THE STELLAR HALOS OF MASSIVE ELLIPTICAL GALAXIES. III. KINEMATICS AT LARGE RADIUS

SUDHIR RASKUTTI1, JENNY E. GREENE1,2, AND JEREMY D. MURPHY1,2
1 Department of Astrophysics, Princeton University, Princeton, NJ 08540, USA
2 Department of Astronomy, UT Austin, 1 University Station C1400, Austin, TX 78712, USA

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ABSTRACT

We present a two-dimensional kinematic analysis out to ~2–5 effective radii ($R_e$) of 33 massive elliptical galaxies with stellar velocity dispersions $\sigma > 150$ km s$^{-1}$. Our observations were taken using the Mitchell Spectrograph (formerly VIRUS-P), a spectrograph with a large $107 \times 107$ arcsec$^2$ field of view that allows us to construct robust, spatially resolved kinematic maps of $V$ and $\sigma$ for each galaxy extending to at least $2 R_e$. Using these maps, we study the radial dependence of the stellar angular momentum and other kinematic properties. We see the familiar division between slow and fast rotators persisting out to a large radius in our sample. Centrally slow rotating galaxies, which are almost universally characterized by some form of kinematic decoupling or misalignment, remain slowly rotating in their halos. The majority of fast-rotating galaxies show either increases in specific angular momentum outward or no change beyond $R_e$. The generally triaxial nature of the slow rotators suggests that they formed through mergers, consistent with a “two-phase” picture of elliptical galaxy formation. However, we do not observe the sharp transitions in kinematics proposed in the literature as a signpost of moving from central dissipationally formed components to outer accretion-dominated halos.

Key words: galaxies: elliptical and lenticular, cD – galaxies: formation – galaxies: kinematics and dynamics – galaxies: structure

Online-only material: color figures

1. INTRODUCTION

Much attention has been recently paid to the formation and evolution of early-type galaxies (ETGs; including both elliptical (E) and lenticular (S0) galaxies), driven in large part by the discovery that ETGs at $z \sim 2$ are ~2–4 times smaller at fixed mass than their present-day counterparts (van der Wel et al. 2006, 2008; di Serego Alighieri et al. 2005; Daddi et al. 2005; Trujillo et al. 2006; Longhetti et al. 2007; Toft et al. 2007; van Dokkum et al. 2008, 2010; Cimatti et al. 2008; Buitrago et al. 2008; Franx et al. 2008; Damjanov et al. 2009; Cenarro & Trujillo 2009; Bezanson et al. 2009; van de Sande et al. 2011; Whitaker et al. 2012). To explain the rapid size evolution from $z \sim 2$ until today, a two-phase picture of ETG growth has emerged. At early times, ETGs form in a highly dissipative environment, with rapid star formation creating massive, compact cores where most of the stars formed in situ (Kereš et al. 2005, 2009; Khochfar & Silk 2006; De Lucia et al. 2006; Krick et al. 2006; Naab et al. 2007, 2009; Joung et al. 2009; Dekel et al. 2009; Oser et al. 2010, 2012; Feldmann et al. 2010, 2011; Domínguez Sánchez et al. 2011). The second phase, dry accretion, is dominated by collisionless dynamics during which star formation is suppressed and most of the stellar mass increase occurs in the galactic outskirts (Hopkins et al. 2009; van Dokkum et al. 2010; Szomoru et al. 2012; Saracco et al. 2012).

While such a two-phase picture is generally compelling, it is uncertain precisely how and when mass is added (e.g., the balance of major to minor mergers). Simple virial arguments (Cole et al. 2000; Naab et al. 2009; Bezanson et al. 2009) as well as recent cosmological simulations (Hilz et al. 2012, 2013; Oogi & Habe 2013) suggest that major and minor mergers have very different effects. Violent relaxation in major mergers generally results in moderate, factor of ~2–3, increases in the half-mass radius for every merger event. Meanwhile, mass buildup via minor mergers deposits more mass in the outskirts, resulting in ~five-fold increases in the radius for similar growth in mass (Hilz et al. 2012). Simulations therefore currently favor a 1 : 5 mass ratio in mergers (Oser et al. 2012; Lackner et al. 2012; Gabor & Davé 2012). However, incomplete modeling of feedback processes (e.g., active galactic nucleus, AGN, and supernovae winds) makes these results uncertain.

Kinematic observations of local ellipticals also contain important information. It has long been known that ETGs are well separated into those that rotate and those that do not (e.g., Bertola & Capaccioli 1975; Illingworth 1977; Davies et al. 1983). The former tend to have lower stellar mass, disky isophotes, and cuspy light profiles, while the latter are triaxial, cored, and massive (e.g., Bender et al. 1989; Kormendy & Bender 1996; de Zeeuw 1985; Franx et al. 1991; de Zeeuw & Franx 1991; van den Bosch et al. 2008). Modern integral-field studies have provided strong confirmation of this general bimodal picture with excellent statistics (e.g., Emsellem et al. 2004, 2007, 2011; Cappellari et al. 2007, 2011; Krajnovic et al. 2011) and have made interesting comparisons with cosmological simulations (Khochfar et al. 2011; Davis et al. 2011; Serra et al. 2014).

In the context of two-phase assembly, it is thought that the global properties of each family can be linked to their formation history. Slow rotators (SRs) are thought to accrete most of their mass in minor dry mergers with up to ~three major mergers (Khochfar et al. 2011). This explains both their low net rotation and their preponderance of kinematically decoupled cores (KDCs) that are likely long-lived remnants of mergers (e.g., Kormendy 1984; Forbes et al. 1994; Carollo et al. 1997; Emsellem et al. 2004, 2007, 2011; Krajnovic et al. 2008). In contrast, fast rotators (FRs) likely grew predominantly through cold gas accretion with at most one major merger (Bois et al. 2011; Khochfar et al. 2011; Davis et al. 2011; Serra et al. 2012) and thus have high rotation velocities.

However, this picture remains uncertain because most observations are limited to within the half-light radius of the galaxy. In contrast, if late-stage growth occurs through dry accretion,
then most of the dynamical changes occur beyond the half-light radius, where stars have longer relaxation times and so carry a record of the merger history (van Dokkum 2005; Duc et al. 2011; Romanowsky & Fall 2012). It is also only in the outer regions that observations become sensitive to dark matter, for which there are concrete predictions from cosmological simulations. Therefore, wide-field kinematic data are required to provide more direct signatures of two-phase growth.

A number of kinematic measurements of ETGs out to a large radius have been made using spatially sparse measurements of planetary nebulae and globular clusters (Méndez et al. 2001; Coccato et al. 2009; Strader et al. 2011; McNeil-Moylan et al. 2012; Arnold et al. 2011; Pota et al. 2013). Most recently, Arnold et al. (2013) presented spatially well-sampled measurements of 22 massive ETGs out to ∼4R_e, as part of the SAGES Legacy Unifying Globulars and GalacXyS (SLUGGS) survey. They showed that a significant fraction of their galaxies (particularly S0s) show a transition from rotation to dispersion-dominated beyond ∼R_e. They interpreted this as a transition between a central dissipational component, formed at early times, and an outer halo-dominated region formed through later dry merging.

However, without full two-dimensional (2D) kinematic coverage from integral-field spectroscopic (IFS) studies of stellar continua, these results alone can be difficult to interpret. Thus far, at large radius, most studies of stellar kinematics either utilize one or two long-slit positions (Carollo & Danziger 1994; Thomas et al. 2011) or focus on individual objects with IFS (e.g., Weijmans et al. 2009; Proctor et al. 2009; Coccato et al. 2010; Murphy et al. 2011). By contrast, Greene et al. (2012, 2013) assembled a sample of 33 massive, local ETGs with observations extending over ∼2–4 R_e. They studied stellar population gradients, finding that most stars in the outskirts were comparatively old and metal poor, consistent with accretion from much smaller galaxies. While they were able to constrain when the stars at large radius formed, dynamical studies are much better suited to revealing where they were formed and how they were assembled.

In this study, we extend the Greene et al. survey by studying the stellar kinematics in conjunction with the stellar populations. We begin in Section 2 by briefly discussing the galaxy sample, before describing our observations, reduction methods, and dynamical modeling in Section 3. In Section 4, we discuss the basic kinematic characteristics of our galaxies at large radius, with particular reference to the SR and FR paradigm. We then go on to explore the possible theoretical implications of our results in Section 5 before concluding in Section 6.

