on the Na D feature. Although their analysis provides circumstantial evidence in favor of [Na/Fe] driving trends in Na I, their measurements leave room for IMF variations in a subset of their galaxies, which are stacked over $\sigma \sim 150$–300 km s$^{-1}$.

Sodium is produced primarily through the Ne–Na chain, which can be activated during core burning in massive stars (e.g., Woosley & Weaver 1995; Kobayashi et al. 2006, 2011; Decressin et al. 2007) or at the base of the convective envelope in intermediate-mass stars on the asymptotic giant branch (AGB), a process known as hot bottom burning (e.g., Cottrell & Da Costa 1981; Denisenkov & Denisenkova 1990; Ventura & D’Antona 2008a, 2008b; Karakas 2010). Although the dredge-up of heavy elements to the outer envelope of AGB stars is most efficient at low metallicities, solar-metallicity AGB stars may still produce and eject non-negligible quantities of sodium (e.g., Mowlavi 1999; Karakas et al. 2002; Herwig 2005).

In addition to IMF and [Na/Fe] variations, CvD12 determined that Na I could be strengthened by decreasing the number of horizontal branch and AGB stars, or the number of extremely cool giants (M7IIIs). However, both of these effects substantially weaken the TiO0.89 feature, which we observe to be nearly constant over the radii where Na I varies most steeply. While our interpretation of Na I and other features is self-consistent within the framework of our adopted SPS models, some recent studies have cautioned against using sodium indices to investigate the IMF. Spiniello et al. (2015b) noted inconsistencies between predicted sodium depths from different SPS models, while Smith et al. (2015a) found disagreement between the total mass-to-light ratios in two lensing galaxies and the IMF and [Na/Fe] values inferred from the Na D and 1.14 $\mu$m Na features.

7.3. Carbon versus Nitrogen Abundance Variations

The CN$_1$ index is sensitive to carbon and nitrogen abundance and exhibits a strong radial trend in both galaxies. Our other carbon-sensitive feature, C$_2$4668, does not decline as steeply as CN$_1$ from $r = 0$ to $r \sim 0.1$ r$_{eff}$, and thus it is tempting to interpret the trend in CN$_1$ as a decrease in nitrogen abundance. However, our comparison with the SPS models by CvD12 suggests that a gradient in [C/Fe] is better able to reproduce the observed trends in CN$_1$ and C$_2$4668. This counterintuitive result occurs in part because CN$_1$ is more sensitive to [Z/H], such that the metallicity gradient in each galaxy drives a seemingly exaggerated gradient in CN$_1$ strength. Nonetheless, the absolute values of CN$_1$ relative to [Fe] indicate that nitrogen is mildly enhanced at all radii, with [N/Fe] $\approx +0.2$. Neither CN$_1$ nor C$_2$4668 are sensitive to sodium abundance or IMF variations.

Carbon is produced by helium fusion in the cores of stars and released into the interstellar medium (ISM) via stellar winds or SNe II. Models of massive stars ($m > 10 M_{\odot}$) produce sizable carbon yields at solar and slightly lower metallicities (e.g., Meynet & Maeder 2002b; Dray & Tout 2003; Dray et al. 2003). In intermediate-mass stars, the final carbon yield is sensitive to initial mass and metallicity, as hot bottom burning efficiently converts carbon to nitrogen. At solar metallicity, stars with $m \approx 2.5$–4 $M_{\odot}$ transport carbon-rich material to the surface during third dredge-up events, without reaching sufficient temperatures for hot bottom burning (e.g., Renzini & Voli 1981; Gavilán et al. 2005; Herwig 2005; Karakas & Lattanzio 2014; Ventura et al. 2015). Abundance patterns in the Milky Way disk and nearby star-forming galaxies—particularly an upturn in [C/O] toward solar metallicity—have prompted differing interpretations of the
dominant source of carbon enrichment in these environments. On one hand, the absolute quantities of carbon and oxygen are consistent with open-box models of chemical evolution in star-forming galaxies, employing massive star yields (e.g., Gustafsson et al. 1999; Henry et al. 2000). Conversely, observations of nearly constant [C/Fe] over ~1 dex in [Fe/H] suggest that the ISM becomes carbon-enriched on timescales similar to SNe Ia, pointing to intermediate-mass stars as the main supplier (e.g., Chiappini et al. 2003; Bensby & Feltzing 2006).

Nitrogen is produced via the CN cycle. Whereas primary nitrogen production is driven by the mixture of hydrogen- and helium-burning regions in the first generation of stars, the nitrogen abundance of moderate- and high-metallicity stellar populations is dominated by secondary production from later generations whose interiors are already seeded with carbon. Similar to sodium, nitrogen production may occur in the cores of massive stars or in the stellar envelopes of AGB stars above ~4 $M_{\odot}$ (e.g., Renzini & Voli 1981; Woosley & Weaver 1995; Gavilán et al. 2005; Ventura & D’Antona 2008a, 2008b; Karakas & Lattanzio 2014). Observations of [N/Fe] in the Galactic disk and halo—including globular clusters ranging from [Fe/H] approximately −2.5 to [Fe/H] approximately −0.5—are consistent with contributions from both massive and intermediate-mass stars (e.g., Chiappini et al. 2005; Hirschi 2007 cf. Cohen et al. 2005).

