Hα SPECTROSCOPY OF GALAXIES AT z > 2: KINEMATICS AND STAR FORMATION1

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ABSTRACT

We present near-infrared spectroscopy of Hα emission lines in a sample of 16 star-forming galaxies at redshifts 2.0 < z < 2.6. Our targets are drawn from a large sample of galaxies photometrically selected and spectroscopically confirmed to lie in this redshift range. We have obtained this large sample with an extension of the broadband U∗G∗R color criteria used to identify Lyman break galaxies at z ~ 3. The primary selection criterion for IR spectroscopic observation was proximity to a QSO sight line; we therefore expect the galaxies presented here to be representative of the sample as a whole. Six of the galaxies exhibit spatially extended, tilted Hα emission lines; rotation curves for these objects reach mean velocities of ~150 km s^-1 at radii of ~6 kpc, without corrections for inclination or any other observational effect. The velocities and radii give a mean dynamical mass of (M) > 4 × 10^10 M⊙. We have obtained archival Hubble Space Telescope images for two of these galaxies; they are morphologically irregular. One-dimensional velocity dispersions for the 16 galaxies range from ~50 to ~260 km s^-1, and in cases in which we have both virial masses implied by the velocity dispersions and dynamical masses derived from the spatially extended emission lines, they are in rough agreement. We compare our kinematic results with similar measurements made at z ~ 3 and find that both the observed rotational velocities and velocity dispersions tend to be larger at z ~ 2 than at z ~ 3. We also calculate star formation rates (SFRs) from the Hα luminosities and compare them with SFRs calculated from the UV continuum luminosity. We find a mean SFR_Hα of 16 M⊙ yr^-1 and an average SFR_Hα/SFR_UV ratio of 2.4, without correcting for extinction. We see moderate evidence for an inverse correlation between the UV continuum luminosity and the ratio SFR_Hα/SFR_UV, such as might be observed if the UV-faint galaxies suffered greater extinction. We discuss the effects of dust and star formation history on the SFRs and conclude that extinction is the most likely explanation for the discrepancy between the two SFRs.

Subject headings: galaxies: evolution — galaxies: high-redshift — galaxies: kinematics and dynamics — stars: formation

On-line material: color figures

1. INTRODUCTION

Our knowledge of star-forming galaxies at high redshift has increased enormously in the past 10 years, particularly at z ~ 3; large samples of galaxies at these redshifts are now known (Steidel et al. 1999, 2003), and they have been studied in both the rest-frame UV (Pettini et al. 2000; Shapley et al. 2003) and optical (Shapley et al. 2001; Papovich, Dickinson, & Ferguson 2001; Pettini et al. 2001), as well as at submillimeter (Chapman et al. 2000; Adelberger & Steidel 2000) and X-ray (Nandra et al. 2002) wavelengths to some extent. Much less is known about galaxies at z ~ 2. Because these objects lack strong spectroscopic features in the optical window, they have traditionally been difficult to identify. This is unfortunate, as z ~ 2 is likely the epoch in which a large fraction of the stars in the present-day universe formed (Madau, Pozzetti, & Dickinson 1998; Blain et al. 1999), in which bright QSO activity reached its peak (Schmidt, Schneider, & Gunn 1995; Pei 1995; Fan et al. 2001), and in which rapidly star-forming galaxies of compact and disordered morphologies became the normal Hubble sequence galaxies of the z < 1 universe (Dickinson 2000).

The situation is improving, however. With the advent of sensitive IR detectors, observations of rest-frame optical
features are now feasible and have been carried out successfully. Teplitz, Malkan, & McLean (1998) reported 11 Hα emitters discovered in a narrowband IR imaging survey; Yan et al. (1999) and Hopkins, Connolly, & Szalay (2000) used slitless spectroscopy with the near-infrared camera and multiobject spectrograph (NICMOS) on the Hubble Space Telescope (HST) to study the Hα luminosity function and star formation rate (SFR) in galaxies at z < 1.9. Objects at z ~ 2 are, in fact, ideally suited for ground-based IR spectroscopy, since Hα falls in the K band, [O iii] and Hβ in the H band, and [O ii] in the J band. This coincidence has been exploited with recent observations employing near-IR spectrographs on 8–10 m telescopes; most of these have focused on Hα emission (Kobulnicky & Koo 2000; Lemoine-Busserolle et al. 2003). Among these spectra is a rotation curve of a galaxy at z ~ 2 that reaches a velocity of \( \geq 200 \) km s\(^{-1} \) (Lemoine-Busserolle et al. 2003), suggesting that near-IR spectroscopy may be able to provide the most detailed kinematic information yet available on galaxies at high redshift. It is also clear from most of the above results that SFRs measured from Hα are consistently higher than those measured from the UV continuum luminosity; this is in accordance with observations at z ~ 1 (Glazebrook et al. 1999; Tresse et al. 2002) and at lower redshifts (see, e.g., Bell & Kennicutt 2001; also see Sullivan et al. 2000 and Buat et al. 2002 for comparisons of Hα and UV SFRs). The difference is generally accounted for by the differing sensitivities of the Hα and UV continuum SFR diagnostics to the presence of dust and to star formation history.

In this paper, we present Hα spectroscopy in the K band of 16 UV-selected galaxies in the redshift range 2.0 < z < 2.6. In \( \S \) 2, we describe our target selection process, observations, and data reductions. In \( \S \) 3, we comment individually on any noteworthy features of the galaxies. Section 4 addresses the kinematics of the galaxies: we discuss the rotation curves in \( \S \) 4.1 and the one-dimensional velocity dispersions in \( \S \) 4.2. In \( \S \) 5, we calculate SFRs from Hα and rest-frame UV emission and compare them, and we discuss our conclusions in \( \S \) 5.2. We use a cosmology with \( H_0 = 70 \) km s\(^{-1} \) Mpc\(^{-1} \), \( \Omega_m = 0.3 \), and \( \Omega_\Lambda = 0.7 \) through-out. In this cosmology, the universe at z = 2.3 is 2.8 Gyr old, or 21% of its present age, and a proper distance of 8.2 kpc subtends an angular distance of 1\(^\circ\).

2. TARGET SELECTION AND OBSERVATIONS

The objects discussed here are drawn from a large sample of galaxies photometrically selected and spectroscopically confirmed to be in the redshift range 2.0 \( \leq z \leq 2.6 \). We summarize the selection technique here; a more complete discussion will be given in a forthcoming paper. We have extended the broadband color criteria used to select galaxies at z \( \sim 3 \) (Steidel & Hamilton 1993; Steidel, Pettini, & Hamilton 1995; Steidel et al. 1996) to other regions of the (\( U_n - G \)) versus (\( G - R \)) plane, identifying candidates according to the following conditions:

\[
\begin{align*}
G - R &\geq -0.1, \\
U_n - G &\geq G - R + 0.2, \\
G - R &\leq 0.3(U_n - G) + 0.2, \\
U_n - G &< G - R + 1.0.
\end{align*}
\]

We refer to these as “BX” objects (e.g., Q1700-BX691); 92% of the objects satisfying these criteria are galaxies in the redshift range 1.6 \( \leq z \leq 2.8 \), with 72% in the range 2.0 \( \leq z \leq 2.6 \). These criteria were developed by calculating the colors that typical z \( \sim 3 \) Lyman break galaxies (LBGs) would have if they were placed at z \( \sim 2 \); they are therefore designed to select objects with similar intrinsic spectral energy distributions (SEDs) at both redshifts (Adelberger 2002). Our sample also contains four “MD” objects (e.g., Q1623-MD107); these objects are detected in the \( U_n \) band and meet the criteria

\[
\begin{align*}
G - R &< 1.2, \\
U_n - G &\leq G - R + 1.5, \\
U_n - G &> G - R + 1.0.
\end{align*}
\]

They have the redshift distribution \( \langle z \rangle = 2.79 \pm 0.27 \) (Steidel et al. 2003), so that the low-redshift end of the distribution encompasses objects with z \( \leq 2.6 \). Both the BX and MD candidates are restricted to R \( \leq 25.5 \) (roughly equivalent to R \( \leq 26 \) at z \( \sim 3 \)). The two remaining objects in our sample, Q0201-B13 and CDFb-BN88, satisfy the BX criteria but have different names because they predated the systematic use of the z ~ 2 selection technique. Once candidates are photometrically identified, we confirm their redshifts with rest-frame UV spectra obtained with the Low Resolution Imaging Spectrometer (LRIS; Oke et al. 1995) on the Keck I telescope. The redshifts from the UV interstellar absorption lines and Ly\( \alpha \) when present are listed in Table 1, and spectra for two of the objects are shown as examples in Figure 1. The rest-frame UV observations will be described in detail elsewhere.

The galaxies targeted for IR spectroscopy were selected as part of an ongoing project examining the interplay between galaxies and the intergalactic medium (IGM), in which we combine spectroscopy of faint star-forming galaxies with QSO absorption-line observations of the IGM in the same volume (Adelberger et al. 2003). A detailed comparison of the galaxies and the IGM requires accurate measurements of the galaxy redshifts and, ultimately, an understanding of the SFRs, masses, and ages of galaxies near the QSO lines of sight; therefore, the primary selection criterion (beyond the color criteria described above) for the present sample was proximity to a QSO sight line. This naturally results in a sample with a wide range of UV properties (as distinguished, for example, from the galaxies in the z ~ 3 sample of Pettini et al. 2001, which were selected to be particularly UV-bright).