2. THE GALAXY SAMPLE, OBSERVATIONS, AND DATA REDUCTION

The observations analyzed here were taken with the George and Cynthia Mitchell Spectrograph (the Mitchell Spectrograph, formerly VIRUS-P; Hill et al. 2008) on the 2.7 m Harlan J. Smith telescope at McDonald Observatory. The Mitchell Spectrograph is an integral-field spectrograph composed of 246 fibers covering a 107′′ × 107′′ field of view with a one-third filling factor. Each of the 246 fibers subtends 4′′/2, and they are assembled in an array similar to Densepak (Barden et al. 1998). The Mitchell Spectrograph has performed a very successful search for Lyα emitters (Adams et al. 2011; Finkelstein et al. 2011; Blanc et al. 2011) and has become a highly productive tool to study spatially resolved kinematics and stellar populations in nearby galaxies (Blanc et al. 2009; Yoachim et al. 2010; Murphy et al. 2011; Adams et al. 2012).

We use the low-resolution (R ∼ 850) blue setting of the Mitchell Spectrograph. Our wavelength range spans 3550–5850 Å with an average spectral resolution of 5 Å FWHM. This resolution delivers a dispersion of ∼1.1 Å pixel−1 and corresponds to σ ≈ 150 km s−1 at 4300 Å, our bluest Lick index. Each galaxy was observed for a total of ∼two hr on source with one-third of the time spent at each of three dither positions to fill the field of view. Initial data reduction is accomplished using the custom code Vaccine (Adams et al. 2011; Murphy et al. 2011), which performs basic bias subtraction, wavelength calibration, cosmic-ray rejection, sky subtraction, and spectral extraction. Final processing and flux calibration is performed using code developed for the VENGA project (Blanc et al. 2009, 2013). The details of our data reduction are described in Murphy et al. (2011), Greene et al. (2012), and Murphy et al. (2013).

Properties of the entire sample of massive galaxies are shown in Table 1. The sample, selected from the Sloan Digital Sky Survey (SDSS; York et al. 2000), is identical to that presented in Greene et al. (2013) and details of the selection criteria can be found there. However, briefly, galaxies were chosen to have central stellar velocity dispersions σ_c > 150 km s−1, to be observable in a single 107′′ × 107′′ pointing, and to have u − r > 2.2 (Strateva et al. 2001). We then removed spiral galaxies by hand. Finally, only galaxies with half-light radii at least twice the fiber diameter of 4′′/2 were included.

Figure 1 shows some of the key characteristics of our sample compared to that of the volume-limited ATLAS3D survey as well as the more recent SLUGGS survey. By focusing on high stellar velocity dispersion, we have deliberately selected a population of more massive and more distant ellipticals than the ATLAS3D and SLUGGS samples. As a result of their distance they also tend to be more compact on the sky.

We also show the distribution of maximum radii R_{max}, defined as the exterior radius of the outermost spatial bins (Figure 1). Beyond R_{max} we cannot achieve our limiting signal-to-noise ratio (S/N) of 15 even in bins extending over half the face of the galaxy and with a width of R_e. Our maximum radii extend well beyond the ATLAS3D sample in both kiloparsecs and R_e, and achieve depth comparable to the SLUGGS sample. However, we mention two caveats. First, as in our prior papers, we adopt the SDSS ”model” radius (based mostly on the de Vaucouleurs fit; de Vaucouleurs 1948; Graham et al. 2005) as the effective radius (R_e). In principle, galaxy profile shape is a function of mass (e.g., Caon et al. 1993; Kormendy et al. 2009), but fitting the galaxies with a fixed Sérsic (n) index of four has the benefit that we are less sensitive to both sky subtraction errors (Mandelbaum et al. 2005; Bernardi et al. 2007) and to the detailed shape of the light profile in the very faint wings (e.g., Lackner & Gunn 2012). In the effort to have a uniform analysis, we have therefore adopted the effective radii published by the SDSS, which tend to be small compared to literature values. Furthermore, our outermost radii correspond to measurements over wide bins in both the radial (R_e) and azimuthal (π) directions, and so it is worth bearing in mind that while we reach large radius we do so at low spatial resolution.

Finally, we will often examine properties of our sample as a function of stellar mass. Stellar masses are based on the stellar population synthesis (SPS) presented in Greene et al. (2013) based on Lick index modeling within ∼R_e (Graves & Schiavon 2008). Using the α-enhanced models of Schiavon (2007),
SDSS $r$-band photometry, and assuming a Salpeter initial mass function (IMF), we derive a luminosity-weighted global $M/L$. The inferred stellar masses are subject to systematics from emission-line contamination, which primarily affects H$eta$ and therefore the stellar ages (e.g., Graves et al. 2007). As a sanity check, we extract $K$-band luminosities from the Two Micron All Sky Survey Extended Source Catalog (available online3; Huchra et al. 2012), and use the empirical scaling of Cappellari (2013) based on kinematics to calculate an independent stellar mass. We find agreement within $\sim 30\%$ in all cases. Given the order-of-magnitude range probed by our galactic sample, we are therefore able to robustly separate galaxies into mass bins.

3. ANALYSIS: KINEMATIC MODELING

We briefly outline here the higher-level analysis (source masking and binning) involved in preparing the data for kinematic measurements. We then describe the extraction of kinematic parameters using the penalized PiXel Fitting (pPXF) technique of Cappellari & Emsellem (2004).

3.1. Source Masking

Before coadding or fitting any spectra, we first mask out any fibers on the integral-field unit (IFU) that are dominated by foreground sources. Close to half of our galaxies (NGC 219, NGC 661, NGC 677, IC 301, NGC 1286, IC 312, NGC 1267, NGC 3837, NGC 3842, NGC 4065, NGC 4952, NGC 6127, NGC 664, NGC 7509, and NGC 7684) require masking in some part beyond $R_e$, though in most cases the external sources are not extended and so do not affect more than one or two fibers.

Two galaxies, NGC 1267 and NGC 6482, also have bright stars between us and the galaxy center, which contaminate four fibers on the integral-field unit (IFU) that are dominated by foreground sources. Close to half of our galaxies (NGC 219, NGC 661, NGC 677, IC 301, NGC 1286, IC 312, NGC 1267, NGC 3837, NGC 3842, NGC 4065, NGC 4952, NGC 6127, NGC 664, NGC 7509, and NGC 7684) require masking in some part beyond $R_e$, though in most cases the external sources are not extended and so do not affect more than one or two fibers.

3.2. Stellar Ages

We use the penalized PiXel Fitting (pPXF) technique of Cappellari & Emsellem (2004) to derive the inferred stellar masses and ages. We employ the penalized PiXel Fitting (pPXF) technique of Cappellari & Emsellem (2004) to derive the inferred stellar masses and ages. The inferred stellar masses are subject to systematics from emission-line contamination, which primarily affects H$eta$ and therefore the stellar ages (e.g., Graves et al. 2007). As a sanity check, we extract $K$-band luminosities from the Two Micron All Sky Survey Extended Source Catalog (available online3; Huchra et al. 2012), and use the empirical scaling of Cappellari (2013) based on kinematics to calculate an independent stellar mass. We find agreement within $\sim 30\%$ in all cases. Given the order-of-magnitude range probed by our galactic sample, we are therefore able to robustly separate galaxies into mass bins.

3.3. Stellar Velocities

We use the penalized PiXel Fitting (pPXF) technique of Cappellari & Emsellem (2004) to derive the inferred stellar masses and ages. The inferred stellar masses are subject to systematics from emission-line contamination, which primarily affects H$eta$ and therefore the stellar ages (e.g., Graves et al. 2007). As a sanity check, we extract $K$-band luminosities from the Two Micron All Sky Survey Extended Source Catalog (available online3; Huchra et al. 2012), and use the empirical scaling of Cappellari (2013) based on kinematics to calculate an independent stellar mass. We find agreement within $\sim 30\%$ in all cases. Given the order-of-magnitude range probed by our galactic sample, we are therefore able to robustly separate galaxies into mass bins.

3.4. Stellar Rotation Curves

We use the penalized PiXel Fitting (pPXF) technique of Cappellari & Emsellem (2004) to derive the inferred stellar masses and ages. The inferred stellar masses are subject to systematics from emission-line contamination, which primarily affects H$eta$ and therefore the stellar ages (e.g., Graves et al. 2007). As a sanity check, we extract $K$-band luminosities from the Two Micron All Sky Survey Extended Source Catalog (available online3; Huchra et al. 2012), and use the empirical scaling of Cappellari (2013) based on kinematics to calculate an independent stellar mass. We find agreement within $\sim 30\%$ in all cases. Given the order-of-magnitude range probed by our galactic sample, we are therefore able to robustly separate galaxies into mass bins.

