THE EPOCH OF DISK SETTLING: z ∼ 1 TO NOW

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ABSTRACT

We present evidence from a sample of 544 galaxies from the DEEP2 Survey for evolution of the internal kinematics of blue galaxies with stellar masses ranging $8.0 < \log M_*/(M_\odot) < 10.7$ over $0.2 < z < 1.2$. DEEP2 provides galaxy spectra and Hubble imaging from which we measure emission-line kinematics and galaxy inclinations, respectively. Our large sample allows us to overcome scatter intrinsic to galaxy properties in order to examine trends in kinematics. We find that at a fixed stellar mass, galaxies systematically decrease in disordered motions and increase in rotation velocity and potential well depth with time. Massive galaxies are the most well ordered at all times examined, with higher rotation velocities and less disordered motions than less massive galaxies. We quantify disordered motions with an integrated gas velocity dispersion corrected for beam smearing ($\sigma_g$). It is unlike the typical pressure-supported velocity dispersion measured for early type galaxies and galaxy bulges. Because both seeing and the width of our spectral slits comprise a significant fraction of the galaxy sizes, typical pressure-supported velocity dispersion measured for early type galaxies and galaxy bulges. Because both seeing and the width of our spectral slits comprise a significant fraction of the galaxy sizes, $\sigma_g$ integrates over velocity gradients on large scales which can correspond to non-ordered gas kinematics. We compile measurements of galaxy kinematics from the literature over $1.2 < z < 3.8$ and do not find any trends with redshift, likely for the most part, because these data sets are biased toward the most highly star-forming systems. In summary, over the last $\sim$8 billion years since $z = 1.2$, blue galaxies evolve from disordered to ordered systems as they settle to become the rotation-dominated disk galaxies observed in the universe today, with the most massive galaxies being the most evolved at any time.

Key words: galaxies: evolution – galaxies: formation – galaxies: fundamental parameters – galaxies: kinematics and dynamics

Online-only material: color figures

1. INTRODUCTION

In the standard picture of disk galaxy formation, baryons enter into dark matter halos and dissipate to form disks at their centers (Rees & Ostriker 1977; White & Rees 1978; Fall & Efstathiou 1980; Blumenthal et al. 1984). The accretion of baryons onto galaxies is expected to be an ongoing process, and it is not yet known how galaxy disks respond to it or how they evolve as mass accretion rates change. Only recently have hydrodynamic simulations of galaxy formation been run with enough resolution to study this in detail for up to a few tens of galaxies (e.g., Governato et al. 2007, 2009; Bournaud et al. 2009; Ceverino et al. 2010; Brook et al. 2011; Kimm et al. 2011; Martig et al. 2012, and references therein). Such simulations have yet to address the evolution of internal galaxy kinematics over a significant period of time, which is the cleanest observational probe of disk galaxy assembly. Internal kinematics tell us directly about the dynamical state of galaxies, reveal the potential well depths of individual galaxy–dark-matter halo systems, and can be measured for a large sample of galaxies over a significant range in redshift.

We have acquired a wealth of information about blue galaxies over the last $\sim$8 billion years since $z = 1.2$ which can be roughly divided into two categories: those which imply a significant amount of evolution and those which do not. Among the observations which do not imply much evolution are those of galaxy luminosity functions. Luminosity function studies find that the number density of blue galaxies is unchanging, and that blue galaxies fade by only $\sim$1 $B$-band magnitude since $z \sim 1$ (e.g., Willmer et al. 2006; Faber et al. 2007; Bell et al. 2004). Similarly, studies of stellar mass functions of blue galaxies find no evolution to within uncertainties (Bundy et al. 2006; Borch et al. 2006; Pozzetti et al. 2010; although see Drory et al. 2009). In addition, galaxy sizes are only marginally smaller at $z = 1$ compared to local galaxies (by a factor of 1.4; Dutton et al. 2011). However, despite all this evidence for a slowly evolving population, there are some strong indications of substantial evolution. Compared with blue galaxies of similar stellar masses today, those at $z \sim 1$ have significantly higher star formation rates by a factor of $\sim$10 (e.g., Noeske et al. 2007), higher molecular gas fractions (for at least a few of the...
brighter galaxies which have been observed so far) by a factor of ~2-4 (Daddi et al. 2010; Tacconi et al. 2010), and more disturbed morphologies (e.g., Abraham et al. 1996; Abraham & van den Bergh 2001). In summary, blue galaxies do not evolve much since z ~ 1 in luminosity, stellar mass, or size, but they do evolve strongly in star formation rate, (likely) molecular gas fraction, and morphology. In this paper, we attempt to understand this discrepancy and the mechanisms behind it by studying the internal kinematics of blue galaxies since z ~ 1.

Due to the large intrinsic scatter in the kinematic properties of blue galaxies (Weiner et al. 2006a, 2006b; Kassin et al. 2007), a sizable sample (>100) which is representative in terms of galaxy properties is required to study internal galaxy kinematics over a significant look-back time. The first large study to address the kinematic evolution of blue galaxies since z ~ 1 was Weiner et al. (2006a, 2006b) who used data for 1089 galaxies from the TKRS Survey. Among other things, they found that about one-third to one-half of emission-line galaxies over 0.1 < z < 1.5 have a significant or dominant component of disordered motions, as measured via an integrated gas velocity dispersion (σg; as discussed in Section 4.1). Weiner et al. (2006a) proposed a new velocity indicator to trace galaxy potential well depths. It incorporates both rotation velocity (Vrot) and σg: S ≡ √2Vrot + σg.

Kassin et al. (2007, hereafter K07) followed up on Weiner et al. (2006a, 2006b). Their data set consisted of 544 galaxies from the DEEP2 Survey over 0.1 < z < 1.2 with medium-resolution spectroscopy from which kinematics were measured and Hubble/ACS imaging. The Hubble images were used to measure galaxy morphologies and axial ratios (which were used by K07 to correct rotation velocities for inclinations of galaxies to the line of sight). The main results of K07 are as follows.

1. K07 showed that scatter in the stellar mass Tully–Fisher relation (TFR), i.e., the relation between galaxy stellar mass and Vrot, is mostly to low Vrot and is a strong function of morphology. Galaxies which scatter to low Vrot generally have disturbed or compact Hubble morphologies. Similarly, from samples of 33 and 68 galaxies in the IMAGES Survey at z ~ 0.6, Flores et al. (2006) and Yang et al. (2008), respectively, found a large scatter in the TFR due to galaxies with “perturbed or complex kinematics.” Most previous studies of Tully–Fisher at both low and high redshifts tried to minimize scatter by selecting galaxies which are morphologically well-ordered disks (e.g., Verheijen 1997; Kassin et al. 2006; Pizagno et al. 2007, and references therein for low redshift, and, e.g., Conselice et al. 2005; Míller et al. 2011, and references therein for z < 1.5).

2. K07 demonstrated that galaxies which scatter to low Vrot in the TFR have a significant contribution to their kinematics from disordered motions (as quantified by σg).

3. K07 showed that when Vrot and σg are combined into a velocity indicator created to trace galaxy potential well depths (S0.5 as defined above), a tight relation with stellar mass results. This relation is independent of galaxy morphology, non-evolving since z = 1.2, and coincident with the Faber–Jackson relation for early-type galaxies. It demonstrates that galaxies are likely approximately virialized since z ~ 1 in that they have all the energy they will have today already at z ~ 1. This tightening of Tully–Fisher once S0.5 is adopted was later found by other observational studies (Cresci et al. 2009; Puech et al. 2010; Lemoine-Busserolle & Lamareille 2010; Lemoine-Busserolle et al. 2010; Vergani et al. 2012; Catinella et al. 2012) and numerical simulations of interacting galaxies (Covington et al. 2010).

