1. INTRODUCTION

Are galaxies fundamentally a simple family of collapsed objects, whose gross structure is describable by a few basic parameters, or are they highly complex systems whose structural properties are determined by a myriad of internal and external factors?

If the former, there must be an analogous construct to the stellar Hertzprung-Russell diagram that testifies to deep, systemic structural patterns among galaxies and serves as a guide to a simple, if not entirely complete, analytic description of galactic structure. The study of stellar structure offers a beautiful example of the power of reductionism in astrophysics. By focusing on the HR diagram, investigators solved the problem of stellar structure without needing to address other unsolved problems, such as the origin of the initial mass function. The observation that the position of main sequence stars on the HR diagram is insensitive to their location in the Galaxy indicates that their structure does not depend sensitively on parameters that vary from one place to another. We now know that mass is the primary determinant of where a star lies on the main sequence. Other physical characteristics, such as age, metallicity, and rotation, affect stellar colors and magnitudes (and therefore should be included in a complete model of stellar structure), but they are relatively minor factors along the main sequence and can be neglected in the interest of isolating the basic physics.

Among galaxies there are hints of analogous “sequences”. These are referred to as galaxy scaling laws and include the Faber-Jackson (FJ; Faber & Jackson 1976) and Tully-Fisher relations (TF; Tully & Fisher 1977), the Fundamental Plane (FP; Djorgovski & Davis 1987, Dressler et al. 1987), and the Fundamental Manifold (FM; Zaritsky et al. 2006a,b). Although it is not yet evident that any of these is as fundamental for galaxies as the main sequence is for stars, they do imply that a limited number of parameters characterize the gross properties of at least certain subsets of galaxies.

There are two arguments against using existing galaxy scaling laws as guides to a fuller description of galactic structure. First, existing scaling laws work only over a limited range of galaxy types and luminosities. While this is not an insurmountable obstacle — not all stars lie on the main sequence — it suggests that the current scaling laws are incomplete and that they will not lead to a description of all galaxies. Second, for historical reasons related to the empirical nature of the scal-
ing laws, their current formulation is not optimal with respect to possible theoretical constructs. For example, one determination of the Fundamental Plane has log $r_e = 1.24 \log \sigma - 0.82 \log I_e + \gamma$ (Jørgensen et al. 1996), where $r_e$ is the half-light radius, $\sigma$ is the velocity dispersion, $I_e$ is the surface brightness within $r_e$, and $\gamma$ is a constant. It is unlikely that a simple theory would reproduce the $1.24$ and $0.82$ coefficients.

In this paper, we attempt to address both of these shortcomings. Although we are not the first to hope to identify a unifying description of galaxies (see $k$-space: Burstein et al. 1997), we achieve three of our key goals: 1) to find an empirical relationship for all galaxies that has comparable scatter to those relations identified previously for limited subsets of galaxies (TF, FJ, FP, and FM), 2) to isolate the critical additional knowledge beyond the virial theorem that is needed to derive this relationship, and 3) to begin constructing the bridge between a purely empirical relationship that utilizes observables and a theoretical one that is based on physical parameters.

In summary, we begin from basic dynamical principles and examine the dimensionality of the family of galaxies, ranging from dSph’s to brightest cluster galaxies and from disks to spheroids. We address our basic question — how uniform are the gross structural properties of galaxies? — by determining that a single scaling relation exists that spans all luminosities and galaxy types and by quantifying its scatter. We employ an extended version of the fundamental plane formalism that reproduces the structural properties of all galaxies at a level comparable to that achieved with either the TF relation for disks or the FP for spheroids. We establish that connecting this new scaling relation to the virial theorem requires knowledge only of the mass-to-light ratio within $r_e$, $\Sigma_e$, and that $\Sigma_e$ can be accurately modeled as a function of the observed structural parameters themselves. We proceed to describe $\Sigma_e$ as a combination of the fraction of baryons converted into stars, $\eta$, and the degree to which those stars are packed within the dark matter halo, $\xi$. Using our empirical findings, we then calculate these two physical parameters for all of our galaxies and compare $\eta$ with independent measurements. The aim of this work is to define simple expressions for basic physical parameters of galaxies that may illustrate which physical processes drive the observed patterns of galactic structure, with the expectation that this will focus subsequent, more detailed theoretical work.

2. THE DATA

To determine the degree to which all galaxies are structurally similar, we need structural parameter measurements for galaxies ranging from spheroids to disks and giants to dwarfs. Part of the legacy of distinct scaling relations for different classes of galaxies are studies that provide the relevant information only for those particular classes of galaxies. For example, there are extensive studies of spheroidal galaxies (e.g., Jørgensen et al. 1996) that are entirely distinct from those of spirals (e.g., Springob et al. 2007). This dichotomy is partly due to the techniques necessary to measure the internal dynamics for disks and spheroids, but it also leads to the use of different photometric systems and definitions. It is impossible to resolve all of those differences, and many existing galaxy samples cannot be included here because they lack some necessary measurements. We describe the spheroid and disk samples that we use below. These constitute a heterogeneous dataset, but span the full range of galaxy types and luminosities, and require minimal corrections for internal comparisons. It is a testament to the robustness of our results that the many differences among the samples that we either ignore or only crudely correct (such as correcting the photometry to $I$ band on the basis of average colors for different galaxy populations) do not derail this investigation.

2.1. Spheroids

Since Zaritsky et al. (2006), there has been one key improvement in the available data on low-mass spheroids. Simon & Geha (2007) present velocity dispersions, and a uniform set of structural parameters, for eight additional Local Group dSph’s, including some of the lowest luminosity systems known. Adding these data to the Zaritsky et al. (2006) compilation greatly increases our sample for extreme values of luminosity, internal velocity, and effective radius. The lack of such data earlier precluded our use of this range in the fitting of the FM, and instead we showed that an extrapolation of the FM accurately fits galaxies in this parameter range (Zaritsky et al. 2006b). Here, we fit to both the previous data for the entire range of spheroid masses (Zaritsky et al. 2006b, and references therein) and the new data for low mass spheroids (Simon & Geha 2007).