3.5. Stellar Masses

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Figure 1. Characteristics of our galaxy sample (black) as compared to the volume-limited ATLAS$^{3D}$ survey of ETGs (gray; Cappellari et al. 2011) and the 22 massive galaxies in the SLUGGS survey (blue; Arnold et al. 2013). We show the $K$-band magnitude and half-light radii (top left), the distribution of central dispersions ($\sigma_c$) as a function of luminosity (top right), the distribution of maximum observed radii (bottom left), and the distribution of Hubble types (bottom right). We note that the radii are measured by the SDSS for our galaxies using a deVaucouleurs fit to the light profile, whereas they are based on RC3 for the ATLAS$^{3D}$ and SLUGGS galaxies. For clarity, we have truncated the histogram at bottom left. In the truncated bins, there are 120, 95, and 30 ATLAS$^{3D}$ galaxies, respectively.

(A color version of this figure is available in the online journal.)

out these fibers but instead deal with the emission lines in our fitting procedure (see Appendix A).

3.2. Spatial Binning

We require a minimum S/N of 15 (justified in Appendix A) to extract robust kinematics, but only the very central individual fibers have such high S/N. Therefore, we must perform our analysis on radially binned spectra. All spectra are resampled onto a common wavelength grid over the range $4000 \AA < \lambda < 5420 \AA$. Both spectra and errors are then weighted by their flux, coadded, and renormalized. We use flux-weighted addition with iterative sigma clipping, which provides a simple and reliable estimate of the coadded errors. The spectra combined in this manner are nearly identical to those derived from the biweight estimator (Beers et al. 1990) employed in Murphy et al. (2011).

The size of each spatial bin is set by the minimum S/N requirement. The innermost fibers that pass this threshold are analyzed without further coaddition. We then bin in elliptical annuli set by the axial ratio measured from SDSS. Each radial bin begins with a width of $0.5 R_e$ along the major axis and is further separated into five angular bins in each quadrant, each with equal width in $\sin \theta$. Spectra are folded across the minor axis, so we are left with 10 angular bins in total (Gebhardt et al. 2000, 2003; McConnell et al. 2012). When an angular bin falls below the S/N threshold, it is merged with its nearest neighbors until we are left with only two angular bins, one on each side of the major axis, at a given radius. If more binning is required, then the size of the bin is increased radially by 0.1 $R_e$ until we cross the S/N threshold or the edge of the IFU is reached. With this procedure we are typically able to probe out to $\sim 4 R_e$ with full angular information available only for the inner bins.

Figure 2 demonstrates our binning scheme. In the case of the spatially extended galaxy NGC 4952, shown in the top panel of Figure 2, we are able to retain many individual fibers and then eventually end with five purely radial bins of varying width. Even here, we can only resolve angular structure out to $\sim 1.5 R_e$, whereas the outermost bin runs over the edge of the IFU. NGC 426 (bottom), while still quite massive, is one of our smallest galaxies on the sky. It has a much smaller inner region and only three radial bins. Nevertheless, because the galaxy is so compact, we are able to probe out to $\sim 3 R_e$.

3.3. Kinematics

In principle, stellar velocity dispersions can be measured in a number of ways, including Fourier techniques such as the cross-correlation (Tonry & Davis 1979) and the Fourier quotient (Simkin 1974; Sargent et al. 1977). However, now that computational costs are no limitation, direct pixel-by-pixel fitting (Burbridge et al. 1961; Rix & White 1992) allows for masking of emission lines and does not suffer from windowing problems. We employ the direct fitting pPXF technique of Cappellari & Emsellem (2004) to calculate our stellar kinematics. In brief, pPXF convolves a library of stellar templates with a line-of-sight velocity distribution (LOSVD) function that is modeled as a Gauss–Hermite series (van der Marel & Franx 1993; Gerhard 1993):

$$L(v) = \frac{e^{-\frac{(v - V)^2}{\sigma^2}}}{\sigma \sqrt{2\pi}} \left[ 1 + \sum_{m=3}^M h_m H_m(y) \right],$$

(1)

where $y = (v - V)/\sigma$ and the $H_m$ are the Hermite polynomials. The free LOSVD parameters $\{V, \sigma, h_i\}$ are fit by minimizing over a given objective function using the Levenberg–Marquardt
Figure 2. Locations of bins for galaxies NGC 4952 (top) and NGC 426 (bottom). We show fiber positions for one dither (crosses), bin locations, and the major (red) and minor (blue) axes. Radial bins vary in size between 0.5 and 1 $R_e$. We note that a typical observation involves three dithers of the IFU so that sky coverage is three times denser than shown.

(A color version of this figure is available in the online journal.)

method for nonlinear least squares problems. The objective function itself is regularized to favor Gaussian profiles so that

$$\chi^2_p = \chi^2 (1 + \lambda^2 D^2),$$

$$D^2 \approx \sum_{m=3}^{M} h_m^2,$$  \hspace{1cm} (2)

with $\lambda \sim 0.7$ found to work well empirically (Cappellari et al. 2011). We find no significant deviations from Gaussian LOSVDs in our data, so we simply set $\lambda = 0$, or equivalently fix all Hermite moments to zero, and the problem reduces to pixel-fitting by standard $\chi^2$ minimization with a Gaussian LOSVD. We fit over a large wavelength range that starts just redward of the 4000 Å break and extends to the Fe lines at 5420 Å. Over this region the continuum is well modeled with multiplicative Legendre polynomials of order 10, and the presence of emission lines has little systematic effect on the derived kinematics. A more detailed justification for our choice of wavelength region, continuum polynomial degree, and LOSVD can be found in Appendix A.

Errors for our Gaussian fits were estimated using a Monte Carlo method. We started with the noiseless fit to each spectrum and added Gaussian-distributed noise to each pixel according to its error array. The new noisy spectrum was then fit using pPXF. When repeated over many realizations of the added noise, this produces an estimate of the errors in our fits to $V$ and $\sigma$. In a small number of galaxies, measured dispersions fell well below the instrumental dispersion ($\sigma \lesssim 100 \text{ km s}^{-1}$), and measured errors approached $\sim 20\%$. These measurements were deemed unreliable and ignored in all further analysis.

Our stellar templates were chosen from SPS spectra, as generated by the Flexible SPS (FSPS) code (Conroy et al. 2009) calibrated to the observational data in Conroy & Gunn (2010), with an intrinsic resolution of 2.5 Å FWHM. Because pPXF is sensitive to the completeness of the stellar library (Cappellari et al. 2011), we adopted a wide range of ages, 3 Gyr $< t <$ 13.5 Gyr, and alpha-enhancements, $0 < [\alpha/\text{Fe}] < 0.4$, alongside a Chabrier IMF for our template library. We then allowed each binned spectrum to fit to a weighted sum of these templates. We used SPS models rather than stars to gain some additional insight into the stellar populations of our galaxies. However, we did cross-compare with stellar templates and examine our sensitivity to template mismatch in detail, with resulting systematic errors in our kinematic estimates of $\sim 10$–20 km s$^{-1}$.

### 3.4. Robustness of the Kinematic Fits

Our extracted kinematics are subject to both statistical errors and systematic uncertainties in the continuum, the degree of non-Gaussianity in our LOSVD, the choice of stellar templates, and the presence of emission lines in certain galaxies. We therefore tested the robustness of our kinematic fits to all of these uncertainties in Appendix A. As a summary, we show in Figure 3 example fits to the central and outermost fibers in NGC 4952 and NGC 426. We see that the effects of template mismatch are relatively small, though not entirely negligible, especially in the case of NGC 426.

We also show comparisons of our central velocity dispersions to literature data in Figure 4. Almost all of our galaxies have dispersions in the SDSS catalog (Blanton et al. 2005), and we supplement these with the lists compiled by Whitmore et al. (1985), McElroy (1998), and most recently Ho et al. (2009). We match the SDSS aperture relatively well, whereas the Ho et al. (2009) measurements had a similar 2" × 2" aperture, and the Whitmore et al. (1985) and McElroy (1998) compilations were placed on a 2" × 4" system. As can be seen from Figure 4, we find a small systematic negative bias in our dispersion
calculations of around 20 km s\(^{-1}\) on average. The low resolution of our fibers means that we blend dispersions out to larger radius than SDSS and so expect to find systematically smaller dispersions. Furthermore, this bias is typically less than \(\sim 2\sigma\) and is much smaller than the large measured dispersions of \(\gtrsim 150\) km s\(^{-1}\).