4. K07 found that the majority of scatter in the TFR at low redshift is at lower stellar masses (M∗ < 1010 M⊙). They found that the scatter at higher masses was low at low redshift and increased with increasing redshift to z = 1.2. K07 hypothesized that this meant higher mass galaxies have been settling onto the TFR since z = 1.2, and that lower mass galaxies are settling onto the TFR today. Similarly, studies with the IMAGES Survey argue for significant kinematic evolution since z ~ 0.6 (e.g., Yang et al. 2008; Neichel et al. 2008; Puech et al. 2008).

The K07 study leaves a number of open issues.

1. First, although it is clear that galaxies are evolving in Vrot and σg since z = 1.2, this evolution is not quantified.

2. Second, it is also clear from K07 that kinematic evolution is a function of galaxy stellar mass, but this is not quantified or addressed in detail.

3. Finally, although K07 found that the relation between S0.5 and stellar mass does not evolve to within uncertainties since z = 1.2, it has yet to be determined whether galaxies evolve in S0.5.

In this paper, we address these open issues with a more sophisticated analysis of the data set in K07. In Section 2, we detail how the K07 sample was selected; this was not included in K07 because it was a letter paper and did not have the space to do so. In Section 3, we discuss the stellar mass and Hubble size measurements which are adopted from other studies, and describe the measurement of emission line extents made in this paper. In Section 4, since it was not addressed in detail in K07, we describe how Vrot and σg are measured from emission lines in galaxy spectra and discuss what they measure. We then show how Vrot, σg, and S0.5 evolve with redshift in Section 5, and discuss the influence of galaxy stellar mass and size on this evolution in Section 6. In Section 7, we quantitatively define a settled disk galaxy and study how the fraction of settled disk galaxies evolves with redshift. Our findings are compared with previous measurements of galaxy kinematics in the literature over 0 < z < 3.8 in Section 8. Conclusions are given in Section 9. A ΛCDM cosmology is adopted throughout (h = 0.7, Ωm = 0.3, ΩΛ = 0.7), and all logarithms are base 10.

2. SAMPLE SELECTION

In this paper, we use the data set of K07. Since K07 was a letter paper, it did not include a detailed description of how its galaxy sample was selected, so we include it here. One of the main differences between K07 and most other studies of galaxy kinematics lies in its sample selection. Typically, constraints on galaxy morphology are applied at the outset to remove disturbed and major-merger galaxies. K07 did not place any constraints on morphology. They included all galaxies with emission lines which were bright enough to measure kinematics from. Since disturbed morphology and disordered motions (as measured by σg) are correlated, removing galaxies with disturbed morphologies would introduce a strong bias toward only the most rotation-dominated systems (K07). Little or no evolution in internal galaxy kinematics would be found for a sample selected in this manner. Moreover, such a sample would not be representative of galaxies at higher redshifts since they tend to have disturbed morphologies (e.g., Griffiths et al. 1994; Windhorst et al. 1995; Abraham et al. 1996; Abraham 1996; Abraham & van den Bergh 2001).
The K07 sample derives from a very large collection of 9715 galaxies with solid spectroscopic redshifts from Keck/DEIMOS (Faber et al. 2003) in field 1 of the DEEP2 Survey (2007 May catalog), as described below. Field 1 is home to the AEGIS multi-wavelength survey (Davis et al. 2007). The limiting magnitude of DEEP2 is $R_{AB} < 24.1$ and galaxies in field 1 are not subject to a color selection (Willmer et al. 2006; Newman et al. 2012). In Figure 1, we show rest-frame color–magnitude diagrams for galaxies in field 1 of DEEP2 and highlight the K07 sample. The K07 sample provides good coverage over galaxy mass. Although it is moderately biased toward blue galaxies at a fixed mass, the effect is not severe.

In the following, we detail how galaxies were selected from field 1 of the DEEP2 Survey to be in the K07 sample. First, although DEEP2 reaches a redshift of $z = 1.5$, K07 chose to be conservative and limit their sample to $z = 1.2$, leaving 8787 galaxies. This helps to avoid the high-redshift end of the survey where the selection is in the rest ultraviolet and becomes dependent on color (Willmer et al. 2006). It also ensures that galaxy axis ratios, which are used to correct rotation velocities for inclinations of galaxies to the line of sight, are measured from Hubble imaging which has not yet shifted into the ultraviolet since these wavelengths may not trace the bulk of the stellar mass of galaxies. Next, galaxies were chosen to have Hubble Space Telescope/ACS imaging at $V$ and $I$, which further reduces the sample to 3523 galaxies. This is because there are portions of field 1 which are not imaged by Hubble. Aside from removing galaxies which did not have Hubble imaging, this requirement did not further affect our sample selection because the Hubble images are deeper than the spectral survey. For our most important selection, galaxies with bright enough emission lines to measure kinematics ($\geq 10^{-17}$ erg s$^{-1}$ cm$^{-2}$) were chosen, leaving 1692 galaxies.

Galaxies were further selected by K07 to have inclinations measured from Hubble images between $30^\circ < i < 70^\circ$, and spectrographic slits with position angles aligned to within $40^\circ$ of their major axes. These cuts leave a sample of 755 galaxies. Inclinations are measured from $V + I$ band Hubble images using the SExtractor software package (Bertin & Arnouts 1996), as described in Lotz et al. (2008), and have an uncertainty of $\sim 10^\circ$. The inclination requirement avoids nearly face-on galaxies for which inclination measurements are very uncertain and minimizes the effects of dust in the determination of stellar mass for highly inclined systems. However, if the morphology of a galaxy was deemed by eye to be disturbed enough such that its inclination could not be reliably determined, it was included in the sample but not corrected for inclination. There are only 24 of these galaxies and they are flagged in most of the following analysis. Removing them from the sample does not significantly affect the results of this paper. For the slit position angles, due to the large slit width ($1^\prime$) compared to the apparent sizes of galaxies in our sample ($\sim 3^\prime$) and the effects of seeing, accurate kinematics can be measured if slit position angles are offset by up to $40^\circ$ from galaxy major axes (Figure 13 of Weiner et al. 2006a). Finally, if an emission line was affected by a sky line or an instrumental artifact, the corresponding galaxy was removed from the sample, leaving a total of 544 galaxies in the K07 sample. No constraints on morphology were applied.