2.2. Disks

We focus on three particular disk samples: Pizagno et al. (2007), Springob et al. (2007), and Geha et al. (2006). Here we briefly describe the various data sets.

Of the three samples, the Pizagno et al. (2007) sample allows the simplest comparison to the spheroid samples. The authors provide half-light radii, $i$-band magnitudes, and a range of velocity measures from their optical rotation curves. As they did for their Tully–Fisher analysis, we use their $V_{50}$ measurement, which is a measure of the rotation velocity at a radius that encloses 80% of the galaxy light. We correct the $i$-band magnitudes to Johnson by subtracting 0.4 mag (Fukugita et al. 1995). The next simplest sample for comparison is that of Springob et al. (2007), who provide HI measurements of the rotation and $I$-band photometry. They do not tabulate half-light radii, so we calculate them based on the measured profiles they do provide, the radius that encloses 83% of the light and the radius of the 23.5 mag (sq. arcsec)$^{-1}$ isophote, assuming an exponential surface brightness profile. Among galaxies for which all of the relevant data exist, we only reject systems with $cz < 2500$ km sec$^{-1}$, to avoid the local flow field.

Lastly, the Geha et al. (2006) sample is distinct because it is primarily composed of low luminosity systems with very large gas mass fractions. Because gas fractions are low in normal spirals (Read & TRENTAM 2005), the gas can be ignored with little impact when studying scaling relations like TF for such spirals. However, studies of low mass galaxies show that accounting for all the baryons is critical in maintaining the scaling relation (McGaugh et al. 2000, McGaugh 2005, Geha et al.)
The potential energy is expressed as the ordered component of the kinetic energy as zero. We evaluate the trace of this equation and express it in quantitative detail in [3.2] and [3.3].

We begin with the tensor virial theorem, which is

$$\frac{1}{2} \frac{d^2 I_{jk}}{dt^2} = 2T_{jk} + \Pi_{jk} + W_{jk},$$  \hspace{1cm}(1)$$

where $T$ and $\Pi$ are the contributions to the kinetic energy tensor from the ordered and random motions, $W$ is the potential energy tensor, and $I$ is the moment of inertia tensor. In steady state, the left hand side of Eq. 1 is zero. We evaluate the trace of this equation and express the ordered component of the kinetic energy as $\frac{1}{2} A_0 M v_e^2$ and the random as $A_1 M \sigma^2$, where $v_e$ is the circular velocity in disk galaxies, $\sigma$ is the line-of-sight velocity dispersion for spheroids, $M$ is the mass of the system, and the $A$'s represent the correction factors obtained by fully evaluating the appropriate integrals. Similarly, the potential energy is expressed as $-B_0 GM^2/R$, where $R$ is a characteristic radius that we define to be the half-light radius, $r_e$, and $B_0$ is a correction factor obtained by fully evaluating the appropriate integral. Hence, without loss of generality,

$$A_0 v_e^2 + A_1 \sigma^2 = B_0 \frac{GM}{r_e}. \hspace{1cm}(2)$$

All of the possible real-world complications are encapsulated in the yet unspecified $A$'s and in $B_0$, and, in principle, these could be extremely complicated functions of the formation history and environment of galaxies. The only assumption that we have made so far is that the virial theorem holds over these radii, which is reasonable for galaxies because $r_e \ll r_{vir}$.

To numerically evaluate Eq. 2 we now introduce two sets of simplifying assumptions that we will eventually test by determining whether we reproduce the observations. First, is the kinematic simplification. We reduce the number of $A$ parameters, by requiring $A_0 v_e^2 + A_1 \sigma^2 \equiv AV^2$, where $V \equiv (\frac{1}{2} v_e^2 + \sigma^2)$. This simplification is accurate if we are dealing with isothermal spheres and isotropic velocity dispersions. In such systems, at large radii, $v_e$ for a purely rotationally-supported population equals $\sqrt{2} \sigma$ for a purely pressure-supported population. Furthermore, in such a pressure-supported system, the internal velocity dispersion is equal to the line-of-sight velocity dispersion. To evaluate $V$ for disk galaxies, we will use the measured $v_e$ and set $\sigma = 0$, while for spheroidal galaxies we will use the measured $\sigma$ and set $v_e = 0$.

Although the kinematic simplification relies on highly specific assumptions, both disks and spheroids satisfy the relevant conditions well, and this conversion has been used previously in various contexts (Burstein et al. 1997; Kassin et al. 2007). Optical disks are characterized by flat rotation curves, which imply that the mass profile is that of an isothermal sphere over these radii, and that the velocity tracers, H II regions or neutral hydrogen, are on circular orbits (see Faber & Gallagher 1979). Spheroids also lie in mass distributions that are consistent with being isothermal spheres (Gavazzi et al. 2007), and their stellar velocity dispersions are nearly isotropic if the system is a slow rotator (Cappellari et al. 2007). Due to the nature of our spheroid samples, we expect that there are strong selection biases against fast rotators among the more luminous systems (i.e., they would often be removed from Fundamental Plane studies), and the lowest luminosity systems show little rotation (Walker et al. 2007). Therefore, our sample is likely to satisfy the assumptions involved in the kinematic simplification, but we discuss possible signatures of failure in \[3.5\].

Continuing in our attempt to convert Eq. 2 into an equation that we can numerically evaluate, our second simplification involves the replacement of the difficult-to-measure $M$ with $M_e$, the mass enclosed at $r_e$. We refer to this as the mass simplification. We rewrite $M_e$ as $T_e L_e$, so that it is expressed as a function of observable quantities: $L_e$ and $T_e$, the luminosity ($= \pi r_e^2 I_e$) and the mass-to-light ratio within $r_e$, respectively. We then replace $B_0$ with $B$ to account for the unknown difference between $M$ and $M_e$.