Models of fast-rotating massive stars can boost CNO yields by mixing the hydrogen shell and helium-burning core (e.g., Meynet & Maeder 2002a, 2002b). In contrast, hot bottom burning in AGB stars will drive a strong anti-correlation between [C/Fe] and [N/Fe] unless a second mechanism is responsible for producing one of these elements. Although this anti-correlation has been observed in some globular clusters (e.g., Cohen et al. 2005; Ventura & D’Antona 2008b), the radial variation of CN$_{1}$ and C$_{2}$4668 in NGC 1023 and NGC 2974 is inconsistent with opposing gradients in [C/Fe] and [N/Fe]. Rather, the trend of rising [C/Fe] at constant [N/Fe] suggests separate sources of carbon and nitrogen production. Henry et al. (2000) reached a similar conclusion after compiling data from individual stars in the Galactic disk and halo, plus Galactic and extragalactic H II regions.

7.4. Abundance Ratios in Composite Stellar Populations

The stellar populations of early-type galaxies are typically old, with high metallicities resulting from multiple generations of star formation and ISM enrichment in a deep potential well. Their high [$\alpha$/Fe] ratios could arise from short star formation timescales or a top-heavy IMF, both of which rapidly seed the ISM with $\alpha$-process elements via SNe II (e.g., Worthey et al. 1992; Thomas et al. 1999, 2005). Here we briefly explore scenarios that could yield an excess of sodium and carbon in the centers of early-type galaxies, with steep abundance gradients to larger radii.

The most straightforward hypothesis for excess sodium and carbon is a larger fraction of the stars responsible for producing these elements. This could be the direct result of an IMF with a shallower slope above ~10 $M_{\odot}$ if sodium and carbon are produced in massive stellar cores. The form of the IMF at high densities is an ongoing challenge for models of star formation, and may be especially sensitive to the initial gas density structure and the role of turbulence in driving fragmentation (e.g., Chabrier et al. 2014; Krumholz 2014). However, IMF variations cannot be invoked to explain correlated gradients in [C/Fe] and [Na/Fe] if AGB stars are the dominant source of both sodium and carbon. This is because the IMF above ~2 $M_{\odot}$ sets the number of stars that experience hot bottom burning, which exerts opposite influences on carbon and sodium yields.

Another factor in the observed excesses is the amount of enriched stellar ejecta accreted onto existing and newly forming stars, during the peak of star formation. For instance, the high stellar densities in globular clusters allow for prolific accretion onto existing stars, as long as the cluster is massive enough to retain low-velocity ejecta (e.g., Renzini 2008; Conroy 2012; compare to Fenner et al. 2004). Using the deprojection procedure of Gehhardt et al. (1996), we find that the luminosity densities of NGC 1023 and NGC 2974 rise from 2–$6 L_{\odot}$ pc$^{-3}$ at 0.1 $r_{eff}$ to 200–400 $L_{\odot}$ pc$^{-3}$ at 0.01 $r_{eff}$, comparable to the average densities of some globular clusters. An extremely high value of [Na/Fe] ~1 dex has been measured in the central 15 pc of M31 (Conroy & van Dokkum 2012b; Zieleniewski et al. 2015), while red giants in the Galactic bulge and Galactic globular clusters both exhibit [Na/Fe] between 0 dex and +0.5 dex (e.g., Lecureur et al. 2007; Johnson et al. 2014, 2015; Roediger et al. 2014). Although support for this mechanism in globular clusters is still contentious, the rapid increase in sodium abundance toward these galaxies’ densest regions is at least a plausible consequence of pollution by stellar ejecta.
Compiled measurements of sodium, carbon, and nitrogen in other early-type galaxies do little to clarify the observations reported herein. Spectra of the central ≈0.6–1 kpc in early-type galaxies exhibit stronger CN1 features and steeper variation of Na D versus (Fe) than composite stellar population models for elliptical galaxies or the Galactic bulge (Trager et al. 2008; Serven & Worthey 2010; Tang et al. 2014). Graves et al. (2007) and Johansson et al. (2012) report slightly higher carbon enhancement than nitrogen enhancement in stacked spectra of SDSS galaxies, while Greene et al. (2013, 2015) report higher [N/Fe] than [C/Fe] for a combined sample of 82 galaxies. Although stacked early-type galaxy spectra allegedly range from 0 dex to +1 dex in [N/Fe], the variations between different studies are larger than the inferred trends within any individual sample, suggesting systematic errors in at least some measurements of [N/Fe].

