A SURVEY OF GALAXY KINEMATICS TO Z ∼ 1 IN THE TKRS/GOODS-N FIELD.

I. ROTATION AND DISPERSION PROPERTIES


ABSTRACT

We present kinematic measurements of a large sample of galaxies from the Team Keck Redshift Survey in the GOODS-N field. We measure line-of-sight velocity dispersions from linewidths of integrated emission for 1089 galaxies with median redshift 0.637, and spatially resolved kinematics for a subsample of 380 galaxies. This is the largest sample of galaxies to z ∼ 1 with kinematics to date, and allows us to measure kinematic properties without morphological pre-selection. Emission linewidths provide a dynamical measurement for the bulk of the blue galaxy population. To fit the spatially resolved kinematics, we construct models with both line-of-sight rotation amplitude and velocity dispersion as fit parameters. Integrated linewidth correlates well with a combination of the spatially-resolved velocity gradient and dispersion, and is a robust measure of galaxy kinematics. The spatial extents of emission and continuum are similar and there is no evidence that linewidths are affected by nuclear or clumpy emission. The measured rotation gradient is a strong function of slit position angle alignment with galaxy major axis, but integrated linewidth is largely independent of slit alignment. Even in a subsample of galaxies with well-aligned slits, there are galaxies whose kinematics are dominated by dispersion (V/σ < 1) rather than rotation. These are probably objects with disordered velocity fields, not dynamically hot stellar systems. About 35% of the spatially resolved sample are dispersion dominated; galaxies that are both dispersion dominated and bright exist at high redshift but appear rare at low redshift. This kinematic morphology may yield a probe of the evolutionary state of these objects. Kinematic morphology is linked to photometric morphology in HST/ACS images: dispersion dominated galaxies include a higher fraction of irregulars and chain galaxies, while rotation dominated galaxies are mostly disks and irregulars. Only one-third of chain/hyphen galaxies are dominated by rotation; high redshift elongated objects cannot be assumed to be inclined disks. In a companion paper, we use the linewidths and rotation to measure evolution in the Tully-Fisher relation.

Subject headings: galaxies: distances and redshifts — galaxies: evolution — galaxies: fundamental parameters — galaxies: high-redshift — galaxies: structure — surveys

1 INTRODUCTION

Galaxy redshift surveys to z ∼ 1 allow the measurement of evolution in properties of the galaxy population at lookback times of half the present age of the Universe. To date, a number of surveys have studied galaxy properties such as luminosities, colors, radii, morphology and environment. The internal kinematics of galaxies are equally interesting, as a physical probe of individual objects and to allow the measurement of scaling relations of the galaxy population. However, measuring kinematics requires moderate to high-resolution spectroscopy, which has until recently been difficult to obtain for large numbers of faint galaxies.

This paper measures kinematics of galaxies from emission lines, using Keck/DEIMOS spectra from the Team Keck Redshift Survey (TKRS) in the GOODS-N (Great Observatories Origins Deep Survey) field (Wirth et al. 2004; Giavalisco et al. 2004). The TKRS provides spectra of 1437 galaxies drawn from a magnitude limited sample to RAB < 24.4, at resolution R ∼ 2100. We select 1191 galaxies with good emission line detections and measure 1089 emission line velocity dispersions from integrated emission, with median < z >= 0.637. A subsample of 464 are selected for modeling spatially resolved rotation and dispersion profiles, of which 380 yield good-quality measurements. We use these spatially resolved measures to probe the kinematic properties of high redshift galaxies and to test the integrated linewidths. In Paper II (Weiner et al. 2006), we use the linewidths and rotation velocities to measure evolution in the Tully-Fisher relation.

A number of previous works have observed galaxy internal kinematics from 0.1 < z < 1.0, for the purpose of measuring Tully-Fisher relations. The pioneering studies of Vogt et al. (1996, 1997) modeled rotation curves for 17 galaxies of disky morphology with median < z >= 0.47 by combining Keck/LRIS slitlet spectra with structural information from HST photometry. Several subsequent studies of rotation curves with similar modeling proce-
dures have contained 20-100 galaxies with median redshifts \( \sim 0.4 - 0.5 \) (e.g., Simard & Pritchet 1998; Vogt 2000; Ziegler et al. 2002; Milvang-Jensen et al. 2003; Böhm et al. 2004; Bamford et al. 2005; Conselice et al. 2005; Nakamura et al. 2006; Metevier et al. 2006). Generally these samples have been morphologically selected to be inclined disky objects, of which a majority show measurable rotation.

Here we study a sample with emission line kinematics that is essentially selected only on magnitude and emission line strength. We measure one-dimensional integrated velocity dispersion (linewidth), and for a subsample, spatially resolved rotation profiles; we discuss the properties of these velocity measures in Sections 2 and 5. We show that the integrated linewidth is a fairly robust measure of the characteristic velocity of a galaxy, expanding the scope of the study beyond galaxies that are selected to be orderly rotating disks. Indeed, we find from the spatially resolved rotation profiles that a significant number of high-redshift galaxies show kinematics that do not appear to be orderly rotation.

We adopt a LCDM cosmology with \( h = 0.7 \), \( \Omega_M = 0.3 \), and \( \Omega_\Lambda = 0.7 \). Magnitudes quoted in this paper are in the AB system unless explicitly indicated as Vega. Section 2 discusses the sample and measurement methods, and section 8 presents the properties of the sample and completeness. Sections 4 and 5 study the simulated and empirical properties of the kinematic measurements: integrated linewidths and spatially resolved velocities. In Paper II we use the kinematics to measure the evolution in the Tully-Fisher relation with redshift.

2. SAMPLE, VELOCITY MEASUREMENTS, AND PHOTOMETRY

2.1. Properties of the spectroscopic sample

The parent sample for our kinematic measurements is the Team Keck Redshift Survey (TKRS) in the GOODS-N field. The selection and observations are described at length by Wirth et al. (2004) and we present a few relevant details here. Data and images of TKRS galaxies may be retrieved from the TKRS website at http://www2.keck.hawaii.edu/science/tksurvey/

The TKRS sample is magnitude selected to \( R_{AB} = 24.4 \). No color or morphological selection was applied, but there is a mild surface brightness selection (see Willmer et al. 2006), which may eliminate a few faint high-z reddened edge-on galaxies. The sampling completeness (ratio of galaxies with spectra to galaxies meeting selection criteria) is \( \sim 75\% \) and the redshift success rate is \( \sim 70\% \) (\( > 80\% \) for \( R_{AB} < 23 \)). Most galaxies for which spectra were taken but redshifts could not be determined are faint, blue, and probably at \( z > 1.5 \), where [O II] \( \lambda 3727 \) disappears into the night-sky OH line forest.

TKRS observations used the Keck II telescope and DEIMOS spectrograph with a 600 lines/mm grating, yielding a sampling of 0.119"/pixel and 0.648 Å/pixel. Typical wavelength coverage was 4600–9800 Å. 18 slit masks were observed, each for 60 minutes total exposure time. The slit width was 1.0". In the mask designs, slit position angles (PAs) could be tilted to follow the major axis of elongated objects, by up to 30 degrees away from the nominal perpendicular-to-dispersion direction. Galaxy PAs were measured from ground-based \( R \)-band imaging before mask design. When slits were tilted, the slit width was adjusted to keep the width along the dispersion direction at 1.0", keeping the spectral resolution constant regardless of slit PA.

The TKRS data were reduced and redshifts measured with the DEIMOS pipeline software developed by the DEEP project, described in Davis et al. (2003) and Wirth et al. (2004); TKRS data are very similar to DEEP2 data, save that DEEP2 uses a 1200 lines/mm grating. Candidate redshifts were measured automatically and verified by visual inspection by members of Team Keck.

End data products include 2-d spectra for each slitlet and both optimal and boxcar extracted 1-d spectra for each object. We used the 2-d spectra to measure rotation curves and the 1-d spectra to measure linewidths of integrated emission. In this paper we always use the boxcar extraction, never the optimal: the optimal extraction weights different regions of the galaxy light profile unequally, which makes the physical meaning of the optimally extracted spectrum somewhat obscure. The boxcar extraction window diameter is set by the reduction software to 1.5 times the FWHM of the object measured in the 2-d spectrum. For nearly all galaxies, larger extraction windows do not make a significant difference to the measured linewidths, because the emission intensity is centrally peaked (see also Section 4.2).

2.2. Emission line measurement in the 1-d spectra

Our goal in fitting linewidths to integrated emission is to obtain a kinematic measurement for as many galaxies as possible, without applying cuts to the sample. Several previous studies have used linewidths of integrated emission to measure kinematics of small samples of galaxies at intermediate redshift (Rix et al. 1997; Mallen-Ornelas et al. 1999).

2.2.1. Line fitting

We developed an automated program to fit emission lines in all TKRS galaxies with secure redshifts (quality code 3 or 4 indicating two spectral features, Wirth et al. 2004). The LINEFIT program takes a galaxy redshift and list of common emission lines; at the predicted location of each line, it takes the wavelength, flux, and error data from a 40 Å window and fits a gaussian profile, using a Levenberg-Marquardt non-linear least squares \( \chi^2 \) minimization (Press et al. 1992).

The fit has four free parameters: continuum level, line intensity, velocity, and velocity dispersion. For the [O II] \( \lambda\lambda 3726.0, 3728.8 \) doublet, the program can fit a doublet with the wavelength ratio fixed and the intensity ratio fixed or free; for the TKRS data, we fixed the doublet intensity ratio at 1.4 (the mean ratio of red/blue components in high-S/N data measured with the 1200 lines/mm grating). The least squares fitter yields best-fit values and error estimates for all parameters. Fitting in the 40 Å window does not provide an adequate measure of the continuum in low-S/N spectra and so LINEFIT also measures a robust continuum by taking the biweight of data in two 80 Å windows on either side of the emission line.

2.2.2. Instrumental resolution

This sample relies heavily on the measurement of velocity dispersion, which in turn can be strongly affected
by the instrumental spectral resolution \( \sigma_{\text{inst}} \). Conventionally, the restframe intrinsic line-of-sight velocity dispersion \( \sigma_{1d} \) of a line is given by

\[
\sigma_{1d} = \frac{c}{\lambda_{\text{obs}}} \sqrt{\sigma_{\text{obs}}^2 - \sigma_{\text{inst}}^2},
\]

where \( \sigma_{1d} \) is in km s\(^{-1}\), \( \lambda_{\text{obs}} \) is the observed wavelength in Å, and \( \sigma_{\text{obs}} \) and \( \sigma_{\text{inst}} \) are the measured line dispersion and instrumental resolution, both in Å. As a rule of thumb, measurements for \( \sigma_{1d} < c\sigma_{\text{inst}}/\lambda_{\text{obs}} \) are not very reliable because small errors in the observed width have a large effect on the inferred dispersion. We use \( \sigma_{1d} \) to denote the restframe velocity dispersion derived from the 1-dimensional extracted spectrum, which is integrated over the extraction window. Throughout these papers, observed quantities are given in Å and restframe velocity quantities in km s\(^{-1}\). This paper refers to several dispersion and velocity quantities, in observed and restframe, and 1-d and 2-d spectra; these are summarized in Table 1.