To study the evolution of galaxy kinematics for a sample of blue galaxies which is mass limited at all redshifts, in Section 5.1 we limit the K07 sample to galaxies with stellar masses over $9.8 < \log M_*(M_\odot) < 10.7$, as demarcated in Figures 1–3. Since the stellar mass function of blue galaxies does not evolve significantly since $z \sim 1$ (Borch et al. 2006; Bundy et al. 2006; Pozzetti et al. 2010), we do not change this stellar mass range with redshift. This cut removes 274 galaxies from the K07

![Figure 1. Rest-frame $U-B$ color (AB system) vs. stellar mass diagrams for galaxies with solid spectroscopic redshifts in field 1 of the DEEP2 Survey (gray points) and for the K07 sub-sample which is used in this paper (black points) are shown in bins of redshift. The K07 sample provides good coverage over galaxy mass. Although the K07 sample is moderately biased toward bluer galaxies at a fixed mass, the effect is not severe. Dotted lines demarcate the mass-limited sample used later in this paper.](image-url)
The relationships between kinematic quantities ($\sigma_g$, $V_{\text{rot}}$, $S_0.5$) and stellar mass are shown in bins of redshift for the K07 sample. Stellar masses are from Lin et al. 2007. The $V_{\text{rot}}$ and $S_{0.5}$ relations were shown previously in K07, and we show the $\sigma_g$ relation here for completeness. While large scatter is found for the $\sigma_g$ and $V_{\text{rot}}$ relations, the $S_{0.5}$ relation is significantly tighter and does not evolve to within uncertainties since $z = 1.2$. The fit to the $S_{0.5}$ relation for the lowest redshift bin is shown as a solid line (slope of 0.30 ± 0.2, intercept of 1.93 ± 0.01 at log $M_*$ = 10 $M_\odot$; K07) and is repeated in the higher redshift bins as a dashed line. It is consistent with the Faber–Jackson relation for early type galaxies, where $\sigma$ is measured from stellar absorption lines (K07). Hashed regions denote areas where the survey is not sensitive, and dotted lines demarcate the mass-limited sample used later in this paper. If a galaxy is deemed too morphologically disturbed to accurately determine an inclination (9% of the sample), $V_{\text{rot}}$ is not inclination corrected and the galaxy is shown as an upper limit symbol in the $V_{\text{rot}}$ and $S_{0.5}$ plots and an open circle in the $\sigma_g$ plot.

Sample, leaving 270. Throughout the paper, we will refer to this as the "mass-limited sample."

3. STELLAR MASS AND SIZE MEASUREMENTS

In this paper, we will study the relationship between galaxy kinematics and stellar mass, building upon the scaling relations studied in K07. We adopt stellar mass measurements from Lin et al. (2007) via private communication in 2011, as was done in K07. The uncertainties on these stellar mass measurements are $\sim 0.25$ dex.

In addition to the effects of stellar mass on galaxy kinematics, we will also look at galaxy sizes. Two size measurements are studied: emission line extent and continuum size. In this paper, we measure emission line extents from ground-based DEEP2 spectra from the same lines used to measure kinematics. However, unlike the kinematic measurements, no seeing correction is applied. The spatial extent of the line emission is measured as follows for a given galaxy. For details on the method, see Weiner et al. (2006a). First we measure the spectral continuum by collapsing the two-dimensional spectrum in wavelength over a 15 Å range around the line and two 100 Å spatial ranges on either side of the line. We then fit a Gaussian profile along the slit using a nonlinear least-squares routine and adopt the resulting full width at half-maximum as our measurement of emission line extent. For the galaxy continuum sizes, we adopt measurements made from Hubble images using the GIM2D software package (Simard et al. 2002) by Dutton et al. 2011 and E. Cheung et al. (in preparation). To take into account band-shifting with redshift, sizes are measured from $V$- and $I$-band images for galaxies at redshifts less than and greater than $z = 0.6$, respectively. Since the continuum sizes are measured from Hubble images, they are unaffected by seeing.

4. KINEMATIC MEASUREMENTS

Measurements of internal galaxy kinematics from emission lines are adopted from K07. In this section, we discuss some relevant details and the phenomena they describe. Further details on how these measurements were made are given in Weiner et al. (2006a, 2006b) for a similar survey with a lower spectral resolution: $R \sim 2100$ compared with $R \sim 5000$ for the K07 sample.

For each galaxy the emission line used to measure kinematics is the one with the highest signal to noise in its spectrum. For the vast majority of galaxies, the Hα $\lambda 6563$, [O II] $\lambda\lambda 3726.0, 3728.8$, and [O III] $\lambda 5007$ lines are used. Rotation velocities on the flat parts of the rotation curves ($V_{\text{rot}} \times \sin(i)$,
where \( i \) is the inclination of a galaxy to the line of sight) and integrated gas velocity dispersions (\( \sigma_g \)) were measured simultaneously from the emission lines, and the effects of seeing (typically \( \sim 0.7'' \)) were taken into account. Our spectral resolution allows for \( V_{\text{rot}} \times \sin(i) \) and \( \sigma_g \) to be measured down to \( \sim 5 \) and \( \sim 15 \) km s\(^{-1} \), respectively. An uncertainty of 10 km s\(^{-1} \) is adopted for both \( V_{\text{rot}} \times \sin(i) \) and \( \sigma_g \) to account for random errors and the dependence of model parameters on the assumed seeing and scale radius of the rotation curve. Although many of the rotation curves do not “turn over” due to seeing, our model is still able to fit for the rotation velocity on the flat part of the rotation curve (Weiner et al. 2006a, Section 2.3.2). In addition, it has been demonstrated using deeper data with the same telescope/instrument which observe a turnover in the rotation curve for 90\% of galaxies that spectra of our depth do not show a bias in \( V_{\text{rot}} \) (Figure 6 of Miller et al. 2011). Benefits of the deeper data (as used in Miller et al. 2011) are smaller errors in \( V_{\text{rot}} \times \sin(i) \) (and therefore less scatter) and the ability to probe galaxies with fainter emission lines. Except for the 24 galaxies for which reliable inclinations could not be determined (Section 2), values of \( V_{\text{rot}} \times \sin(i) \) are corrected for galaxy inclinations measured from the Hubble images. The results of this paper do not change significantly if these 24 galaxies are removed from the sample.

4.1. What \( \sigma_g \) and \( V_{\text{rot}} \) Measure

The integrated gas velocity dispersion we measure (\( \sigma_g \)) is unlike the typical pressure-supported velocity dispersion measured for early type galaxies or galaxy bulges. This is the case for two reasons. First, \( \sigma_g \) is measured from emission lines which trace the gas in galaxies, as opposed to absorption lines which trace stars. Gas, unlike the collisionless stars in an early type galaxy, can dissipate energy and therefore cannot remain in a high dispersion equilibrium state with crossing orbits. Second, because the spectral slits used in the DEEP2 Survey are wide compared to the apparent sizes of the galaxies observed (1'' slit versus \( \sim 3'' \) galaxies), \( \sigma_g \) effectively integrates velocity gradients on scales at and below the seeing limit (Weiner et al. 2006a; Covington et al. 2010; Epinat et al. 2010). For values of \( \sigma_g \) less than \( \sim 35 \) km s\(^{-1} \), which is the upper limit for well-ordered disk galaxies in the local universe (Figure 15 of Epinat et al. 2010), \( \sigma_g \) measures the relative motions of individual star-forming regions in galaxy disks. However, for values of \( \sigma_g \) greater than \( \sim 35 \) km s\(^{-1} \), \( \sigma_g \) integrates over velocity gradients which can correspond to non-ordered gas kinematics such as small-scale velocity gradients, gas motions due to star formation, or superimposed clumps along the line of sight. In this paper,
we collectively refer to these velocity gradients as “disordered motions.”

To test for interference from $V_{\text{rot}}$ in measurements of $\sigma_g$, in Section 5 we compare $\sigma_g$ measured for galaxies in our mass-limited sample with galaxies from DEEP2 in the same stellar mass range which are face-on in Hubble images (i.e., $i < 30^\circ$). We find no significant difference in the trends of $\sigma_g$ with redshift between these two samples, making it unlikely that the rotation velocity of a galaxy interferes with a measurement of its $\sigma_g$.