7.5. Is 0.1 \( r_{\text{eff}} \) a Special Radius?

Even while the causes of excess sodium, carbon, and nitrogen are murky, we have shown that the most extreme stellar populations in NGC 1023 and NGC 2974 reside in their innermost regions. In both objects, the strengths of Na I, Ca II, and CN1 relative to other indices change abruptly near 0.1 \( r_{\text{eff}} \), leading us to question whether this scale marks a transition in the galaxy’s previous star formation environment, or a structural landmark from the assembly of distinct progenitors. Seeking supporting evidence for unique behavior at 0.1 \( r_{\text{eff}} \), we have examined Hubble Space Telescope (HST) photometry from Lauer et al. (2005) to examine each galaxy’s surface brightness profile, V–I color, and ellipticity out to \( \approx 0.2 \ r_{\text{eff}} \). We also examined the more extended surface brightness profiles from Krajnović et al. (2005) and Scott et al. (2009), as well as our measurements of \( \nu \) and \( \sigma \) for each radial bin. We illustrate the photometric data in Figures 13 and 14, and the kinematic data in Appendix A.1 (Figure 15).

Generally speaking, neither galaxy exhibits an abrupt feature near 0.1 \( r_{\text{eff}} \) in its stellar kinematics or broadband light. In NGC 2974, \( \sigma \) is the dominant kinematic component inside 0.1 \( r_{\text{eff}} \), whereas rotational \( \nu \) dominates beyond 0.2 \( r_{\text{eff}} \). NGC 2974 also has a central dust feature, which intersects the major axis near 0.05 \( r_{\text{eff}} \). However, the absence of similar features in NGC 1023 suggests that they are not closely connected to the sharp abundance variations.

7.6. Other Reports of IMF-sensitive Index Gradients

To date, few studies have sought to measure IMF gradients within individual early-type galaxies. Most recently, La Barbera et al. (2016) fit radial trends in TiO0.89 and four temperature- and gravity-sensitive TiO features in a massive early-type galaxy (\( \sigma \approx 300 \ \text{km s}^{-1} \)) at redshift \( z \approx 0.057 \).
Their measurements are consistent with a bimodal IMF whose slope above \( \sim 0.5 M_\odot \) declines from a central value of \( \alpha \approx 3 \) to a Milky-Way-like IMF beyond \( 0.5 r_{\text{eff}} \). La Barbera et al. (2016) have measured constant FeH strength out to \( \approx 0.2 r_{\text{eff}} \) (\( \sim 1.6 \) kpc), which disfavors a varying unimodal IMF. Our measurements of FeH in NGC 1023 and NGC 2974 exhibit a similar trend at \( r \leq 0.2 r_{\text{eff}} \), and probe physical scales several times smaller than the central bin of \( \sim 700 \) pc adopted by La Barbera et al. (2016).

Zielenskiewicz et al. (2015) have measured a rapid increase in Na I over the central 20 pc of M31, with no corresponding increase in FeH. Similar to our interpretation above, they infer a steep gradient in [Na/Fe]. The central 40 pc of M32 do not exhibit strong radial trends in Na I or FeH.

Martín-Navarro et al. (2015a) have measured gradients in IMF-sensitive features in three galaxies, using long-slit data covering 4500–10000 \( \AA \). Near the centers of their two high-mass galaxies, NGC 4552 and NGC 5557, they find that Na I\(_{\text{DS}}\) varies steeply relative to the total metallicity indicator [MgFe], similar to the trends we find above. Their lower-mass object, NGC 4387, shows very little radial variation in Na I\(_{\text{DS}}\) or in inferred stellar population properties, aside from total metallicity. Whereas we have carefully accounted for telluric absorption near 8190 \( \AA \) (see Section 3.2 and Appendix A.3), Martín-Navarro et al. (2015a) place less confidence in their telluric correction and exclude the Na I\(_{\text{DS}}\) index from their SPS models. They do not measure the FeH feature, and telluric emission restricts their assessment of the Ca II feature to the second line in the triplet. However, they observe and model other features between 5800 and 6400 \( \AA \) that we do not access with LRIS: most notably the Na D index and two TiO indices.

Martín-Navarro et al. (2015a) have reported a strong IMF gradient in NGC 4552, resolved to \(~ 0.1 r_{\text{eff}} \) or \(~ 300 \) pc. They adopt the same bimodal IMF form as La Barbera et al. (2016) and likewise measure a Milky-Way-like IMF at 0.7 \( r_{\text{eff}} \), while at the center of NGC 4552 they find an extreme slope of \( \alpha \approx 4 \) above 0.5 \( M_\odot \). They illustrate that Na I\(_{\text{DS}}\) and Na D exhibit similar gradients in NGC 4552 despite different sensitivities to [Na/Fe], and assert that IMF gradients mainly drive the variations in Na I, while Na D permits [Na/Fe] variations up to 0.25 dex. While the combined coverage of Na D and Na I provides useful leverage, the modeling approach of Martín-Navarro et al. (2015a) warrants caution: they fit selected line indices to SPS models by Vazdekis et al. (2012), after applying correction factors to adjust the measured indices from inferred \( \alpha/Fe \) to solar abundances. The overt dependence on \( \alpha/Fe \) is particularly troubling for NGC 4552, where the \( \alpha/Fe \) gradient reported by Martín-Navarro et al. (2015a) is much steeper than the trends typically observed for early-type galaxies (e.g., Sánchez-Blázquez et al. 2007; Spolaor et al. 2010).