With DEIMOS and 1.0′′ slits, the profile of night sky lines or calibration arcs is somewhat flat-topped, less peaked than a gaussian. This flat-topping is pronounced from modeling of 2-d spectrum. The variations’ effect on the derived dispersions is small: for a small galaxy with \( \sigma_{1d} = 50 \text{ km s}^{-1} \), the peak error induced is ~ 2 km s\(^{-1}\), and the error declines rapidly for larger \( \sigma_{1d} \).

2.2.3. Velocity dispersion sample

There are 1437 galaxies with redshifts, TKRS spectra, and magnitudes. We fit emission lines in each of these objects. For velocity dispersion purposes we then reject all lines that do not have a 4 sigma intensity detection. The 4 sigma line catalog contains 2595 lines over 1191 galaxies.

Galaxies can have several lines, and the fit parameters are independent. To obtain one estimate of velocity dispersion for each object, we take the weighted mean of the measurements of squared intrinsic velocity dispersion, \( \sigma_{1d}^2 \); using the square properly accounts for lines that are narrower than the nominal instrumental resolution, which have \( \sigma_{1d}^2 < 0 \). We use a weighted rms of the dispersions as the error estimate. We exclude a tail of 85 galaxies that have both error(\( \log \sigma_{1d} \)) > 0.25 and error(\( \sigma_{1d} \)) > 30 km s\(^{-1}\) to reject low-quality fits.

Some line fits have an observed width \( \sigma_{\text{obs}} \) that is smaller than the nominal instrumental width. Although this is formally physically impossible, it is expected in the presence of noisy data, slit underfilling, and variations in the instrumental resolution. After combining all lines, 196 of 1089 galaxies are “kinematically unresolved,” with widths close to or less than instrumental, so that the formal velocity dispersion is undefined or has a large error in \( \log \sigma_{1d} \). When we restrict to \( M_B < -18 \), the cutoff for our Tully-Fisher fits in Paper II, 104 of 913 are kinematically unresolved in \( \log \sigma_{1d} \), under the criteria error(\( \log \sigma_{1d} \)) > 0.25, error(\( \sigma_{1d} \)) < 30, and \( \sigma_{1d} < 25 \text{ km s}^{-1} \). Eliminating these galaxies from the sample preferentially rejects low-velocity galaxies and leads to a bias, so for plotting and fitting purposes we assign them a low value, \( \log \sigma_{1d} = 1.4 \pm 0.2 \). The results of fitting do not depend strongly on the exact value assigned. Note that a few other galaxies have log \( \sigma_{1d} < 1.4 \) yet low formal error on \( \log \sigma_{1d} \), usually because they have very strong and well-measured emission lines. In Section 3 of Paper II we outline a fitting method which treats the unresolved galaxies more robustly by fitting the ensemble of observed width \( \sigma_{\text{obs}} \) before the instrumental resolution is subtracted.

Some galaxies with very bright emission lines can have formally very small errors. It is lubris to take these errors literally, since we can hardly expect to measure

<table>
<thead>
<tr>
<th>Quantity</th>
<th>units</th>
<th>description</th>
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</thead>
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<tr>
<td>( \sigma_{\text{obs}} )</td>
<td>Å</td>
<td>Line dispersion measured in 1-d spectrum</td>
</tr>
<tr>
<td>( \sigma_{\text{inst}} )</td>
<td>Å</td>
<td>Instrumental resolution</td>
</tr>
<tr>
<td>( \sigma_{1d} )</td>
<td>km s(^{-1})</td>
<td>Intrinsic, instrumental-subtracted line-of-sight restframe dispersion in 1-d spectrum</td>
</tr>
<tr>
<td>( V_{\text{rot}} )</td>
<td>km s(^{-1})</td>
<td>Restframe line-of-sight rotation velocity from modeling of 2-d spectrum</td>
</tr>
<tr>
<td>( V_{\text{rot}}/\sin i )</td>
<td>km s(^{-1})</td>
<td>Inclination-corrected rotation velocity</td>
</tr>
<tr>
<td>( \sigma_{2d} )</td>
<td>km s(^{-1})</td>
<td>Restframe line-of-sight intrinsic dispersion from modeling of 2-d spectrum</td>
</tr>
<tr>
<td>( S_K )</td>
<td>km s(^{-1})</td>
<td>Combined velocity, ( \sqrt{K V_{\text{rot}}^2 + \sigma_{2d}^2} )</td>
</tr>
<tr>
<td>( V_c )</td>
<td>km s(^{-1})</td>
<td>True circular rotation velocity</td>
</tr>
</tbody>
</table>
velocity dispersions of distant galaxies to \(< 5\%\). To be realistic and to prevent small errors from dominating fits, we add 0.03 in quadrature to the error on log $\sigma_{1d}$, to cut off the low tail of the error distribution. The results are not sensitive to the exact value used; the median error for the sample of 913 brighter than $M_B = -18$ is 0.084 in log $\sigma_{1d}$. As discussed in Paper II, the intrinsic scatter in log $\sigma_{1d}$ dominates over the errors on individual points.

2.3. Rotation curve measurements

The DEIMOS slitlet spectra preserve spatial information and it is common to see emission lines with a velocity gradient. Spatially extended emission can be used to measure a rotation curve. However, the spatial extent of emission is only a few times the seeing, so “beam smearing” is large and the effect of seeing must be modeled. The rotation curve is also affected by the inclination, slit width, and slit alignment with respect to the major axis of the galaxy. We measured rotation curves for a subsample of objects in order to study the relation between rotation velocity and integrated linewidth.

2.3.1. Previous high-redshift rotation curve modeling

Previous efforts to measure rotation curves at intermediate to high redshifts have approached these problems by modeling the intrinsic emission intensity and velocity distribution, subjecting them to seeing and slit effects, and fitting models to the data to obtain a measure of the rotation velocity. Vogt et al. (1996, 1997) pioneered work in this field, using HST/WFPC2 imaging to model the galaxy light distribution and parameters such as inclination and position angle, and fitting to Keck/LRIS slit spectra, varying the model rotation velocity. Subsequent works in this field have followed similar modeling programs, applying seeing and slit effects to a 2-d model of the light and velocity fields (e.g., Simard & Pritchet 1998; Ziegler et al. 2002; Milvang-Jensen et al. 2003; Böhm et al. 2004; Bamford et al. 2005, 2006; Conselice et al. 2005; Nakamura et al. 2006; Metevier et al. 2006).

These programs have generally focused on relatively small numbers of galaxies ($\sim 10 - 100$), in some cases selected on morphology or spectra to be fairly normal rotating disks. They also require high-resolution imaging, preferably from HST, to obtain structural parameters. Most galaxies in the TKRS have deep HST/ACS imaging from the GOODS survey (Giavalisco et al. 2004), and full modeling of the rotation curves is in progress. However, such modeling requires fitting of structural parameters to ACS multidrizzled data and is beyond the scope of this paper.

2.3.2. Rotation curve modeling from spectra alone

In the spirit of obtaining kinematic measurements for as many galaxies as possible, we developed a simplified method for fitting seeing-compensated rotation curves using only the information contained in the 2-d spectra. This program, ROTCURVE, works by constructing models of the unblurred spatially resolved emission intensity, velocity and dispersion, blurring them along the slit to model seeing, and fitting to the data. Because it only has one dimension of spatial information, the rotation model and the seeing convolution are 1-d functions along the slit, and there is no compensation for disk inclination or slit position angle.

We chose a subsample of galaxies for rotation curve fitting using cuts in intensity of the strongest emission line and in spatial extent along the slit. The strongest emission line was required to have integrated intensity \(> 3000 \, \text{e}^-/\text{pixel} \, \AA \) in the summed 1-d spectrum. A gaussian was fit to the light profile along the slit and we required $\sigma_{\text{light}} > 0.4''$, equivalent to FWHM $> 0.94''$. 464 galaxies were selected for ROTCURVE fitting. Of these 445 also had ACS imaging and ellipticity/position angle data, and 380 of the rotation curve fits were judged to be good by visual inspection.

ROTCURVE fits to a single emission line for each object. It first fits an emission line to data in each row of pixels, using a similar algorithm to LINEFIT, to obtain profiles of velocity and dispersion along the slit, and rejects rows with discrepant values using automatic criteria, testing for e.g. large row-to-row jumps. It measures the light distribution along the slit of the continuum plus emission, fits a gaussian to this profile, and subtracts the assumed seeing (here 0.7'') in quadrature to determine the intrinsic, unblurred intensity profile, modeled as a gaussian $G(x)$ with dispersion $r_1$. A minimum $r_1 = 0.2''$ is imposed to keep intrinsic profiles of small objects from becoming pointlike.

About half the TKRS masks have seeing $= 0.7''$ and the remainder have seeing up to 1.0'', determined from the spectra of identified stars and the distribution of fitted widths of galaxies. Assuming a smaller seeing than the actual leads to a small underestimate of $V_{\text{rot}}$. Assuming a larger seeing than the actual causes the ROTCURVE modeling to fail on small objects, because it derives a too-small intrinsic spatial extent $r_1$, and the rotation velocity is poorly constrained due to the assumed large seeing blur.

ROTCURVE then constructs models of the intrinsic position-velocity distribution along the slit. The velocity model is an arctangent rotation curve centered at the peak of continuum+emission light, with a spatially-constant velocity dispersion, so that the intensity in position-velocity space before blurring by seeing and instrumental resolution is:

\[
I(x, v) = G(x)\exp\left(-\frac{(v - V(x))^2}{2\sigma_{2d}^2}\right),
\]

\[
G(x) = \frac{I_{\text{rot}}}{\sqrt{2\pi}\sigma_{1r}}\exp\left(-\frac{(x - x_0)^2}{2\sigma_{1r}^2}\right),
\]

\[
V(x) = V_{\text{rot}}\frac{2}{\pi} \arctan(x/r_s).
\]

$G(x)$ is the intrinsic gaussian light distribution along the slit. $V(x)$ is the rotation curve with asymptotic circular velocity $V_{\text{rot}}$ and knee radius $r_s$, and $\sigma_{2d}$ is the velocity dispersion, assumed constant along the slit. For the case of the [O III] 3727 doublet, we use a double gaussian for the distribution in velocity, with intensity ratio 1:4.