### 3.5. Tracing Angular Momentum

In moving from an inner disk or bulge-like component to an outer stellar halo, we may expect changes in how much of the galaxy angular momentum is stored in random as opposed to ordered motion. With long-slit spectroscopy, typically only the ratio of maximum observed rotational velocity (\(V_{\text{max}}\)) to central dispersion (\(\sigma_c\); Illingworth 1977; Binney 1978b; Davies et al. 1983) can be measured. With IFS, which provides full 2D kinematic information, we can construct a more robust measure incorporating both radial and spatial variations. Binney (2005) introduced the ratio of the luminosity-weighted integrated quantities (\(\langle V^2 \rangle\) and \(\langle \sigma^2 \rangle\)). However, weighting by the surface brightness alone tends to overestimate the importance of central regions and confine very different kinematic structures, such as organized rotation versus small central KDCs. To counteract this limitation, the Spectrographic Areal Unit for Research on Optical Nebulae (SAURON) survey introduced the parameter \(\lambda_R\) (Emsellem et al. 2007), which weights by radius as well as flux and therefore measures the projected baryonic specific angular momentum:

\[
\lambda_R \equiv \frac{\langle R |V| \rangle}{\langle R \sqrt{V^2 + \sigma^2} \rangle},
\]

where the brackets indicate a flux-weighted sum within an ellipse of mean radius \(R\). In calculating \(\lambda_R\), we adopt the approach of Wu et al. (2014) and slightly modify the above definition. Instead of taking the absolute value of the velocity, we sum over the actual velocity separately on both sides of the rotation axis. This allows positive and negative noise terms to cancel, resulting in a smoother profile.

Errors on \(\lambda_R\) are estimated using the formal fit errors to \(V\) and \(\sigma\). Whereas systematic errors in the pPXF fits are likely an important factor, particularly in the inner regions (Emsellem et al. 2011), they will tend to have roughly the same effect on all galaxies. Therefore, these error estimates are at least indicative of the relative differences between galaxies.

Using \(\lambda_R\), Emsellem et al. (2007) found that SRs and FRs could be quite robustly separated, with SRs being separated by \(\lambda(R_e) \lesssim 0.1\) and FRs by \(\lambda(R_e) \gtrsim 0.1\). Emsellem et al. (2011) and Krajnović et al. (2011), looking at the full ATLAS3D sample, found that this simple picture was slightly blurred by inclination effects because a flattened system viewed face-on would have a profile similar to a nearly spherical galaxy seen at a large inclination angle. However, with a modified definition of FRs, \(\lambda(R_e) \gtrsim 0.31 \times \epsilon_e\), the same picture of two dichotomous families separated by their kinematics and formation processes still holds (e.g., Bender et al. 1989; Kormendy & Bender 1996; de Zeeuw 1985; Franx et al. 1991; de Zeeuw & Franx 1991; van den Bosch et al. 2008).

We calculate \(\lambda_R\) evaluated at the effective radius for each galaxy and classify them as SRs or FRs based on the Emsellem et al. (2011) definition. Twenty one of our galaxies are FRs, and the remaining 12 are SRs. As we will see below, there are some borderline cases, galaxies classified as FR that are right at the boundary within \(\sim R_e\) but then do not rotate at all in their outer parts. Even sticking to the strict definition, we have a much higher percentage of SRs than the 14% found in the ATLAS3D sample. We also note that these classifications are entirely derived from the kinematics within \(R_e\). In Section 5.2 we will explore changes in \(\lambda_R\) with radius.

### 3.6. Kinemetry

Beyond just the angular momentum content with radius, we can also investigate different kinematic components in the galaxies. We turn to kinemetry (Krajnović et al. 2006) to help identify and characterize substructures in these maps. Kinemetry extends the basic assumption of photometry, that the surface brightness of ETGs is constant to within \(\lesssim 1\%\) along best-fit ellipses, to higher-order moments of the LOSVD. It assumes that symmetric (even) moments, such as the dispersion, are constant along ellipses while antisymmetric (odd) moments, such as the velocity, satisfy a simple cosine law to first order. Therefore, by fitting these kinematic parameters in elliptical annuli we may obtain simple radial profiles of the velocity and dispersion, showing the scales at which important kinematic transitions occur.

In particular, application of kinemetry to our velocity maps allows us to derive radial profiles of the kinematic position angle (PA\(_{\text{kin}}\)) and flattening (\(q_{\text{kin}}\)) of our best-fit ellipses. We may furthermore decompose the velocity along these ellipses into
where is the ellipse radius and is the systemic velocity, set to a constant across all radii. The simple cosine law decomposition is dominated by the first-order term, which captures the rotation curve. By choosing best-fit ellipses we effectively minimize all higher order terms up to , which tend to occur in transitions between components rotating at different velocities or PA.

This kinematic analysis is essentially identical to that performed for the SAURON galaxies in Krajnović et al. (2008) and the ATLAS3D sample in Krajnović et al. (2011), but because our data are so different we uncover different kinds of structures. Our galaxies have on average about 40 binned data points out to ~3–4 compared to the thousands of points available to ATLAS3D galaxies within . We cannot resolve classic kinematically decoupled components, but we cover much larger-scale features.

Our sample characteristics are also different; a large fraction display little to no net rotation. These galaxies must be treated differently because the determination of best-fitting ellipses for a velocity map close to zero everywhere is highly degenerate. Therefore, for cases where we have very low velocities or PA we follow the approach of Krajnović et al. (2008) and rerun the kinematic analysis assuming or peak in , or rapidly declining dispersion profiles at large radius, most are consistent with remaining flat beyond , whereas most FRs occupy a much broader range of dispersions, particularly within . In this large radius limit, most unresolve the stellar kinematics out to distances well beyond most existing samples.

In Figure 5, we show the velocity, velocity dispersion, and profiles for all galaxies. In general, we find that is declining gently (~23% per decade in radius on average), as has been observed many times at smaller radius (e.g., Jorgensen et al. 1997) and has also been reproduced in simulations (e.g., Remus et al. 2013; Wu et al. 2014). Whereas some galaxies appear to show rising dispersion profiles at large radius, most are consistent with remaining flat beyond within the measurement uncertainties. However, the two most massive galaxies in our sample, NGC 677 and UGC 4051, do show significant, albeit small (~5% above ), rises in dispersion. The velocity dispersion profiles also appear to show a rough split between FRs and SFRs. Most SFRs have comparatively flat dispersions, particularly within . By contrast, FRs tend to show more rapidly declining dispersion profiles out to .

Given the integral nature of , in most cases galaxies reach a limiting value of at ~2 . This large radius limit, most SFRs have , whereas most FRs occupy a much broader continuum above . Classifications based on kinematics within are therefore quite accurate out to much larger radii. The main exceptions are the galaxies NGC 677, IC 301, and NGC 3837, which are classified as FRs based on but at large radius show characteristic of minimal rotation.

This is also clear if we consider the behavior of as a function of observed ellipticity (Binney 1978b). In Figure 6, we show galaxies on the plane at , , and . Very few galaxies show significant changes in even beyond . Almost all changes are restricted to increases in ordered rotation among FRs, which tend to continue rotating out to .
enough decreases to transition from fast rotation within Re profiles tend to be flat or rising for the SC FRs, as shown in radii well beyond Re. The only galaxies that show significant enough decreases to transition from fast rotation within Re to slow rotation in their outskirts are the three galaxies identified in the previous paragraph, which uniformly also have higher ellipticity in their outskirts.

4.2. Kinematic Classification

We now turn to identifying substructures based on kinemetry. We first classify each galaxy as SC or MC, and then classify each component as either DR, LV, KT, or KD. Thirteen (40%) of our galaxies are SC systems, a slightly higher percentage than the 31% in the SAURON sample. We do not necessarily expect these numbers to align because the two samples cover different mass ranges and, in addition, we are unable to resolve central structures with sizes \( \lesssim 1 \) kpc. Of the SCs, only one (IC 1152) is an SR, and the remaining 12 are SC FRs. Almost universally, the SC in these cases shows DR and close to perfect alignment between kinematic and photometric PA. Furthermore, the \( \lambda_R \) profiles tend to be flat or rising for the SC FRs, as shown in Figure 5. There are one or two examples with small kinematic twisting (NGC 219 and UGC 1382) as well as two disk-like rotators (NVSS J032053+413629 and IC 312) that show strong kinematic misalignment in the sense that \( \lambda_{PA_{\text{kin}}} \) deviates from the photometric PA by close to 90° at large radius.

Of the MC galaxies, 33% contain an LV component in the center with the rotation curve increasing outward. An additional 28% have a KT. The remaining 39% contain a KD ranging in size from 1 to 7 kpc. We now describe the properties of these subclases.