We now apply the kinematic and mass simplifications to Eq. 2 rewriting it as

$$AV^2 = BG \pi T_e r_e I_e. \hspace{1cm}(3)$$

Therefore, we discuss the Geha et al. (2006) sample separately in [3.4]. We use their inclination- and turbulence-corrected velocities, and transform from $r$ to $I$ magnitudes using the colors of late type spirals and the tabulations of Fukugita et al. (1993).
Finally, we take the logarithm of both sides and rearrange terms to obtain
\[
\log r_e - \log V^2 + \log I_e + \log \Upsilon_e - \log A + \log B = \text{const.}
\]

(4)

This equation leads to the rather dispiriting conclusion that galaxies populate at least a six dimensional parameter space — more if yet unspecified parameters, such as \( \Upsilon_e \), are actually functions of additional parameters, like age, metallicity, formation history, bulge-to-disk ratio, or environment. Surprisingly, as shown in Figure 1, galaxies populate a limited region of the \( (r_e, I_e, V) \) space, indicating a much lower dimensionality.

One way in which the dimensionality of the galaxy family might be reduced from that suggested by Eq. 4 is if \( \Upsilon_e \), \( A \), and \( B \) are functions only of \( r_e, I_e \), and \( V \). A simple variant of this scaling is referred to as “homology”, in which the functional forms are assumed to be power laws. Because of the logarithms, the end effect of rewriting Eq. 4 in such a variant is a change in the coefficients of the \( \log V^2 \) and \( \log I_e \) terms. Therefore, the assumption of homology results in a prediction that galaxies lie on a plane in the \( (r_e, I_e, V) \) space. The values of the coefficients describe the tilt of that plane. The success of the Fundamental Plane description for giant ellipticals (Djorgovski & Davis 1987; Dressler et al. 1987; Jørgensen et al. 1996; Bernardi et al. 2003) demonstrates that, over the limited mass range of these galaxies, homology assumption holds surprisingly well. This success was extended in the \( \kappa \)-space formalism of Burstein et al. (1997), where different classes of objects were found to lie on different planes. However, the failure of a single plane to describe the distribution of all spheroidal galaxies demonstrates that over a more extended mass range, which includes the most and least massive spheroids, homology does not hold (Zaritsky et al. 2006a).

Here we take a different approach in that we (1) assume that all galaxies (faint, luminous, disk, and spheroid) fall on a single manifold in the \( (r_e, I_e, V) \) space and (2) examine the behavior of \( \Upsilon_e \) that would make that possible. This approach is motivated by our earlier finding that the behavior of \( \Upsilon_e \) is both simple and quantitatively reasonable for all spheroids (Zaritsky et al. 2006a) — leading to what we termed the Fundamental Manifold (FM) of spheroids. So emboldened, we now assert that for all galaxies deviations from homology are dominated by the behavior of \( \Upsilon_e \), ignoring variations in \( A \) and \( B \) among galaxies. Our approach here represents a philosophical departure from ours and others’ earlier work, which usually focused on establishing or quantifying the tight empirically-derived scaling relationships (e.g., the FP or FM), because we posit the existence of a fundamental manifold of all galaxies and then examine the implications.

3.2. The Simplicity of Galaxies

The treatment described in 3.1 and culminating in Eq. 4 is incomplete. The simple theoretical approach fails because it does not predict the low dimensionality of the data seen in Figure 1. On the other hand, the purely empirical treatment of fitting a manifold to the data in the \( (r_e, I_e, V) \) space fails because it does not connect the actual functional form to a physical framework. Much like the case with the FP coefficients, directly fitting the data will subsume the behavior of \( \Upsilon_e, A, \) and \( B \) in Eq. 4 into the coefficients of the various structural terms (see axes in Figure 1). Instead, we merge the two approaches by retaining the values of the coefficients derived from the virial theorem treatment as given in Eq. 4 and assert that the most distinct break from homology occurs in \( \Upsilon_e \), set \( A \) and \( B \) to be constants, and then solve for \( \Upsilon_e \),

\[
\log \Upsilon_e = \log V^2 - \log I_e - \log r_e + \text{const.,}
\]

(5)

This approach may seem like only mathematical sleight-of-hand, but we will quantitatively test our association of \( \Upsilon_e \) with the dominant departures from homology in 3.3.

To proceed, we evaluate \( \log \Upsilon_e - \text{const.} \) using Eq. 5 and plot the results in Figure 2. We then fit for the function, \( \log \Upsilon_e^f \), that describes these data and also plot the calculated values using this fit in Figure 2. Because we are fitting to a distribution of points in a 3-space, the fitting function will depend on two variables, and the natural choices are those that are distance independent, \( V \) and \( I_e \). We want to minimize the fitting order, while still capturing the behavior of the distribution. As demonstrated by Zaritsky et al. (2006a), there is at least a second-order dependence on \( \log \sigma \) and some dependence on \( \log I_e \), and so we fit to second-order in both \( \log V \) and \( \log I_e \) and include cross-terms. For this fit, we use only a randomly selected one-sixth of the Springob et al. (2007) sample to avoid having that sample dominate the fit. We present the coefficients of our fit in Table 1, but, because of the heterogeneous nature of the data and our avoidance of any type of Malmquist-like corrections (Willick 1994), these numbers are far from definitive.

The distinction between this work, with its complex characterization of \( \Upsilon_e \), and either FP or \( \kappa \)-space, with their assumption of homology, becomes evident when examining Figure 2. The projections of the data and the fitting function in Figure 2 illustrate how even in projection the functional form that describes \( \Upsilon_e \) deviates from power laws. The upper panels contain the inferred values of \( \log \Upsilon_e - \text{const.} \) from Eq. 5 vs. either \( \log V \) or \( \log I_e \). The lower panels, which show the fitted values, \( \log \Upsilon_e^f \), and therefore have no intrinsic scatter, illustrate how the bulk of the observed scatter in the upper panels comes simply from the projection of a complicated surface onto these axes. In other words, the reason why galaxies of the same \( V \) have a range of \( \Upsilon_e \)’s is not primarily because there is intrinsic scatter — say, due to age or metallicity — but rather because galaxies have a range of \( I_e \). For a given \( V \) and \( I_e \), the scatter in \( \Upsilon_e \) is much smaller than that observed in Figure 2. To be specific, the scatter for the entire sample about the fit is 0.094 dex (24% rms in \( \Upsilon_e \)). In contrast, the observed scatter in \( \log \Upsilon_e \) in the upper left panel of Figure 2 for \( 1.9 < V < 2 \) is 0.22 dex (66% rms in \( \Upsilon_e \)).