The unblurred $I(x, v)$ is then blurred for seeing with a 1-d gaussian in the spatial direction. The seeing has the effect of mixing gas at different velocities together, smoothing out velocity gradients and increasing the observed velocity dispersion at gradients (see Section 2.3 for an illustration of this effect). ROTCURVE then takes
moments of the blurred $I_{\text{blur}}(x, v)$ in the velocity direction to produce a model rotation curve and dispersion profile, and computes $\chi^2$ of the data–model. It also fits for an offset in velocity since the published redshifts can vary from the systemic velocity, especially when there are large velocity gradients.

The model parameters that can be varied are $V_{\text{rot}}$, $\sigma_{2d}$, and $r_{v}$. For each galaxy, we construct a grid of models over $V_{\text{rot}}$ and $\sigma_{2d}$. Because the models are fairly simple and involve a series of 1-d convolutions, a brute-force minimization is practical; the minimum in $\chi^2$ on the grid is always unambiguous and well localized. The best-fit values of $\sigma_{2d}$ are near-quantized in units of the grid spacing (here 5 km s$^{-1}$) due to the minimum-finding technique we used.

The rotation scale length $r_{v}$, describing how fast the rotation curve rises, is not strongly constrained by the ROTCURVE approach due to the seeing blur and the lack of 2-d modeling and position angle information. We chose a fixed $r_{v} = 0.2''$ for all galaxies, which can fit most rotation profiles; 0.1'' and 0.3'' fit worse for most galaxies. The knee radius and circular velocity are moderately covariant because the rotation curve turnover is not well resolved; changing $r_{v}$ from 0.2'' to 0.1'' or 0.3'' changes $V_{\text{rot}}$ by about 0.1 dex in the mean; larger $r_{v}$ causes larger $V_{\text{rot}}$. The effect on $V_{\text{rot}}$ caused by assuming 0.5'' or 0.9'' seeing is about 0.05 dex. The combination of $V_{\text{rot}}$ and $\sigma_{2d}$ in quadrature, discussed in Section 5.2 below, changes by only half as much as $V_{\text{rot}}$.

Figure 1 shows ACS $I$-band images of four example galaxies at $z \approx 1$ from the TKRS. Figure 2 shows postage stamp images of their emission line spectra, and Figure 3 shows their rotation and dispersion profiles fit by ROTCURVE. In Figure 3, the points are velocity and dispersion from the spectra; the dashed and solid lines show the best-fit model before and after applying the seeing blur. These galaxies are relatively clean examples of a dichotomy in kinematic profiles that is common in the TKRS data.

TKRS 2021 and 3168 show the familiar shape of a rotation curve. Beam smearing by the seeing not only smooths out the gradient in velocity, but induces a peak in the observed dispersion; the intrinsic dispersion is significantly less than the observed. TKRS 5627 and 10023 are less familiar. They have quite small rotation, but require a velocity dispersion component to fit the data, with $\sigma_{2d} > V_{\text{rot}}$. Galaxies like TKRS 5627 and 10023 are common in our sample and are the reason we formulated ROTCURVE to include the velocity dispersion $\sigma_{2d}$ as a second free parameter in the modeling. Note that these galaxies are relatively small but not extreme starbursts; they are not compact, nor very faint. We discuss rotation and dispersion dominated galaxies further in Sections 5.1 and 6 below.

We rarely see a rotation curve in which the observed points clearly roll over onto the flat part of the rotation curve, especially at $z \gtrsim 0.4$. This is partly due to the limited extent of the data, but frequently a more important effect is the seeing blur, which makes the observed rotation curve rise shallower than the true rise. The effect seen in TKRS 3168 in Figure 3 is common: the de-blurred model rotation curve has neared its asymptotic value while the observed data are still rising. Despite the lack of a flat-part in the observed data, the fitted values faithfully represent the observed velocity spread. Objects in which the data covered only a small spatial extent and the fitted velocity extrapolated beyond the data were rejected as erroneous fits.

Because the rotation curve data points are highly correlated, $\chi^2$ does not yield errors on $V_{\text{rot}}$ and $\sigma_{2d}$ directly. The fitted velocity $V_{\text{rot}}$ is a good representation of the gradient seen in the rotation curve, but subtler details such as the true errors on $V_{\text{rot}}$ and its dependence on the spatial extent of the data will require further Monte Carlo simulation. Here and in Paper II, measuring Tully–Fisher evolution with $V_{\text{rot}}$ and $\sigma_{2d}$ is secondary to using them to probe the nature of galaxy kinematics, and as a test of the meaning of integrated linewidth $\sigma_{1d}$.

As a check on the fits and models, ROTCURVE uses the observed row-by-row-fit rotation velocity and dispersion profile to reconstruct the 2-d data, and subtracts it from the original data to produce a residual map. It also produces reconstructed 2-d data from the best-fit blurred model (convolving back to the instrumental resolution). The reconstruction from the row-by-row fits is generally very good. The reconstruction from the model is also generally good, although it leaves residuals in cases such as an asymmetry in emission intensity, since the model is symmetric by construction. In principle, the models could be fit directly to the 2-d data without ever reducing to a 1-d rotation curve, but the rotation curve is a useful tool for evaluating the data and model.

The ROTCURVE fitting procedure runs automatically. Afterwards we inspected the rotation and dispersion profiles to reject bad or erroneous fits. 380 of the 445 galaxies passed this inspection. The dominant causes of failures are: discrepant points in the rotation curve which evade ROTCURVE’s automatic rejection; asymmetry which offsets the photometric center from the kinematic center; or small spatial extent of the rotation curve: we rejected most objects for which the usable rotation curve data spanned less than 1''.

ROTCURVE departs from previous high-redshift rotation curve modeling by making the velocity dispersion $\sigma_{2d}$ a free parameter; to our knowledge, other models have all fixed the dispersion to some low value. Fixing the dispersion is probably acceptable for samples of only morphologically-normal inclined disk galaxies observed with well-aligned slits, where rotation is the chief kinematic support and is unambiguously detected. However, as seen for TKRS 5627 and 10023 and shown in Section 5.1 there are galaxies with low rotation and large dispersion in our broader sample, and for these, fitting without a dispersion term will yield erroneous rotation velocities.

The dispersion term $\sigma_{2d}$ in ROTCURVE does not have to correspond to a literal gas velocity dispersion similar to the velocity dispersion of stars in an spheroidal galaxy. Because we are measuring nebular emission lines that occur in gas at $T \sim 10^4$ K, the gas in any individual H II region will have a dispersion of only 8–10 km s$^{-1}$. Taken literally, a dispersion $\sigma_{2d} \sim 30$ km s$^{-1}$ implies a gas temperature of $T \sim 10^6$ K, which is an unfavorable place on the ISM cooling curve. It is more likely that the dispersion comes from relative velocities of discrete H II regions.

Values of $\sigma_{2d} > 20$ km s$^{-1}$ can represent an effective dispersion, caused by the blurring of velocity gradients on scales at or below the seeing limit. Such a seeing-induced
dispersion $\sigma_{2d}$ can appear for slits which are aligned close to the minor axis of the galaxy and miss the resolved velocity gradient, as shown in Section 4.2. But for TKRS 5627 and 10023, and similar galaxies in our sample, the slit was well aligned with the photometric major axis, yet there is almost no ordered velocity gradient. The effective dispersion $\sigma_{2d}$ must be explained by non-ordered or disturbed gas kinematics on angular scales well below the seeing blur; these motions may not even have a preferred plane. The geometry of the H II regions, and why they have not dissipated into a rotating disk, cannot be measured with these seeing-limited observations.

2.4. Photometry

Nearly all TKRS galaxies have $BVIz$ photometric measurements from the GOODS ACS catalog (Giavalisco et al. 2004). Ground-based photometry in $UBVRIz'(HK')$ for a large field including GOODS-N is available from Capak et al. (2004). We used the 2.8″ diameter aperture magnitudes from the GOODS cata-

![ACS I-band images for the example galaxies whose rotation and dispersion are shown in Figure 3: TKRS 2021, 3168, 5627, and 10023. The images are 3″ on a side; north is up and west is to the right. The panels are labeled with redshift (in the image), TKRS ID, restframe $M_B$, $U - B$, and linewidth log $\sigma_1$. The DEIMOS slit PAs are 51°, 14°, 37°, and 39° respectively, north through east. The galaxies were classified as edge-on, LSB/irregular, chain, and hyphen/chain morphology, respectively.](image1)

![Postage stamps of the DEIMOS spectra for the example galaxies whose rotation and dispersion are shown in Figure 3: TKRS 2021, 3168, 5627, and 10023. The spectra have been sky-subtracted, and rectified for display purposes so that columns are constant wavelength. The galaxy continua, at low S/N/pixel, are not visible in these postage stamps. Each image shows the emission line used for ROTCURVE fitting, the [O II] 3727 doublet for 2021, 3168, and 10023, and [O III] 5007 for 5627. TKRS 2021 and 3168 show tilted emission lines, the signature of rotation curves, but TKRS 5627 and 10023 show very little velocity gradient.](image2)
Fig. 3.— Rotation and dispersion profiles for four example galaxies with well aligned slits. TKRS 2021 and 3168 at $z = 1.00$ and 1.28 are rotation dominated; TKRS 5627 and 10023 at $z = 0.85$ and 1.02 are dispersion dominated. The slit PA offsets are 6°, 9°, 3°, and 10°. The points are the observed rotation and dispersion along the slit; filled circles are the data used by ROTCURVE while crosses were rejected by the program. The dashed curves show the intrinsic rotation and dispersion model profiles, and solid curves are the models after the seeing blur is applied. In panels (c) and (d) the solid curve overlies the dashed curve. The fitted rotation velocities and dispersions are $V_{\text{rot}} = 149, 97, 16, 14$ km s$^{-1}$ and $\sigma_{2d} = 5, 5, 39, 30$ km s$^{-1}$ respectively.

log and the 3″ diameter magnitudes from the Capak catalog. For all but the largest, lowest-redshift galaxies, aperture corrections are small, so we omit them. Of the 1440 TKRS galaxies, 1423 have matches with optical magnitudes in the Capak et al. catalog. Fourteen of the remainder have magnitudes from the GOODS ACS catalog, and only 3 have neither.

The Capak et al. $HK'$ data are shallower than the optical data and the depth is not constant over the GOODS field. We used only aperture $HK'$ magnitudes that have errors < 0.3 mag, yielding $HK'$ for 919 TKRS galaxies. With this error cut, the fraction of TKRS galaxies with $HK'$ magnitudes reaches 50% at $HK' = 22.3$ (AB).