Using the same modeling approach and bimodal IMF form, Martín-Navarro et al. (2015b) reported a high-mass slope \( \alpha \approx 4.0 \) out to \( 1.5 r_{\text{eff}} \) in the compact, high-\( \sigma \) galaxy NGC 1277, with a mild trend toward \( \alpha \approx 3.5 \) in the central 0.5 \( r_{\text{eff}} \) (600 pc). For this object, Martín-Navarro et al. (2015b) found strong gradients in Na I\(_{\text{DS}}\), Na D, and metallicity, compared to relatively weak trends in TiO, TiO\(_2\), and [Mg/Fe]. The results for NGC 1277 agree qualitatively with our observations of NGC 1023 and NGC 2974 on similar radial scales, and with widespread trends in \([Z/H]\) and \( \alpha/Fe \) (e.g., Tamura et al. 2000; Weijmans et al. 2009; Greene et al. 2013, 2015). Finally, Martín-Navarro et al. (2015c) have presented data from 24 galaxies in the CALIFA survey (Sánchez et al. 2012), binning each galaxy into several elliptical annuli. Although they find a significant correlation between the inferred IMF slope and metallicity of each spectrum, they do not compare any measurements directly with \( r \). We therefore cannot assess whether galaxies in the CALIFA sample contain IMF or abundance gradients at the spatial scales we have probed for NGC 1023 and NGC 2974.

La Barbera et al. (2013) assessed stacked spectra from SDSS and noted that the individual galaxy spectra enclosed varying fractions of \( r_{\text{eff}} \). They subdivided two of their stacked spectra (\( \sigma = 100 \) km s\(^{-1}\) and \( \sigma = 200 \) km s\(^{-1}\)) into narrow bins of \( r / r_{\text{eff}} \) and found minimal variations in the strengths of TiO indices and Na I\(_{\text{DS}}\) from aperture sizes of 0.3 \( r_{\text{eff}} \) to 1.4 \( r_{\text{eff}} \). In other words, their \( \sigma = 200 \) km s\(^{-1}\) stack exhibited stronger IMF-sensitive features at all enclosed radii. Still, we note that any radial gradients in abundances or the IMF would be diluted by the luminosity-weighted SDSS apertures. Our finding that the steepest gradients in NGC 1023 and NGC 2974 occur well inside 0.3 \( r_{\text{eff}} \) may also bear upon the absence of gradients reported by La Barbera et al. (2013).

Further advances in stellar template libraries and atmospheric models will yield improved predictions for the integrated-light signatures of simultaneous variations in abundances and the IMF. In the meantime, models whereby abundance variations are restricted to \([Z/H]\) or \( \alpha/Fe \) must be employed with caution, in light of abundance gradients for individual elements. An interesting case study is provided by La Barbera et al. (2016), who attempt to rescale their observed index strengths to solar abundances, based on relations between a given index strength, \( \alpha/Fe \), and \([Z/H]\). Their approach is informed in part by their assessment of radial trends in \( \alpha/Fe \) and \([C/Fe]\). We speculate that the approach of La Barbera et al. (2016) is better suited to the gravity-sensitive TiO features they measure than to the Na I or Ca II features discussed herein, since \([Ca/Fe]\) and [Na/Fe] are known to deviate from trends in \( \alpha/Fe \). We look forward to further work that may support this example and identify other regimes where IMF gradients can be robustly disentangled from nuanced abundance variations.

8. CONCLUSION

We have used Keck/LRIS to analyze optical and near-infrared stellar absorption features along the major axis of two early-type galaxies with central \( \sigma \) of 217 and 247 km s\(^{-1}\). We have measured 13 line indices for species of H, C\(_2\), CN, Na, Mg, Ca, TiO, Fe, and FeH, from spatially resolved spectra covering 3100–5560 \( \AA \) and 7500–10800 \( \AA \). We have examined each index on scales of \(~ 100 \) pc (1″) near the center of each galaxy, and in larger bins extending to 4.0 kpc (75″ or 1.6 \( r_{\text{eff}} \)) for NGC 1023 and 3.0 kpc (30″ or 0.8 \( r_{\text{eff}} \)) for NGC 2974.