To further investigate what $\sigma_g$ and $V_{\text{rot}}$ measure, in Covington et al. (2010) we performed mock observations of a suite of simulations of major mergers of disk galaxies. These simulations provided model galaxies in various stages of disorder, ranging the gamut from well-ordered disks to merger remnants. The mock observations were performed just as the actual observations. Galaxies were redshifted to $z \sim 0.3$ and $z \sim 1.0$ and seeing, slit width, and detector pixel size were taken into account. Our algorithm for fitting kinematics was found by Covington et al. (2010) to be successful at reproducing $\sigma_g$, but was found to underestimate $V_{\text{rot}}$ by up to 30%, independent of merger stage or redshift. However, as we note above, Miller et al. (2011) did not find a systematic difference in $V_{\text{rot}}$ between the deeper data and data similar to ours. Therefore, if $V_{\text{rot}}$ is underestimated by up to 30%, it is probably underestimated by this much in both our sample and in the deeper Miller et al. (2011) data set.

5. EVOLUTION OF GALAXY KINEMATICS

In this section, we examine how the kinematics of blue galaxies evolve with redshift. First we examine the full K07 sample, and then we study a mass-limited sub-sample. We return to the full sample again in Section 7.

5.1. The Full K07 Sample

In Figure 2 we show $\sigma_g$, $V_{\text{rot}}$, and $S_{0.5}$ versus stellar mass in bins of redshift for the K07 sample. The $V_{\text{rot}}$ and $S_{0.5}$ relations were already shown in K07; here we show the $\sigma_g$ relation for completeness. The $V_{\text{rot}}$ versus stellar mass relation (i.e., the stellar mass Tully–Fisher relation) shows large scatter to low $V_{\text{rot}}$ at all redshifts (K07), as does $\sigma_g$ versus stellar mass. However, when $V_{\text{rot}}$ and $\sigma_g$ are combined into $S_{0.5}$ (a tracer of potential well depth; Weiner et al. 2006a; K07), the resulting relation with stellar mass tightens significantly and does not evolve with redshift since $z = 1.2$ to within uncertainties (K07). Figure 2 also shows that at lower redshift higher mass galaxies have on average larger values of $V_{\text{rot}}$ and smaller values of $\sigma_g$ than at higher redshift (K07). It is also clear from this figure that at lower redshift lower mass galaxies have low values of $V_{\text{rot}}$ and high values of $\sigma_g$ (K07); they are too faint to be observed at higher redshifts in our sample.

These trends are illustrated more clearly in Figure 3 (left column) where the quantity $V_{\text{rot}}/\sigma_g$, the ratio of ordered to disordered motions in a galaxy, is plotted versus stellar mass in bins of redshift.13 The galaxies define an upper envelope in $V_{\text{rot}}/\sigma_g$ versus stellar mass space which does not evolve since $z = 1.2$. However, galaxies evolve within the envelope: with increasing time (i.e., decreasing redshift) they move away from the bottom of the plot toward the upper envelope, and this happens first for massive galaxies. This evolution is quantified

13 In the evaluation of $V_{\text{rot}}/\sigma_g$, a minimum value of $\sigma_g$ of 15 km s$^{-1}$, which is the lowest value which we can measure, is adopted to avoid dividing by small numbers with relatively large uncertainties.

Figure 4. For the mass-limited sample, the distribution of galaxy stellar masses among the redshift bins in Figure 3 is shown. It demonstrates that the average stellar mass of the sample is not the same at all redshifts: it is lower at lower redshift. This is likely because higher mass galaxies are leaving the sample to become early types. This phenomenon works in the opposite direction to our results, making them lower limits to the intrinsic evolution, as explained in Section 5.2.

5.2. A Mass-limited Galaxy Sample

To investigate these trends of $V_{\text{rot}}/\sigma_g$ with redshift for all but the very lowest and very high mass galaxies in our sample, we use a mass-limited sample of galaxies with stellar masses over $9.8 < \log M_*(M_\odot) < 10.7$ (vertical dotted lines in Figures 1–3), as described in Section 2. For the remainder of this section and for Section 6, we will focus on this mass-limited sample of 270 galaxies. In Figure 4, for the mass-limited sample we plot the distribution of galaxy stellar masses among the redshift bins in Figure 3. It shows that the average stellar mass is not the same for all redshift bins: at lower redshifts it is shifted toward lower masses. This is likely because higher mass galaxies are leaving the sample as they transform to red early type galaxies (e.g., Faber et al. 2007). This trend works in the opposite direction to our results, as we will discuss later in this section. Therefore, the evolution we find is interpreted as a lower limit to the intrinsic evolution.

Figure 5 shows the evolution of $\sigma_g$, $V_{\text{rot}}$, and $S_{0.5}$ with redshift for the mass-limited sample. All three quantities have large intrinsic scatter. We will demonstrate that a portion of the scatter is due to stellar mass or size in Section 6. Medians of the individual measurements in bins of redshift are shown as red triangles in Figure 5. Errors on these medians are calculated by bootstrap re-sampling the data in each redshift bin. Bootstrap resampling is used as a standard method for estimating the statistical error without assumptions about the shape of the distribution. We re-sampled with replacement from the data
Figure 5. Evolution of $\sigma_g$, $V_{\text{rot}}$, and $S_{0.5} \equiv \sqrt{0.5V_{\text{rot}}^2 + \sigma_g^2}$ with redshift for the mass-limited sample ($9.8 < \log M_*(M_\odot) < 10.7$) is shown. Galaxies increase in $\sigma_g$ and decrease in $V_{\text{rot}}$ and $S_{0.5}$ with increasing redshift. Galaxies are plotted as black symbols, as described in Figure 2. Binned medians are shown as red triangles with error bars representing the error on the medians determined by bootstrap re-sampling the data. Linear fits to the binned medians are shown as red lines. Median errors on the individual measurements are shown in the lower right-hand corners of the plots, and include uncertainties in galaxy inclinations for $V_{\text{rot}}$ and $S_{0.5}$.

Figure 6. Evolution of $\sigma_g/S_{0.5}$, $V_{\text{rot}}/S_{0.5}$, and $V_{\text{rot}}/\sigma_g$ with redshift for the mass-limited sample is shown. The first two of these ratios remove the dependence on potential well depth (i.e., $S_{0.5}$) in the $\sigma_g$ and $V_{\text{rot}}$ plots in Figure 5. Symbols, error bars, and fits are the same as in Figure 5.

1000 times and calculated the dispersion of the sample medians. This dispersion is adopted as the error on the median points. It accounts for the spread in the individual data points due to both intrinsic variation and observational error. The errors on the medians are small because the sample is large and there are many points in each redshift bin.