Our primary interests are to measure consistent rest-frame absolute blue magnitude $M_B$ and color $U - B$, and a rest infrared magnitude $M_J$ and $R - J$ color. We convert to rest $B$ and $J$ because the observed filters cover or come relatively close to these restframe bands over $0 < z < 1.5$, minimizing extrapolation. We used the template-fitting $K$-correction procedure described in previous DEEP papers (Weiner et al. 2005; Willmer et al. 2006) to convert observed colors into $K$-correction and restframe color. Briefly, this method uses redshifted templates: 34 spectra of local galaxies with wavelength coverage 1200Å – 1 µm (Kinney et al. 1996) for $M_B$ and $U - B$; and 9 templates generated by PEGASE (Fioc & Rocca-Volmerange 1997) representing E, Sb and Sd SEDs at 1, 5, and 10 Gyr for $M_J$ and $R - J$. To analyze,
for example, a galaxy at $z = 0.8$ with $R - I = 1.2$, the templates are redshifted to $z = 0.8$ and their observed $R - I$ colors synthesized. Since the templates’ restframe $U - B$ colors and $K$-corrections from $I$ to $B$ are known, we fit a low order polynomial to $U - B$ as a function of $R - I$ and evaluate this fit at $R - I = 1.2$ to find $U - B$ for the galaxy under analysis.

This procedure works best when the observed filter pair transforms relatively closely to the wavelength of the restframe filters, as is the case for $R - I$ at $z = 0.8$ into rest $U - B$. When the transformation is not close, there is larger scatter about the fit of $U - B$ as a function of observed color, so choosing an appropriate filter pair is important.

To derive the restframe $U - B$ and $M_B$ presented here, we used the filter pairs of Capak $B - V, R - I$, and $I - z$, switching over from one pair to the next at $z = 0.6, 1.1$ respectively. For $\Delta z = 0.1$ around the switchover redshift we interpolate to make a smooth transition. For rest $R - J$ and $M_J$ we use the observed $I - HK'$ filter pair and the $HK'$ magnitude.

In practice, the $K$-corrections are fairly stable. However, certain filter pairs produce discordant results for restframe colors: e.g. ACS $B - V$ and $V - i$ produce colors for galaxies at $z = 0.5$ that are $\sim 0.1$ mag offset. This problem is most obvious with the ACS filter pairs and with the Capak $V - R$ color. In general, a warning sign of the problem shows up as template mismatch in a color-color plot: for certain combinations of redshift and color pairs, galaxies and redshifted templates do not fall on exactly the same locus. The reasons for these mismatches are not clear; they may be a combination of small zero-point shifts and imperfect filter/instrument response curves. The effect is small on absolute magnitudes, and relative color measurements at a given redshift are reliable, but measurements of absolute color evolution over a large range in redshift can be affected.

We found that using the Capak $B - V, R - I, I - z$ color sets minimizes the effect of these mismatches; using the ACS filters produces slightly abnormal trends in restframe color with redshift. Comparing the absolute magnitudes and colors from the Capak color sets and from the fully independent ACS $B - V, V - i, i - z$ sets, we find that 95% of the objects have a magnitude difference $< 0.33$ and a color difference $< 0.26$, yielding $1\sigma$ errors of 0.12 in $M_B$ and 0.09 in $U - B$. The errors on observed optical magnitudes from Capak et al. (2004) are 0.05-0.07 mag at the TKRS limit; additional scatter is propagated into the absolute magnitudes by the observed color error and the template scatter in the $K$-correction procedure.

The median error on $HK'$ magnitude for galaxies with kinematic measurements is 0.14 mag. Although we are using model rather than empirical SEDs to $K$-correct the IR magnitude, galaxy SEDs have less variety in the IR than the optical and so the $K$-correction depends only weakly on the specific templates used. The error on the IR observations dominates over the IR template scatter.

3. SAMPLE MAGNITUDE, COLOR AND COMPLETENESS

Of the 1440 TKRS galaxies, 1423 have magnitudes from Capak et al. (2004) and 14 have magnitudes from ACS (Giavalisco et al. 2004). 893 galaxies have magnitudes and a linewidth determination, and an additional 196 are kinematically unresolved. Of these 1089, 913 are brighter than $M_B = -18$, a limit we impose for Tully-Fisher fitting in Paper II. 681 of the 1089 with kinematic data have a reliable $M_J$ and 647 of these are brighter than $M_J = -19$. Table 2 lists TKRS galaxies, positions, redshifts, observed magnitudes, restframe magnitudes and colors, and linewidths.

Figure 4 shows the restframe optical color-magnitude distribution of TKRS galaxies and the location of the 1089 galaxies with and 348 without measured linewidths. The TKRS galaxies exhibit the color bimodality now well-established locally and to $z \sim 1$ (Strateva et al. 2001; Bell et al. 2004; Wirth et al. 2004; Weiner et al. 2005). Both red and blue galaxies show a shallow color-magnitude relation: brighter galaxies are redder in the mean. The majority of galaxies for which we fail to get a good linewidth are on the red side of the bimodality, $U - B > 0.95$, because those galaxies have weak or no emission lines (e.g. Weiner et al. 2005). Among the blue galaxies, linewidth failures are rare and fairly randomly distributed. We examined each failure and found that most are due to low line flux or night sky residuals. The failure rate in blue galaxies is small and there is no evidence that failures occur preferentially at large or small dispersions.

At low redshift, blue galaxies in the TKRS sample show the well-known color-magnitude relation; fainter galaxies are bluer (upper left panel of Figure 4). At higher redshift, the faint limit is due to the TKRS magnitude selection; the selection limit in apparent $R$ magnitude corresponds to a tilted line in the restframe $M_B, U - B$ plane (e.g. lower left panel of Figure 4). The tilt of this line changes with redshift. In Paper II we test the effect of the selection limit on Tully-Fisher relations by defining an approximately mass-matched sample, applying the $z \sim 0.9$ tilt at all redshifts and a magnitude cut that evolves similarly to $L^\ast$. This cut is shown by the diagonal lines in Figure 4.

The redshift completeness of the TKRS is $\sim 70\%$ to $R_{AB} = 24.4$, discussed by Wirth et al. (2004). Redshift failures in the TKRS are mostly faint blue galaxies that are probably at $z > 1.5$. Here we discuss the linewidth completeness, i.e. the fraction of galaxies with good linewidths over galaxies with redshifts.

Figure 4 shows the linewidth completeness as a function of rest $U - B$ color. The completeness is roughly constant for blue galaxies but drops sharply for red galaxies. Because red galaxies are bright, a histogram of completeness as a function of rest $M_B$ for the whole sample actually drops at bright magnitudes.

Red galaxies and blue galaxies are two distinct populations and the bulk of our measurements are blue galaxies, so in this paper we are constraining the behavior of the blue galaxy population. Figures 6 and 7 show the linewidth completeness of the sample restricted to TKRS galaxies on the blue side of the color bimodality, $U - B < 0.95$. Linewidth completeness is nearly constant with either absolute or apparent magnitude, with a small tendency to be lower for galaxies bright in absolute magnitude (lower emission EW) or faint in apparent magnitude (lower apparent flux). The lack of any strong dependence on magnitude reflects the fact that intrinsically-faint galaxies tend to have high emission equivalent width.
Because completeness of the linewidth sample depends strongly only on color, we have a fair sample of the blue galaxy population, and our measurements will not be strongly affected by selection effects. Of course, any evolution measurement or interpretation will apply only to blue galaxies.

4. PROPERTIES OF KINEMATIC MEASURES

The limited spatial resolution of high-redshift spectra makes the interpretation of kinematic measures less obvious than in local galaxies. Our goal in this section is to establish the properties of our sample and determine the effect of observational limitations on the measures of dispersion and rotation.

There has been some controversy over how well measures such as integrated linewidth probe galaxy kinematics. Modeling simulated observations of disk velocity fields with true circular velocity $V_c$, Rix et al. (1997) found that for their observational parameters, the average integrated linewidth $<\sigma>/V_c = 0.6$ with substantial scatter ($\sim 0.15$) depending on the unknown position angles and inclinations, where $<\sigma>$ incorporates an average over inclination but $V_c$ is the true value. For random orientations, $<\sin i> = 0.79$, leaving an average factor of 0.76 for $<\sigma>/V_c$. From observations of local galaxies, Kobulnicky & Gebhardt (2000) found that the $O$ II emission linewidth tracks the $H$ I linewidth $W_{20}$ well for most galaxies, using $\sigma = 0.28 W_{20}$ (both uncorrected for inclination), but the $O$ II linewidth is low in 2/22 extreme cases. The $H$ I width $W_{20}$ is the full-width of the $H$ I profile at the 20% flux level. This relation is roughly consistent with the Rix et al. relation since $W_{20} \approx 2(W_c \sin i + 15 \text{ km s}^{-1})$ (Tully & Fouque 1985).

Lehnert & Heckman (1996) showed a tendency for edge-on IR-luminous starburst galaxies to have nuclear emission linewidth that is low compared to the expected velocity dispersion of the full potential; these galaxies are mostly fairly large and the nuclear emission does not probe the full potential. Barton & van Zee (2001) observed four blue compact dwarf galaxies and found that $\sigma(H\alpha)$ falls below optical $V_{rot}$ and $H$ I $W_{50}$. However, their four galaxies average $\sigma/W_{20} = 0.7$, and the two with $21$ cm data have $\sigma/W_{50} = 0.27$ (all quantities uncorrected for inclination). These are actually fairly consistent with the $<\sigma>/V_c$ offset of Rix et al. and the linewidth / $H$ I width factor of Kobulnicky & Gebhardt. Rotation curves can also be affected: kinematic distortions and truncations could cause galaxies to have low measured rotation (Barton et al. 2001; Kannappan & Barton 2004).

Perhaps the most serious discrepancy between optical and $H$ I width is found in a sample of 10 local blue compact galaxies (BCGs; Pisano et al. 2001), which show $W_{20}(H\beta)/W_{20}(H\alpha) = 0.66 \pm 0.16$. In terms of dispersion this implies $\sigma(H\beta)/W_{20}(H\alpha) = 0.18$. These galaxies are a fairly special population with high emission equivalent widths and small sizes, $r_e = 0.6 - 1.9$ kpc, smaller than average for intermediate-z BCGs. They are most similar to NGC 4449, the furthest outlier in the sample of Kobulnicky & Gebhardt (2000), which has a much larger $H$ I extent than optical; and to the compact narrow emission-line galaxies (CNELGs, Koo et al. 1995) in their sizes. In the sample of Pisano et al., the optical linewidths are most affected when $W_{20}(H\alpha) < 150$ km s$^{-1}$, which corre-
Fig. 4.— Absolute magnitude and color for TKRS galaxies in 4 redshift ranges. Blue Xes: galaxies with good linewidths; red circles: galaxies with poorly measured linewidth. The bulk of linewidth failures are in the red side of the color bimodality. The horizontal and diagonal lines show a magnitude and color selection that constructs samples whose depth is matched to the selection limit at $z = 0.9$ and an evolving $L^*$. correspond to an unaffected optical $\sigma < 45$ km s$^{-1}$; smallest galaxies can be the most seriously affected.