There are 10 MC FRs, which come in a few varieties. Three of them have disky kinematics everywhere except in a small LV region in the center. Two such examples of these, NGC 474 and NGC 661, are identified in Figure 7, which shows radial profiles of \( k_1 \), \( \lambda_{PA_{\text{kin}}} \), and \( k_6/k_1 \) as well as 2D kinematic maps for these two galaxies. Very likely these rapid drops in velocity and \( \lambda_R \) point to small rotating components that are unresolved by our observations. In particular, our observations of NGC 474 and NGC 5982 show low velocities in their central fibers, whereas higher resolution SAURON kinematics identify KDCs rotating
at $\sim 50$ km s$^{-1}$ within 1 kpc. The velocities also appear to drop in the outer parts of the FRs, but this is likely due to our large spatial and angular bins at large radius.

Another four of the MC FRs are typified by NGC 474, shown in the bottom panel of Figure 7. These relatively slowly rotating FRs contain two distinct disk-like components, in the case of NGC 474 separated by a PA shift of about 15$^\circ$ at 2 kpc. The transition is also marked by a clear hump in $k_1$ and a minimum of $k_1$. The SAURON kinematics of NGC 474 also show an additional inner disk-like component at 0.8 kpc (Krajnović et al. 2008) that we do not detect, empirically determining that structures with sizes $\leq 7''$ are not discernible in our data.

There are three remaining MC FRs (NGC 677, shown in the top of Figure 8, NGC 3837, and IC 301), and these are the most difficult to classify. Whereas technically they satisfy the FR criterion, their $\lambda_R$ values are borderline between FRs and SRs, and they do not rotate at all beyond $\sim 1.5$–2 $R_e$. From Figure 6, we see that all of these are low-ellipticity galaxies, which never rotate particularly fast in the sense that $\lambda(2R_e) \lesssim 0.15$. NGC 677 exemplifies this class. NGC 677 also has an interesting outer dispersion profile that appears to start to rise again at around 3 $R_e$ (10 kpc) on both sides of the galaxy along the minor axis, as has been seen in a few central galaxies (see, e.g., Dressler 1979; Kelson et al. 2002; Loubser et al. 2009; Jimmy et al. 2013; Murphy et al. 2013 for other examples of dispersion profiles rising outward).

In fact, these three borderline cases have kinemetric profiles very similar to five of the MC SRs. Specifically, they all have a central component with low-amplitude rotation and large angular differences between photometric and kinematic PAs, which then transitions to an LV component at larger radius. NGC 5127 (Figure 7, top left) is one good example. The three borderline cases were classified as FRs only because the scale of the inner rotating component is a bit larger than for the typical MC SRs. Therefore, while we technically count these three galaxies as FRs, perhaps they are better considered as SRs with a very extended KD in the center. These central KD components, with sizes of 2.2–7 kpc, are considerably larger in size than KDCs (0.2–1.8 kpc in SAURON; Kormendy 1984; Forbes et al. 1994; Carollo et al. 1997; Krajnović et al. 2008), but otherwise they are kinematically quite similar.

Finally, beyond the one SC SR and the five MC SRs with KD components, we see one more type of MC SR, comprising five galaxies that show steadily increasing $\lambda_R$ profiles in Figure 5. As can be seen from Figure 6, none of them increase their rotation enough to become FRs in their outskirts. All of the five galaxies, and particularly NGC 6482, also show evidence of misalignment between their photometric and kinematic PAs.

We see this in Figure 9, which plots the misalignment angle ($\Delta PA_{\text{kin}} - \Delta PA_{\text{phot}}$) of the outermost component in each galaxy, generally covering radii between $\sim 0.5$–2.5 $R_e$. Here, $\Delta PA_{\text{kin}}$ and $\Delta PA_{\text{phot}}$ are calculated independently in best-fit elliptical annuli, using kinemetry applied to our kinematic data and $r$-band
Figure 7. Kinematic and kinemetric maps for galaxies NGC 661 (left) and NGC 474 (right). In each case we show 1D radial kinemetric profiles including the PA (top), first coefficient in the harmonic dispersion expansion $k_1$ (the rotation curve; top middle), and $k_5/k_1$ (middle). Below are 2D maps of the velocity (bottom middle) and velocity dispersion (bottom) for each galaxy. NGC 661 is very similar to most of the SC FRs in our sample, with flat $k_5/k_1$ and PA and a rotation profile that flattens or decreases slightly beyond $\sim R_e$. It also possesses a more pronounced LV region in its inner kiloparsecs, which we believe is characteristic of an unresolved KD component. NGC 661 is a more typical MC FR, with a clear transition between two disk-like components at 2 kpc.

photometry, respectively. The average misalignment angle for a given galaxy or component is then found by taking a luminosity-weighted average over all radii in that component. Because we restrict our attention to the range $[-90^\circ, 90^\circ]$, this is comparable to the kinematic misalignment angle $\sin \Psi = |\sin PA_{\text{kin}} - \sin PA_{\text{phot}}|$ defined by Franx et al. (1991). We choose to only show the outer component to avoid any strong luminosity bias toward central regions and to avoid the rapid transitions in PA_{\text{kin}} seen between different components.

In the FRs, PA_{\text{kin}} is well defined, and in almost all cases is aligned with PA_{\text{phot}}. It is more difficult to determine the situation for the SRs because they are nearly round and have poorly defined PA_{\text{phot}}. However, the five MC SRs with increasing $\lambda_R$ profiles have better defined and quite large misalignment angles. NGC 6482 specifically, highlighted in Figure 9, is misaligned by $\sim 60^\circ$. Such misalignment is typically interpreted as evidence of triaxiality because projection effects in triaxial galaxies can lead to observed differences between the angular momentum vector and the major axis (Statler 1991). Therefore, we suggest that at least half of our SR galaxies probably have triaxial structure. This fits in with the existing picture of SRs within $R_e$, which show signs, based on their photometry, of being mildly triaxial (Binney 1978a; Tremblay & Merritt 1995, 1996; Krajnovi\'c et al. 2008; Krajnovi\'c et al. 2011).

5. DISCUSSION

5.1. Expectations for Large-radius Kinematics

Before we examine the kinematics of our galaxy sample at large radii, we begin by reviewing the possible formation paths for ETGs and the results we may expect from any given formation scenario. The so-called two-phase picture of elliptical galaxy formation (van der Wel et al. 2008; Naab et al. 2009; Oser et al. 2010; Khochfar et al. 2011; van de Sande et al. 2013) posits that the central $\sim 1$–5 kpc of galaxies are initially formed by a fast, dissipational phase, which leaves behind a compact stellar disk with relatively high rotational support $\lambda \sim 0.5$ (Elmegreen 2009; Dekel et al. 2009; Ceverino et al. 2010; Khochfar et al. 2011).
Figure 8. Identical to Figure 7 for galaxies NGC 5127 (left) and NGC 677 (right). NGC 5127 is a typical example of an SR with an extended disk-like KD component at its center. At 5 kpc, there is a sharp transition in PA and a hump in $k_5/k_1$, as the galaxy transitions to an outer LV component. On the other hand, NGC 677 is an example of a galaxy classified as an FR based on $\lambda(Re)$ but displaying all of the same characteristics as NGC 5127. It is only the extended nature of the inner disk-like component that leads to its classification as an FR.

We are also interested in comparing to the picture presented by Arnold et al. (2013), who were able to use the SLUGGS survey to measure kinematics out to $\sim 5 R_e$. They reported falling profiles in local angular momentum, perhaps reflecting transitions in some FRs from an inner disk to an outer halo at $\sim 5$ kpc, most dramatically in NGC 3377. They also found that S0s with more extended disks are most likely to show rising $\lambda$ profiles at large radius whereas elliptical galaxies are most likely to have falling $\lambda$ profiles. Finally, they reported signs of PA alignment between inner disk and outer halo. Together these were used to argue for the two-phase picture and against the formation of disks by late-time major mergers (Hoffman et al. 2009) because 1:1 mergers result in significant kinematic decoupling between the inner disk and outer halo (Hoffman et al. 2010). However, we note that Naab et al. (2013) present a more nuanced view of the origin of SRs and FRs in which either class can emerge from either a recent major merger or a series of minor mergers, depending on the fraction of the in situ star formation and gas richness of the last major merger.

We also compared with the simulations of Wu et al. (2014). This work derives galaxy kinematics at large radii from

2011). At later times, dry merging expands the galaxy’s outskirts in a manner that reduces $\lambda$ and leaves behind rounder and kinematically hotter remnants (e.g., Naab et al. 2009; Hilz et al. 2013; Taranu et al. 2013).

The two-phase picture predicts that ETGs are inherently multicomponent systems, with rotationally supported disks composed primarily of in situ stars at their centers and much rounder halos made up of accreted material. However, observations at large radius remain limited. While KDCs on small scales are interpreted as evidence of prior dissipational merging, most observed ETGs are FRs for which no evidence of such transition has been found, e.g., by ATLAS$^3D$.