We fit linear relations to $\sigma_g$, $V_{\text{rot}}$, and $S_{0.5}$ versus redshift by performing linear least-squares fits to the binned medians, taking into account the errors on the medians. The results are not sensitive to the redshift bins used. We fit to the medians rather than directly to the data because the distributions of the data points are non-Gaussian and the intrinsic spread of the points is significant compared to the individual error bars, which would cause standard least-squares fits to be misleading. To avoid covariances on the fitted parameters, the medians are zero pointed near the middle of the sample when performing the fits. Of the three quantities, the median $\sigma_g$ shows the strongest evolution ($5.0\sigma$). It increases linearly with redshift to $z = 1.2$ (i.e., decreases with time) as

$$\log \sigma_g - 0.42 = (0.25 \pm 0.05)(z - 0.82) + (1.16 \pm 0.01),$$

and the fit has a $\chi^2$ of 1.1. The median $\sigma_g$ increases from $27 \pm 1$ km s$^{-1}$ at $z = 0.2$ to $47 \pm 1$ km s$^{-1}$ at $z = 1.2$. The quantity which shows the second-strongest evolution is the median $V_{\text{rot}}$ ($4.2\sigma$). It decreases with redshift as

$$\log V_{\text{rot}} - 2.00 = (-0.21 \pm 0.05)(z - 0.82) - (0.04 \pm 0.02),$$

and the fit has a $\chi^2$ of 16.1. The median $V_{\text{rot}}$ decreases from $123 \pm 1$ km s$^{-1}$ at $z = 0.2$ to $76 \pm 1$ km s$^{-1}$ at $z = 1.2$. Finally, the median $S_{0.5}$ shows the weakest evolution of the three kinematic quantities ($3.6\sigma$). It decreases with redshift as

$$\log S_{0.5} - 1.92 = (-0.11 \pm 0.04)(z - 0.82) + (0.00 \pm 0.01),$$

and the fit has a $\chi^2$ of 2.8. The median $S_{0.5}$ decreases from $97 \pm 1$ km s$^{-1}$ at $z = 0.2$ to $75 \pm 1$ km s$^{-1}$ at $z = 1.2$.

Some of the evolution found may be due to a changing distribution of galaxy masses in the sample with time. This can be caused by galaxies growing in mass and/or high-mass galaxies quenching their star formation and leaving the sample. To address this we remove the dependence on potential well depth by examining ratios with $S_{0.5}$, namely, $V_{\text{rot}}/S_{0.5}$ and $\sigma_g/S_{0.5}$. These ratios are shown as a function of redshift in Figure 6. They express the fraction of kinematic support which comes from ordered and disordered motions. The median of the ratio $V_{\text{rot}}/S_{0.5}$ decreases with redshift ($3.0\sigma$) as

$$\log V_{\text{rot}}/S_{0.5} - 0.10 = (-0.06 \pm 0.02)(z - 0.82) + (0.00 \pm 0.01),$$

and the fit has a $\chi^2$ of 1.5. The median $V_{\text{rot}}/S_{0.5}$ decreases from $2.8 \pm 0.3$ at $z = 0.2$ to $0.9 \pm 0.1$ at $z = 1.2$. The quantity which shows the third-strongest evolution is the ratio $\sigma_g/S_{0.5}$ ($3.4\sigma$). It increases with redshift as

$$\log \sigma_g/S_{0.5} - 0.67 = (0.30 \pm 0.06)(z - 0.82) - (0.17 \pm 0.10),$$

and the fit has a $\chi^2$ of 2.7. The median $\sigma_g/S_{0.5}$ increases from $12 \pm 1$ at $z = 0.2$ to $22 \pm 1$ at $z = 1.2$.
and the fit has a $\chi^2$ of 4.5. The median of the ratio $\sigma_g/S_{0.5}$ increases with redshift (5.0σ) as

$$\log \frac{\sigma_g}{S_{0.5}} + 0.35 = (0.45 \pm 0.09)(z - 0.82) + (0.01 \pm 0.03),$$

and the fit has a $\chi^2$ of 2.3. As before, these are linear least-squares fits to the median points. These ratios demonstrate that the increasing role of $\sigma_g$ and the declining role of $V_{\text{rot}}$ with increasing redshift are not due to a changing distribution of galaxy masses in the sample.

The evolution found is interpreted to be a lower limit to the intrinsic evolution. As discussed earlier in this section and shown in Figure 4, the average stellar mass of our mass-limited sample is lower at lower redshifts. From Figure 3 it is apparent that on average low-mass galaxies have higher $\sigma_g$ and lower $V_{\text{rot}}$ than more massive galaxies at any redshift (we will investigate this further in Section 6). Therefore, our findings that for galaxies in the mass-limited sample the average $\sigma_g$ and $V_{\text{rot}}$ are lower and higher, respectively, at lower redshift than at higher redshift are interpreted as lower limits to the intrinsic evolution.

In addition to ratios with $S_{0.5}$, we look at $V_{\text{rot}}/\sigma_g$, a ratio of ordered to disordered motions.$^{13}$ This is not an ideal quantity since neither $V_{\text{rot}}$ nor $\sigma_g$ is constant with redshift. Nevertheless, due to the significant trends of $\sigma_g$ and $V_{\text{rot}}$ with redshift, the median $V_{\text{rot}}/\sigma_g$ also shows strong evolution (4.8σ; Figure 6):

$$\log \frac{V_{\text{rot}}}{\sigma_g} - 1.55 = (-0.48 \pm 0.10)(z - 0.82) - (1.13 \pm 0.04)$$

with $\chi^2 = 2.8$.

To determine whether the $V_{\text{rot}}$ of a galaxy influences the measurement of $\sigma_g$, in Figure 7 we examine the evolution of $\sigma_g$ with redshift for galaxies which are face-on in Hubble images (i.e., $i \leq 30^\circ$) and in the same stellar mass range as the mass-limited sample. This is a subset of galaxies for which $\sigma_g$ should be completely secure. We find the same evolution in the median $\sigma_g$ to within uncertainties for face-on galaxies: $\log \sigma_g - 0.42 = (0.24 \pm 0.04)(z - 0.82) + (1.20 \pm 0.02)$, demonstrating that $V_{\text{rot}}$ does not influence the measurement of $\sigma_g$.

6. DOWNSIZING

In this section, we demonstrate that much of the scatter in the relations of $\sigma_g/S_{0.5}$ and $V_{\text{rot}}/S_{0.5}$ with redshift is attributable to galaxy properties such as stellar mass and size, and find that trends with stellar mass and size are of similar strengths. We also demonstrate that there is a threshold in stellar mass and size acting at all redshifts that separates galaxies with high $\sigma_g/S_{0.5}$ and low $V_{\text{rot}}/S_{0.5}$ from those with low $\sigma_g/S_{0.5}$ and high $V_{\text{rot}}/S_{0.5}$.

First we consider stellar mass. In Figure 8, as in Figure 6, we show $\sigma_g/S_{0.5}$ and $V_{\text{rot}}/S_{0.5}$ as a function of redshift for...
the mass-limited sample. However, in Figure 8, galaxies are divided into three stellar mass bins: $9.8 < \log M_*(M_\odot) < 10.1$, $10.1 < \log M_*(M_\odot) < 10.4$, and $10.4 < \log M_*(M_\odot) < 10.7$. Similar trends to those found for the entire mass-limited sample are also found separately for the three mass bins. Interestingly, it is also evident that at all redshifts examined higher mass galaxies are the most kinematically settled (i.e., higher $V_{rot}/S_{0.5}$ and lower $\sigma_g/S_{0.5}$), intermediate-mass galaxies the next most settled, and low-mass galaxies the least settled. This is consistent with downsizing trends in which more massive galaxies attain final structure and star formation rates sooner (e.g., Cowie et al. 1996), and we refer to this phenomenon as “kinematic downsizing.” Furthermore, there appears to be a threshold at $\log M_*=10.4$ and low $V_{rot}/S_{0.5}$ from those with low $\sigma_g/S_{0.5}$ and high $V_{rot}/S_{0.5}$. This is most evident in the median points in Figure 8: those for the lower and intermediate mass bins are very similar, while those for the higher mass bin differ significantly from the other mass bins.