These types of underestimation of kinematic width may happen in high-redshift samples. They might explain some of the discrepancies between previous TF evolution measurements, as Pisano et al. (2001) suggest, especially in samples with high line EW. However, even at high redshift, the extreme BCGs or CNELGs are a minority of blue galaxies (Koo et al. 1995). These galaxies are quite small; even with 1-2 mag brightening, the Pisano et al. (2001) sample would be among the faintest of the $z \sim 1$ galaxies in the TKRS sample. The possibility of BCG-induced offsets does argue in favor of using large samples which are not selected on emission line EW, and in which evolution can be measured internal to the sample.

Ideal measures of high-redshift kinematics would yield 2-d maps with high spatial resolution. This may soon be possible with adaptive optics and integral field spectroscopy, but will remain impractical for large samples for some time. Here we carry out empirical tests on our sample and simulations of seeing-blurred observations to test the properties of linewidth measurements.

4.1. Spatial extent of emission

It is frequently suggested that high-redshift galaxies could have enhanced emission from their centers, such as a nuclear starburst, and that this could produce smaller linewidths because the emission does not probe the full potential, or comes from a part of the rotation curve that is rising (e.g. Lehnert & Heckman 1996). Simard & Pritchet (1998) found that $\sim$ 25% of their galaxies had unresolved emission in their CFHT spectra. Rix et al. (1997) suggested that $\sim$ 20% of their sample might have nuclear emission from high-density gas, based on the [O II] doublet ratio. However, both of these samples are selected to have high EW or blue colors, and are relatively low S/N compared to the TKRS spectra. Another possibility is that line emission could be dominated by one or a few large HII regions and so not probe the full
Fig. 5.— Linewidth completeness as a function of restframe $U - B$ color. Solid line: galaxies with good linewidths; dashed line: galaxies with poorly measured linewidth. The top panel shows absolute numbers and the bottom panel shows good or bad as a fraction of the total with redshifts.

Fig. 6.— Linewidth completeness for blue galaxies as a function of absolute magnitude $M_B$. Solid line: galaxies with good linewidths; dashed line: galaxies with poorly measured linewidth. The top panel shows absolute numbers and the bottom panel shows good or bad as a fraction of the total of blue galaxies with redshifts.

Fig. 7.— Linewidth completeness for blue galaxies as a function of apparent magnitude $I_{AB}$. Solid line: galaxies with good linewidths; dashed line: galaxies with poorly measured linewidth. The top panel shows absolute numbers and the bottom panel shows good or bad as a fraction of the total of blue galaxies with redshifts.

Fig. 8.— Spatial extent along the slit for TKRS galaxies in four redshift ranges. The fitted gaussian FWHMs of emission and continuum are plotted. Filled circles have error on both FWHMs < 0.1", Small Xes have error on one or both FWHMs > 0.1", indicating an unreliable fit. The sizes are seeing-limited around FWHM $\sim 0.7''$, and above that are consistent with equal sizes for emission and continuum.

velocity field of the disk.

We tested the spatial extent of emission in the TKRS
linewidth sample by fitting gaussian profiles along the slit. We collapsed the 2-d data in the wavelength direction over a 15 Å range for emission and two 100 Å ranges on either side of the line for continuum. We then fit gaussians using a non-linear least squares routine.

The fitted spatial widths of emission versus continuum are shown in Figure 8, divided into four redshift ranges. The sizes are seeing-limited around FWHM ~ 0.7′′ and track each other well at larger sizes. The small mask-to-mask seeing variations in the TKRS data will tend to spread galaxies along the 1:1 line, but the relation continues far beyond FWHM ~ 1.0′′. Outliers from the 1:1 line generally have a large error in one size measurement. While this comparison is somewhat limited by seeing, there is no evidence for a large population of nuclear emission or single-HII-region emission. In fact there is strong evidence that emission and continuum size track each other well.

4.2. What integrated linewidths measure: simulation of observations

In order to understand what an integrated linewidth is really measuring, we simulated observations of a disk galaxy at z = 1, using an actual 2-dimensional intensity and velocity field from Fabry-Perot observations of the local galaxy NGC 7171. A similar project was carried out, also using Fabry-Perot velocity fields as input, by Rix et al. (1997). NGC 7171 has a fairly typical disk velocity field with mild spiral streaming motions, and abundant Hβ emission, yielding a 2-d velocity field that samples the disk well with high resolution. It was observed in the Hβ line with the Rutgers Fabry-Perot at the CTIO 4-m Blanco telescope, on October 27 and 28, 1989 by T.B. Williams and R.A. Schommer. The data were reduced into intensity, velocity, and dispersion fields by BJW using procedures described elsewhere (Palunas and Williams 2000; Weiner et al. 2001) and have been previously studied by Palunas (1996). NGC 7171 has a heliocentric velocity of 2740 km s^{-1} and we assumed a distance of 34 Mpc: its magnitude is M_B = -20.0. The resolution of these 2-d maps is 1.5″, the inclination of NGC 7171 is 55°, and its rotation velocity corrected for inclination is V_c = 189 km s^{-1}. It has a flat rotation curve and lies on the Tully-Fisher relation of Sakai et al. (2000).

The original Hα intensity, velocity and dispersion fields of NGC 7171 are shown in the left column of Figure 8, the dispersion field is relatively featureless since the dispersion is usually < 20 km s^{-1} except in the nucleus, where it is increased by seeing blur. We used these fields to reconstruct a 3-d spectral cube. To simulate an observation at z = 1, we rescaled the angular size at z = 1, blurred each plane of the cube by a 0.7″ gaussian to represent seeing, and resampled the cube onto DEIMOS pixels of 0.118″. We then refit through the cube to produce maps of restframe intensity, velocity, and dispersion. The right column of Figure 8 shows the resulting z = 1 maps that correspond to the unblurred maps of the left column.

The blurred velocity and dispersion fields of Figure 8 illustrate an effect we alluded to in the discussion of rotation curve fitting in Section 2.3.2. The beam smearing due to seeing smooths out the rotation velocity gradient, but it produces a strong peak in the velocity dispersion in the center; where the unblurred velocity gradient is strong, the seeing mixes gas at different velocities together. This peak in velocity dispersion is at high Hα intensity and so carries a high weight in integrated measurements.

We used blurred velocity cubes to simulate observations of integrated velocity dispersion over a range of galaxy inclinations and slit-galaxy relative position angle misalignments. To simulate a range of inclinations, we stretched the input NGC 7171 fields and rescaled the velocities before blurring and resampling. We did not allow the dispersion to fall below 8 km s^{-1}, a typical sound speed for H II regions and gas in the ISM. We did not add noise or scale the flux to a real galaxy, as this is not a full simulation of real observations, but a test of the relative contribution of emission at different velocities. Adding noise reduces the detectability of spatially resolved emission at low intensities but does not greatly affect the velocity distribution of the integrated emission.

We then laid down typical 1″ wide slits over a range of relative PAs and extracted a spectrum in a 2.3″ (1.5 FWHM) extraction window, using the intensities, velocities and dispersions of pixels within the slit and window to build up an emission spectrum. The resulting velocity profile can be somewhat non-gaussian and flat-topped, especially when the slit is aligned with the galaxy major axis, but once the profile is convolved with the spectrograph resolution, the non-gaussianity is small. We computed moments to determine the velocity dispersion corresponding to σ_{1d}. Changing the extraction diameter within reasonable limits had little effect on the results, because the bulk of the signal comes from the central emission peak.

Figure 9 plots the ratio of integrated linewidth to projected circular velocity, σ_{1d}/(V_c sin i), as a function of inclination and relative slit position angle. This ratio removes the sin i effect, isolating the properties of the integrated linewidth. There is a small residual effect of inclination, but the variation among the tracks is quite small. The exception is the nearly face-on i = 5° case, where the 8 km s^{-1} minimum dispersion contributes. The chances of observing a face-on, perfectly flat thin disk are very small, especially in the high-z universe where many galaxies are peculiar or irregular. Apart from this special case, the ratio varies by ±15% over the range of PA and inclination.

At a given inclination, the linewidth for misaligned slits is lower, but the linewidth for a perfectly misaligned slit (ΔPA = 90) is only 20% lower than the linewidth for a perfectly aligned slit (ΔPA = 0). The reason is that the observed linewidth comes largely from the central peak in intensity and dispersion, seen in the lower panel of Figure 9. The slit position angle does have a large effect on the observed rotation gradient, of course. Both these effects are seen empirically in our data in Section 4.2.2. The ratio σ_{1d}/(V_c sin i) ~ 0.6 – 0.65 on average. When the distribution of inclinations is accounted for, the ratio is fairly similar to the distribution in Figure 7 of Rix et al. (1997): σ_{1d}/V_c ~ 0.55 in the mean, with a non-gaussian scatter due to the tail of nearly face-on model galaxies with low σ_{1d}.

The upshot of these simulations is that the seeing is

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9 Cerro Tololo Inter-American Observatory is operated by AURA under contract to the NSF.
a powerful integrator, smoothing over the disk and producing dispersion at the location of velocity gradients, so that specific observational parameters like slit PA, width, and extraction diameter do not have a strong effect on the integrated linewidth. However, the slit PA does have a strong effect on the observed spatially-resolved rotation curve. Similar conclusions were reached by Erb et al. (2004). Inclination produces significant scatter in linewidth/velocity ratio merely through the sin $i$ factor.

A limitation is that we have modeled only a thin disk galaxy in orderly and planar rotation. Our comparison of observed rotation velocity and dispersion in Section 5.1 below shows that many galaxies are not dominated by orderly rotation. However, even if the kinematics are...
The inclination factor of sin $i$ strongly affects the observed integrated linewidth. In this study, we do not restrict the sample. In large, relatively high-inclination galaxies with clear disk geometry, the linewidth for a perfectly misaligned slit ($\Delta PA = 90$) is only 20% lower than the linewidth for a perfectly aligned slit ($\Delta PA = 0$). The ratio takes out the inclination dependence, showing that the effect of inclination other than through sin $i$ is small. The exception is the $i = 5^\circ$ case, where the sound speed of the gas, 8 km s$^{-1}$, contributes to the observed linewidth.