We thus focus on the MC galaxies discussed in Section 4 and whether or not the transitions we observe beyond $R_e$ fit into the two-phase formation picture. We consider kinematic transitions between rotation-supported and dispersion-supported regions, how similar they are to the KDCs of Krajnovic et al. (2011), and whether they are accompanied by any similar transitions in $\lambda R$. Finally, we consider the stellar populations associated with each subgroup and whether they are characteristic of a move from in situ to accreted stars.
SRs, including NGC 677, IC 301, and NGC 3837, and highlight NGC 6482 average over all radii. We observe a general trend of greater misalignment among observations.

Because a local determination largely removes the effect of cosmological simulations of galaxy formation. They focus on a lower-mass sample (stellar masses of $\sim 3-5 \times 10^{10} M_\odot$ compared to our $\sim 2-20 \times 10^{10} M_\odot$) with kinematics that extend out to $\sim 6 R_e$. However, they present simulated rotation and angular momentum profiles that correspond quite well with our observations.

5.2. Galaxies with Changing Kinematics

In order to emphasize radial changes, Arnold et al. (2013) consider a spatially varying specific angular momentum $\Lambda$, defined in elliptical annuli rather than full elliptical apertures. Because a local determination largely removes the effect of radial weighting, $\Lambda$ is very similar to the flux-weighted ratio of velocity to dispersion, $(V^2/\sigma^2)$, used by Binney (2005) and Wu et al. (2014). Our elliptical annuli in the central regions are calculated using 5″ windows and outside of this region are aligned with our previously described spatial bins. Additionally, instead of flux weighting, which does not vary much in each elliptical bin, we weight by the measurement errors. Because S/N is correlated with flux, the two methods do not differ much, but our approach is more robust to outlying measurements.

Figure 10 shows rotation curves ($k_1$), normalized velocity dispersions, and $\Lambda$ profiles for galaxies split into SRs and FRs. To highlight the different kinematic transitions observed, we further subdivide our sample into SC systems, MC galaxies with KDs, and other MC galaxies. In all cases, the local measure $\Lambda$ naturally shows much greater variation than $\lambda$ out to large radius. This is partly due to the lower quality spectra in these regions, which means that errors increase outward rather than decreasing as in the cumulative case. However, we truncate the $\Lambda$ profiles where the errors exceed $\pm 0.025$, whereas the changes we observe in $\Lambda$ are larger than this and thus likely real.

5.2.1. FRs at Large Radius

For FRs, the distribution of $\Lambda$ looks qualitatively similar to the 22 galaxies observed by the SLUGGS survey and the numerical results of Wu et al. (2014). In higher-mass FRs, $\Lambda$ tends to decline slightly or remain flat, whereas the majority of the FRs with lower mass tend to have rising $\Lambda$ profiles. Because we can only reach $\sim 2 R_e$ in these lower-mass galaxies, it is possible that we simply have not reached a large enough radius to see the $\Lambda$ profile flatten or fall.

The galaxies with declining $\Lambda$ profiles are predominantly SC disk-like FRs, as can be seen from the leftmost panel of Figure 10. This subset includes the galaxies with the sharpest declines in $\Lambda$: NGC 774 at low mass and UGC 4051 at high mass, both of which have $\Delta \Lambda \sim 0.1-0.2$. These SC FRs also almost all show a decline in the rotation curve beyond $\sim R_e$, which is typically accompanied by increases in $k_5/k_1$ to $\sim 0.3$. The declining S/N and large spatial bins also contribute to the large $k_5/k_1$ values. However, given the rough correspondence between drops in $\Lambda$ and $k_1$, both of which are calculated independently, it seems unlikely that S/N alone is behind the radial changes.

We now ask whether these galaxies are showing signs of the transition from inner disk to outer halo detected by Arnold et al. (2013). As mentioned earlier, none show nearly as rapid a decline in $\Lambda$ as that seen in NGC 3377, so it is...
not clear on a galaxy-by-galaxy basis that we are seeing this transition. However, statistically, we may ask whether we see the correlation between angular momentum gradients and Hubble type seen by Arnold et al. (2013). In Figure 11, we show the radial variations in $\Lambda$ between $R_{\text{max}}$ and $R_e$ (top) and also between $R_e$ and $0.5R_e$ (bottom) for all FRs as a function of the Hubble type and of $\lambda(R_e)$. In this case, we omit the two galaxies with $R_{\text{max}} < 2R_e$ because these lack sufficient data for a robust measurement of $\Lambda(>R_e)$. We also show the corresponding measurements for the SLUGGS and, where possible, ATLAS$^3$D surveys. The former are taken directly from Arnold et al. (2013), whereas for the ATLAS$^3$D survey, values of $\Lambda$ within $R_e$ are calculated from the full 2D stellar kinematics. In both cases, Hubble types are taken from the HyperLeda$^4$ database (Paturel et al. 2003).

As described in Arnold et al. (2013), the fastest-declining SLUGGS galaxies tend to be elliptical, whereas most of those that rotate more outward are S0s. However, we do not notice any such trend for our sample. If anything, the reverse holds true, with our S0s having the fastest-declining $\Lambda$ profiles while the ellipticals show the largest $\Lambda$ increases. Hubble type is not a continuous quantity, but if we naively fit lines to the radial gradient $\Lambda(R_{\text{max}}) - \Lambda(R_e)$ as a function of $T$, then we obtain a positive Pearson correlation coefficient of $r = 0.45$ (with probability of null correlation $p = 0.036$) for the SLUGGS sample as opposed to $r = -0.18$ ($p = 0.32$) for ours and $r = -0.01$ ($p = 0.94$) for the joint sample. This seems to point to a lack of correlation between declining $\Lambda$ and disky galaxies.

We lack the statistical significance to make any strong statement about correlations between morphology and large-scale kinematics. However, as an interesting exercise, we may ask the same question of the entire ATLAS$^3$D sample, as shown in the top right panel of Figure 11. Naturally, in this case we are restricted to $< R_e$, but even within this smaller aperture, we already see gradients comparable to or exceeding the changes out to $\sim 4R_e$. Equally, within this much larger sample, we see no evidence of any difference in $\Lambda$ gradients between the E and S0 galaxies, and a simple fit gives a correlation coefficient of $r = 0.01$, entirely consistent with zero.

As a final comparison between the two samples, we may consider the kinematics and morphology of our fastest declining FR, UGC 4051. Figure 12 shows the velocity and dispersion maps for this galaxy. If there were an embedded disk we may expect that along the major axis, where the disk is located, there would be lower velocity dispersion with respect to the minor axis, which contains mostly halo stars. We see no such evidence of such a feature. Kinematic maps of other rapidly declining galaxies (particularly NGC 774) also show no such behavior, although this effect may only be pronounced if the galaxy were edge-on. Given also our low kinematic resolution this does not necessarily preclude the presence of stellar disks in these systems.

There are a number of key differences between our sample and SLUGGS that may explain the differences in our results. First, from a methodological perspective, our galaxies are binned at much lower spatial resolution, particularly at large radius. However, it seems unlikely that this could explain our dearth of galaxies with pronounced declines in $\Lambda$ as compared to SLUGGS. If anything, averaging over large spatial bins would tend to artificially lower the measured velocity and thus also $\Lambda$.

More physically, our sample covers more massive galaxies, which may tend to have smaller $\Lambda$ gradients. For instance, the simulated galaxies in Wu et al. (2014) show a trend with stellar mass, in the sense that the low-mass FRs are more likely to show declining $\Lambda$ profiles. Perhaps we need to probe even larger radii to see the transition to a halo component in these more-massive galaxies. Thus, our differences with the SLUGGS sample may be simply explained by the bias toward higher mass in our sample.

5.2.2. SRs at Large Radius

For at least half the SRs, the picture is comparatively simple. Aside from the completely nonrotating SC SR IC 1152, five SRs show central kinematically decoupled components characteristic of a transition from an inner disky structure to an outer halo. The decoupled components seem to be similar

\footnote{http://leda.univ-lyon1.fr}
to the KDCs described in Krajnović et al. (2011), which were interpreted as remnants of old, wet, major mergers. If these kinematic transitions actually signal a component with a different formation history, then we could be seeing the remnant of an early dissipational component transitioning to an outer halo (Arnold et al. 2013). On the other hand, these components are large (1–7 kpc) and have low amplitude rotation (Δ ≲ 0.2 as compared to Δ ∼ 0.6). Furthermore, the kinematic and photometric position angles are generally misaligned. For all of these reasons, we believe we are instead seeing signs of triaxiality (e.g., Statler 1991). This triaxiality also likes results from merging, as pointed out for NGC 5982 by Oosterloo et al. (1994). In fact, simulations suggest that triaxiality is strongly correlated with the box orbits that result from specifically dry major mergers (Jesseit et al. 2005, 2007; Hoffman et al. 2009).