Twelve of our 16 galaxies are within 60" of QSOs in fields at (R.A., decl.) = 17\(^{\circ}\)00\(\prime\)m, +64\(\prime\) and 16\(^{\circ}\)23\(\prime\)m, +27\(\prime\) (J2000.0), and have redshifts slightly lower than those of the QSOs themselves; these were observed with NIRSPEC (McLean et al. 1998) on the Keck II telescope in 2002 May. We observed an additional galaxy in the Groth-Westphal field on the same run. The other three objects in the sample (SSA 22a-MD41, Q0201-B13, and CDFb-BN88) were observed with the Infrared Spectrometer and Array Camera (ISAAC; Moorwood et al. 1998) on the Very Large Telescope 1 (VLT 1) in 2000 October and were among the small number of z \( \sim 2–2.5 \) galaxies in the z ~ 3 LBG survey fields at the time. They were also selected because of their UV brightness, the favorable wavelength of Hα relative to night-sky emission lines, and the possibility of measuring rotation.
TABLE 1  
Galaxies Observed

| Galaxy            | R.A. (J2000.0) | Decl. (J2000.0) | z_Lyα | z_ab | z_Hα | # | G−# | Exposure (s) | Telescope/Instrument |
|-------------------|----------------|-----------------|-------|------|------|---|-----|-------------|----------------------|
| CDFb-BN88         | 00 53 52.87    | 12 23 51.25     | ...   | ...  | 2.263| 2.2615|23.14  |0.29 | 12 × 720    | VLT 1/ISAAC          |
| Q0201-B13         | 02 03 49.25    | 11 36 10.58     | ...   | ...  | 2.167| 2.1663|23.34  |0.02 | 16 × 720    | VLT 1/ISAAC          |
| Westphal BX600d   | 14 17 15.55    | 52 36 15.64     | ...   | ...  | 2.1607|2.1607|23.94  |0.10 | 5 × 900     | Keck II/NIRSPEC      |
| Q1623-BX376       | 16 25 05.63    | 26 46 49.12     | 2.415 | 2.408| 2.4085|2.4085|23.31  |0.24 | 4 × 900     | Keck II/NIRSPEC      |
| Q1623-BX428       | 16 25 48.42    | 26 47 40.24     | ...   | 2.053| 2.0538|2.0538|23.95  |0.13 | 4 × 900     | Keck II/NIRSPEC      |
| Q1623-BX432       | 16 25 48.74    | 26 46 47.05     | 2.187 | 2.180| 2.1817|2.1817|24.58  |0.10 | 4 × 900     | Keck II/NIRSPEC      |
| Q1623-BX447       | 16 25 50.38    | 26 47 14.07     | ...   | ...  | 2.149 |2.1481|24.48  |0.17 | 4 × 900     | Keck II/NIRSPEC      |
| Q1623-BX449       | 16 25 50.55    | 26 46 59.63     | ...   | ...  | 2.417 |2.4188|24.86  |0.20 | 4 × 900     | Keck II/NIRSPEC      |
| Q1623-BX511       | 16 25 56.10    | 26 44 44.38     | ...   | ...  | 2.246 |2.2421|25.37  |0.42 | 4 × 900     | Keck II/NIRSPEC      |
| Q1623-BX522       | 16 25 55.76    | 26 44 53.17     | ...   | ...  | 2.476 |2.4757|24.50  |0.31 | 4 × 900     | Keck II/NIRSPEC      |
| Q1623-MD107       | 16 25 53.88    | 26 45 15.19     | 2.543 | 2.536| 2.5373|2.5373|25.35  |0.12 | 4 × 900     | Keck II/NIRSPEC      |
| Q1700-BX428       | 17 01 05.99    | 64 12 10.27     | ...   | ...  | 2.189 |2.1895|25.33  |0.22 | 4 × 900     | Keck II/NIRSPEC      |
| Q1700-BX717       | 17 00 57.00    | 64 12 23.71     | 2.438 | ...  | ...   | ...   | ...   | ... | ...         | ...                  |
| Q1700-MD103       | 17 01 00.20    | 64 44 56.00     | ...   | ...  | 2.308 |2.3148|24.23  |0.46 | 900 + 600   | Keck II/NIRSPEC      |
| Q1700-MD109       | 17 01 04.48    | 64 12 09.28     | 2.295 | 2.297| 2.2942|2.2942|25.46  |0.26 | 4 × 900     | Keck II/NIRSPEC      |
| SSS22a-MD41       | 22 17 39.97    | 00 17 11.04     | ...   | ...  | 2.173 |2.1713|23.31  |0.19 | 15 × 720    | VLT 1/ISAAC          |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

a Vacuum heliocentric redshift of Lyα emission line, when present.

b Vacuum heliocentric redshift from UV interstellar absorption line.

c Vacuum heliocentric redshift of Hα emission line.

d We have not yet obtained a rest-frame UV spectrum of Westphal BX600.

e The Hα redshifts of the galaxies Q1623-BX428 and Q1623-BX511 are somewhat uncertain because of the presence of strong skylines near Hα.

2.1. Data Acquisition

Most of our targets were observed on 2002 May 19 and 20 (UT) with the NIRSPEC spectrograph on the Keck II telescope. NIRSPEC is described in detail by McLean et al. (1998); it uses a 1024 × 1024 pixel (ALADDIN2) InSb detector with 27 μm pixels. In the medium-dispersion mode used for these observations, each detector pixel corresponds to 0″143 in the spatial direction, and the dispersion in the spectral direction is 4.2 Å pixel−1. We used a 0″76 × 42″ entrance slit, which gives a resolving power of R ≈ 1400, corresponding to a spectral resolution of ~15 Å FWHM in the observed frame K band, as measured from the widths of skylines. In almost all cases we were able to place two galaxies on the slit at the same time by setting the appropriate position angle. Because the galaxies are too faint to be acquired directly on the spectrograph slit, we placed them on the slit by offsetting from a nearby bright star or from the QSO with a sight line near the galaxy. Individual exposures were 900 s, and we typically took four exposures of each object, for a total of 1 hr of integration. Between each exposure we reacquired the offset star, moved it along the slit by approximately 5″, and offset once again to the target object. The detector was read out in multiple-read mode, with 16 reads at the start and end of each integration; the results were then averaged to reduce noise. The choice of filter and wavelength range was governed by the expected position of the Hα line based on each galaxy’s optical redshift; we used the NIRSPEC6 and NIRSPEC7 filters, which span the wavelength ranges 1.56–2.32 and 1.84–2.63 μm, respectively. The spectral dispersion allows a range of approximately 0.4 μm to be placed on the detector at one time. Conditions were photometric on both nights, with approximately 0″5 FWHM seeing in the K band.

SSA22a-MD41, Q0201-B13, and CDFb-BN88 were observed on 2000 October 20–22 (UT) with the ISAAC spectrograph on the VLT1. The short-wavelength channel...
of ISAAC (Moorwood et al. 1998) uses a 1024 × 1024 pixel Rockwell HgCdTe array with 18.5 μm pixels. The pixel scale along the 1″ × 120″ slit is similar to that of NIRSPEC, 0″146 pixel−1, but the spectral resolution is 2.5 times higher, with $R \approx 3500$ and skyline widths of ~6 Å FWHM. We observed in the $K$ band, again targeting the expected position of H$_\alpha$ from rest-frame UV redshifts. The position angles were chosen to align with the major axes of the galaxies if any extended structure was apparent in the optical images; this was the case with SSA22a-MD41 and, to a lesser extent, with CDFb-BN88. We also placed a bright star on the slit along with each galaxy to facilitate the determination of offsets between images. We performed an ABBA series of four 720 s exposures, with 10″ offsets between the A and B positions. The object was then reacquired at a different position along the slit, and the procedure was repeated, typically for a total of ~3 hr of integration. Conditions were not photometric, and the seeing varied between 0″5 and 0″6 FWHM. The targets and observations are summarized in Table 1.

2.2. Data Reduction

The fully reduced spectra are shown in Figure 2. The two-dimensional images were reduced with IRAF; preliminary steps included flagging and masking any pixels that exhibited aberrant behavior in the dark and flat-field images, flat-fielding the data using the spectrum of a quartz halogen lamp, and cutting out and rotating the image of the slit. Spatial distortion was corrected by stepping a bright star along the slit at 5″ intervals for the NIRSPEC data and 10″ intervals for those from ISAAC, combining the resulting images, and determining the star trace as a function of slit position. We then applied a wavelength solution to the rectified images by identifying the OH skylines with reference to a list of vacuum wavelengths from the Kitt Peak National Observatory Fourier Transform Spectrograph,$^4$ resulting in two-dimensional images rectified both spatially and spectrally.

For the NIRSPEC objects, we took four 900 s exposures of each galaxy or galaxy pair, moving the object(s) along the slit for each integration. In order to subtract the sky background, we constructed a sky frame from the temporally adjacent images; after scaling and smoothing in the spatial direction, this sky frame was subtracted from the science image. Sky subtraction was done slightly differently for the objects.

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$^4$ Available at [http://www2.keck.hawaii.edu/inst/nirspec/data/oh.lst](http://www2.keck.hawaii.edu/inst/nirspec/data/oh.lst).
ISAAC observations, which were taken using ABBA offsets: a sky frame made from the sum of the A images was subtracted from the B images, and vice versa. Further background subtraction was done for both the NIRSPEC and ISAAC observations by fitting a polynomial in the spatial direction at each wavelength bin, avoiding the positions of any bright objects on the slit; this removed some of the residuals of the skylines. Finally, we produced a fully reduced, two-dimensional spectrogram of each galaxy by registering and averaging the individual frames, excluding bad pixels identified from combined dark and flat-field images. This step also produced a two-dimensional frame of the statistical 1/$\sigma^2$ error appropriate to each pixel. The last step was to extract one-dimensional spectra of each galaxy; this was done by summing the pixels containing a signal along the slit. The same aperture was then used to extract a variance spectrum from the square of the error image described above; the square root of this is a 1/$\sigma^2$ error spectrum, which was used to determine the uncertainties in the line fluxes and widths.

2.3. Flux Calibration

In order to put the one-dimensional spectra onto an absolute flux scale, we observed A0 and A2 stars from the list of UKIRT photometric standards. These typically have $K \simeq 7$ mag, and they were observed at similar air mass and with the same instrumental configuration as the galaxies themselves. Flux calibration was done by scaling the SED of Vega (Colina, Bohlin, & Castelli 1996) according to the magnitude of the standard used and dividing the spectrum of the standard star by this scaled Vega spectrum. This gives a sensitivity function in counts per unit flux density, by which we divided our one-dimensional galaxy spectra. Because the spectra of A stars are relatively smooth at the wavelengths of interest, they provide a measurement of the atmospheric absorption, and dividing our galaxy spectra by the sensitivity function therefore corrects for atmospheric absorption.