If the star formation and emission is more centrally concentrated than in NGC 7171, the relative contribution of high velocity gas on the flat part of the rotation curve is reduced. However, because the central regions do have a velocity gradient, the integrated linewidth remains fairly high, and this is a second order effect. As a test, we artificially boosted the emission intensity inside 1 kpc radius – the central clump of emission – by a factor of 4 and reran the simulations. The integrated linewidth decreased by just $4.5 \pm 1\%$, over the range of inclination and slit PA. Centrally concentrated emission must overwhelm the rest of the galaxy to lower the linewidth significantly.

4.3. The effect of inclination corrections and the lack thereof

The modeling of a blurred NGC 7171 showed that the strongest effect on the observed integrated linewidth is the inclination factor of sin $i$. Classic Tully-Fisher studies correlate velocity and luminosity after correcting for inclination and extinction, and are generally restricted to relatively high-inclination galaxies with clear disk geometry. In this study we do not restrict the sample. In large samples of high-redshift galaxies, correcting for inclination is only practical with HST imaging, and galaxies may have stronger deviations from an ideal thin circular disk geometry, so the relation between ellipticity and inclination is less direct. As groundwork for the Tully-Fisher study of Paper II, here we model the effect on disk Tully-Fisher relations when inclination and extinction corrections are omitted.

Figure 11 shows a model Tully-Fisher relation with and without inclination and extinction corrections. The filled triangles are a simulated “true” Tully-Fisher relation with inverse TF slope $-0.125$ dex/mag and intrinsic scatter 0.0375 dex. The solid diagonal line is a linear fit to these points. The open circles are the same galaxies “observed” at randomly assigned inclinations $i$. The decorrected quantities are velocities $V_{\text{rot}}$ sin $i$ with 0.084 dex observational error added and magnitudes $M_B + A_B$($i$) with 0.11 dex error. The dashed diagonal line is a linear fit to the decorrected points. The lines at right indicate the decoration tracks for a galaxy with log $V_{\text{rot}} = 2.2$ at $i = 10^\circ, 30^\circ, 60^\circ, 90^\circ$. Edge-on galaxies move above the baseline inverse-TF relation due to extinction; face-on galaxies fall below the baseline due to low projected velocities. For $B$ band extinction, galaxies at the median inclination $i = 60$ are nearly unchanged. However, the scatter around the TF relation becomes large and non-gaussian.
galaxies have intrinsic thickness:radius 1:5. The velocity is $V_{rot}\sin i$ with a random-motion component of 25 km s$^{-1}$ added in quadrature, which prevents the face-on galaxies’ velocity from falling to near zero. The solid and dashed lines show the best linear fits respectively to the original and decorrelated points with $M_B < -18$ (using a fit method that compensates for scatter, described in Paper II). The fitted slopes are $-0.126 \pm 0.003$ for the original sample and $-0.105 \pm 0.021$ for the decorrelated sample.

The lines at right show how decorrelation moves a galaxy with log $V_{rot} = 2.2$ for inclinations $10^\circ, 30^\circ, 60^\circ, 90^\circ$. The undoing of these inclination and extinction corrections moves the galaxies onto tracks nearly parallel to the original TF relation – e.g. all the $i = 90^\circ$ galaxies are shifted to fainter magnitudes, so appear above the original TF. For $\gamma_B = 1.57$ and a TF slope $-0.125$, the corrections cancel at $i = 60.5^\circ$, which fortuitously is almost exactly the median inclination of $i = 60^\circ$ for a randomly oriented sample. Thus in $B$-band, the effect of undoing corrections on the TF intercept is relatively small. For the galaxies on a single inclination track, the slope is unchanged, but for the entire sample, the slope of the uncorrected inverse TF relation is shallower.

As shown in Figure 11, the scatter induced by lack of corrections is non-gaussian, although the non-gaussianity is blurred somewhat by the observational errors. The effect on Tully-Fisher fitting depends on the magnitude distribution and limit of the sample. The fitted TF relation changes due to the correlated anti-corrections scattering across the TF ridgeline, the non-gaussian scatter, and the elimination of edge-ons by the magnitude limit. For the realization shown here, a fit to the galaxies brighter than $M_{B,obs} = -18$ yields a velocity intercept shifted down by 0.11 dex at $M_{B,obs} = -20$, a slope of $-0.105 \pm 0.021$, and a greatly increased scatter of 0.19 dex. We emphasize that these values only apply for the realized thin disk assumptions, which likely do not apply to many galaxies in the TKRS – for example, elongated but non-rotating galaxies like TKRS 5627 and 10023, shown in Figures 11 and 2.

Local Tully-Fisher samples require a luminosity or velocity-dependent extinction correction; extinction is higher in larger galaxies (Giovanelli et al. 1995; Tully et al. 1998). Undoing this correction means that an uncorrected inverse TF sample has a $V(M)$ slope steeper than the true slope. In the $B$ band the effect is about 10-15% of the magnitude range of the sample (Tully et al. 1998), so the uncorrected inverse TF slope is $\sim 10 - 15\%$ higher. This could counteract the slope-shallowing effect described above. However, one must tread carefully when applying local extinction corrections to distant samples. Both the extinction effect and the inclination-induced offsets are reasons to attempt comparisons internal to the sample, spanning a range of redshifts.

The general effects of the lack of correction are small shifts in intercept and slope, and a substantial increase in scatter. If the TKRS galaxies with linewidths were all close to the thin rotating disk model, applying inclination and extinction corrections would greatly reduce the scatter in the Tully-Fisher relations fitted in Paper II. In fact, in Paper II we find that applying either the sin $i$ inclination correction, or both inclination and extinction corrections, does not reduce the scatter in Tully-Fisher relations. A small amount of this can be due to statistical errors on inclination, but most is due to the diversity of kinematic properties, galaxies with non-disk shapes, and motions that are not strictly rotation, as we show in Section 5.

4.4. Empirical dependence on slit position angle

Rotation curves of inclined disks should be harder to measure when the slit is not aligned close to the major axis. The modeling of NGC 7171 suggests that integrated velocity linewidths are not as severely affected by slit misalignments. The effect can be tested empirically for the TKRS sample since HST imaging allows measures of the galaxy position angles.

We used a compilation of measurements from ellipse fitting to the ACS $i$-band galaxy images, yielding ellipticity, position angle, and half-light radius. Segmentation images output by the SExtractor program (Bertin & Arnouts 1996) were used to mask out neighboring galaxies and the IRAF task ellipse was run to fit elliptical isophotes. Further results on the galaxy sizes will be reported separately (Melbourne et al. 2006). Here we use the ellipticities and position angles to determine slit misalignments.

![Figure 12](image)

**Figure 12.** Integrated linewidth log $\sigma_{1d}$ as a function of position angle misalignment: offset between slit PA and major axis PA from ellipse fits to HST/ACS images. Large points show the mean and RMS in bins of angle. The small points at log $\sigma_{1d} = 1.4$ are the kinematically unresolved objects. There is no visible trend of measured 1-d linewidth with PA offset.

Figure 12 shows integrated linewidth log $\sigma_{1d}$ as a function of the misalignment between slit and image position angle. The large points show the mean and RMS in bins
of PA offset. (The slitmasks were designed based on PAs from ground based imaging before the HST catalog was available, so the slits are not exactly aligned with HST PAs.) Slit misalignment has no visible effect on linewidth measured from the 1-d spectrum. A fraction of the galaxies in this plot are nearly round, so that the PA is not very meaningful; removing these objects does not change the conclusion. A small trend with PA offset might be expected from the models in Figure 10 but galaxies that are not orderly rotating disks, and galaxies whose ellipticity and kinematics are misaligned, will weaken such a trend.

For the subsample of galaxies with 2-d rotation fits, Figure 13 shows the rotation velocity $V_{\text{rot}}$ as a function of position angle misalignment, offset between slit PA and HST/ACS major axis PA. Round galaxies with ellipticity $e < 0.25$ are plotted as Xes, non-round galaxies are circles. Large points show the mean and RMS of non-round galaxies in bins of angle. Extracted rotation velocities are higher for aligned slits; there is a deficit of high $V_{\text{rot}}$ for misaligned slits.

5. PROPERTIES OF SPATIALLY RESOLVED KINEMATICS

5.1. Rotation versus dispersion dominated galaxies

The two galaxies whose rotation and dispersion profiles are shown in Figure 13 exemplify a trend we found in the entire sample. In order to fit the kinematics, we had to include both velocity $V_{\text{rot}}$ and dispersion $\sigma_d$ in the 2-d modeling of ROTCURVE, discussed in Section 2.3. Quite a few galaxies like TKRS 5627 and 10023 show a low rotation velocity but a significant dispersion.

Table 3 lists galaxy ID, redshift, slit PA offset, and the fitted line-of-sight rotation velocity from seeing-compensated modeling of the 2-d spectra, km s$^{-1}$. For $|\Delta PA| \gtrsim 40^\circ$, rotation velocities are strongly affected by slit misalignment. 4-Line-of-sight dispersion from seeing-compensated modeling of the 2-d spectra, km s$^{-1}$. Values are near-quantized in units of 5 km s$^{-1}$ due to the model grid.

Table 3. Catalog of TKRS rotation and dispersion fits

| TKRS ID | $z$ | $|\Delta PA|^2$ | $V_{\text{rot}}^3$ | $\sigma_d^4$ | morphology$^5$ |
|---------|----|----------------|------------------|-------------|---------------|
| 0000428 | 0.4870 | 13.2 | 14.0 | 15.0 | hyphen |
| 0000448 | 0.4724 | 7.01 | 80.0 | 40.1 | — |
| 0000555 | 0.4589 | 81.0 | 37.8 | 69.6 | — |
| 0000714 | 0.9434 | 52.8 | 21.6 | 48.8 | — |
| 0000760 | 0.5032 | 14.0 | 209.2 | 10.0 | disk |
| 0001126 | 0.9447 | 25.8 | 62.9 | 64.3 | irregular |
| 0001217 | 0.4587 | 0.8 | 4.1 | 59.4 | merger |
| 0001226 | 0.5023 | 13.7 | 0.0 | 65.0 | irregular |
| 0001289 | 0.1137 | 54.5 | 56.5 | 69.9 | — |
| 0001333 | 1.2960 | 80.1 | 46.9 | 74.4 | — |
| 0001432 | 0.7479 | 48.6 | 0.6 | 54.3 | — |
| 0001563 | 0.3758 | 16.4 | 157.0 | 5.0 | edge-on |
| 0001577 | 0.4855 | 2.1 | 110.2 | 5.0 | disk |
| 0001769 | 0.1192 | 66.3 | 50.0 | 65.1 | — |
| 0001808 | 0.0787 | 21.5 | 64.3 | 39.8 | edge-on |
| 0001861 | 1.3630 | 3.0 | 95.1 | 40.0 | disk |
| 0001923 | 0.2755 | 43.0 | 50.8 | 39.9 | — |
| 0001950 | 1.3640 | 45.3 | 21.4 | 89.5 | — |
| 0002011 | 0.4734 | 88.4 | 9.3 | 24.8 | — |
| 0002012 | 1.0010 | 0.4 | 104.4 | 55.0 | disk |

Note. — The complete version of this table is in the electronic edition of the Journal. The printed edition contains only a sample.