In both galaxies, radial declines in the \( (Fe) \) index and multiple indices of Mg, Ca, and C suggest an overall metallicity gradient and shallower gradients in \( \alpha/Fe \), [Ca/Fe], and [C/Fe]. However, the Na I index at 8190 \( \AA \) exhibits significantly steeper gradients, particularly at \( r < 0.1 r_{\text{eff}} \) or \( r < 300 \) pc. The FeH index at 9915 \( \AA \) mirrors the gradual decline of \( FeH \) rather than the steep decline in Na I. The data presented herein are among the first to track FeH as a function of radius, and to demonstrate different radial trends in Na I and FeH, even while both indices are sensitive to cool dwarf stars.
We interpret the steep gradient in the Na i index as reflecting a rapid decline in [Na/Fe] over the central ~300 pc of each galaxy. On similar scales, the Ca ii index declines relative to Fe, and other Mg and Ca indices, to a degree that would require a very strong gradient in [Na/Fe] if our interpretation is to match models by CvD12. IMF gradients may contribute to the respective trends of Na i, Ca ii, and FeH in NGC 1023 and NGC 2974, but only if the IMF is bimodal, with a similar slope for $m < 0.4 M_\odot$ at all radii. The CNi index also varies rapidly near the center of each galaxy, and a qualitative comparison to stellar population synthesis models indicates that this is due to a large-scale gradient in [C/Fe], with uniform enhancement in [N/Fe].

Our study poses a number of outstanding issues to be pursued in future work. As we have emphasized above, the physical properties of stellar populations are highly degenerate with individual line indices, and some of the trends we have presented—most notably the relative variations in Na i, FeH, and (Fe)—defy simple qualitative arguments. Rigorous stellar population synthesis modeling will expand upon the qualitative comparisons we have performed herein and allow for more robust interpretations of the physical trends in NGC 1023 and NGC 2974. Moreover, our search for radial IMF trends within two galaxies cannot fully inform claims of IMF variation over a large range of integrated galaxy properties. To this end, we have observed five additional galaxies spanning $\sigma \sim 140–400$ km s$^{-1}$, approaching the range explored by survey-driven investigations of IMF variation. These objects will also strengthen our understanding of internal trends near 0.1 $e_{\text{eff}}$ and clarify whether this scale truly marks a transition point for star formation physics in galaxies.

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APPENDIX A
SYSTEMATICS IN LINE INDEX MEASUREMENTS

Herein we derive our total systematic error $\epsilon_{\text{sys}}$, which we have included above in Section 4.1. Figures 5 and 6 above include all systematic terms, while Figures 7 and 8 include all systematic terms except for the telluric absorption error in Na i.

A.1. Kinematic Corrections

In order to make an unbiased comparison between absorption-line strengths at different radii, each spectrum within a single galaxy must be shifted to the same rest frame and convolved to the same velocity dispersion. For each spectrum, we measure $v$ and $\sigma$ using the template reconstruction procedure pFXF from Cappellari & Emsellem (2004). We use a subset of template spectra from the MILES library of empirical stellar spectra (Sánchez-Blázquez et al. 2006), and perform a fit over the wavelength range 3650–5400 Å. We simultaneously fit for the strengths of emission lines, assuming that gas and stars exhibit the same kinematics. Spectra on the LRIS red arm are assumed to match the kinematics derived from blue-arm data for the same spatial bins. We display the radial profile of $v$ and $\sigma$ for each galaxy in Figure 15.

At high S/N, uncertainties in $v$ and $\sigma$ are dominated by systematic errors, particularly from template libraries that do not fully reproduce a galaxy’s underlying stellar population. For this work, we do not attempt to directly assess our
systematic errors in kinematic moments, but rather test the variation in line index strengths over a conservative range of assumed $v$ and $\sigma$. Previous investigations using similar wavelength coverage and a variety of stellar templates have found total errors of $\pm 10$ km s$^{-1}$ in $v$ and $\pm 20$ km s$^{-1}$ in $\sigma$ (Barth et al. 2002; Cappellari & Emsellem 2004). For the SAURON galaxy sample, Emsellem et al. (2004) found a scatter of $15 – 18$ km s$^{-1}$ in comparisons between their pPXF-based measurements of $\sigma$ and previous $\sigma$ values in the literature. For our trials, we adopt the conservative assumption that $v$ and $\sigma$ each have errors of $\pm 20$ km s$^{-1}$. We have run pPXF using an alternative subset of MILES stellar templates and found that the resulting variations in $v$ and $\sigma$ were well within this range.