The uncertainties in the flux calibration process are both substantial and difficult to quantify; however, we have attempted to estimate them in several ways. As described above, we extracted 1/$\sigma$ error spectra for each of the galaxies; these primarily reflect the noise of the sky background. By integrating the flux in the variance ($\sigma^2$) spectrum at the position of H$\alpha$ and taking the square root of the result, we can measure the random error associated with the observation; this is $\leq 10\%$. More difficult to measure are systematic errors: the largest sources of uncertainty are the flux lost because of imperfect centering of the objects on the slit, seeing and seeing variations, and the possibility of the objects being larger than the slit itself. We can get a sense of the importance of these effects by comparing the fluxes received in each of the individual exposures that were co-added to produce our final spectra. We find that flux levels between exposures vary by about 30\% ($1\sigma$); this

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5 Available at http://www.jach.hawaii.edu/JACpublic/UKIRT/astronomy/calib/ukirt_stds.html.
includes random as well as systematic error. The uncertainty in the mean flux of our three or four exposures is then 15%–20%. This accounts for variations in object centering and seeing, but not for flux consistently lost because of the width of the slit. As the galaxies observed are small (seeing, but not for flux consistently lost because of the width of the slit). We assume that in most cases the flux loss is not significant; however, a few of the galaxies are particularly irregular and extended, and in these cases the flux loss may be significant. We can perform a further check by calibrating the same object with several different standard stars; in doing so we find variations in flux of 15% at maximum, and usually much less (again, 1σ). Because we have K-band photometry for one of the galaxies in our sample (Q1623-BX691, one of the few in which we detect a continuum signal), we can compare the photometric flux with the continuum flux; we find that our spectrum underestimates the photometric flux by a factor of 1.3, or about 25%. Because the continuum is so faint, this measurement is subject to large errors and is more a test of our sky subtraction than of our spectrophotometry. We have also extracted one-dimensional spectra of the standard stars with a variety of aperture widths, in order to determine whether an aperture correction might be necessary; we find that less than 5% of the flux is lost with the apertures used to extract the galaxy spectra. As this is much smaller than other sources of error, no aperture correction was applied. Based on all of these tests, we take our measured fluxes as uncertain by about 25%. This uncertainty propagates directly into the derived luminosities and SFRs, and it is adopted in the analyses that follow.

3. COMMENTS ON INDIVIDUAL OBJECTS

While our selection process naturally leads to a wide range of UV properties, with median aperture widths, in order to determine whether an aperture correction might be necessary; we find that less than 5% of the flux is lost with the apertures used to extract the galaxy spectra. As this is much smaller than other sources of error, no aperture correction was applied. Based on all of these tests, we take our measured fluxes as uncertain by about 25%. This uncertainty propagates directly into the derived luminosities and SFRs, and it is adopted in the analyses that follow.

Q1623-BX376.—This is one of the brightest rest-frame UV objects in our sample and the only one in which the SFR calculated from the UV emission is unambiguously higher than that from the Hα emission (see §4.1). In ground-based imaging it appears extended, with a fainter component extending ~2′5 to the west. The association between the two components is less clear with higher resolution imaging (see Fig. 3); however, the Hα emission also consists of two lines at the same redshift, separated by ~2′5. We have extracted spectra for both components, as shown in Figure 2; the primary component is labeled Q1623-BX376a and the fainter Q1623-BX376b. Because our optical photometry treated both components as a single extended object, we sum the fluxes from both lines in order to calculate the Hα SFR in § 5.

Q1623-BX428.—Unfortunately, this galaxy lies at a redshift such that Hα falls very close to a strong skyline, to which we have lost significant flux. This can be seen clearly in Figure 2, where the skyline falls just to the left of Hα. Because of the loss of flux, we are able to place a lower limit on the Hα SFR, but the sky subtraction has affected the line profile such that the velocity dispersion cannot be determined.

Q1623-BX447.—This is one of the six galaxies for which we derived rotation curves from tilted Hα emission lines; it is also one of the few for which we have HST imaging, which shows it to be morphologically complicated (see Fig. 3). We also see from the HST image that our slit was offset from the most extended axis of the galaxy by ~60′.

Q1623-BX511.—Of the six galaxies for which we were able to derive rotation curves, this has the smallest Hα flux and hence the smallest spread in velocity and the largest uncertainties. The Hα emission falls between two bright skylines, as can be seen in Figure 2. At μ = 25.37, it is among the faintest UV objects in our sample as well.

Q1700-BX691.—This is the only galaxy in which we clearly detect [N ii] λ6549, 6583 and [S ii] λλ6717, 6734 emission lines as well as Hα. All of the lines are tilted in the two-dimensional spectra, providing strong evidence for rotation. The Hα rotation curve reaches a velocity of ~240 km s^{-1} at ~9 kpc, with no sign of flattening; this is clearly a massive system. The fact that we see [N ii] and [S ii] lines suggests a relatively high metallicity; however, we defer a calculation until we are able to obtain measurements of [O iii] in the H band. Interestingly, this is among the faintest UV objects in our sample, with μ = 25.33. A K-band image of this object (Teplitz et al. 1998; H. I. Teplitz 2002, private communication) shows it to be extremely red, with μ - K = 5.10. The K-band image also shows that our slit was fortuitously aligned with the major axis.

Q1700-MD103.—This galaxy has the strongest Hα emission in our sample and hence the largest Hα-derived SFR, 27 M_⊙ yr^{-1}. It is also one of the six objects in which we detect rotation.

Westphal BX600.—One of the six objects in which we detect rotation, this galaxy is second only to Q1700-BX691 in rotational velocity and implied mass. We detected Hα emission serendipitously, while observing the nearby z ~ 3 galaxy Westphal MD115. This object had been previously classified as a z ~ 2 galaxy candidate based on its rest-frame UV colors, but it has not yet been observed with LRIS. Although we have no optical redshift, we believe the line detected here to be Hα, because its UV colors are entirely consistent with a redshift of z = 2.16; the contamination fraction in the optical color selection process is less than 10%, with most of the interlopers being galaxies at low redshift (z = 0.05–0.15). We do not know of any strong emission lines that would fall in our spectral window for a galaxy in this redshift range; for a redshift of z = 0.008, He i
would fall at the wavelength of the observed line, but then we would also expect to see stronger \( \text{Br}\gamma \) emission at 2.18 \( \mu \)m, which we do not.

**SSA22a-MD41.**—This is one of the three galaxies that were observed with the ISAAC spectrograph on the VLT. Conditions were not photometric during the ISAAC run, so we are only able to place a lower limit on the H\( \alpha \) SFR. We detect rotation in the H\( \alpha \) emission, with a large spatial extent of nearly \( \pm 10 \) kpc.

**Q0201-B13 and CDFb-BN88.**—These are the other two galaxies observed with ISAAC. As with SSA22a-MD41, we place lower limits on the SFR from H\( \alpha \). Q0201-B13 shows some evidence of rotation in a slight tilt of the emission line, but the S/N is too low to construct a reasonable rotation curve.

**Q1623-BX432, Q1623-BX449, Q1623-BX522, Q1623-MD107, Q1700-BX717, and Q1700-MD109.**—These are the remaining objects in the sample. They span a factor of 3 in H\( \alpha \) luminosity, from Q1623-BX432 at the bright end to Q1623-BX449 at the faint end, but none show evidence of velocity shear. Our only kinematic information about these objects comes from the velocity dispersion; for three of the fainter objects (Q1623-BX449, Q1623-MD107, and Q1700-BX717), we were only able to place an upper limit on this quantity.

**Nondetections.**—There are 10 galaxies that we observed with NIRSPEC but failed to detect. Four of these are accounted for by two observations in which we did not detect either of the galaxies we placed on the slit; in the cases of the other six, we detected one of the galaxies on the slit but missed the other. For one of these the optical redshift was unknown, so our hopes for detecting it were not high. These 10 nondetections could have a variety of explanations, including errors in our optical redshifts (which are of
marginal quality in many cases), in the astrometry, or in the guiding and tracking of the instrument and telescope. The objects could also be intrinsically faint because of extinction or a decline in the SFR, as discussed in § 5.

4. KINEMATICS

4.1. Rotation

Six galaxies in our sample of 16 show evidence of velocity shear, in the form of a spatially resolved, tilted Hα emission line. We have constructed rotation curves for these objects by fitting a Gaussian profile in wavelength to the emission line at each spatial location along the slit, summing three pixels in the spatial direction at each point in order to approximate the seeing of ~0\textacuted{prime}5. Velocity offsets were measured with respect to the systemic redshift of the galaxy as determined from the central wavelength of the integrated Hα emission line; when possible, the spatial center was defined by summing the spectra in the dispersion direction without including the emission line and locating the center of the continuum. For those with no apparent continuum emission (Q1700-MD103 and Q1623-BX511), the center was defined as the spatial center of the emission line. The two-dimensional emission lines are shown in Figure 4 and the rotation curves in Figure 5. The observed velocities range from ~50 to ~240 km s\textsuperscript{-1}, comparable to those observed in local galaxies and up to z ~ 1 (Vogt et al. 1996, 1997). In most cases they show no sign of flattening at a terminal velocity; the blueshifted end of the curve of Westphal BX600 is the only one that appears to flatten, and this is probably caused by imperfect subtraction of an adjacent skyline.

There are several systematic effects to be considered here; most of them result in an underestimate of the rotational velocity. Except in the case of SSA22a-MD41, no attempt was made to align the slit with the major axis of the galaxy (position angles were chosen in order to place two objects on the slit; see § 2); in fact, in most cases our ground-based images do not have sufficient resolution to allow the determination of a major axis. In the K'-band image of Q1700-BX691, however, it appears that here our slit was fortuitously aligned with the major axis of the galaxy. We also have an HST WFPC2 image of Q1623-BX447 (see Fig. 3), in which it is apparent that the position angles of the slit and the galaxy differ by ~60\textdegree. In the other three cases, the slit and the major axis were misaligned by an unknown amount.