In the same way, we have argued that the SRs with rising A profiles also show clear signs of triaxiality (as typified by NGC 5982 and NGC 6482). They generally show some evidence of a central LV component that transitions to slow DR. In addition, the PA tends to be misaligned with the photometric axis in the central regions. NGC 6482 particularly shows strong kinematic misalignment of between 20° and 50° out to at least ~2 R_e. Based on their complicated kinematics, both galaxies have been put forward as recent merger remnants (Statler 1991; Oosterloo et al. 1994; Del Burgo et al. 2008). While more detailed comparisons are needed, it seems likely from simulations that a series of minor mergers are needed to reproduce both the low λ and generic triaxial properties of the MC SRs (e.g., Bois et al. 2011).

5.3. Correlations with Stellar Populations

We now ask whether there are any differences in the stellar populations of our sample as a function of λ. For instance, if high λ is a signpost of dissipational formation, we might expect younger, more metal-rich stellar populations in the outer parts of FRs. Following Greene et al. (2013), we construct composite spectra as a function of radius, dividing the sample into FRs and SRs. To try and mitigate the strong impact of σ_e we restrict our attention to galaxies with central stellar velocity dispersion σ_e, as measured by the SDSS, greater than 200 km s^{-1}. There are 10 SRs and 12 FRs included in our stacked spectra.

We construct composite spectra as described in Greene et al. (2013). In brief, we first subtract emission lines iteratively using continuum fits (e.g., Graves et al. 2007). Then, we divide each spectrum by a heavily smoothed version of itself to remove the continuum and combine them using the biweight estimator (Beers et al. 1990). We then measure the Lick indices and invert them to infer the ages, metallicities, and abundance ratios at each radial bin for the SRs and FRs, using EZ_Ages (Graves & Schiavon 2008). In addition to stellar age, [Fe/H], and [α/Fe] abundance ratios, the code also iteratively solves for the [C/Fe] and [N/Fe] abundance ratios, the former based mostly on the C_{2},λ4668 Swann band and the latter on the blue CN bands.

We note that the absolute values of [C/Fe] and [N/Fe] are uncertain because they depend directly on the oxygen abundance. Oxygen, as the most abundant heavy element, has a large indirect impact on the spectra, but because there are no broadband O indices, we must assume a value for [O/Fe]. Here we assume that it tracks the other α elements. Because the C gets bound up in CO molecules, the assumed oxygen abundance has a significant effect on the modeled [C/Fe] and therefore [N/Fe] (Graves et al. 2007; Greene et al. 2013). Specifically, if we lowered the assumed [O/Fe] to a solar value, the [C/Fe] and the [N/Fe] would fall, whereas their relative trend is robust (see discussion in Greene et al. 2013).

The radial profiles of our measured stellar population properties are shown in Figure 13. There are no significant differences between SRs and FRs. However, there are some intriguing hints. First of all, the FRs appear to have a slight tendency to get older in the outermost bins. In fact, we see a weak trend for positive age gradients as well when we consider individual galaxies, but it is not statistically significant. If true, we may be seeing the transition from stellar disk to stellar halo in the FRs. Over the past year, we have gathered data for twice as many galaxies, which will allow us to bin in both σ_e and λ.

We are left with a slightly ambiguous picture of how our galaxy sample ties into two-phase galaxy formation. Our observed FRs may show signs of a transition from inner disk to outer halo through small drops in the net rotation. However, these are typically not accompanied by the significant drops in angular momentum reported in Arnold et al. (2013) or any significant change in stellar populations. Nor are the observed drops in angular momentum correlated with E galaxies, as we might expect if S0s were characterized by more extended disks. Perhaps this is entirely a function of mass because simulations of two-phase galaxy assembly by Wu et al. (2014), with which our observations seem to agree quite well, show fewer angular momentum transitions as we move to higher mass.

6. SUMMARY AND FUTURE WORK

We have presented wide-field 2D kinematic LOSVDs (out to radii between 2 and 5 R_e) for a sample of 33 massive elliptical galaxies previously described in Greene et al. (2013). Our sample comprises 12 SRs and 21 FRs, with classifications based on kinematic information out to R_e. By design, this is a higher fraction of SRs than the volume-limited ATLAS3D and SLUGGS samples.

Despite covering a broad range of central dispersions, sizes, and environments, we find that most of the galaxies can be well classified on the basis of their kinematic and kinemetric information. A majority of the FRs are SC disk-like rotators, with any decoupled components usually being in the form of central low-velocity regions that likely signal unresolved rotation. They do show some tentative indications of transitioning from stellar disk to halo beyond R_e, but we observe no galaxies with the dramatic drops in angular momentum reported in Arnold et al. (2013). Generally, our FR galaxies continue rotating as far out as we observe. A majority of the SRs meanwhile show KD components with disk-like properties at their center, but these typically rotate more slowly and are much larger than the KDCs found in SAURON.

Our work, along with SLUGGS, represents an early effort to classify the outer parts of massive elliptical galaxies based on their kinematic properties. If we interpret the ubiquitous MC nature of the SRs as evidence for different formation histories, then we see some evidence for an “inner” and “outer” component, with a transition ~5 kpc. However, without more concrete comparisons with theory, it is hard to say whether we are seeing different phases of elliptical galaxy growth or just triaxial galaxies in projection.

Furthermore, many of the trends we observe are relatively uncertain due to the small size and incomplete selection of our sample. We are currently in the process of doubling our sample, which combined with more detailed dynamical modeling of our galaxies, should be able to provide more insight into elliptical galaxy formation and particularly two-phase assembly.
Figure 13. Radial gradients in age, [Fe/H], [Mg/Fe], [C/Fe], [N/Fe], and [Ca/Fe] as calculated by EZ_Ages from the Lick indices measured in the composite spectra. We show both the measurements for SR (circles) and FR (squares) galaxies as a function of $R$ in kiloparsecs (left) or $R/R_e$ (right).

(A color version of this figure is available in the online journal.)

Specifically, dynamical studies, which reveal the dark matter (DM) fraction, velocity anisotropy, and gravitational potential, should, in combination with stellar population results, be able to constrain both when and where outer halo stars were assembled. By offering a more direct comparison with cosmological-scale simulations of elliptical galaxy formation, we may then be able to comment more conclusively on exactly when and how the most massive galaxies were formed.

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APPENDIX A

TESTS FOR ROBUSTNESS OF THE KINEMATIC FITS

We show here the results of a series of tests conducted to characterize the robustness of our fits to $S/N$, continuum fitting, shape of the LOSVD, template mismatch, and masking of emission lines. These results were used to motivate our fiducial choice of wavelength region (4000 Å–5420 Å), our minimum $S/N$ threshold, the degree of our continuum polynomial fit, and the assumption of a Gaussian LOSVD.

A.1. $S/N$ Thresholds

We begin by briefly testing the response of pPXF to varying $S/N$, in order to justify our minimum $S/N$ threshold of 15. This is done by fitting each of the templates in our library, convolved with a Gaussian LOSVD with mean zero and dispersion 300 km s$^{-1}$, over a variety of $S/N$. A single realization at a given $S/N$ is found by adding Gaussian random noise to each pixel with a standard deviation set by the pixel flux divided by $S/N$. When this is repeated over 100 Monte Carlo iterations at each $S/N$, we characterize the bias and scatter in our kinematic fits as a function of $S/N$. Fits are made using the whole library of templates so that we do not underestimate the scatter, and the process is repeated for each template to test for any systematic effects with galaxy templates. We test over our fiducial range of 4000 Å–5420 Å, and because the degree of the continuum polynomial is unimportant for this test, we assume a low-order polynomial of degree 4.

The results, shown in Figure 14, first show no bias in the derived dispersions as a function of $S/N$. There is perhaps a slight bias in the inferred velocity (of $\sim 5$ km s$^{-1}$); however, this is significantly smaller than both the velocity uncertainty and the pixel separation. The uncertainty in the derived dispersions rises fairly dramatically for $S/N \lesssim 10$. We therefore conservatively adopt a minimum $S/N$ threshold of 15, where uncertainties are around $\pm 15$ km s$^{-1}$.
Figure 14. S/N vs. measured kinematics for a Gaussian LOSVD of mean zero and dispersion 300 km s$^{-1}$. Error bars show 1σ uncertainties on the derived values estimated over 100 noise realizations. Values are averaged over the whole library of templates. Our chosen threshold of S/N = 15 is also shown (red dashed line). (A color version of this figure is available in the online journal.)