We are now ready to evaluate the degree to which Eq. 5 describes our set of galaxies. Replacing \( \log \Upsilon_e - \text{const.} \) with \( \log \Upsilon_e^f \) we evaluate Eq. 5 and plot a rearrangement of the terms in Figure 3. By construction, Eq. 5 is satisfied on average when \( \log \Upsilon_e - \text{const.} \) is replaced
Fig. 2.— Projections of log $\Upsilon_e$ and log $\Upsilon_f$. We plot the projections of log $\Upsilon_e - \text{const.}$, determined from Eq. 5, vs. log $V$ and log $I_e$ in the upper panels. In the lower panels, we plot the values of log $\Upsilon_f$ for every galaxy in our sample using the fit given in Table 1. The lower panels illustrate how even with no intrinsic scatter in log $\Upsilon_f$ the projections show significant apparent scatter. We conclude that the bulk of the apparent scatter in the upper panels is due to the effects of projecting the complicated surface onto these axes rather than observational errors or intrinsic scatter.

TABLE 1

| Constant | log $V$ | log $I_e$ | log$^2 V$ | log$^2 I_e$ | log $V$ log $I_e$ |
|----------|---------|-----------|-----------|------------|-----------------|
| 2.12 | -0.01 | -1.05 | 0.07 | 0.13 | 0.14 |

by log $\Upsilon_f$, which is evident in Figure 3. The actual test of our approach comes from examining the scatter about the mean and whether distinct galaxy populations fall off the mean trend. If galactic structure depends strongly on parameters not included in this simple description, then the scatter will be large. In other words, two galaxies that are identical in the quantities $V$, $r_e$, and $I_e$ could, in principle, have very different values of $\Upsilon_e$ due to a dependence of $\Upsilon_e$ on accretion history, age, varying degrees of mass loss, or many other possible physical effects. These differences in $\Upsilon_e$ are not accounted for in $\Upsilon_f$, thereby potentially leading to a large scatter about the mean. However, the scatter is only 0.094 for the entire sample. For reference, the scatter in this new relation for all galaxies is comparable to the scatter observed in either FP or TF studies for the relevant subset of galaxies. The scatter can be reduced slightly, to 0.084, if we correct each galaxy sample separately for zero point shifts. These inferred zero point shifts, obtained by calculating the mean offset relative to the 1:1 line, are all comparable to plausible photometric errors, and generally correspond to a few hundredths of a magnitude.

The success of placing all galaxies onto a single surface in the $(r_e, I_e, V)$ space demonstrates that, to within the scatter ($< 25\%$), the family of galaxies is a two parameter sequence, i.e., measuring two of these structural...
parameters specifies the third. This implies that potentially important factors in galaxy development, such as environment, nuclear activity, star formation history, and accretion history, do not play a significant role in determining galactic structure unless they either move galaxies along the surface in \((r_e, I_e, V)\) space or act in concert to preserve the manifold as the locus of equilibrium points of galactic structure. To reiterate, the important aspect of Figure 3 is not its linear nature, which is a result of our assertion that a fundamental manifold exists for all galaxies, but rather the low scatter and lack of any systematic departures for specific classes of galaxies, both of which imply that the assumptions that we have made so far are appropriate to this level of precision. In other words, random or systematic variations of \(A\) and \(B\) across either the mass range of galaxies or galaxy types, variations from isothermality, and any other factors that are not considered contribute scatter that is at most the observed scatter, which is comparable to that measured in TF or FP studies. We have achieved the first of the goals described in \([1]\) and now proceed to examine whether our attribution of the departures from homology to \(\Upsilon_e\) is correct.

### 3.3. The Physical Validity of \(\Upsilon^f_e\)

The mathematical trick of placing all of the galaxy formation physics beyond the virial theorem into \(\Upsilon_e\) potentially masks the importance of \(A\) and \(B\). To check whether \(\Upsilon^f_e\) truly reflects \(\Upsilon_e\), or whether it is in actuality a composite of various terms, we compare \(\Upsilon^f_e\) to independent determinations of \(\Upsilon_e\). We do this for both normal ellipticals and dSphs.

First, we compare to values of \(\Upsilon_e\) derived from a full Schwarzschild analysis of the 2D line-of-sight velocity distributions, \(\Upsilon^{Sch}_e\), of normal ellipticals [Cappellari et al. 2006, 2007]. Because of the unknown constant in the definition of \(\Upsilon^f_e\) relative to \(\Upsilon_e\), we have the freedom to normalize \(\Upsilon^f_e\) to best match the Cappellari et al. (2006) data, which we do below (Figure 4). Figure 4 illustrates...
suggest an uncertainty in this number of average offset, modest and has a nearly undetectable effect on the scal-
dredths. Using this correspondence, we replace the con-
Walker et al. (2007) analysis does not. The dSph data suggest a
clude anisotropic velocity distributions, the W alker et al.
ysis of normal ellipticals, which has the freedom to in-
Cappellari et al. (2006) note are fast rotators and filled circles rep-
represent those that are not. The line is the 1:1 correspondence. The
filled circles, which are the most appropriate comparison sample,
show only 0.06 dex scatter (15% in Υ_e). For the Milky Way dSph
galaxies (triangles), we compare the mass-to-light ratio derived
from fitting NFW profiles to kinematic data (W alker et al. 2007)
with our estimates of Υ_e using Υ_e'. The unknown constant relating
Υ_e' to Υ_e is set to ensure agreement in the mean values of Υ_e' in
D and Υ_e and that value (−0.8) is then adopted for Eq.

the excellent correspondence between Υ_e and Υ_Sch. The
agreement is particularly good (0.06 dex rms, 15% in Υ_e) for the galaxies that are most appropriate for our
construction, namely those where the velocity dispersion dominates over systemic rotation and anisotropy
measures are small (|β, γ, δ| < 0.15 as measured by Cappellari et al. 2007). The scatter for those with large
anisotropies is significantly greater (0.17 dex rms, 48% in Υ_e), suggesting that a full knowledge of A and B would
decrease the scatter in Figure 3 among those galaxies that do not fully satisfy the basic assumptions of our
approach.