Next we examine trends with size. We consider two size measurements: Hubble half-light radius which is not affected by seeing (top two plots) and emission line extent which is affected by seeing and not corrected for its influence (bottom two plots). Galaxies in size bins show similar trends to the full mass-limited sample. However, at all redshifts the largest galaxies are the most well ordered (high $V_{rot}/S_{0.5}$, low $\sigma_g/S_{0.5}$), the intermediate-sized galaxies the next well ordered, and the smallest galaxies the least well ordered. There appears to be a threshold at 4 kpc which corresponds to the threshold in stellar mass seen in Figure 8.

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

**Figure 9.** Same as Figure 8, except galaxies from the mass-limited sample are divided into three size bins: <4 kpc (black squares), 4–6 kpc (gray circles), and >6 kpc (red triangles). Two size measures are considered: Hubble half-light radius which is not affected by seeing (top two plots) and emission line extent which is affected by seeing and not corrected for its influence (bottom two plots). Galaxies in size bins show similar trends to the full mass-limited sample. However, at all redshifts the largest galaxies are the most well ordered (high $V_{rot}/S_{0.5}$, low $\sigma_g/S_{0.5}$), the intermediate-sized galaxies the next well ordered, and the smallest galaxies the least well ordered. There appears to be a threshold at 4 kpc which corresponds to the threshold in stellar mass seen in Figure 8.

(Except the galaxies are color-coded according to size instead of stellar mass. For both size measurements, three size bins are shown: <4 kpc, 4–6 kpc, and >6 kpc. Figure 9 shows that on average at all redshifts examined the largest galaxies are the most kinematically well ordered, the smallest the most disordered, and intermediate-sized galaxies have properties in between the two. This is the case for both size measurements. It demonstrates that emission lines, which we use to measure galaxy kinematics, are likely good tracers of the spatial distribution of the galaxy continua observed in Hubble images. It also demonstrates that we are able to measure reliable rotation velocities for even the small galaxies in our sample. Similar to the stellar mass bins, there is also a size threshold. It is at 4.0 kpc, which corresponds to the threshold in stellar mass ($\log M_*=10.4$) in the size versus stellar mass relation for the mass-limited sample.

Figures 8 and 9 also demonstrate that the evolution in Figures 5 and 6 is not due to a special population of high-redshift galaxies with high values of $\sigma_g$ and low values of $V_{rot}$. It occurs even if only massive/large galaxies are considered.

### 7. SETTLING FRACTION

To better quantify how blue galaxies evolve in $\sigma_g$ and $V_{rot}$, we use these parameters to define a kinematically settled disk
galaxy and then study the fraction of settled disk galaxies as a function of stellar mass and redshift. We return again to the full K07 galaxy sample. For the definition of a settled disk, we first look to the distribution of $V_{\text{rot}}/\sigma_g$ in Figure 3 and then to Hubble morphologies. Since we regard higher mass blue galaxies to be on average kinematically settled disks at low redshift, we look to their values of $V_{\text{rot}}/\sigma_g$ in Figure 3. A typical value for galaxies with $\log M_*(M_\odot) > 9.8$ is $\sim 3$ (i.e., log $V_{\text{rot}}/\sigma_g = 0.48$). We now consider Hubble morphologies. K07 and S. A. Kassin et al. (in preparation) show that for the full K07 sample, Hubble morphologies are correlated with $V_{\text{rot}}/\sigma_g$ such that galaxies with normal disk-like morphologies via inspection by eye have higher values than galaxies which appear more disturbed. We find that $V_{\text{rot}}/\sigma_g \sim 3$ indeed provides a reasonable division between normal disk-like and disturbed morphologies, as demonstrated by Hubble images of six galaxies from the K07 sample in Figure 10. In addition, $V_{\text{rot}}/\sigma_g \sim 3$ provides a good separation between the “rotating disks” and “perturbed rotators” in the IMAGES Survey at $z \sim 0.6$ (Puech et al. 2007, Figure 6). The median $V_{\text{rot}}/\sigma_g$ for galaxies in the local GHASP Survey (Epinat et al. 2010) is 6.3 with an rms scatter of 3.3, indicating that disk galaxies in the local universe are even more kinematically quiet than those which pass our “settled” criterion.

This quantitative definition of a settled disk galaxy (i.e., $V_{\text{rot}}/\sigma_g > 3$) can be used to measure the fraction of blue galaxies which are settled, $f_{\text{settle}}$. The evolution of $f_{\text{settle}}$ with redshift for the full K07 sample divided into four stellar mass bins is shown in Figure 11. All bins show increasing $f_{\text{settle}}$ with decreasing redshift (i.e., increasing $f_{\text{settle}}$ with time). For example, $f_{\text{settle}}$ increases over $0.2 < z < 1.2$ from 40% to 89% for $10.3 < \log M_*(M_\odot) < 10.7$ and from 31% to 65% for $9.8 < \log M_*(M_\odot) < 10.3$. For the less massive bins, we probe smaller ranges in redshift. These are lower limits to the intrinsic evolution, as discussed in Section 5.2. Furthermore, at all redshifts the higher the stellar mass of the galaxy population, the higher its value of $f_{\text{settle}}$. The same qualitative behavior is found for settled galaxies defined as $V_{\text{rot}}/\sigma_g > 1-4$, except for the lowest mass bin.

8. KINEMATIC MEASUREMENTS IN THE LITERATURE

In this section, we compare our mass-limited sample with measurements in the literature for local galaxies and for galaxies at similar redshifts. We also compile kinematic measurements from the literature and for galaxies at higher redshifts. Measurements of $S_0$, $V_{\text{rot}}$, and $\sigma_g$ from the literature are shown in Figure 12, and are detailed below in order of increasing redshift. In the panels on the left and right in Figure 12, galaxies are color-coded according to stellar mass (for a Chabrier 2003
Figure 12. Quantities plotted here are the same as those shown in Figure 5, except here the $z$ axes are expanded to include data from the literature. In the plots on the left and right galaxies are color-coded according to stellar mass and emission line extent, respectively, unless noted in Section 8. For the local GHASP survey, only sample medians are shown (large open black triangles) with error bars depicting the rms scatter. Large filled symbols denote medians of large samples at $z \lesssim 1.2$: the mass-limited sample from this paper (“DEEP2,” triangles), IMAGES (circles), and MASSIV (squares). Individual galaxies from these large samples are shown as small open symbols: DEEP2 (gray circles; not colored according to mass/size), IMAGES (circles), and MASSIV (squares). At $z \gtrsim 1.2$, only individual galaxies are shown: large open symbols with error bars denote galaxies where rotating disk models were fit, and small filled symbols without error bars denote galaxies where models were not fit (for these galaxies, $V_{\text{shear}}$ and a median $\sigma_g$ are plotted). Galaxies from Wisnioski et al. (2011) are shown as small filled triangles, from Wright et al. (2007, 2009) as large open squares, from Lemoine-Busserolle & Lamareille (2010) and Epinat et al. (2009) (“L-BL/E”) as large open circles, from Bournaud et al. (2008) as a large open circle, from van Starkenburg et al. (2008) as a large open circle, from SINS as large open stars and small filled circles, from Law et al. (2009) as small filled triangles, from Lemoine-Busserolle et al. (2010) (“L-BL”) as large open circles and a single filled circle, and from AMAZE/LSD as large open squares and small filled squares.

initial mass function, IMF) and emission-line extent, respectively, unless noted below. The mass-limited sample is also shown in Figure 12 as small gray open circles (labeled “DEEP2”) with sample medians shown as large filled triangles and linear fits to the medians as solid black lines. All literature measurements are from integral field spectroscopy (IFS). To compare our data set with local galaxies, a large homogeneous sample is needed, and the GHASP survey (Epinat et al. 2010) provides this. Figure 12 shows median values of $S_{0.5}$, $V_{\text{rot}}$, $V_{\text{shear}}$, and $\sigma_g$. 