In order to assess the kinematic error terms for each line index, we have tested five spectra from NGC 1023. The innermost spectrum spans radii from $0.5$ to $2.0$ and has an $S/N = 119$ over the wavelength range used for the pPXF fit, and $\sigma = 216$ km s$^{-1}$. The outermost spectrum spans $50'' – 75''$ and has an $S/N = 38$ and $\sigma = 94$ km s$^{-1}$. For a given spectrum, we perform two sets of trials wherein we vary the assumed velocity and velocity dispersion, $v_0$ and $\sigma_0$. In one set of trials, we fix $\sigma_0$ to the best-fit $\sigma$ from pPXF and sample $v_0$ from a normal distribution with a dispersion of $20$ km s$^{-1}$ (centered on the best-fit $v$ from pPXF). For each of the 100 trials sampling $v_0$, we convolve the spectrum from $\sigma_0$ to $\sigma = 230$ km s$^{-1}$, shift to $v_{\text{rest obs}} = v_{\text{rest}} + v_0/c$, and measure the absorption-line indices. For each absorption feature, we define a systematic error term $c_\sigma$ as the standard deviation in index strength over all 100 trials.

Figure 17. (a) Line strength of the Na I feature vs. the input systemic velocity ($v_0$), for a spectrum covering major-axis radii from $+0'5$ to $+2'0$ in NGC 1023. (b) Na I line strength vs. input velocity dispersion ($\sigma_0$). In each case, the spectrum is convolved from $\sigma_0$ to $\sigma = 230$ km s$^{-1}$ before measuring the line index. (c) Rest-frame spectrum of the Na I feature, before convolution to $\sigma = 230$ km s$^{-1}$. The red segment indicates the Na I line region, and the blue segments indicate the pseudo-continuum regions. The blue dashed line is the linear fit to the pseudo-continuum, used in the index measurement. (d) Rest-frame spectrum at two separate velocity shifts. (e) Rest-frame spectrum convolved to 230 km s$^{-1}$ from two separate $\sigma_0$ values.

Figure 18. Panels are the same as Figure 17. This spectrum spans major-axis radii from $-50''$ to $-30''$ in NGC 1023. The velocity dispersion is smaller than the central spectrum in Figure 17, and the Na I line is significantly weaker.
In Table 3, we present the values of \( \epsilon_{I0} \) and \( \epsilon_{\sigma0} \) for 13 different line indices, averaged over our five test spectra. We make particular note of the NaI index, which is two to three times stronger at the galaxy center than at large radii. This index exhibits a similar absolute value of \( \epsilon_{I0} \approx 0.025 \) Å at all radii, while \( \epsilon_{\sigma0} \) scales approximately linearly with the index strength. The trends in \( \epsilon_{I0} \) and \( \epsilon_{\sigma0} \) for both galaxies’ NaI indices are illustrated in Figure 16. Figures 17 and 18 show individual spectra of the NaI region for NGC 1023, with variations in \( v_0 \) and \( \sigma_{0} \) and the resulting smoothed spectra. Although the inner spectrum (Figure 17) has a much deeper NaI feature and much larger intrinsic \( \sigma_{0} \), the change in index strength with respect to \( v_0 \) is similar to the outer spectrum (Figure 18).

As indicated in Table 3, systematic errors from kinematic fitting are typically ~1%–5% of the line index strength. In cases of low statistical noise, the \( \epsilon_{I0} \) and/or \( \epsilon_{\sigma0} \) term is comparable to the level of random variance between different data subsets. This is true for index measurements based on high-S/N spectra near the center of each galaxy, and even toward large radii for the Fe, Mg b, and Ca II features. On the other hand, the NaI and Mg I0.88 features are relatively sensitive to the velocity shift and broadening of the underlying spectrum, such that the kinematic error terms make a substantial contribution to the overall error budget even when the S/N is modest.

A.2. Contamination from Emission Lines

Emission lines from warm gas are visible contaminants in our spectra throughout NGC 2974 and at the center of NGC 1023. We have experimented with two well-known routines to remove the emission component and assess the underlying stellar absorption features: pPXF by Cappellari & Emsellem (2004) and GANDALF by Sarzi et al. (2006). In addition to the stellar template library used to fit a galaxy spectrum, pPXF supports Gaussian emission-line templates at the rest wavelengths of several gas species. The strength of each emission line is varied freely, while the emission-line kinematics (v and \( \sigma \)) are assumed to match the stellar kinematics. Using the output template data provided by pPXF, we separate the stellar template and emission-line components, and subtract the sum of the emission lines from our original galaxy spectrum. This is performed in the same run where we measure v and \( \sigma \).

The GANDALF routine adds more flexibility to the emission-line fitting: the gas component(s) are permitted to have different kinematics from the stars, and the relative flux and kinematics of each emission line may either be fit freely or coupled to another line. In practice, the routine performs best when the stellar kinematics are first estimated using pPXF (while masking the emission lines or fixing their kinematics as above), and supplied as an initial guess for the subsequent GANDALF fit. We have used GANDALF successfully for NGC 2974, whose strong emission-line components are easily recognized. As before, we isolate the emission-line component of the best-fitting spectrum and subtract it from our original galaxy spectrum. Any emission in NGC 1023 is too subtle for GANDALF to separate cleanly, and it confuses the low-order stellar continuum with a superposition of extremely broad emission lines. Therefore, we restrict our use of GANDALF to NGC 2974.