Second, we examine whether this correspondence holds
across the range of galaxy masses. In Figure 4 we in-
clude values of log Υ_e for Galactic dSphs estimated us-
ing NFW model fits to the extensive kinematic data of
Walker et al. (2007). Unlike the Schwarzschild anal-
ysis of normal ellipticals, which has the freedom to in-
clude anisotropic velocity distributions, the Walker et al.
(2007) analysis does not. The dSph data suggest a
slightly different constant offset between log Υ_e' and
log Υ_e (−0.78 rather than −0.82), but this change is
modest and has a nearly undetectable effect on the scal-
ing relation when ignored (see Figure 3B). We adopt the
average offset, −0.8, as the normalization constant and
suggest an uncertainty in this number of a few hun-
dredths. Using this correspondence, we replace the con-

4 The calculated Υ_e's use masses enclosed within r_e as calculated from the published fits, courtesy of Matthew Walker.

1:1 correspondence well, although the correspondence in
the left and right panels is the exclusion of the ellipti-
cals that show evidence for rotation or anisotropic ve-
locity dispersions. The data in both panels follow the
1:1 correspondence well, although the correspondence in
the right panel is striking. The scatter in that panel is
0.04 dex, or less than 10% in the parameter values them-
selves. We conclude that to a level of precision between
10 and 25% (the scatter measured using these indepen-
dently measured values of Υ_e and the scatter measured
using our fitting function, Υ_e', respectively), Υ_e en-
compases all of the additional physics necessary to proceed
from the virial theorem to a description of galactic struc-
ture. Thus, we achieve the second goal listed in §1.

3.4. Evolving onto the Manifold

For various reasons, the small scatter seen in Figures
3 and 5 is remarkable. Even if r_e and V are the same in
two similar galaxies, one might expect variations in the
stellar mass-to-light ratios, Υ_e, of more than 50%, which
would introduce scatter via variations in Υ_e. We suspect
that at least part of the reason for the low observed scatter
lies in the selection of galaxies in TF and FP stud-
ies, which generally favor evolved, dynamically-relaxed
galaxies, which are unlikely to exhibit dramatic varia-
tions in Υ_e. Therefore, we now return to the last of our

log r_e − log V^2 + log I_e + log Υ_e + 0.8 = 0, (6)

where one can either evaluate Υ_e in some independent
manner or express it in terms of V and I_e using the fit
given in Table 1 and replacing log Υ_e + 0.8 with log Υ_e'.

The applicability of the same normalization constant
for both normal ellipticals and dSphs supports the con-
tention that structural variations, as reflected by changes
in A and B, are modest over most of the mass scale
covered in Figure 3. Using these independently derived
measures of Υ_e, we now return to Eq. 3 use the lit-
value for Υ_e rather than our fitting function,
and plot the results in Figure 5. The difference between
the left and right panels is the exclusion of the ellipti-
cals that show evidence for rotation or anisotropic ve-
locity dispersions. The data in both panels follow the
1:1 correspondence well, although the correspondence in
the right panel is striking. The scatter in that panel is
0.04 dex, or less than 10% in the parameter values them-
selves. We conclude that to a level of precision between
10 and 25% (the scatter measured using these indepen-
dently measured values of Υ_e and the scatter measured
using our fitting function, Υ_e', respectively), Υ_e en-
compases all of the additional physics necessary to proceed
from the virial theorem to a description of galactic struc-
ture. Thus, we achieve the second goal listed in §1.

Fig. 4.— A comparison of mass-to-light ratios derived from in-
dependent means, Υ_e' in and our estimates of Υ_e using Υ_e'. For
normal ellipticals (circles), we compare the mass-to-light ratio de-
2 log V − log I_e + log Υ_e + 0.8 = 0, (6)

Fig. 5.— The scaling relationship, Eq. 6 using Υ_e' in place of
Υ_e. Data and symbols are as in Figure 3. The left panel includes
all of the spheroids with Υ_e', and the scatter is 0.09 dex about
the 1:1 line with a mean offset of 0.005. In the right panel, we have
removed the ellipticals with either significant rotation or anisotropy
Cappellari et al. 2004, 2007), and the scatter drops to 0.04 dex
about the 1:1 line with a mean offset of 0.004.
our fitting formula for $\Upsilon_e$ for a majority of baryons are in the gas (or, more precisely, baryons are in stars, it is clearly inadequate when the luminosity may be an adequate proxy when most of the closed mass. In light of previous studies, while optical tions, such as Eq. 6, depended on a proxy for the en-
and 3, it is evident that the derivation of later equa-
lationships if one considers total baryonic content instead of just that in the stellar component. Reviewing Eqs. 2
of gas-rich and gas-poor galaxies have consistent scaling re-
Figure 6. However, as demonstrated with regards to the ple do fall off the surface, as shown in the upper panel of Figure 6. Nevertheless, if these galaxies either convert their gas to stars or if we properly account for their entire baryonic content within $r_e$, then we expect that they will satisfy the same scaling relation as all other galaxies.

3.5. Revisiting our Simplifications

Before we proceed to discuss further implications of these results, we step back to explore how a failure to satisfy the assumptions invoked in our simplifications of the virial theorem would manifest itself in our evaluation of Eq. 6. The potential “failures” fall into three classes.