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[The rest of the text continues with references and further details related to the plots and data being discussed.]
and $\sigma_g$ for galaxies in GASP as large open black triangles at $z = 0$. Error bars on these points depict the rms scatter of the sample. Although GASP spans a larger range in stellar mass than our mass-limited sample; $9.0 < \log M_\star (M_\odot) < 11.7$ for a “diet” Salpeter IMF (Epinat et al. 2008; which is roughly 0.15 dex higher than the Chabrier 2003 IMF used in this paper), the sample medians are consistent with extrapolations of our relations to $z = 0$. Individual stellar mass measurements for galaxies in GASP are unavailable to create a more comparable sample.

Kinematic measurements for 47 out of 68 galaxies in the IMAGES IFS Survey which have stellar mass measurements in the same range as our mass-limited sample are shown as small open circles in Figure 12 (M. Puech 2011, private communication; Puech et al. 2008; Neichel et al. 2008; Yang et al. 2008). Sample medians are shown as large filled circles at the median redshift of the survey, $z = 0.6$. The sizes used are continuum half-light radii. Although IMAGES has a similar selection to our survey, the median $V_{\text{rot}}$ and $\sigma_g$ of IMAGES are larger than ours at $z = 0.6$ by 0.23 and 0.18 dex, respectively. The measurement methods are sufficiently different for IMAGES compared to our methods that it is difficult to compare the two data sets. However, it is possible that the IMAGES median $\sigma_g$ is higher because, unlike our procedure of fitting for $V_{\text{rot}}$ and $\sigma_g$ simultaneously, they are fit for separately in IMAGES. This may result in $\sigma_g$ measurements which are biased high because pixels with the highest signal to noise will be ignored when they are fit for separately (e.g., Davies et al. 2011).

The remaining points in Figure 12 plot data for galaxies beyond $z = 1.2$. Kinematic data are difficult to obtain at these redshifts since emission lines are redshifted to near-infrared wavelengths where the sky is bright in continuum and line emission, making spectroscopy difficult. Pioneering studies of galaxy kinematics at $z \gtrsim 1$ with single-slit near-infrared spectrographs gave the first glimpse of the kinematic state of galaxies at these earlier times, albeit only the most highly star-forming systems (e.g., Erb et al. 2004, 2006). More recently, there has been a boom in IFS observations of galaxy kinematics at these redshifts. However, to obtain enough signal to noise to measure kinematics in a reasonable amount of observing time, all samples at these redshifts are unfortunately still biased toward galaxies with the brightest emission lines, which are the most highly star-forming systems.

The first set of points beyond $z \sim 1.2$ in Figure 12 shows kinematic measurements for 29 out of 46 galaxies from the MASSIV Survey (small open squares; Contini et al. 2012; Vergani et al. 2012). These galaxies have stellar masses in the same range as our mass-limited sample and a median redshift of 1.2. Medians in $\log M_\star (M_\odot)$, $V_{\text{rot}}$, and $\sigma_g$ for the MASSIV sample are shown as large filled squares. The lower mass galaxies in MASSIV (9.8 < $\log M_\star (M_\odot) < 10.3$) have median values of these quantities which are consistent with the lower mass galaxies in our mass-limited sample. However, the higher mass galaxies (10.3 < $\log M_\star (M_\odot) < 10.7$) have median values which are greater than the higher mass galaxies in our mass-limited sample. This is especially the case for $V_{\text{rot}}$ which has a median value which is 0.20 dex larger than that for the higher mass galaxies in our mass-limited sample at $z = 1$. This difference is most likely due to sample selection, since galaxies in MASSIV are chosen to be the very brightest galaxies in the VVDS Survey (Contini et al. 2012).

Moving to higher redshift in Figure 12, we note that many IFS observations of galaxies at $z \gtrsim 1.5$ have kinematics which cannot be fit by a rotating disk model. This is due to a few factors: a non-ordered velocity field, small spatial extent, and/or low signal to noise. For these galaxies, we adopt half of the velocity shear across the face of the system ($(1/2) \times V_{\text{shear}}$) as $V_{\text{rot}}$, where $V_{\text{shear}}$ is the difference between the minimum and maximum rotation velocities and is not corrected for inclination. These galaxies are shown as small filled symbols without error bars in Figure 12 to differentiate them from galaxies which were modeled as rotating disks and are shown as large open symbols with error bars.

For 13 extremely high star-forming galaxies at $z \sim 1.3$, we adopt measurements from Wisnioski et al. (2011) which are not modeled as rotating disks (small filled triangles in Figure 12). Next, for eight galaxies at $z \sim 1.5$, we adopt measurements from S. Wright (2011, private communication) for observations presented in Wright et al. (2007, 2009). Galaxies which consist of two or more spatially separated components are treated as individual systems. Four of these galaxies were modeled as rotating disks (large open squares) and four were not (small filled squares). For galaxies which were so modeled, values of $V_{\text{rot}}$ are not corrected for galaxy inclinations. For the Wright et al. (2007, 2009) sample, all but the highest value of $\sigma_g$ can be explained by a residual seeing halo and are therefore not likely physical. For an additional eight galaxies at $z \sim 1.5$, we adopt data from Epinat et al. (2009) and Lemoine-Busserolle & Lamareille (2010) which analyze the same observations. Weabbreviate these references as “L-B/L/E.” For both studies, eight galaxies are modeled as rotating disks. Values of $V_{\text{rot}}$ and $\sigma_g$ are consistent between the two studies to within uncertainties except for one galaxy, VVDS 020147106. For this galaxy we adopt $V_{\text{rot}}$ from Epinat et al. (2009) since their model does not extrapolate significantly beyond the observed velocity field. For the remaining seven galaxies, fitted quantities from Lemoine-Busserolle & Lamareille (2010) are adopted. These eight galaxies are shown in Figure 12 as large open circles. We do not show data for two additional galaxies from Lemoine-Busserolle & Lamareille (2010) which were not able to be modeled, one of which is also in Epinat et al. (2009). One of these galaxies, VVDS 020461235, does not have a measurement of $\sigma_g$. The other galaxy, VVDS 020116027, has a velocity field which differs significantly between the two studies, likely indicating low signal to noise. Finally, we show best-fit parameters for one galaxy at $z = 1.6$ from Bournaud et al. (2008) as large open circles in Figure 12.