We find that the best-fitting emission spectrum varies for different sets of stellar templates used in pPXF, and with the degree to which the relative emission strengths of different species are allowed to vary in GANDALF. We therefore define a systematic error term \( \epsilon_{\text{gas}} \) as the standard deviation of trial measurements for a given absorption-line index, when different settings are used for the emission-line removal. For NGC 2974, the trials include two alternative stellar template libraries—one a subset of the empirical MILES library—for pPXF, and two settings for the relative emission-line strengths in GANDALF. In one GANDALF trial, the flux of each emission line is treated as a free parameter, and in the other trial we fix the relative strengths within the [O II], [O III], [N I], and [Ar IV] multiplets. In NGC 2974, Balmer emission lines impact the CN1, b, and H\( \beta \) absorption features. For H\( \beta \), we find that \( \epsilon_{\text{gas}} \approx 6\% \) of the absorption-line strength, and bTIO is impacted at the \( \approx 5\% \) level as a result of H\( \beta \) contaminating the red pseudo-continuum. The Mg b and C\( g \)6688 indices exhibit small systematic errors from [N I] and [Ar IV] contamination, respectively. For the average index measurements presented in Section 5 and Figures 5–8 we have adopted pPXF as our default tool for emission line removal, as we find it performs better at distinguishing between relatively narrow emission lines and broad variations in the galaxy continuum relative to the stellar templates.

For NGC 1023, we determine \( \epsilon_{\text{gas}} \) using two trials: a pPXF trial with our default template library, and a trial with no emission line fitting. A third trial with an alternative template library for pPXF does not differ substantially for NGC 1023, and we exclude it so as not to dilute \( \epsilon_{\text{gas}} \). As with NGC 2974, we find a \( \approx 6\% \) impact on the H\( \beta \) index, and possible low levels of contamination for the CN1 and Mg b absorption features. In Figure 19, we show example spectra from both galaxies, before and after emission-line removal.

A.3. Overlap of Redshifted Na I and Telluric H\( \text{2} \)O

We have attempted to remove telluric absorption features from our galaxy spectra by comparing them to a grid of model atmospheric transmission spectra over the observed wavelength range of 9310–9370 Å. Although our corrected spectra look...
reasonable by eye, we aim to quantify the level of uncertainty near the 8190 Å Na I feature and the corresponding bias in our measurement of the Na I line index. To this end, we have performed trials where we multiplied the strength of our best-fitting transmission spectrum for each science exposure by values of 0.9, 1.1, and 1.2, and repeated all data processing and analysis steps starting from telluric division of individual frames. In Figure 20, we display the resulting spectra for each galaxy, from our central spatial bin and an outer spatial bin.

For NGC 1023 (Figure 20(a)), contamination by the deep H2O feature at 8230 Å is visible for a telluric correction of −10% and +20% relative to the best fit. Beyond a crude visual estimate of our possible error range for telluric correction, we can take advantage of the fact that NGC 1023 and NGC 2974 both have rotational velocities of ∼200 km s⁻¹, such that the Na I feature is shifted by ∼10 Å over the length of our slit.

If the Na I line or pseudo-continuum regions are severely contaminated by a telluric feature, we should see systematic differences in our index measurements from opposite sides of the galaxy. This is illustrated in Figure 21. For each panel, we have overplotted all four subsamples used to compute our random errors in the Na I index (see Section 4.1). For the trial where we adjusted our transmission spectra by −10% (Figure 21(a)), our measurements of the Na I index on opposite sides of the galaxy are clearly offset. We see similar asymmetry for the trial with +20% adjustment, though it is not displayed in Figure 21. Our other two trials (no adjustment and +10%, corresponding to Figures 21(b) and (c)) both exhibit overlapping measurements from opposite sides of the galaxy and do not produce obviously poor spectra. We therefore estimate our plausible systematic error from telluric correction in terms of the difference between our Na I index measurements from
these latter two trials. Specifically, we have adjusted our final Na I index measurement in each spatial bin of NGC 1023 to the average value from the two trials. In each bin, we define the 1σ systematic error term as the percent deviation between the two trials, equal to \( \frac{1}{\sqrt{2}} \) times the percent difference in index measurements.

Our random errors in each line index are derived from subsets of data spanning both sides of the galaxy (Section 4.1), and therefore some of the scatter in Figure 21 is already incorporated in the random error term for Na I. However, Figure 21 also exhibits a systematic offset between the three panels, indicating that poor telluric correction introduces an overall bias in addition to increased scatter from the shift in observed wavelengths of Na I. We therefore keep the \( \epsilon_{\text{tel}} \) term as defined above, to account for the plausible bias level from over- or under-corrected telluric features.