In addition, the inclinations of the galaxies are not known. Given a random inclination and a random slit orientation, we will, on average, underestimate the rotational velocity by a factor of \((\pi/2)^2\approx 2.5\), where a factor of \(\pi/2\) [the inverse of the average value of \(\sin x\) over the interval \((0, \pi/2)\)] comes from each effect. Also, because all or most of each galaxy falls within the slit, the velocity we measure at each spatial point along the slit is biased away from the maximum projected velocity at the major axis by the lower velocities of points away from the major axis. We must also consider the possibilities of uneven distribution of Hα emission and noncircular motions; both of these are likely, given the irregular morphologies of the galaxies (see Fig. 3). A concentration of Hα away from the major axis of the galaxy would lead to an underestimate of the rotational velocity.

Fig. 4.—Two-dimensional spectra of the galaxies for which we have derived rotation curves, showing the tilt in the Hα emission line. From left to right and top to bottom, the galaxies are Q1700-BX691 at \(z = 2.1895\), Westphal BX600 at \(z = 2.1607\), SSA22a-MD41 at \(z = 2.1713\), Q1623-BX447 at \(z = 2.1481\), Q1700-MD103 at \(z = 2.3148\), and Q1623-BX511 at \(z = 2.2421\). A tilted [N ii] \(\lambda 6584\) emission line is visible above Hα in the spectrum of Q1700-BX691. The x-axis is spatial, with 1\textacuted{prime} scale bars shown, and y is the dispersion direction.
but the effect of noncircular motions is more difficult to predict. Typically, many of these effects are modeled and corrected for in rotation curves for less distant galaxies (Vogt et al. 1996, 1997; Swaters et al. 2003). Given the chaotic, or unknown, morphologies in our sample, we have not attempted to model these corrections.

We have used archival HST WFPC2 images that contain two of these galaxies, SSA22a-MD41 (in the F814W filter; proposal ID 5996) and Q1623-BX447 (F702W; proposal ID 6557). We reduced the images following the drizzling procedure outlined in the HST Dither Handbook (Koekemoer et al. 2002); see Fruchter & Hook (2002) for more details. The images are shown in Figure 3, with the position of the slit marked. Neither appears to be a well-formed disk; most of the rest-frame UV emission in SSA22a-MD41 is concentrated in a knot at the southwest edge, and Q1623-BX447 shows two distinct areas of emission. It is interesting to contrast these with images of two other galaxies for which we did not detect rotation: Figure 3 also shows images of Q1623-BX432 and Q1623-BX376, which are also contained in the Q1623 pointing and also appear irregular. This demonstrates the difficulty of predicting the kinematics of these objects from even high-resolution imaging; complicated morphologies make inclinations and major axes difficult to determine, and objects with similar UV continuum morphologies may exhibit quite different Hα kinematic properties. We also point out that the Hα and UV emission may not be coincident; Pettini et al. (2001) observed nebular line emission extending ~1″ beyond the UV emission in a galaxy at z = 3.2, and similar effects have been seen in local galaxies (Leitherer et al. 1996; de Mello et al. 1998; Johnson et al. 2000). Specifically, Conselice et al. (2000) compared Hα and UV emission in six nearby starburst galaxies, finding that the Hα and UV fluxes were well correlated in three of the systems, but that they showed different morphologies in the other three.

Although we have no direct evidence that these galaxies are in fact disks, we make this assumption in order to use the radius r and the circular velocity $v_c$ to calculate the enclosed mass,

$$M_{\text{dyn}} = v_c^2 r / G .$$  \hspace{1cm} (3)

Since we have neither well-defined terminal velocities nor spatial centers for these objects, we have calculated lower limits on the masses by using half of the total spread in both velocity and distance, for $v_c$ and r, respectively. We obtain an average dynamical mass of $\langle M \rangle \geq 4 \times 10^{10} M_\odot$; individual masses for each galaxy are shown in Table 2. As the Hα emission traces only the central star-forming regions of these objects, which are probably baryon-dominated, the masses derived are underestimates of the total halo masses of the galaxies. We can use an order-of-magnitude argument to estimate the total masses: for $\Omega_b = 0.02 h^{-2}$ and $\Omega_m = 0.3$, $\Omega_m / \Omega_b \sim 7$, and the universe contains about 6 times more dark than baryonic matter. We therefore expect the total masses of the galaxies to be about 7 times larger than their stellar masses, and we place a lower limit of $M \gtrsim 3 \times 10^{11} M_\odot$ on the typical halo mass of these galaxies. This is generally consistent with mass estimates from the clustering properties of LBGs at $z \sim 3$: Adelberger et al. (1998) find a typical mass of $8 \times 10^{11} h^{-1} M_\odot$ for a $\Lambda$CDM model, based on the number density and correlation length of the galaxies. Other analyses yield similar results (Baugh et al. 1998; Giavalisco & Dickinson 2001). We defer an analysis of the clustering of the $z \sim 2$ galaxies to a later work.
We can also compare our mean baryonic mass with the median stellar mass from population synthesis models found for LBGs at $z \sim 3$ by Shapley et al. (2001), $m_{\text{star}} = 1.2 \times 10^{10} h^{-2} M_\odot$; again, the two are in rough agreement.

There are few other examples of such rotation curves at redshifts of $z \gtrsim 1$. Lemoine-Busserolle et al. (2003) have recently reported a rotation curve of a gravitationally lensed galaxy at $z = 1.9$; the rotation curve looks much like those we present here, with $v \gtrsim 200$ km s$^{-1}$ at a radius of $\sim 1''$, although when the lensing correction is applied this radius corresponds to only $\sim 1$ kpc. Genzel et al. (2003) have used millimeter interferometry to observe rest-frame 335 $\mu$m continuum and CO (3–2) line emission from a massive submillimeter galaxy at $z = 2.8$; their data indicate a rotating disk with velocity $\gtrsim 420$ km s$^{-1}$ at $\sim 8$ kpc in radius. From observations of [O iii] at $z \sim 3.2$, Moorwood et al. (2003) present a rotation curve with a velocity of 108 km s$^{-1}$ at $\sim 12$ kpc. Also, in observations of [O iii] and H$\beta$ in 15 LBGs at $z \sim 3$, Pettini et al. (2001) see two spatially resolved and tilted emission lines, but the observed velocities reach only $\sim 50$ km s$^{-1}$. Simply counting the instances of rotation shows that the two samples are different at the 95% confidence level; the difference is actually more significant, because this test does not account for the larger rotational velocities at $z \sim 2$.

It is interesting that we see stronger evidence for rotation in a sample of similar size at $z \sim 2$, and we spend a moment speculating on the possible reasons for this. Poorer seeing during the $z \sim 3$ observations could perhaps account for the differences; this does not explain the larger values of the velocity dispersion $\sigma$ that we see at $z \sim 2$ (see § 4.2), however, as these should be unaffected even if the lines are spatially unresolved. It might then be that H$\alpha$ is a more sensitive probe of rotation and velocity dispersion than [O iii] because of higher surface brightness; but Pettini et al. (2001) typically measured [O iii] $\lambda$5007/H$\beta$ $\sim 3$, and H$\alpha$/H$\beta$ $\sim 3$ as well, so H$\alpha$ and [O iii] $\lambda$5007 should have roughly comparable strengths in the $z \sim 3$ galaxies. We also note that in rotation curves for which they had both H$\alpha$ and [O iii] $\lambda$5007 data, Vogt et al. (1996) found that the flux distributions and velocities of the two lines matched well. Lemoine-Busserolle et al. (2003) also have both H$\alpha$ and [O iii] $\lambda$5007 observations for their rotation curve, and again the two lines give comparable results. The differences could also be due to S/N effects; but the $z \sim 3$ galaxies were generally observed with longer integration times than those in the current sample, and their spectra have S/N comparable to or higher than that of those presented here. We should also discuss the possibility that we may be observing different populations of galaxies at $z \sim 2$ and 3. We therefore consider the evidence for other intrinsic differences between galaxies at the two redshifts. The most obvious of these is apparent UV luminosity; the galaxies of Pettini et al. (2001) are brighter than those presented here, with only a few exceptions. This is simply because the brightest galaxies were selected for IR observation at $z \sim 3$, but not at $z \sim 2$. As discussed in § 2, however, the $z \sim 2$ selection criteria were chosen so that the galaxies they select would have SEDs similar to those of galaxies at $z \sim 3$. If we are indeed looking at different sets of objects at $z \sim 2$ and $z \sim 3$, both the average and range of their far-UV properties must be similar (although we do sample the luminosity function more deeply at $z \sim 2$). It is also possible that we are observing the two samples to different radii: surface brightness is a strong function of redshift, scaling as $(1+z)^2$, and this may limit the radii to which we can observe the galaxies at higher redshift. Star formation progressing to larger radii in the disks at later times could produce a similar effect. It is also possible that our stronger evidence for rotation reflects an...
increase in the number of rotating galaxies and their rotational speeds between \( z \sim 3 \) and 2. With the present data such a conclusion would be premature, however, since we cannot rule out all observational effects.