1Redshift.
2Absolute value of the offset between DEIMOS slit position angle and photometric major axis PA in HST/ACS I images, degrees.
3Line-of-sight rotation velocity from seeing-compensated modeling of the 2-d spectra, km s$^{-1}$. For $|\Delta PA| \gtrsim 40^\circ$, rotation velocities are strongly affected by slit misalignment.
4Line-of-sight dispersion from seeing-compensated modeling of the 2-d spectra, km s$^{-1}$. Values are near-quantized in units of 5 km s$^{-1}$ due to the model grid.
5Morphological type from visual classification. Only galaxies with $|\Delta PA| < 40^\circ$ and ellipticity $> 0.25$ were classified.
show dispersion profiles which are not sharply peaked, although the limited spectral resolution of TKRS makes dispersion profiles rather noisy.

We classified galaxies into rotation- and dispersion-dominated, based on whether $V_{\text{rot}} > \sigma_{2d}$ or vice versa. Figure 14 plots $\sigma_{2d}$ versus $V_{\text{rot}}$; the placement of the dividing line is somewhat arbitrary, but intended to separate galaxies whose main kinematic support is from order-ly rotation, and galaxies where dispersion (or the disordered gas motions that $\sigma_{2d}$ may represent) plays a major role. When roundish galaxies with $e < 0.25$ and those with misaligned slits, $|\Delta PA| > 40^\circ$, are excluded, there are 185 galaxies with good 2-d fits from ROTCURVE. Of these, 118 are rotation dominated and 67 (36%) are dispersion dominated. Thus two-thirds of the subsample have kinematics basically similar to local rotating galaxies – which was by no means guaranteed – but over one-third of this subsample have kinematics that are inconsistent with a thin rotating disk model.

The nature of the dispersion dominated galaxies is a puzzle. They are not literally dispersion-supported elliptical galaxies. Comparing rotation and dispersion dominated galaxies (RDGs and DDGs) in magnitude and color, the DDGs are only slightly different, 0.05 bluer in median $U - B$ and equal in median brightness, and their morphologies are late type; we discuss DDG and RDG properties further in Section 6. The DDGs’ velocity dispersion is unlikely to indicate a literal dynamically hot pressure-supported tracer population like stars in spheroidals. We are measuring velocities from nebular lines that come from $\sim 10^4$ K gas, so the dispersion in individual H II regions is only 8-10 km s$^{-1}$. The larger values of $\sigma_{2d}$ found in DDGs could come from the relative motions of the ensemble of gas clouds – chaotic, disordered, or out-of-plane velocity fields that are smoothed over by the seeing, or that have strong misalignments between photometry and kinematics. However, the geometry of the motions and whether they will eventually dissipate and settle into a disk cannot be resolved in these spectra.

If the seeing blur caused a bias against the detection of rotation in small objects, it could make objects appear dispersion dominated by masking the true rotation gradient. In principle, the ROTCURVE fitting method is seeing-compensated. For a very small object with a rotation gradient that suffers greatly from seeing blur, it yields a shallow minimum in $\chi^2$; models with an intrinsic rotation gradient and with a dispersion both fit the data, so there is a large error on $V_{\text{rot}}$ rather than a bias. In practice, we rejected objects with a very small diameter of velocity data, $< 1''$. In Section 6 we discuss the sizes of RDGs and DDGs and show that the DDGs are only mildly smaller, so they are not simply caused by an observational bias against rotation. Intrinsic nonroundness or errors in the ellipticity and PA measurements could cause a few face-on disks to appear in the DDG sample, but there are too many elongated DDGs to explain away.

Dispersion dominated galaxies occur over the full redshift range of our sample and are not strictly a high-redshift population. Figure 15 plots magnitude against redshift for the sample with 2-d ROTCURVE modeling, with points coded for rotation or dispersion domination. DDGs exist at low redshift, but are relatively faint there; it is possible that the dispersion/rotation fraction is higher at high redshift, although the sample size and selection effects make any conclusion preliminary.

5.2. Comparison of integrated linewdiths and spatially resolved kinematics

A key question for using linewidths of integrated emission as a characteristic velocity scale is how well they correlate with spatially resolved kinematic measures. In Section 4.2 we tested models of seeing-blurred integrated emission from a rotating disk and found that linewidth $\sigma_{1d}$ correlated well with projected circular velocity $V_c \sin i$; the chief scatter between $\sigma_{1d}$ and true $V_c$ is induced by inclination. In this section we test the relation of linewidth to rotation and dispersion from spatially resolved fits empirically using the 1-d and 2-d kinematic fits in TKRS. These quantities are line-of-sight, so no inclination correction is applied.

The existence of rotation and dispersion dominated galaxies suggests that neither 2-d measures, $V_{\text{rot}}$ nor $\sigma_{2d}$, by itself adequately represents the velocity scale of every distant galaxy. Figures 16 and 17 plot the 2-d velocity and dispersion, $V_{\text{rot}}$ and $\sigma_{2d}$, against the 1-d integrated linewidth, $\sigma_{1d}$. Point types are coded by whether the galaxy’s 2-d kinematics are rotation or dispersion dominated. The clustering of points with log $\sigma_{1d} = 1.4$ are galaxies kinematically unresolved in 1-d.

Figures 16 and 17 are the flip-side of each other. Each 2-d quantity, when it dominates, correlates with the 1-d measure $\sigma_{1d}$, but falls well below $\sigma_{1d}$ when it does not dominate. Either used alone would leave some galaxies
with egregiously small velocities.

For rotation dominated galaxies, there is a fair amount of scatter between $V_{rot}$ and $\sigma_{1d}$, but in general these quantities are correlated, with $\sigma_{1d}$ offset below $V_{rot}$. But for dispersion dominated galaxies, $V_{rot}$ is low and does not reflect the kinematic support seen in $\sigma_{1d}$. Conversely, $\sigma_{2d}$ correlates well with $\sigma_{1d}$ in dispersion dominated galaxies. But rotation dominated galaxies can be fit without requiring 2-d dispersion, so $\sigma_{1d}$ falls below $\sigma_{2d}$. In the RDGs, $\sigma_{1d}$ is capturing the seeing-induced dispersion.

The inadequacy of each 2-d quantity $V_{rot}$ and $\sigma_{2d}$ by itself motivated the design of ROTCURVE, which fits both simultaneously. To represent a characteristic velocity derived from the 2-d ROTCURVE fits, we define a “combined velocity scale” $S_K$:

$$S_K^2 = KV_{rot}^2 + \sigma_{2d}^2,$$  \hspace{1cm} (5)

where K is a constant $\leq 1$. The scale $S_K$ combines rotation and pressure or random/disordered-motion support, just as Tully-Fisher studies have done to model an observed integrated H i linewidth (e.g. Tully & Fouque 1985). The simplest combination is $S_{1.0}$, with $K = 1$. This is in some sense an estimator of rotation velocity plus a turbulent-motion correction.

However, setting $K < 1$ makes $S_K$ a better estimator of the velocity dispersion $\sigma$ of the entire potential, because rotation velocity and dispersion contribute differently to the support of a gravitationally bound system. For example, in an isothermal potential with a flat rotation curve, a population with isotropic velocity dispersion and no net rotation has $\sigma = V_c/\sqrt{2}$, suggesting that with $K = 0.5$, $S_{0.5}$ is a good estimator of $\sigma$ of the potential. In general, for a spherically symmetric tracer distribution with density $\propto r^{-\alpha}$ and isotropic velocity dispersion, $V_c$ varies slowly with radius, $\sigma = V_c/\sqrt{\alpha}$ (Binney & Tremaine 1987). Real galaxies in the range at or beyond the peak of the baryonic contribution to the rotation curve, where rotation curves are measured, have $\alpha = 2 - 3$ for a sphered mass distribution, so $K = 0.3 - 0.5$ is reasonable.

Figures 15 and 16 plot the combined velocity scales $S_{1.0}$ and $S_{0.5}$ against 1-d linewidth $\sigma_{1d}$. Combined velocity alleviates the shortcomings of $V_{rot}$ and $\sigma_{2d}$, eliminating artificially low velocity measurements. Both $S_{1.0}$ and $S_{0.5}$ show strong correlations with $\sigma_{1d}$. For the subsample with aligned slits and $e > 0.25$, the mean offset $\log S_{1.0} - \log \sigma_{1d}$ is 0.15 dex with RMS 0.17 dex; for $S_{0.5}$ the mean and RMS log offset are 0.06 and 0.14. The rotation estimator $S_{1.0}$ shows its rotation velocity heritage; rotation dominated galaxies have $S_{1.0} > \sigma_{1d}$, relatively close to the $\sigma = 0.6V_c$ line of Rix et al. (1997). RDGs and DDGs are offset in $S_{1.0}$; the offset in $S_{0.5}$ is smaller. When the dispersion-analog $S_{0.5}$ is plotted against $\sigma_{1d}$, the correlation with $\sigma_{1d}$ tightens, and the offset between $S_{0.5}$ and $\sigma_{1d}$ is reduced, because both are estimating a velocity dispersion of the potential.

The good correlation between 1-d integrated linewidth...
Section 4.2, the seeing is a powerful integrator. The 1-d dispersion fits has two major implications. First, 1-d rotation velocity alone will not suffice. Constructing a Tully-Fisher relation using $V/\sigma$ versus integrated linewidth $\log \sigma_{1d}$, Open circles: dispersion dominated galaxies, $V_{\text{rot}} < \sigma_{2d}$, with $e > 0.25$. Filled triangles: rotation dominated galaxies, $V_{\text{rot}} > \sigma_{2d}$, with $e > 0.25$. Small Xes: round galaxies or misaligned slits. The diagonal line is the 1:1 line. For dispersion dominated galaxies, $\sigma_{1d}$ and $\sigma_{2d}$ are correlated; for rotation dominated galaxies, $\sigma_{1d}$ captures the velocity scale while $\sigma_{2d}$ becomes small.

6. DISCUSSION: THE NATURE OF ROTATION AND DISPERSION DOMINATED GALAXIES

The existence of rotation and dispersion dominated emission line galaxies – essentially two modes of dynamical support, or a sort of kinematic morphology – raises the question of their nature and evolution. Rotation is well understood in local galaxies; dispersion dominated galaxies are the real puzzle. The size of the TKRS sample yields enough RDGs and DDGs to compare the physical properties and morphologies of these galaxies.