We observed NGC 2974 during the second half of our observing night, and telluric H2O in our spectra is not as strong as for NGC 1023 (see Figure 20(b)). However, our −10% and +20% atmospheric transmission trials once again produce offsets in the Na I index measurements from opposite sides of the galaxy. Therefore, we define \( \epsilon_{\text{tel}} \) for NGC 2974 in the same manner as for NGC 1023, and adjust our average index values accordingly. For NGC 2974, we compute a maximum \( \epsilon_{\text{tel}} \) of 3.8%, versus 13.4% for NGC 1023. For both galaxies, we add \( \epsilon_{\text{tel}} \) in quadrature with other systematic terms, as indicated in Table 3.

APPENDIX B
ALTERNATIVE DEFINITIONS OF THE SODIUM 8190 Å AND FeH WING-FORD INDICES

In recent investigations of IMF-sensitive absorption features, CvD12 and La Barbera et al. (2013) have proposed two different definitions of the Na I absorption index near 8190 Å. We compare the corresponding line and pseudo-continuum regions in Figure 22. In the version by CvD12, both pseudo-continuum regions are immediately adjacent to the line region, such that the red pseudo-continuum lies directly on the overlapping TiO band. The Na I SDSS index from La Barbera et al. (2013) defines a narrower line region and moves both

Figure 22. Comparison of the Na I and Na I SDSS indices defined in Table 2. In each panel, the red segment indicates the line region, and the blue segments indicate the pseudo-continuum regions. The blue dashed line is the linear fit to the pseudo-continuum, used in the index measurement. The example galaxy spectrum is the same as in Figure 17, prior to convolution to \( \sigma = 230 \text{ km s}^{-1} \).

Figure 23. Ratio of Na I and Na I SDSS to \( \langle \text{Fe} \rangle \) as a function of radius. Top: NGC 1023, with the outermost spatial bin extending to 1.6 \( r_{\text{eff}} \). Bottom: NGC 2974, with the outermost spatial bin extending to 0.8 \( r_{\text{eff}} \). The gray shaded area in each panel indicates the scale of the single-aperture measurement by van Dokkum & Conroy (2012).
pseudo-continua to regions outside the Na I+TiO blend. This generates a shallower linear fit to the continuum and produces larger equivalent widths. However, we find that the offset between our measured Na I and Na ISDSS line strengths is nearly the same at all radii in NGC 1023 and NGC 2974. In Figure 23, we show the ratios Na I/(Fe) and Na ISDSS/(Fe) as a function of radius in NGC 1023 and NGC 2974. For both definitions, the relative strength of the sodium index rises steeply from $r_{0.1}$ to the galaxy center. For all figures and discussion above, we follow the Na I index definition from CvD12.

The relative strengths of the FeH, Na I, and (Fe) absorption features are crucial for our interpretation of abundance versus IMF gradients in NGC 1023 and NGC 2974. The FeH index is notoriously difficult to measure, as spectra near 9900 Å suffer from bright telluric emission lines and relatively low instrumental throughput. While the Wing-Ford feature corresponds to the principal FeH bandhead in this region, the shape of the nearby pseudo-continuum is also influenced by overlapping bands of TiI, TiO, and CrH (e.g., McLean et al. 2003; Cushing et al. 2005, CvD12). To check whether our observed radial trends in FeH are sensitive to the precise placement of the line and pseudo-continuum regions, we have repeated our measurements using four variants of the index definition. These are illustrated in Figure 24. The first variant is the definition by CvD12, which we list in Table 2 and use for all analyses and figures above. In this version, the line region is defined to match the deepest part of the FeH bandhead, possibly reducing contamination from overlapping TiO. Our second variant instead uses a larger portion of the FeH trough (9902.3–9962.3 Å) and moves the red pseudo-continuum accordingly to 9967.3–9982.3 Å. The third and fourth variants match the first two, except with the blue pseudo-continuum moved from 9852.3–9877.3 Å to 9862.3–9887.3 Å.

We display the radial trends of FeH/(Fe) for each variant in Figure 25. None of the adopted FeH variants alter our main finding: that FeH decreases relative to (Fe) going from 0.1 $r_{\text{eff}}$ into the center of each galaxy, and thereby opposes the trend in Na I/(Fe) at these same radii. However, there is evidence of some deviation at $r > 0.5 r_{\text{eff}}$ in NGC 1023, such that the variants using the full absorption trough (variants 2 and 4) show an increase in FeH toward large $r$, whereas the original definition by CvD12 and our similar variant 3 show a slight decrease toward large $r$. This may be caused by a faint sky line near 9970 Å rest, which overlaps with the red pseudo-continuum in our full-trough variants. Traces of this line are visible in Figure 3(b) and for the two outermost spectra in Figure 4(c).
Figure 25. Ratio of FeH to (Fe) as a function of radius, using the four definitions of the FeH index in Figure 24. Left: NGC 1023, with good data for FeH extending to 1.0 r$_{eff}$. Right: NGC 2974, with good data for FeH extending to 0.26 r$_{eff}$. The gray shaded area in each panel indicates the scale of the single-aperture measurement by van Dokkum & Conroy (2012).

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