It is interesting to consider objects such as these in the context of hierarchical models of galaxy formation. We compare our data with predictions of the properties of LBGs at \( z \sim 3 \) (Mo, Mao, & White 1998, 1999), although it is not yet clear how the current sample and the \( z \sim 3 \) galaxies are related. LBGs are thought to be the central galaxies of the most massive dark halos present at \( z \sim 3 \), and they are predicted to be small and to have moderately high halo circular velocities but low stellar velocity dispersions. For a \( \Lambda \)CDM cosmology, Mo et al. (1999) predict that the median effective radius \( R_{\text{eff}} \) (defined as the semimajor axis of the isophote containing half of the star formation activity) is about 2 \( h^{-1} \) kpc, and most galaxies should have \( R_{\text{eff}} \) between 0.8 and 5 \( h^{-1} \) kpc. While the maximum radial extent of some of our rotation curves is larger than this, it is likely that the galaxies are visible at radii beyond \( R_{\text{eff}} \), and these predictions are consistent with our measurements of half-light radii from the WFPC2 images. Mo et al. (1999) also predict a median halo circular velocity of 290 km s\(^{-1}\) for \( \Lambda \)CDM, with most galaxies falling between 220 and 400 km s\(^{-1}\) and a median stellar velocity dispersion of \( \sim 120 \) km s\(^{-1}\). Both of these predictions are reasonably consistent with our data, considering that we have not corrected our circular velocities for inclination or slit alignment effects and that our velocities are lower limits because of the lack of flattening in the rotation curves. In fact, as noted above, the \( z \sim 2 \) galaxies are a better match to these predictions than the \( z \sim 3 \) LBGs, which have observed rotational velocities of only \( \sim 50-100 \) km s\(^{-1}\) and velocity dispersions of \( \sim 70 \) km s\(^{-1}\).

Finally, additional observations will clarify the kinematics of the \( z \sim 2 \) sample. High-resolution imaging in both the optical and the IR will allow a determination of the morphologies of the galaxies and the extent of the rest-frame optical emission; spectroscopic observations with varying position angles will provide strong constraints on rotating disk models. We are also optimistic about the possibility of obtaining a larger sample of rotation curves, since those presented here represent almost 40% of the galaxies observed. Looking farther into the future, integral field IR spectrographs that provide kinematic information at high spatial resolution over a contiguous region encompassing the entire galaxy will be ideal for probing the dynamics of high-redshift galaxies; this may be the only way that the kinematic major axes of these objects can be determined.

4.2. Velocity Dispersions

We can obtain a limited amount of information about the dynamics and masses of the galaxies by simply measuring the widths of the emission lines. We have measured the one-dimensional velocity dispersion \( \sigma \) by fitting a Gaussian profile to each emission line, measuring its FWHM, and subtracting the instrumental broadening in quadrature from the FWHM. The instrumental broadening was measured from the widths of skylines and is \( \sim 15 \) A for NIRSPEC and \( \sim 6 \) A for ISAAC. The velocity dispersion is then the corrected FWHM divided by 2.355. We find a mean velocity dispersion of \( \langle \sigma \rangle \sim 110 \) km s\(^{-1}\), with a maximum of 260 km s\(^{-1}\). The dispersions for each galaxy are shown in Table 2, with 1\( \Delta \), uncertainties from propagating the errors in each Gaussian fit (to avoid confusion stemming from overuse of the symbol \( \sigma \), we use \( \Delta \), to represent the standard deviation in the velocity dispersion). Most of the lines are resolved; for those that are not we have set an upper limit of 2\( \Delta \). Our average velocity dispersion is \( \sim 60\% \) higher than that found from the widths of [O\( ii \)] \( \lambda 5007 \) and H\( \beta \) at \( z \sim 3 \) by Pettini et al. (2001), who found a median of \( \sim 70 \) km s\(^{-1}\).

Assuming that these velocities are due to motion of the gas in the gravitational potential of the galaxy, we can estimate the masses of the galaxies. For the simplified case of a uniform sphere,

\[
M_{\text{vir}} = 5\sigma^2 (r_{1/2}/G).
\]

From the \( \text{HST} \) image of the galaxies in the Q1623 field, we find \( r_{1/2} \approx 0''2 \), which in our adopted cosmology corresponds to \( \sim 1.6 \) kpc at \( z = 2.3 \). We use this value to calculate the masses shown in Table 2. Accounting for the lower limits on four of the objects by using ASURV (rev. 1.2; Lavalley, Isobe, & Feigelson 1992), a software package that calculates the statistical properties of samples containing limits or nondetections (survival analysis; Feigelson & Nelson 1985), we find a mean mass of \( \sim 2 \times 10^{10} M_{\odot} \); this is in general agreement with the rotationally derived masses in §4.1. As we noted when deriving masses from the rotation curves above, because the nebular emission comes mostly from the central star-forming regions of high surface brightness, the velocity dispersions probably do not reflect the full gravitational potential of the galaxies.

There are several issues to consider in the interpretation of these mass estimates. In addition to the obvious caveats related to the assumption of spherical geometry, the uncertain value of \( r_{1/2} \), and the sometimes large uncertainties in \( \sigma \), we should consider whether or not the line broadening is indeed gravitational in origin. Galaxy-scale, starburst-driven outflows with speeds of several hundred kilometers per second have been shown to be ubiquitous in star-forming galaxies at \( z \sim 3 \) (Pettini et al. 2001). These are measured from the offsets of Ly\( \alpha \) and the interstellar absorption lines with respect to the nebular emission lines taken to define the systemic velocity of the galaxy; Ly\( \alpha \) is consistently redshifted with respect to the systemic velocity, while the interstellar lines are blueshifted. We are unable to determine conclusively whether or not similar outflows exist in the present sample, since in many cases the S/Ns of our rest-frame UV spectra are too low to determine redshifts from Ly\( \alpha \) and interstellar absorption lines with the necessary precision. However, for those objects that have spectra of sufficient quality, we have measured the velocities of the interstellar absorption lines and Ly\( \alpha \) with respect to the H\( \alpha \) redshifts. The results are shown in Figure 6. We see that in this small sample, Ly\( \alpha \) is consistently redshifted by several hundred kilometers per second, but that the interstellar lines are both blueshifted and redshifted with respect to H\( \alpha \). This offers marginal support for the existence of outflows, but clearly a larger sample is necessary. Even if these outflows do exist, however, it is not clear that they would result in an increase in the velocity dispersion. Our velocity dispersions

\footnote{We also find a mean of \( \sim 70 \) km s\(^{-1}\) in the [O\( ii \)] \( \lambda 5007 \) velocity dispersions of a sample of 11 LBGs at \( z \sim 3 \), which we observed with NIRSPEC in 2001 April. These data are unpublished and will be described in detail in a later work.}
are from Hα emission, which we take to be coming primarily from nebular gas at the systemic redshift of the galaxy, not from outflowing material. In addition, a correlation between the velocity dispersion and the speed of the outflow (here defined as the average of \( v_{\text{Ly} \alpha} - v_{\text{neb}} \) and \( v_{\text{neb}} - v_{\text{sys}} \)) might be expected if the line broadening were due to outflowing gas. With this in mind, we have examined a sample of 23 galaxies at \( z \sim 3 \) for which we have both velocity dispersions from the width of the [O iii] \( \lambda 5007 \) emission-line and outflow velocities from the offsets between the nebular, interstellar absorption and Ly\( \alpha \) redshifts. We see no evidence for a strong link between the velocity dispersion and the speed of the outflow; the correlation coefficient between them is 0.13. These considerations lead us to believe that the presence of outflows is not a strong argument against gravitational broadening of the lines.

We are also struck by the spatial complexity of some of these objects. In particular, the Hα emission of Q1623-BX376 appears as two lines at the same redshift but separated by \( 2.5^{\prime} \). The brighter of these, Q1623-BX376a, has the largest velocity dispersion in the sample and shows an asymmetric line profile (see Fig. 2), with a blueshifted tail extending about \( 0.5^{\prime} \) in the opposite direction from the fainter component, Q1623-BX376b. It is primarily this tail that is responsible for the large velocity dispersion. This faint emission is also visible in the WFC2 image shown in Figure 3 (where, unfortunately, the galaxy falls on the border between two of the wide-field detectors). Given the complicated structure of this object, we hesitate to attribute its broad emission line purely to random gravitational motions; galactic mergers or interactions could also produce such broadened emission lines and disturbed morphologies.

As a final test, we compare the one-dimensional velocity dispersion with luminosity. We see from Figure 7 that neither the 1500 \( \AA \) continuum nor the Hα emission-line luminosity correlates with velocity dispersion, either with or without a correction for extinction. Such a lack of correlation is also seen for galaxies at \( z \sim 3 \) (Pettini et al. 2001). This does not necessarily mean that the line widths are unrelated to the masses of the galaxies; it may be that large variations in the mass-to-light ratio are blurring any trend. We conclude that while these caveats are important, none of them provide a compelling argument against using the velocity dispersions to estimate the masses of the galaxies; therefore, for the moment we will continue to do so.

5. STAR FORMATION RATES AND EXTINCTION

Hα emission is one of the primary diagnostics of the SFR in local galaxies, and therefore its observation at high redshift is particularly valuable for the sake of comparison with nearby samples. Redshifts of \( z \lesssim 2.6 \) are the highest at which Hα can currently be detected before it shifts out of the near-IR \( K \)-band window. Except for a few other observations of Hα at \( z > 2 \) (Teplitz et al. 1998; Kobulnicky & Koo 2000), most determinations of the SFR at high redshift have so far been based on the UV stellar continuum and, to a lesser extent, the Hβ emission line (Pettini et al. 2001). Here we compare SFRs for the 16 galaxies in our sample deduced from the Hα flux and from the UV continuum emission; as the two are affected differently by dust and star formation history, our results can in principle tell us about the extinction and stellar populations of the galaxies. We have calculated Hα SFRs following Kennicutt (1998):

\[
\text{SFR} (M_\odot \text{ yr}^{-1}) = 7.9 \times 10^{-42} L(\text{H}\alpha) \quad (\text{ergs s}^{-1}) \tag{5}
\]

The nebular recombination lines are a direct probe of the young, massive stellar population, since only the most massive and short-lived stars (\( M \gtrsim 100 M_\odot \)) contribute significantly to the ionizing flux. Thus, the emission lines provide a nearly instantaneous measure of the SFR, independent of the star formation history. The above equation assumes a Salpeter initial mass function (IMF) with upper and lower mass cutoffs of 0.1 and 100 \( M_\odot \), and case B recombination at \( T_e = 10,000 \text{ K} \). It also assumes that all of the ionizing photons are reprocessed into nebular lines, i.e., that they are not absorbed by dust before they can ionize an atom, and that they do not escape the galaxy.