First, we might have introduced errors that are con-
stant across the galaxy population. An example of such an error would be if we always underestimated the potential energy in our evaluation of the virial theorem by a fixed factor. Such an error would manifest itself as a zero point shift of the data relative to the expectation. Because we do not calculate the specific constant in Eq. 6 from any physical argument, this type of error would be transparently absorbed into the constant term when we determine it using independent measurements, as done in §3.3. For almost all of our discussion, this type of error is difficult to detect but irrelevant.

Second, we might have introduced errors that vary sys-
tematically across the galaxy population. An example of such an error would be if we underestimated the potential energy by a certain factor for low mass systems but overestimated it by a similar factor for high mass systems. Such errors, to the degree that they correlate with at least one of the structural parameters, will lead to changes in the coefficients in Eq. 6 or that describe $\Upsilon_e$ (Table 1), but would not introduce scatter. This effect is analogous to introducing a “tilt” in FP analyses. Identifying this type of error is critical if one aims to understand the specific nature of the fitted relationships such as our fitting for $\Upsilon_e$ for a majority of baryons are in the gas (or, more precisely, baryons are in stars, it is clearly inadequate when the luminosity may be an adequate proxy when most of the closed mass. In light of previous studies, while optical tions, such as Eq. 6, depended on a proxy for the en-
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Figure 6. However, as demonstrated with regards to the ple do fall off the surface, as shown in the upper panel of Figure 6. Nevertheless, if these galaxies either convert their gas to stars or if we properly account for their entire baryonic content within $r_e$, then we expect that they will satisfy the same scaling relation as all other galaxies.

3.5. Revisiting our Simplifications

Before we proceed to discuss further implications of these results, we step back to explore how a failure to satisfy the assumptions invoked in our simplifications of the virial theorem would manifest itself in our evaluation of Eq. 6. The potential “failures” fall into three classes.

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as that describing $\Upsilon_e^I$ or to compare with simulations. We implicitly tested for such effects across galaxy types in §3.2 and across galaxy mass in §3.3. The coefficients derived from the virial theorem and a mass-to-light ratio that scales directly with independently-derived mass-to-light ratios successfully produce a tight scaling relation (Eq. 6 and Fig. 3). This result demonstrates that there is no effective “tilt” either with morphological type or across the full range of galaxy luminosities.

Third, we might have introduced errors that are variable and not systematic across the galaxy population. An example of such an error would be if we have ignored a key determining factor of galactic structure, e.g. the number of nearby neighbors. In naive models, close passages affect the luminosity of the system but do not affect the size or internal kinematics — leading to potential outliers in Eq. 6. Such effects, to the degree that they do not correlate with the remaining structural parameters, will introduce scatter at each point in the $(r_e, I_e, V)$ space. The low scatter in both the entire sample (Fig. 3) and the subsample with independently-measured mass-to-light ratios (Fig. 5) demonstrates that any such effects introduce little noise.

### 3.6. Connecting $\Upsilon_e$ to Physical Parameters

What we have discussed so far are the end-products, or observables $(r_e, I_e, V, \Upsilon_e)$, rather than inputs, or true physical quantities, that determine the structure of galaxies. Two natural candidates for the parameters that drive galactic structure are the mass and angular momentum of a galaxy. For disks, analytic treatments of galaxy formation using these two variables have been relatively successful (Fall & Efstathiou 1980, Dalcanton et al. 1997). Although these models require a few key assumptions that may not be entirely accurate, such as the conservation of angular momentum during collapse, their success, in combination with the results presented here, suggest that simple dynamical models may be able to reproduce the observable properties of galaxies. However, proceeding from such difficult to measure quantities as mass and angular momentum to the observed structure of galaxies in a single step is likely to prove difficult.

We focus instead on what we have learned so far from our analysis. Given that the virial theorem plus $\Upsilon_e$ are all one needs to generate a gross description of galactic structure (eq. 3.1 - 3.3), all of the interesting astrophysics of galaxy formation — at least as related to determining the current, gross structure of a galaxy — is encapsulated in $\Upsilon_e$. What determines differences in $\Upsilon_e$ among galaxies?

First, galaxies might convert a different fraction, $\eta$, of their baryons to stars. Assuming a universal baryon-to-dark matter ratio for halos, this fraction can be measured using the total mass-to-light ratio, $\Upsilon_{200}$, evaluated at $R_{200}$, the radius within which the mass density is 200 times the critical density and the system is roughly virialized. Systematic variations in $\eta$ have already been noted in studies of halo occupation statistics (van den Bosch et al. 2003, Yang et al. 2005), lensing mass measurements (Hoekstra et al. 2005, Mandelbaum et al. 2006), and direct baryon measurements (Lin et al. 2004, Gonzalez et al. 2007). All of these studies show that $\Upsilon_{200}$, and therefore $\eta$, depend on halo mass.

Second, the stars might be concentrated to varying degrees relative to the dark matter due to differences in the assembly history. We quantify the stellar concentration, $\xi$, using $\xi \equiv R_{200}/r_e$. As the stars become more concentrated in the halo, $\xi$ increases and $\Upsilon_e$ decreases.

We now return to Eq. 2 with the aim of extracting from it expressions for the mass fraction of baryons that are converted to stars, $\eta$, as a function of $L/L^*$ for spheroids (upper) and disks (lower). Our data are the small dots. The values from Mandelbaum et al. (2006) are shown as large filled circles with error bars and represent average values for bins of $L/L^*$. This plot includes the cluster spheroids of Zaritsky et al. (2005a) as open triangles, so that we extend the range of $L/L^*$ to the higher luminosities (see text) probed by Mandelbaum et al. (2006).