Figure 15. S/N vs. galaxy characteristics inferred from the best fit templates. We show errors in the inferred age as a function of template age in Gyr (right) and errors in the inferred metallicity as a function of template metallicity in [α/Fe] (left). Error bars again show 1σ uncertainties, and our chosen S/N threshold is overplotted in red. (A color version of this figure is available in the online journal.)

As a sanity check, we also consider how accurately our best-fit templates represent the characteristics of the input template. We show in Figure 15 the errors in our derived ages and metallicities. The inferred ages and in particular metallicities of our fits tend to be quite accurate. At low S/N, older galaxies tend to be biased downward by $\sim 1$ Gyr, and the reverse holds true for the youngest galaxies. This bias, combined with the spread of $\sim 2$ Gyr at a S/N of 15, means that any estimates of galactic age based on our fits are likely to be uncertain by at least 3 Gyr.

A.2. Degree of the Hermite Polynomial

The effect of including Hermite polynomials of differing degree to the LOSVD function specified in pPXF has also been addressed in some detail by Emsellem et al. (2004). Because pPXF selects against large deviations from Gaussianity, we do not expect the exclusion of higher-order Hermite moments to create significant systematic errors. We simply ask whether characteristic galaxies in our sample show any systematic differences when we choose to model the LOSVD as a fourth-order Gauss–Hermite series.

Figure 16 shows the velocity and dispersion profiles for galaxies NGC 4952 and NGC 426 calculated both with and without third- and fourth-order Hermite terms. In both cases we find almost no difference in the velocity profiles as expected. More importantly, the dispersion profiles appear to show no significant differences when we model $h_3$ and $h_4$. Arguably, there is a trend toward slightly lower dispersion in the higher-order case, particularly at large radius or equivalently lower S/N. This again makes sense because some of the LOSVD power is shifted from the Gaussian term to the Hermite series, lowering the dispersion. However, any deviations are well within 1σ and below $\sim 5$ km s$^{-1}$, so we may safely ignore them and accurately model the LOSVD as a Gaussian alone.

A.3. Absorption Features

Although pixel fitting is robust at relatively low S/N, it can be quite sensitive to template mismatch, which introduces feature-dependent systematics into our dispersion estimates. To investigate how robust we are to this problem, we therefore compare results from a variety of different wavelength regions, centered on different strong spectral features: Ca H and K (3650–4050 Å), G band (4215–4575 Å), Hβ (4445–4975 Å), Mg i b (4900–5420 Å), and Fe (5250–5820 Å), where for the Fe region we mask out wavelengths between 5570 and 5610 Å, which often shows strong emission lines. Because each of these regions is relatively small, the continuum is fit well enough by a fourth-order Legendre polynomial, and uncertainties of less than $\sim 2\%$ are introduced by fitting any polynomial of order between $\approx 2$–6.

We compare regions by taking all of the central fibers from a given galaxy, evaluating the fit in each region, and then calculating offsets from the Mg i b measurements. Results showing the median and standard deviation of the offset distribution for each galaxy are shown in Figure 17. We first note that, in general, there does not appear to be a significant offset between any of the different features in the sense that most galaxies show a median offset consistent with zero. Importantly, the average offset between regions including both Mg i b and Fe blends and Fe blends alone appears to be less than $\sim 10$ km s$^{-1}$, significantly smaller than the discrepancies found in, e.g., Barth et al.
The Hβ, Mg, and Fe regions align quite well over the range 150 < σ < 300 km s$^{-1}$, with discrepancies limited to about ±30 km s$^{-1}$ and almost negligible mean offsets. By contrast, Ca H and K shows a mean offset of close to 20 km s$^{-1}$ alongside a much larger scatter. This is relatively unsurprising because the continuum drops sharply near 4000 Å, and the line shape is quite sensitive to spectral type (see discussion and further references in Greene & Ho 2006).

The only possibly problematic region therefore appears to be the G band, which shows a mild trend with dispersion, underestimating the dispersion of the largest galaxies by up to 17 km s$^{-1}$.

(2002). This is perhaps unsurprising because our set of templates includes a range in [α/Fe] above solar, but it is nevertheless reassuring.
Figure 18. Fits to the central fibers of galaxies NGC 426 (left) and NGC 7509 (right), both of which show strong emission lines characteristic of AGN. (A color version of this figure is available in the online journal.)

Figure 19. Measures of goodness of fit as a function of continuum polynomial degree (n) for dispersions calculated over our fiducial region 4000–5420 Å. We show systematic offsets from the median of dispersions evaluated over the G band (4215–4575 Å), Hβ, (4445–4975 Å), the Mg i b (4900–5420 Å), and the Fe lines redward of Mg i b (5250–5820 Å) on the left. In the middle, we have the $\chi^2$ of the fit to each galaxy normalized by the minimum $\chi^2$. Finally, on the right, we show the continuum power as a fraction of the total galaxy power again normalized to the maximum continuum power. Results shown are calculated as averages over the central fibers in all of our galaxies.

Figure 20. Comparison between dispersions as calculated from the Conroy et al. (2009) and Bruzual & Charlot (2003) templates. We show both the dispersions and the offsets between the two calculations. We note that the results are remarkably well correlated.

A.4. Continuum Fitting

Some care must be taken in fitting this larger region because the continuum is likely to vary on average over a range of $\sim$1500 Å. This may not be captured accurately by stellar templates and a fourth-order polynomial alone. On the other hand, if we increase the degree of the continuum polynomial too.
Figure 21. Maps of the stellar kinematics of all galaxies in our sample. We show from left to right: (i) 1D radial map of stellar mean velocity, where each point corresponds to a different bin at possibly different angular positions (top left), (ii) 2D map of stellar mean velocity (top right), (iii) 1D radial map of stellar velocity dispersion $\sigma$ (bottom left), (iv) 2D map of $\sigma$ (bottom right). In a small number of the galaxies, fibers are absent in certain regions due to masking of external sources in those areas. Several galaxies also show nonuniform binning (e.g., IC 1153) due to small astrometric shifts during observation (see, e.g., Greene et al. 2013, for more detail). The outermost bin is shown in all cases, but as mentioned in the text, occasionally measurements here needed to be discarded due to excessive masking or limited field of view. Finally, low dispersions ($\sigma \lesssim 100$ km s$^{-1}$, which are generally unreliable with errors $\gtrsim 20\%$), are shown in the 2D maps but excluded from 1D plots and all calculations of $\lambda$ and other radial kinematic profiles.

(A color version of this figure is available in the online journal.)

much, we may begin to fit the absorption lines themselves. We therefore need to further test the response of pPXF to the degree of the continuum polynomial between 4000 Å and 5420 Å. In particular, we wish to find the right continuum parameter range that strikes a balance between oversimplifying the continuum and overfitting it, which would tend to draw power from the LOSVD.

We do this by successively fitting the central fibers of each galaxy using a range of higher-order polynomials with degree varying between 2 and 20. The derived dispersions are then compared to the dispersions calculated from the $G$ band, $H\beta$, Mg $\text{b}$, and Fe regions alone. Figure 19 shows the resulting systematic offsets from the median dispersion in these regions, the $\chi^2$ of each fit, and the fraction of spectral power in the continuum.

We see that there are systematic offsets of close to $\sim 20$ km s$^{-1}$ for continuum fits of degree less than 10. Even above this value the fit over our fiducial region slightly overestimates the dispersion relative to the individual regions, but given that there is a small systematic offset between Fe and Mg $\text{b}$ regions, this is probably expected. Above 10 there is also a pronounced drop in the $\chi^2$ of the overall fit; however, by this stage we are clearly
Figure 21. (Continued)
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overfitting the continuum because the continuum power rises dramatically. We therefore use a 10th-order fit, which is found to best balance the competition between underestimating the continuum and introducing false structure on the dispersion scale.

A.5. Template Mismatch

As a final sanity check to see how sensitive we are to the issue of template mismatch, we also compare our calculated dispersions to those extracted from a different set of templates. We use Bruzual & Charlot (2003) single-age stellar population models with $\sigma \sim 70 \text{ km s}^{-1}$ resolution as our comparison set and fit over our fiducial wavelength region. The results in Figure 20 show a very tight correlation between the two sets, so either both sets of templates suffer from similar problems or they are both adequate for our set of galaxies.

APPENDIX B

OBSERVED KINEMATICS

We show, in Figures 21(a)–(l), full 2D profiles of the velocity and velocity dispersion of all galaxies, as well as 1D kinematic profiles.

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