For galaxies at $z \sim 2$, data are adopted from the SINS Survey via private communication from N. Förster-Schreiber in 2011 for the most recent models and data as of 2011 August for galaxies in Genzel et al. (2008), Förster-Schreiber et al. (2009), and Cresci et al. (2009). A total of 14 SINS galaxies were modeled as rotating disks (large open stars in Figure 12) and 33 were not (small filled circles). For galaxies from SINS which were not modeled, we estimate $\sigma_g$ as the line-width less the velocity shear (i.e., $v_{\text{obs}}$ from Förster-Schreiber et al. 2009 less $V_{\text{shear}}$). For an additional 16 galaxies at $z \sim 2$ we adopt data from Law et al. (2009). None of these galaxies were modeled as rotating disks, and they are shown as small filled triangles in Figure 12. Three galaxies from Law et al. (2009) consist of two spatially separated components; we consider each of these components as a separate galaxy. In addition, best-fit parameters for one galaxy at $z = 2.03$ from van Starkenburg et al. (2008) are shown as large open circles labeled “van S.”
“L-B”) and one is not (filled circle shown enlarged in Figure 12 because it overlaps an error bar for a different galaxy in the $S_{0.5}$ and $\sigma_g$ plots). In addition, measurements for 19 galaxies at $z \sim 3$ data are adopted from the AMAZE/LSD Survey via private communication from A. Gnerucci in 2011 for data from Gnerucci et al. (2011) and Troncoso et al. (in preparation). A total of 12 of these galaxies were modeled as rotating disks (large open squares) and 7 were not (small filled squares).

We will now attempt to summarize the disparate data sets from the literature over 1.2 < $z$ < 2.5. Overall, there is large scatter in $\sigma_g$, $V_{rot}$, and $S_{0.5}$, and no clear trends with redshift. While some of the scatter is likely due to the range in stellar masses probed, that there are no trends is probably also due to other factors. Namely, only the brightest galaxies are observed at these redshifts, and instrumental effects and poor observational conditions likely play roles. It is also clear that all high-redshift galaxies observed have significant contributions to their kinematics from $\sigma_g$.

On average, distant galaxies beyond the last redshift of our sample divide into two populations (e.g., Law et al. 2009; Förster-Schreiber et al. 2009). (1) The first consists of large massive galaxies with $V_{rot}$ equal to or slightly greater than the largest values which we measure for DEEP2 galaxies, and which have significant values of $\sigma_g$. (2) The second population consists of small lower mass galaxies with low or negligible $V_{rot}$ but with significant $\sigma_g$. These small galaxies are prominent in the Law et al. (2009) sample and the SINS survey, but are also found at lower redshifts in the DEEP2, IMAGES, and MASSIV surveys. Some of the observations at $z > 1.2$ may be too shallow to detect the full rotation gradients, so until these galaxies can be observed with significantly longer exposure times to detect possible faint disks, whether or not all of them lack significant $V_{rot}$ is unclear. Interestingly, at $z \sim 3$, nearly all galaxies are small but have large values of $V_{rot}$ and $\sigma_g$.

9. CONCLUSIONS

We study the internal kinematics of 544 blue galaxies over the last $\sim8$ billion years and find significant evolution. Blue galaxies become progressively more well ordered with time as disordered motions decrease and rotation velocities increase. In addition, galaxy potential well depths continuously increase with time. At all redshifts the most massive galaxies are on average the most kinematically settled, and the least massive galaxies the least kinematically settled. The lowest mass galaxies in our survey, which are observed only at low redshift, are not well ordered even today. They may be in the process of settling or never will become settled disks. There appears to be a threshold at log $M_*=10.4M_\odot$ and 4.0 kpc which separates galaxies with more ordered kinematics from those with more disordered kinematics. All in all, these trends with mass are consistent with downsizing trends for other galaxy properties, and we refer to them as "kinematic downsizing."

We define a kinematically settled disk galaxy as having a ratio of ordered to disordered motions ($V_{rot}/\sigma_g$) greater than three. We find that the fraction of settled disk galaxies, $f_{settle}$, increases with time since $z = 1.2$ for all galaxies over 8.0 < log $M_*(M_\odot)<10.7$. The fraction $f_{settle}$ is larger for more massive galaxy populations, independent of redshift. These qualitative findings do not change if a settled disk galaxy is defined with $V_{rot}/\sigma_g > 1.4$.

We speculate that the steady kinematic settling seen in our data is due to a combination of factors. (1) The frequency of mergers may be decreasing with time. Merging, major but more frequently minor, as is expected in a ΛCDM universe, will stir galaxies up (e.g., Covington et al. 2010). (2) The amount of mass accreted onto galaxies may be decreasing with time. Mass accretion, although smoother than mergers, might still disturb pre-existing disks (see, e.g., Bournaud et al. 2011; Cacciato et al. 2012, for a simple analytic treatment). (3) Galaxies likely have larger molecular gas reservoirs at higher redshift (Daddi et al. 2010; Tacconi et al. 2010). Higher gas fractions should result in more star formation, and feedback from star formation may also stir up the gas in galaxies (e.g., Silk & Norman 2009 and references therein). (4) Finally, higher gas fractions can also lead to violent disk instabilities (e.g., Bournaud et al. 2011; Cacciato et al. 2012 and references therein) which increase random motions, and may also be a step in the direction of more star formation.

At bottom, the primary causative factors of disk settling are likely two-fold: more merging/accretion and higher gas fractions at early times. Faster star formation rates are likely byproducts of these two factors, and increasing potential well depths a byproduct of merging/accretion. Since both factors decline with time, a general kinematic settling with time is expected. Furthermore, both factors are apparently declining earlier in massive galaxies, at least since $z \sim 1$, providing a natural explanation of the kinematic downsizing we find.

It is yet unknown whether disk galaxies in cosmological numerical simulations undergo a kinematic settling akin to what we find in this paper. Only recently have hydrodynamic simulations of galaxy formation been run with enough numerical resolution to study the effects of mass accretion in detail. Simulations find that mass accretes directly onto galaxies from cosmic filaments (e.g., Katz et al. 2003; Birnboim & Dekel 2003; Keres et al. 2005; Ocvirk et al. 2008; Brooks et al. 2009). The effects of accretion have been studied with small samples of simulated galaxies at $z \sim 2$ (e.g., Bournaud et al. 2009; Ceverino et al. 2010). These studies find that mass accretion perturbs disks and leads to violent disk instabilities, but the effects of accretion have yet to be studied for a representative sample of simulated galaxies at lower redshifts. The simulations which have been run to lower redshifts generally focus on reproducing the photometric and structural properties of galaxies (e.g., Governato et al. 2007, 2009; Brook et al. 2011; Martig et al. 2012, and references therein), and not $\sigma_g$, $V_{rot}$, and $S_{0.5}$. On the analytic side, Cacciato et al. (2012) created a simple model for the kinematic evolution of massive disk galaxies at $z \sim 2$. They predict that these galaxies, if still around today, are massive disks with similar rotation velocities but less disordered motions, similar to the kinematic settling we find. Numerical simulations are not yet ripe for studies of the kinematic evolution of blue galaxies since $z \sim 1$, and we look forward to comparisons with future predictions.

Our data are augmented with a compilation of measurements of the kinematics of emission-line galaxies from the literature over 0 < $z$ < 3.8. Observations of local massive disk galaxies reveal few examples where disordered motions (as quantified by $\sigma_g$) play an important role as in similar-mass emission-line galaxies at higher redshifts (e.g., Epinat et al. 2010). Measurements of galaxy kinematics at $z > 1.5$ show few clear trends with redshift, likely primarily due to sample selection since only the most highly star-forming systems at these redshifts can currently be studied, but also due to instrumental artifacts and observational conditions. However, it is clear that higher redshift galaxies have a significant amount of disordered motions, whether or not they show evidence of rotation.
In summary, galaxies seem to have a life cycle: early in their lives they are accreting baryons rapidly, undergoing mergers, and possess a large amount of gas. Later in their lives the accretion decreases along with their gas content. Kinematic settling appears to be a natural, additional facet of this basic evolutionary arc.

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