UV-derived SFRs were calculated from the broadband photometry, using the \( G \) magnitude as an approximation for the 1500 \( \AA \) continuum (at \( z = 2.3 \), the mean redshift of our sample, the central wavelength of the \( G \) filter, 4830 \( \AA \), falls at a rest wavelength of 1464 \( \AA \)). SFRs were calculated as follows (Kennicutt 1998):

\[
\text{SFR} (M_\odot \text{ yr}^{-1}) = 1.4 \times 10^{-28} L_{1500} \quad (\text{ergs s}^{-1} \text{ Hz}^{-1}) \tag{6}
\]

This relationship applies to galaxies with continuous star formation over timescales of \( 10^8 \) yr or longer; for a younger population, the UV continuum luminosity is still increasing as the number of massive stars increases, and the above equation will underestimate the SFR. The assumed IMF is the same as above.

The fluxes and corresponding SFRs are summarized in Table 3, and a comparison of the uncorrected SFRs is shown in the left-hand panel of Figure 8. The error bars reflect the uncertainties in flux calibration of the Hα emission and the UV photometry, about 25% and 10%, respectively; for the Hα spectra this includes both random and systematic error, as discussed in § 2.3, and is likely an underestimate in the noisiest cases. Uncertainties in the conversion from flux to SFR are not included. There are four objects for which we are only able to place lower limits on the SFR from Hα: Q1623-BX428, in which the Hα line fell on top of a strong skyline to which we have lost significant flux, and SSA22a-MD41, Q0201-B13, and CDFb-BN88, which were observed during nonphotometric conditions.
and calibrated with the least extinguished exposure of a standard, in order to place lower limits). Without correcting for extinction, we find \( SFR_{H\alpha} > SFR_{UV} \) in all but five cases; four of these are the lower limits described above. We find \( \langle SFR_{H\alpha}/SFR_{UV} \rangle = 2.4 \); this was computed using ASURV, revision 1.2 (Lavalley et al. 1992; see § 4.2 for description). This result is in qualitative agreement with previous observations of galaxies at \( z \gtrsim 1 \): Yan et al. (1999) find that the global SFR derived from \( H\alpha \) exceeds that from the UV by a factor of \( \sim 3 \), and Hopkins et al. (2000) obtain a

![Fig. 7.—Velocity dispersion \( \sigma \) plotted against the 1500 Å continuum and \( H\alpha \) luminosities, without extinction corrections (a and b, respectively), and corrected as described in the text (c and d, respectively). Arrows indicate upper limits on \( \sigma \). See § 5 for a discussion of the errors in luminosity. [See the electronic edition of the Journal for a color version of this figure.]

![Fig. 8.—Left: SFRs from \( H\alpha \) and UV emission, uncorrected for extinction. Arrows indicate lower limits on the \( H\alpha \) SFR for objects observed during non-photometric conditions (SSA22-MD41, Q0201-B13, and CDFb-BN88) or contaminated by skylines (Q1623-BX428). Errors are 25% in \( SFR_{H\alpha} \) and 10% in \( SFR_{UV} \), reflecting uncertainties in flux calibration. Uncertainties in the conversion from flux to SFR are not included. Right: The SFRs corrected for extinction as described in § 5. The error bars reflect uncertainties in \( E(B-V) \) only; flux calibration errors and errors in conversion from flux to SFR are not included. The dotted lines represent equal rates from \( H\alpha \) and UV emission. [See the electronic edition of the Journal for a color version of this figure.]
measurement of SFR density from Hα at 0.7 ≤ z ≤ 1.8 that is a factor of 2–3 greater than that estimated from UV data. Glazebrook et al. (1999) study a sample of 13 galaxies at z ≈ 1 from the Canada-France Redshift Survey (CFRS); when the same Kennicutt (1998) calibrations are used, their data give an Hα SFR 1.9 times higher than the UV SFR, without applying an extinction correction (Yan et al. 1999). It is also comparable to the results of Bell & Kennicutt (2001), who find (SFR$_{H\alpha}$/SFR$_{UV}$) = 1.5 for galaxies with SFR ≥ 1 $M_\odot$ yr$^{-1}$ in a sample of 50 nearby star-forming galaxies. There is clearly a trend for the Hα-derived SFRs to be higher than those from the UV luminosity, in spite of differing selection criteria; both the Yan et al. (1999) and Hopkins et al. (2000) samples were selected in the IR, while ours is UV-selected, and the Bell & Kennicutt (2001) sample is drawn from local galaxies observed by the Ultraviolet Imaging Telescope (UIT). We discuss possible reasons for this trend below. We also note that the one remaining object with a larger UV SFR, Q1623-BX376, is a somewhat unusual case. It is bright and extended in the UV, and the Hα emission appears in two distinct lines at the same redshift but separated by 2.5. Since the UV photometry encompassed both components, we have added the flux from both lines to calculate the Hα SFR, but it is clear from the WFPC2 image of Q1623-BX376 (Fig. 3) that the fainter of the two components is largely off the edge of the slit; therefore, we have likely missed some of the Hα emission.

There are at least two possible explanations for the larger Hα SFRs: dust extinction and the two SFR indicators' differing sensitivities to the ages of stellar populations and star formation histories. Our observations are consistent with the assumption that the UV emission generally suffers greater extinction than the Hα, as would be the case if both pass through the same clouds of dust. However, in analogy to local starbursts, it may be the case that the UV and nebular line emission come from different regions in the galaxies and encounter different amounts of dust accordingly (Calzetti 1997). In particular, it has been suggested that the most massive stars are still embedded in the dust clouds in which they formed, leading to greater extinction of the nebular line emission. This may be the case with Q1623-BX376, which is bright in the rest-frame UV, with Lyα emission and strong interstellar absorption lines, but undistinguished when observed in the rest-frame optical.

We can estimate the UV extinction using the observed broadband colors and an assumed SED; we have calculated $E(B-V)$ in this way, using the $G-R$ colors and an SED corresponding to continuous star formation with an age of 320 Myr, the median age found for LBGs at z ≈ 3 by Shapley et al. (2001). Because extinction corrections are highly sensitive to errors in color measurements, we have made an effort to quantify the uncertainties and biases in our photometry. We added a large number of artificial galaxies of known colors and magnitudes to the actual images and then recovered them using the same photometric tools that we applied to the real data (see Adelberger 2002; Steidel et al. 2003). We then selected artificial galaxies whose recovered colors match our selection criteria and sorted them into bins by

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### Table 3

**Fluxes and Star Formation Rates**

| Galaxy         | $z_{H\alpha}^{a}$ | $\delta$ | $G-R$ | $F_{H\alpha}^{b}$ | $L_{H\alpha}^{c}$ | $E(B-V)^{d}$ | Uncorrected SFR$_{H\alpha}^{e}$ | Corrected SFR$_{H\alpha}^{f}$ | Uncorrected SFR$_{UV}^{g}$ | Corrected SFR$_{UV}^{h}$ | SFR$_{H\alpha}$/SFR$_{UV}^{i}$ |
|---------------|-----------------|---------|------|----------------|----------------|-----------|-------------------------------|-----------------------------|-----------------------------|-----------------------------|-------------------------------|
| CDFb-BN88 ...... | 2.2615          | 0.29    | 2.6  | 1.0            | 0.146          | >8        | >14                           | 26 ± 3                      | 106 ± 31                    | >0.3                        | >0.3                          |
| Q0201-B13 ...... | 2.1663          | 0.02    | 2.4  | 0.8            | 0.004          | >7        | >7                            | 26 ± 3                      | 27 ± 6                     | >0.3                        | >0.3                          |
| Westphal BX600 ...... | 2.1607          | 0.10    | 6.3  | 2.2            | 0.048          | 17 ± 4    | 21 ± 3                        | 14 ± 1                      | 22 ± 11                     | >1.2                        | >1.2                          |
| Q1623-BX376 ...... | 2.4085          | 0.24    | 5.3  | 2.4            | 0.111          | 19 ± 5    | 29 ± 3                        | 26 ± 3                      | 84 ± 27                     | >0.7                        | >0.7                          |
| Q1623-BX428 ...... | 2.0538          | 0.27    | 2.7  | 0.8            | 0.073          | >7        | >7                            | 26 ± 3                      | 27 ± 6                     | >0.3                        | >0.3                          |
| Q1623-BX432 ...... | 2.1817          | 0.10    | 5.4  | 1.9            | 0.048          | 15 ± 4    | 18 ± 4                        | 8 ± 1                       | 13 ± 5                     | >1.9                        | >1.9                          |
| Q1623-BX447 ...... | 2.1481          | 0.17    | 5.6  | 1.9            | 0.082          | 15 ± 4    | 21 ± 4                        | 8 ± 1                       | 18 ± 12                     | >1.9                        | >1.9                          |
| Q1623-BX449 ...... | 2.4188          | 0.26    | 1.8  | 0.8            | 0.094          | 6 ± 2     | 9 ± 2                         | 6 ± 1                       | 18 ± 13                     | >1.0                        | >1.0                          |
| Q1623-BX511 ...... | 2.2421          | 0.42    | 3.4  | 1.3            | 0.194          | 10 ± 3    | 22 ± 4                        | 3 ± 0.3                     | 22 ± 3                     | >3.3                        | >3.3                          |
| Q1623-BX522 ...... | 2.4757          | 0.31    | 2.8  | 1.3            | 0.0132         | 11 ± 3    | 18 ± 4                        | 8 ± 1                       | 35 ± 12                     | >1.4                        | >1.4                          |
| Q1623-MD107 ...... | 2.5373          | 0.12    | 3.7  | 1.9            | 0.043          | 15 ± 4    | 18 ± 4                        | 5 ± 1                       | 8 ± 9                      | >3.0                        | >3.0                          |
| Q1700-BX691 ...... | 2.1895          | 0.22    | 7.7  | 2.8            | 0.108          | 22 ± 6    | 33 ± 12                       | 4 ± 0.4                     | 10 ± 12                     | >5.5                        | >5.5                          |
| Q1700-BX717 ...... | 2.4353          | 0.20    | 3.8  | 1.8            | 0.087          | 14 ± 4    | 20 ± 3                        | 7 ± 1                       | 18 ± 15                     | >2.0                        | >2.0                          |
| Q1700-MD103 ...... | 2.3148          | 0.46    | 8.2  | 3.4            | 0.224          | 27 ± 7    | 64 ± 11                       | 8 ± 1                       | 88 ± 56                     | >3.4                        | >3.4                          |
| Q1700-MD109 ...... | 2.2942          | 0.26    | 2.8  | 1.1            | 0.124          | 9 ± 2     | 14 ± 3                        | 3 ± 0.3                     | 12 ± 14                     | >3.0                        | >3.0                          |
| SSA22a-MD41 ...... | 2.1713          | 0.19    | 7.9  | 2.8            | 0.097          | >22       | >32                           | 23 ± 2                      | 61 ± 26                     | >1.0                        | >1.0                          |
| Mean value...... | 2.2787          | 0.21    | 4.6  | 1.8            | 0.101          | 16       | 26                            | 12                         | 35                        | 2.4                         | 2.4                            |

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*a Vacuum heliocentric redshift of Hα emission line.