Several other studies of intermediate and high redshift galaxies have found objects inconsistent with rotation, similar to the DDGs. Simard & Pritchet (1998) found 25% of their galaxies had “kinematically anomalous” [O II] emission. These objects had centrally concentrated emission; we find below that DDGs are smaller in both continuum and emission. Erb et al. (2004) found that spectra of 13 elongated galaxies at $z \sim 2$ rarely show rotation. Bershady et al. (2005) obtained HST/STIS spectra of six luminous compact blue galaxies and found low $V/\sigma$; the STIS velocity dispersion confirmed ground-based integrated linewidth. From integral field spectroscopy, Flores et al. (2006) found that $\sim 2/3$ of 35 galaxies at $0.4 < z < 0.75$ had either mildly decentered or non-rotating kinematics; some of these may be dispersion dominated. Our TKRS survey establishes that the dispersion dominated galaxies are relatively common and not restricted to specially selected samples.

It is unclear what the local counterparts of dispersion dominated galaxies could be. Many local studies of galaxy kinematics, in order to study the distance scale or rotation curves and dark matter, have selected against galaxies with disordered kinematics. However, even very small galaxies down to $M_B \sim -15 - 16$ are generally dominated by rotation (e.g. Swaters et al. 2002). Tully-Fisher studies have considered the contribution of turbulent motions to the linewidth; Tully & Fouque (1985) claim that turbulent motions are only significant for very small rotation velocities $V \lesssim 25$ km s$^{-1}$, but this is based on an idealized model. Kannappan & Barton (2004) find a larger percentage of kinematically anomalous galaxies in close pairs; these mostly show distorted or truncated rotation curves, but a few are unusual enough that...
seeing-blur could make rotation gradients undetectable. It is also possible that evolution makes bright dispersion dominated emission line galaxies rare at the present day.

6.1. Comparative Properties of Rotation and Dispersion Dominated Galaxies

Rotation and dispersion dominated galaxies do exist over the full redshift range of our sample, as seen in Figure 15. There is some sign that at \( z < 0.4 \), DDGs are only found at faint magnitudes. This might reflect an evolution either in kinematics or in magnitude and emission strength. To compare the properties of luminous RDGs and DDGs, and to avoid being pulled by faint objects visible only at low redshift, we show distributions of galaxy properties for a sample restricted to \( z > 0.4 \), and with aligned slits and ellipticity \( e > 0.25 \) as before.

The distributions of \( z > 0.4 \) RDG and DDG restframe magnitude and color \( M_B \) and \( U - B \) are shown in Figures 20 and 21. At \( z > 0.4 \), the two types have indistinguishable magnitude distributions. The DDGs are bluer in the median than the RDGs, but only by 0.05 mag. Comparing the RDG and DDG distributions with the Kolmogorov-Smirnov statistic gives a 93% probability that they are identical in \( M_B \) and a 15% probability that they are identical in \( U - B \). The DDG color distribution covers almost the whole of the range of the blue galaxy population, so it appears that DDGs are not solely unusual blue objects, e.g. compact H II regions or extreme starbursts.

The size distributions of \( z > 0.4 \) RDGs and DDGs are shown in continuum and in emission, in Figures 22 and
Fig. 22.— Radius distribution in half-light radius $R_{hl}$, kpc, from HST images, for rotation and dispersion dominated galaxies at $z > 0.4$, with aligned slits and $e > 0.25$. Solid line: rotation dominated galaxies, $V_{rot} > \sigma_{2d}$. Dashed line: dispersion dominated galaxies, $V_{rot} < \sigma_{2d}$. RDGs are larger in the mean than DDGs, though the size distributions overlap.

Figure 23.— Emission extent: total range (diameter), in arcsec, of data used in the rotation/dispersion fit in the Keck spectra, for rotation and dispersion dominated galaxies at $z > 0.4$, with aligned slits and $e > 0.25$. Solid line: rotation dominated galaxies, $V_{rot} > \sigma_{2d}$. Dashed line: dispersion dominated galaxies, $V_{rot} < \sigma_{2d}$. RDGs are larger in the mean than DDGs, though less so in half-light radius. The ranges in emission extent are similar, implying that DDGs are real and not just objects too small to detect rotation in ground-based spectra.

6.2. Morphologies of Rotation and Dispersion Dominated Galaxies

To explore further any systematic differences between rotation and dispersion dominated galaxies, we made a morphological classification of the sample of 116 RDGs and 67 DDGs that have aligned slits and ellipticity $> 0.25$. We inspected ACS I-band images from the GOODS-N data. The classifications are cataloged in Table 3.

Because the physical resolution is limited and high redshift galaxies are known to exhibit a greater degree of morphological peculiarity (e.g. Abraham et al. 1996), we defined a simplified system of morphological types.

We found no spheroidals in the RDG/DDG sample.
classes are: disks, Sb-Sd; irregulars, both low and high surface brightness; edge-on disks; “chain” and “hyphen” galaxies; and mergers. Chain galaxies are elongated objects with bright knots (e.g. Cowie, Hu, & Songaila 1995). Hyphen galaxies are thin, small but elongated, with little substructure. We only defined galaxies as mergers if they clearly had multiple components, tidal tails, or major disturbances associated with mergers. Many high-z galaxies are somewhat peculiar or asymmetric and we did not count these as evidence of mergers. The percentages of morphological types for RDGs and DDGs are listed in Table 4 for both the full sample and the sample restricted to z > 0.4, where RDGs and DDGs have similar luminosity.

The clearest results from Table 4 are that rotation dominated galaxies are generally disky, or irregular, and very rarely chain or hyphen galaxies. Dispersion dominated galaxies sometimes appear disky, but are more often irregular, and a substantial number are chain or hyphen galaxies. Hardly any DDGs were edge-on disks, which is understandable since these are most likely to have detectable rotation. Mergers are not a large fraction of either RDGs or DDGs.

Restricting the sample to z > 0.4 changes the ratios little, other than to decrease the number of edge-on disk RDGs. There is a definite offset in morphology between RDGs and DDGs, but also substantial overlap. These morphologies are subjective; the link between kinematic and photometric morphologies will be addressed further with larger samples and objective measures in the DEEP2 survey.

A significant number of galaxies were classed as chain or hyphen, types which are rare at low redshift. Two-thirds of the chain/hyphen galaxies were DDGs; only one-third of these elongated objects were dominated by rotation. TKRS 5627 shown in Figures 1 and 3 is an example of a chain galaxy, elongated but nonrotating. Similar objects have been found at z ∼ 2 by Erb et al. (2004): their slit spectra of 13 elongated galaxies showed dispersion, but rarely rotation. These results suggest that kinematic surveys must use caution in interpreting ellipticity: elongated objects may not be inclined disks and may not be rotating.

The higher fraction of peculiar objects at high redshift suggests that galaxies evolve in photometric morphology, with a greater fraction of seemingly irregular galaxies at z ∼ 1 (e.g. Abraham et al. 1996; Lotz et al. 2006). Possibly they also evolve in kinematic morphology. Luminous dispersion dominated galaxies appear at z ∼ 1 but are uncommon locally; even faint local blue galaxies are usually dominated by rotation (e.g. Swaters et al. 2002). Perhaps DDGs settle from a disordered or non-planar kinematic state into more orderly rotation; or their disordered kinematics are dominated by bright star forming regions which then fade to allow a more ordered background to be seen; or they evolve in luminosity by fading more than the overall population; or they cease forming stars and both fade and drop out of emission-line kinematic samples, leaving behind dispersion-supported faint red galaxies.

7. CONCLUSIONS

We have measured line-of-sight kinematic linewidths σ₁d for ∼ 1000 galaxies in the Team Keck survey of the GOODS-N field and spatially resolved line-of-sight rotation (Vₗ₀) and dispersion (σ₂d) profiles for 380 of these. Most galaxies with linewidths are on the blue side of the color bimodality. Linewidths from integrated spectra are a measure of internal kinematics that is relatively robust against observational effects, based on simulations of velocity fields and on comparisons of the linewidths with the spatially resolved kinematics. However, the unknown geometries of high-redshift velocity fields, scatter in galaxy ellipticities, and the lack of correction for projection into radial velocities mean that there is a fair amount of scatter between an individual galaxy linewidth measurement and a true circular velocity or dynamical mass estimate. For rotating galaxies, σ₁d ∼ 0.6Vₑ, in the mean, due to a combination of the inclination and the fact that σ₁d is less than line-of-sight Vₗ₀; this factor should be kept in mind when estimating dynamical masses.

The rotation and dispersion profiles of spatially resolved galaxies show that not all galaxies exhibit a conventional rotation curve. Galaxies can be roughly divided into rotation and dispersion dominated, with Vₗ₀ > σ₂d or vice versa. Dispersion dominated galaxies are blue, mostly irregular, and are not ellipticals; they probably have an effective dispersion, from disordered kinematics which are integrated over by the seeing. Dispersion dominated galaxies exist at all redshifts in our sample, but low-z DDGs are quite faint.

When line-of-sight rotation and dispersion are combined to make an estimate of the overall dispersion of the potential, as in S₀.₅ = 0.5Vₗ₀² + σ₂d², the result correlates well with the integrated linewidth σ₁d, demonstrating both that σ₁d is a robust velocity indicator and that it is possible to construct scaling relations with velocity for a population of diverse kinematic properties. In Paper II we use the linewidths to measure evolution in the Tully-Fisher relation.

At z ∼ 1, rotation and dispersion dominated galaxies have similar magnitudes and colors, but somewhat different size and morphology distributions. Rotation dominated galaxies are mostly disk and irregular types; dispersion dominated galaxies are in the mean smaller in physical half-light radius, and ∼ 60% of DDGs are irregular and chain/hyphen types. Only a small fraction of either RDGs or DDGs are obvious mergers. About two-thirds of chain and hyphen galaxies are dispersion dominated: elongated high-redshift objects cannot be assumed to be inclined rotating disks. It is not clear what

<table>
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<th>Type</th>
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the local counterparts of dispersion dominated galaxies might be; integral field spectroscopy, especially with adaptive optics, may shed some light on their nature at high redshift.

There is some evidence that dispersion dominated galaxies are rare at bright magnitudes at low redshift, just as previous studies have shown that irregular photometric morphologies in bright galaxies are more common at high redshift than locally (e.g. Abraham et al. 1996; Lotz et al. 2006). It is possible that galaxies evolve in kinematic morphology, settling into ordered rotation, or that luminosity evolution causes them to appear more ordered, or to drop out of bright emission-line samples. These and other possibilities are avenues for further study with larger samples and quantitative morphological measurements.

REFERENCES

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