We rewrite Eq. 2 as appropriate at the virial radius, $R_{200}$.

$$A_{200} V_{200}^2 = \frac{B_{200} GM_{200}}{R_{200}},$$

where $M_{200} \equiv \frac{4}{3} \pi R_{200}^3 \rho_{200}$, $\rho_{200} \equiv 200 \rho_{\text{crit}}$, and $R_{200} \equiv \xi r_e$, where $\rho_{\text{crit}}$ is the universal critical mass density at the present epoch. To make further progress, we set $V = V_{200}$. This is patently incorrect both because the dark matter potential itself is unlikely to be isothermal out to $R_{200}$ (Navarro et al. 1997) and any central concentration of the baryons will affect $V$. However, any constant fractional differences — for example, $V = 1.2 V_{200}$ for all galaxies — will be absorbed later into our normalization. What do concern us, but are ignored here, are differences in this velocity scaling that depend on the properties of the galaxy (Courteau et al. 2007). This problem might be correctable in an iterative scheme (i.e., assume a non-isothermal potential, estimate $\xi$, evaluate the difference between $V$ and $V_{200}$, correct $V_{200}$, and iterate until convergence) or in a more sophisticated model of galaxy formation (Somerville et al. 2007), but both of these remedies require some model assumptions and lead us from the analytic descriptions that we aim to explore. Work is needed to determine the magnitude of the error introduced by our simple treatment.

Continuing, we define $\eta$ through the equation
\[ L = \frac{\eta f_B M_{200}}{\Upsilon_*}, \]  

(8)

where \( \Upsilon_* \) is the mass-to-light ratio of the stellar population, \( L \) is the total luminosity, and \( f_B \) is the baryon mass fraction. Algebra enables us to derive equations for \( \xi \) and \( \eta \):

\[ \xi = \left( \frac{3A_{200}}{800\pi \rho_{crit} B_{200} G} \right)^{\frac{1}{2}} \frac{V}{r_e} \]  

(9)

and

\[ \eta = \left( \frac{800\pi B_{200}^3 \rho_{crit}}{3f_b A_{200}^2} \right)^{\frac{1}{2}} \frac{L \Upsilon_*}{V^3}. \]  

(10)

We express the combination of these two quantities as

\[ \log \xi + \log \eta = -2 \log V + \log r_e + \log I_c + \log \Upsilon_* + \text{const}. \]  

(12)

We know from (3,2) that we can replace the three leading terms on the right hand side with \(- \log \Upsilon_* \) to within a constant, so

\[ \log \xi + \log \eta = - \log \Upsilon_* + \log \Upsilon_* + \text{const}. \]  

(13)

Because \( \Upsilon_* = f(V, I_c) \), as defined in Table 1, \( \log \eta + \log \xi \) is also a function \( V \) and \( I_c \).

To provide a more direct example of the possible use of these equations, we use the results from Mandelbaum et al. (2006) to evaluate the constant terms (including the assumed constant terms \( A_{200} \) and \( B_{200} \)) in Eqs. (9) and (10). Mandelbaum et al. (2006) use results from weak lensing to evaluate the fraction of baryons in Eqs. 9 and 10. Mandelbaum et al. (2006) use results for \( \eta \) to that found by Mandelbaum et al. (2006), although at somewhat larger values of \( L/L^* \). There are many technical reasons (such as the use of different bandpasses, subtleties in the definition of total magnitudes, and complications introduced by intrachuster light for these most massive spheroids) that preclude any conclusion about whether there is a true discrepancy. In general, we agree quite well both qualitatively and quantitatively with their results. This agreement, in turn, suggests that \( A_{200} \) and \( B_{200} \) do not vary strongly as a function of mass or morphological type.

We proceed now to calculate \( \eta \) and \( \xi \) as a function of \( V \) for all of our galaxies and show the results in Figure 8. Here, to within the flaws in our simple derivation and the heterogeneous sample, is a full description of how baryons turn into stars and distribute themselves in all galaxies ranging from dSphs to BCGs. There are several striking results. First, the relatively large values of \( \eta \) for dwarf spheroidals are primarily driven by \( \xi \) rather than by \( \Upsilon_* \), which is surprisingly constant across the full range of \( V \). Second, at a given \( V \), ellipticals and spirals have similar values of \( \eta \). Therefore, the difference in their values of \( \Upsilon_* \) are due primarily to differences in \( \xi \). Third, there is a steady decline in \( \eta \) for \( \log V > 15.0 \) (\( V > 32 \text{ km s}^{-1} \)) even for the spheroids, among which large variations in \( \Upsilon_* \) are less likely. Systems with comparable \( V \) to the Milky Way, \( 149 < V < 163 \text{ km s}^{-1} \) or alternatively \( 210 < v_e < 230 \text{ km s}^{-1} \), have \( \eta = 0.14 \pm 0.04 \), with the spheroids being on average 5 times more concentrated than the disks. All of these results await resolution of two key open questions in the evaluation of \( \xi \) and \( \eta \): 1) how to treat the difference between \( V \) and \( V_{200} \) and 2) whether the structural terms are as well-behaved at \( R_{200} \) as they are at \( r_e \). Nevertheless, this analysis illustrates how we might construct a bridge between the empirical relations based on observables and more theoretical ones based on fundamental physical parameters. Thus, we achieve the third goal listed in 11.

4. SUMMARY

We have shown that all classes of galaxies, ranging in mass from dwarf spheroidals to brightest cluster galaxies, and in type from spheroids to disks, fall on a two dimensional surface in the observable space \((r_e, I_c, V)\), where \( V^2 = \frac{1}{2} v_e^2 + \sigma^2 \), over three orders of magnitude in \( r_e \), with less than 25% scatter. The scatter about that surface is comparable to that observed in Fundamental Plane and Tully-Fisher studies in which the range of galaxy types and luminosities is much more limited. The TF and FP relationships are subsets of the manifold presented here. This finding alone demonstrates that the structure of all galaxies can be described with a highly limited set of parameters. The observational ones, \((r_e, I_c, V)\), may not be optimal, even though they do a remarkably good job.