*b Line flux in units of 10$^{-17}$ erg s$^{-1}$ cm$^{-2}$.

*c Luminosity in units of 10$^{42}$ erg s$^{-1}$.

*d From G−R colors, corrected as described in § 5.

*e SFR from Hα luminosity, uncorrected for extinction.

*f SFR from Hα luminosity, corrected for extinction.

*g SFR from G magnitude, uncorrected for extinction.

*h SFR from G magnitude, corrected for extinction.

*i Ratio of uncorrected SFRs.

j For those quantities containing lower limits, statistics are computed using survival analysis, as discussed in § 5.

7 Yan et al. (1999) and Glazebrook et al. (1999) assume $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0.5$. Using this cosmology lowers our SFRs by 3%–10%; the ratios of the Hα and UV rates are, of course, unaffected.
color and $B$ magnitude. We used these to measure the mean and dispersion of $\Delta (G - B) = [(G - B)_{\text{meas}} - (G - B)_{\text{true}}]$, where the mean indicates systematic biases in the recovered colors and the dispersion reflects the characteristic measurement error, $\sigma (G - B)$. For the brightest galaxies in our sample ($B < 23.5$), both of these quantities are small: $\langle \Delta (G - B) \rangle \approx 0.03$ and $\sigma (G - B) \approx 0.05$. For those with $B > 25$, we find $\langle \Delta (G - B) \rangle \approx 0.04$ and $\sigma (G - B) \approx 0.14$. For each galaxy in our sample, we have used these statistics to correct the measured $G - B$ color for the bias, and the color error has been propagated to determine uncertainties in $E(B-V)$; these range from 0.03 for the brightest galaxies to 0.08 for the faintest.

After calculating $E(B-V)$ in this way, we used the Calzetti et al. (2000) extinction law to correct the $G$ magnitudes and then used these to recalculate the UV SFRs. For the sake of comparison, we have also corrected the H$\alpha$ fluxes, assuming the same values of $E(B-V)$; we found this to give better agreement between the corrected UV and H$\alpha$ SFRs than the Calzetti (1997) relation $E(B-V) = (0.44 \pm 0.03) \log (E_u(B-V))$ [where $E_u(B-V)$ is the color excess of the stellar continuum and $E_u(B-V)$ is that of the nebular emission lines]. There may be some justification for this: if indeed there are galactic-scale outflows in these galaxies, as in those at $z \sim 3$, then a screen of outflowing material may be obscuring all regions equally. Unfortunately, we have no way of independently measuring the nebular extinction with our current data, as we do not have $H$-band measurements of H$\beta$. It should also be noted that the uncertainties inherent in flux calibration are too large to allow a reliable measurement of the Balmer decrement even if we had been able to obtain H$\beta$ fluxes; for a Balmer decrement of 10%, expected for our mean $E(B-V) = 0.10$ mag, we would need to measure each line flux with an accuracy of 5% or less, far better than our current capabilities. The issue is further complicated by the fact that H$\alpha$ and H$\beta$ lie in different bands and cannot be observed simultaneously, so there may be a systematic offset between the flux calibrations of the two observations. It will therefore be difficult to test the Calzetti model directly.

A comparison of the extinction-corrected SFRs is shown in the right-hand panel of Figure 8. They are in better agreement than the uncorrected SFRs, with $(SFR_{H\alpha}/SFR_{UV}) = 1.2$ and a reduction in the scatter of 50% ($1 \sigma$; again accounting for the lower limits on four of the H$\alpha$ SFRs). As emphasized above, the extinction correction is highly sensitive to uncertainties in the $G - B$ colors; the errors bars reflect the errors in $E(B-V)$ determined above, propagated through to the SFRs. Not shown are uncertainties in the extinction law, flux calibrations, or conversion of flux to SFR, all of which are considerable. Given these sources of error and the uncertainty in the value of $E(B-V)$ that should be used for the nebular emission, the extinction-corrected SFRs should be taken with caution.

In Figure 9, we plot the ratio $SFR_{H\alpha}/SFR_{UV}$ against the rest-frame UV continuum luminosity; none of these quantities have been corrected for extinction. We include data from Pettini et al. (2001), who used H$\beta$ fluxes and the standard ratio H$\alpha$/H$\beta = 2.75$ (Osterbrock 1989) to calculate SFRs from recombination lines in galaxies at $z \sim 3$. We have also included unpublished data from our NIRSPEC run in 2001 April; these are LBGs at $z \sim 3$, and SFRs have been calculated in the same way as in Pettini et al. (2001). These data will be discussed in detail in a future paper. The dotted curves represent lines of constant nebular line SFR, and the number at the top of each curve is its SFR$_{H\alpha}$ in units of $M_\odot$ yr$^{-1}$. UV luminosity is computed from the $G$ magnitude for the $z \sim 2$ sample; the center of the $G$ filter corresponds to $\sim$1500 Å at $z = 2.3$. For the $z \sim 3$ sample, we use the $B$ magnitude, corresponding to $\sim$1700 Å at $z = 3$. SFRs for the Pettini et al. (2001) and 2001 April samples were calculated from H$\alpha$ emission, assuming H$\alpha$/H$\beta = 2.75$ and applying the Kennicutt (1998) conversion from H$\alpha$ to SFR. Errors are suppressed for clarity, but are $\sim$25% in SFR$_{H\alpha}$ and 10% in SFR$_{UV}$ and $G$, as discussed in the text. See Pettini et al. (2001) for discussion of errors in the SFRs from H$\beta$. [See the electronic version of the Journal for a color version of this figure.]

![Figure 9](image.png)
many objects with faint H\alpha emission would fall in the lower left-hand corner of the plot; this is apparent when we add the objects we failed to detect to the figure (shown as stars). We have plotted only those objects that were placed on the slit with another galaxy that was detected, so that we know our astrometry was correct. We have placed upper limits on their H\alpha SFRs by assigning a maximum SFR$_{\text{H}\alpha}$ corresponding to 1 \sigma less than the flux of our weakest detection, and we have calculated UV SFRs based on their photometry as with the rest of the sample. It is clear from this exercise that the absence of data points in the lower left is a selection effect; such galaxies would have undetectably small SFRs. The absence of data points in the upper right is more significant, as these objects would be easily detectable; from the curves of constant SFR$_{\text{net}}$, we see that any galaxies falling here would have extremely large SFRs. In spite of these cautions, we believe that this figure is consistent with a model in which reddening is the primary cause of the discrepancy between the two SFR indicators.

Changes in the SFR on short timescales could also be reflected in our differing SFRs, since H\alpha emission is a more instantaneous measure of the SFR than the UV emission. The nebular recombination lines are the reprocessed light of only the most massive ($M \gtrsim 10^5 M_\odot$) and short-lived stars, while the UV emission probes a wider mass range ($M \gtrsim 5 M_\odot$). Therefore, a starburst that has begun in the past $\sim 10^8$ yr will not yet have reached full UV luminosity and will have an underestimated UV SFR, whereas a decline in star formation will cause an immediate decrease in H\alpha emission as the most massive stars die off. In a large sample of galaxies with redshifts $0 < z < 0.4$, Sullivan et al. (2000) find that the UV flux indicates a consistently higher SFR than the H\alpha and that the discrepancy is best explained by short bursts of star formation superimposed on a smooth star formation history. Such a model could also explain the larger UV SFR of a galaxy such as Q1623-BX376; however, this relationship between the UV and H\alpha SFRs is strongest at the fainter end of the Sullivan et al. (2000) sample, whereas Q1623-BX376 would fall at the bright end. As noted above, there were several galaxies that we observed but failed to detect. This could be explained by a decline in the SFR, but because of the difficulties presented by the sky background in the IR, the marginal quality of some of our optical redshifts, and the possibility of errors in astrometry or the guiding and tracking of the instrument and telescope, these objects have not been included in the statistical comparison of SFRs.

In the following paragraphs we explain why we believe that a young stellar population is not the primary cause of the discrepancy between the SFRs. As we have no information on the ages of the stellar populations of the galaxies in our sample, we assume that they are similar to those of LBGs at $z \sim 3$, although as we have pointed out above, the samples at $z \sim 2$ and 3 have different kinematic properties, and the $z \sim 3$ sample tends to cover brighter UV luminosities. The stellar populations of LBGs at $z \sim 3$ are now well studied (Shapley et al. 2001; Papovich et al. 2001), and the Papovich et al. (2001) sample includes some galaxies in the range $z = 2-2.5$. Population synthesis models for a sample of 81 LBGs by Shapley et al. (2001) give a median age since the onset of the most recent episode of star formation of $t_d \sim 320$ Myr, with more than 40% having $t_d > 500$ Myr and 25% having $t_d < 40$ Myr. We might then expect $\sim 25\%$ of our sample to have an underestimated UV SFR; however, the youngest galaxies in the Shapley et al. (2001) sample are also the most extinguished and have the highest SFRs. Among those with $t_d < 100$ Myr, the mean $E(B-V)$ is 0.27, higher than that of any of the objects in our sample and 3 \sigma higher than our sample mean of 0.10. The mean SFR among the same subset is 261 $M_\odot$ yr$^{-1}$, far higher than that of any of the objects in our sample even after correcting for extinction. Assuming that star-forming galaxies at $z \sim 2$ are similar to those at $z \sim 3$, it is therefore unlikely that the stellar populations of our sample are young enough to account for the difference in SFRs.

Papovich et al. (2001) fit a set of detailed models to 33 LBGs in the Hubble Deep Field–North, finding that the age distribution is strongly dependent on metallicity, IMF, the choice of extinction law, and the assumed star formation history. It is possible to vary these parameters to make the ages young enough to lead to an underestimate of the UV SFR; the youngest ages, $(t) \approx 40$ Myr, are given by a Scalo IMF with 0.2 $Z_\odot$. Although this may be a reasonable estimate for the metallicity of these objects—Pettini et al. (2001) find 0.1–0.5 $Z_\odot$ for galaxies at $z \sim 3$—the theoretical stellar atmospheres used in the population synthesis models are not well tested for low metallicities, and the results should therefore be treated with caution. More generally, even ages as young as these cannot fully explain the discrepancy between the SFRs. The mean factor of 2.4 difference between the H\alpha and UV rates would require the average UV luminosity to have reached only $\sim 40\%$ of its full value, which occurs less than 5 Myr after the beginning of a burst of continuous star formation. Such an extremely young age is unphysical; the time required for a burst of star formation to propagate across a galaxy is approximately the dynamical timescale, and $t_{\text{dyn}} \approx 30$ Myr for galaxies of the masses and sizes found in $z = 4$. We can state the timescale argument in another way as well: the average stellar mass of our galaxies, $\langle M \rangle \sim 4 \times 10^{10}$ $M_\odot$, combined with an assumed age of 2 Gyr, gives a characteristic $M \sim 20$ $M_\odot$ yr$^{-1}$, about the same as our mean H\alpha SFR of 16 $M_\odot$ yr$^{-1}$. This implies that the current SFRs of the galaxies are similar to their past averages over the last 2 Gyr and that a current burst is unlikely. Assuming an age younger than 2 Gyr, a mass larger than our lower limit of $4 \times 10^{10}$ $M_\odot$, or significant gas recycling results in a current SFR less than the past average, excluding a current burst even further.

The effects of dust and star formation history are indistinguishable in individual cases; in the sample taken as a whole, the systematic depression of SFR$_{\text{UV}}$ relative to SFR$_{\text{H}\alpha}$ suggests that extinction is the dominant effect, since variations in star formation history would induce scatter in the plots rather than systematic effects. Our knowledge of star formation and extinction at high redshift generally supports this conclusion. A moderate amount of extinction is indicated by our data, with a mean $E(B-V)$ of 0.10 (corresponding to $A_{1500} \sim 1$ mag and attenuation by a factor of $\sim 2.5$, using the Calzetti et al. 2000 extinction law); in studies of LBGs at $z \sim 3$, Shapley et al. (2001) find a median dust attenuation factor of $\sim 4.5$ at $\sim 1500$ Å, while Papovich et al. (2001) find a factor of 3.0–4.4, depending on metallicity. Our results also provide some support for previous estimates of UV extinction at high redshift: if the H\alpha extinction is assumed to be about the same as it is in local galaxies, a typical factor of 2, and if we assume that the factor of $\sim 2.4$ reduction in SFR$_{\text{UV}}$ relative to SFR$_{\text{H}\alpha}$ is due to extinction, then we obtain a UV extinction factor of $\sim 5$, the same as that applied to the UV luminosity density at $z \sim 3$ by Steidel
et al. (1999). We also note that this is in general agreement with the average UV attenuation factor of 5–6 obtained from studies of the X-ray luminosity of LBGs at $z \sim 3$ (Nandra et al. 2002). In summary, while we cannot rule out the effects of star formation history entirely, our results are consistent with other estimates of extinction in galaxies at high redshift, and such extinction naturally explains the differences we see in the H$\alpha$- and UV-derived SFRs.

6. SUMMARY AND CONCLUSIONS

We have presented H$\alpha$ spectroscopy of 16 galaxies in the redshift range $2.0 < z < 2.6$; this is so far the largest sample of near-IR spectra of galaxies at these redshifts. The galaxies were selected based on their broadband rest-frame UV colors, using an adaptation of the technique used to select Lyman break galaxies at $z \sim 3$. Those observed here are drawn from a large sample of such galaxies, with redshifts already confirmed; because proximity to a QSO sight line was the primary selection criterion for near-IR observation, we believe the 16 galaxies presented here to be representative of the sample as a whole. We have analyzed the spectra in order to determine the kinematic and star-forming properties of the galaxies, and we reach the following conclusions.

1. Six of the 16 galaxies show spatially extended, tilted H$\alpha$ emission lines, such as would be produced by ordered rotation. Rotation curves for these galaxies show a mean velocity of $\sim 150$ km s$^{-1}$ at a mean radius of $\sim 6$ kpc; these are lower limits obtained by taking half of the total range in both velocity and distance. Measuring from the spatial location of the continuum and the dynamical center of the lines, we obtain a maximum velocity of $\sim 240$ km s$^{-1}$ and a maximum radius of 10 kpc in the most extreme cases. We have obtained archival HST images for two of these galaxies, and they appear to be morphologically irregular, as do all of the other galaxies in our sample for which we have such images. Because of their chaotic morphologies, we have not attempted to model any corrections to the rotation curves. We have used the lower limits on the rotational velocity and radius of each galaxy to derive a dynamical mass; we obtain a mean of $\langle M \rangle \geq 4 \times 10^{10} M_\odot$. Because H$\alpha$ emission probes only the central star-forming regions of the galaxies, we expect their total halo masses to be several times larger. These results are in general agreement with the predictions of models of hierarchical galaxy formation for LBGs at $z \sim 3$.

2. Values of the one-dimensional velocity dispersion $\sigma$ range from 50 to 260 km s$^{-1}$, with a mean of $\sim 110$ km s$^{-1}$. Assuming that the line widths are due to gravitational motions in the potentials of the galaxies, the mean virial mass implied is $2 \times 10^{10} M_\odot$; this is in general agreement with the masses we obtain from the rotation curves. We consider other possible origins for the broadening of the lines, including large-scale outflows, mergers, and interactions.

3. Both the rotational velocity $v_c$ and the velocity dispersion $\sigma$ tend to be larger at $z \sim 2$ than at $z \sim 3$. We see evidence of rotation in $\sim 40\%$ of our sample, whereas Pettini et al. (2001) found such evidence in only $\sim 10\%$ of a sample of similar size at $z \sim 3$. Furthermore, we find rotational velocities of $\sim 150$ km s$^{-1}$, as compared to $\sim 50$ km s$^{-1}$ at $z \sim 3$. Our mean value of $\sigma$, $\sim 110$ km s$^{-1}$, is $\sim 60\%$ larger than the value found at $z \sim 3$ by Pettini et al. (2001). We have considered possible selection effects that may explain these systematic differences, but have not found a convincing explanation. It may be that the redshift dependence of surface brightness allows us to sample to larger radii at $z \sim 2$, or that our photometric selection criteria pick out different populations of galaxies at $z \sim 2$ and $z \sim 3$. It is also possible that the effect is real and reflects the growth of disks between these two epochs.

4. We use the H$\alpha$ luminosity to calculate the star formation rates of the galaxies, and compare these to the SFRs derived from the rest-frame UV continuum luminosity. We use the calibrations of Kennicutt (1998) in both cases. We obtain a mean SFR$_{H\alpha}$ of $16 M_\odot$ yr$^{-1}$ and a mean SFR$_{H\alpha}$/SFR$_{UV}$ ratio of 2.4. After correcting both luminosities for extinction using the Calzetti et al. (2000) extinction law, we find SFR$_{H\alpha}$/SFR$_{UV} = 1.2$, with a 50% reduction in scatter. We discuss the effects of extinction and star formation history on the SFRs and conclude that extinction is the more likely explanation for their discrepancy. We also see a moderate correlation between the ratio SFR$_{H\alpha}$/SFR$_{UV}$ and the UV luminosities of the galaxies, such that UV-faint galaxies have a higher SFR$_{H\alpha}$/SFR$_{UV}$. Such an effect could be produced if the fainter galaxies undergo more extinction.

5. Finally, we expect that many of the points discussed here will become clearer as the sample of near-IR observations of galaxies at these redshifts grows. The photometric technique for selecting galaxies at $z \sim 2$ has so far produced hundreds of galaxies with confirmed redshifts in this range, and further observations of their kinematics, line fluxes, and morphologies will shed light on star formation, extinction, and the formation of disks at high redshift.

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REFERENCES

Adelberger, K. L. 2002, Ph.D. thesis, California Institute of Technology
Adelberger, K. L., & Steidel, C. C. 2000, ApJ, 544, 218
Adelberger, K. L., Steidel, C. C., Giavalisco, M., Dickinson, M., Pettini, M., & Kellogg, M. 1998, ApJ, 505, 18
Adelberger, K. L., Steidel, C. C., Shapley, A. E., & Pettini, M. 2003, ApJ, 584, 45
Baugh, C. M., Cole, S., Frenk, C. S., & Lacey, C. G. 1998, ApJ, 498, 504
Bell, E. F., & Kennicutt, R. C., Jr. 2001, ApJ, 548, 681
Blain, A. W., Smail, I., Ivison, R. J., & Neri, J.-P. 1999, MNRAS, 302, 632
Buat, V., Boselli, A., Gavazzi, G., & Bonfanti, C. 2002, A&A, 383, 801
Calzetti, D. 1997, AJ, 113, 162
Calzetti, D., Armus, L., Bohlin, R. C., Kinney, A. L., Koornneef, J., & Storchi-Bergmann, T. 2000, ApJ, 533, 682