The small scatter about the mean relation implies that a host of potential physical phenomena such as environmental effects, star formation history, nuclear activity, accretion history, and feedback are either (1) relatively unimportant in determining the structure of galaxies, (2)
Fig. 8.— Mass fraction of baryons that are converted to stars, $\eta$, (top) and stellar concentration, $\xi$, (bottom) as a function of $V$ for our entire sample (spheroids represented with filled circles, disks with open circles). Various results are in evidence, including the dramatic decrease in $\eta$ for the dSphs, the similarity in $\eta$ among spirals and spheroids in the regime where they overlap in $V$, the systemic decline in $\eta$ with increasing $V$ for $\log V > 1.5$, and the generally greater $\xi$ for spheroids relative to disks in that same velocity range.

move galaxies along this well-defined relationship, or (3) balance each other so as to define the mean relation as the locus of galactic structure equilibria.

We developed a simple analytic treatment in which we asserted the existence of a fundamental manifold of galaxies. By requiring the simple virial theorem derivation to result in a two dimensional manifold in observed space, we specify the behavior of the mass-to-light ratio within $r_e$, $\Upsilon_e$. We then tested this assertion by comparing our inferred values of $\Upsilon_e$ to those derived independently from much more sophisticated modeling for both normal ellipticals and dSphs. The agreement is quantitatively excellent, with less than 15% scatter in mass-to-light ratios for those galaxies that satisfy our dynamical criteria. The observed manifold is described by

$$\log r_e - \log V^2 + \log I_e + \log \Upsilon_e + 0.8 = 0,$$

where we also provide a fitting function for $\log \Upsilon_e$ in terms of $V$ and $I_e$. The equations presented here are numerically appropriate for $r_e$, $V$, $I_e$, and $\Upsilon$ in units of kpc, km s$^{-1}$, $L_\odot$/pc$^{-2}$, and solar units, respectively, and based primarily on $I$-band observations.

We then discuss what the inferred behavior of $\Upsilon_e$ may mean for the physical characteristics of the galaxies. In particular, we speculate that the two principal determinants of $\Upsilon_e$ are the mass fraction of baryons that are turned into stars, $\eta$, and the degree to which the stars are spatially concentrated relative to the dark matter, $\xi = R_{200}/r_e$. We derive equations for both quantities in terms of unknown structural parameters and the observables. We relate the two quantities using the expression
that we derived for $\Upsilon_e$. Finally, we use independent measures of $\eta$ (Mandelbaum et al. 2006) to solve for the unknown structural terms for one set of galaxies and then compare the behavior of $\eta$ across other luminosities and galaxy types as determined both from our analysis and that independent weak lensing study. This comparison leads to simple expressions for $\eta$ and $\xi$,

$$\eta = 1.9 \times 10^{-5} \frac{(L/L^*)\Upsilon_e}{V^3}$$

(15)

and

$$\xi = 1.4 \frac{V}{r_e}$$

(16)

We are then able to extend the measurements of $\eta$ and $\xi$ to the full range of galaxies. As rough guides, we find that, for most galaxies, $0.04 < \eta < 0.6$ and $10 < \xi < 200$, although these can be evaluated on a galaxy-by-galaxy basis. Systems with comparable $V$ to the Milky Way, $149 < V < 163$ km s$^{-1}$ or alternatively $210 < v_e < 230$ km s$^{-1}$, have $\eta = 0.14 \pm 0.04$, with the spheroids being on average 5 times more concentrated than the disks. Overall, we reach a set of general conclusions. First, the relatively large values of $\Upsilon_e$ for dwarf spheroidals are primarily driven by $\eta$ rather than by $\xi$, which is surprisingly constant across the full range of $V$. Second, at a given $V$, ellipticals and spirals have similar values of $\eta$ (<10% difference for spheroids and disks with $149 < V < 163$ km s$^{-1}$). Therefore, the difference in their values of $\Upsilon_e$ is due primarily to differences in $\xi$. Third, there is a steady decline in $\eta$ for log $V > 1.5$ ($V > 32$ km s$^{-1}$).

The data used here fall short of the ideal sample from which to properly derive the quantitative values that mathematically describe the manifold, primarily due to the heterogeneous nature of the amalgamated sample. Nevertheless, the sample does demonstrate that the range of galaxy structure is dominated by only two parameters. The lower scatter obtained either for a single sample (0.06 dex for the Springob et al. [2007] disk sample) or for independently derived $\Upsilon_e$’s (0.04 dex when using both the Cappellari et al. [2006] data for ellipticals and the Walker et al. [2007] data for dSphs) suggest that a homogeneous sample might show that the myriad of possible influences on galactic structure (environment, accretion history, AGN activity, star formation history, and others) contribute at most a ~10% scatter to the scaling relationship presented in Eq. (13).

The existence of a highly constrained surface on which galaxies lie does not eliminate the need for additional physics. In particular, as we have hinted throughout, many physical effects might move galaxies along the surface or perhaps counter-balance to move galaxies back to the equilibrium surface described by the manifold. As such, future galaxy models may be more constrained by the distribution of galaxies on the surface rather than perpendicular to it. Our heterogeneous sample is ill-suited to say much about the distribution of sources on the surface. Much work still remains.

We close by returning to the analogy of stellar structure. It is evident that we are still far from a physical theory of galactic structure, but that we have progressed in several key aspects. First, we have now demonstrated that the entire family of galaxies can be described by sets of two parameters (e.g., $V$ and $I_e$ or $\eta$ and $\xi$). This finding motivates the search for relatively simple expressions of galactic structure that are connected to a small set of physical parameters, such as mass and angular momentum. Second, we have identified the principal characteristic that remains to be explained, namely $\Upsilon_e$. The virial theorem plus an understanding of $\Upsilon_e$ are all that are necessary to predict the size, internal kinematics, or luminosity of a galaxy, when given the other two. This in turn places the focus on understanding what determines the fraction of baryons that are turned into stars and how those stars are packed within the dark halo. If those quantities can then be connected to more fundamental parameters, such as mass and angular momentum, then one could proceed from the physical parameters directly to the observables. At that point, we will have indeed produced equations of galactic structure.

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