Recent photometric studies have shown that early-type galaxies at fixed stellar mass were smaller and denser at earlier times. In this Letter, we assess that finding by deriving the dynamical mass of such a compact quiescent galaxy at z = 1.8. We have obtained a high-quality spectrum with full UV–NIR wavelength coverage of galaxy NMBS-C7447 using X-Shooter on the Very Large Telescope. We determined a velocity dispersion of 294 ± 51 km s$^{-1}$. Given this velocity dispersion and the effective radius of 1.64 ± 0.15 kpc (as determined from Hubble Space Telescope Wide Field Camera 3 F160W observations) we derive a dynamical mass of (1.7 ± 0.5) $\times 10^{11}$ M$_{\odot}$. Comparison of the full spectrum with stellar population synthesis models indicates that NMBS-C774 has a relatively young stellar population (0.40 Gyr) with little or no star formation and a stellar mass of $M_{*} \sim 1.5 \times 10^{11} M_{\odot}$. The dynamical and photometric stellar masses are in good agreement. Thus, our study supports the conclusion that the mass densities of quiescent galaxies were indeed higher at earlier times, and this earlier result is not caused by systematic measurement errors. By combining available spectroscopic measurements at different redshifts, we find that the velocity dispersion at fixed dynamical mass was a factor of $\sim 1.8$ higher at $z = 1.8$ compared with $z = 0$. Finally, we show that the apparent discrepancies between the few available velocity dispersion measurements at $z > 1.5$ are consistent with the intrinsic scatter of the mass–size relation.

**Key words:** galaxies: evolution – galaxies: formation – galaxies: structure
ACDM cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$. All broad-band data are given in the AB-based photometric system.

2. OBSERVATIONS AND REDUCTION

The target is selected from the NEWFIRM Medium-Band Survey (NMBS; van Dokkum et al. 2009b; Whitaker et al. 2011). This target, NMBS-C7447 ($\alpha = 15^h00^m06^s955$, $\delta = 02^d17^m33^s603$), was selected as it is among the brightest ($K_{\text{tot}} = 19.64$), quiescent galaxies in the COSMOS field. As the galaxy was selected for its apparent magnitude, it is probably younger than the typical quiescent galaxy at its redshift ($\pm 0.03$ Gyrs, an age of $0.40$ Gyrs, SFR of 0.002 $M_\odot$ yr$^{-1}$), $A_V = 0.20$, solar metallicity, and a redshift of 1.800 (see Figure 1). In order to account for systematic uncertainties (e.g., Conroy et al. 2009), we will assume an error of $\sim 0.2$ dex in $M_*$.

The galaxy is not detected at 24 $\mu$m, leading to a $3\sigma$ ($\sim 20 \mu$Jy) upper limit to the dust-enshrouded SFR of $<15 M_\odot$ yr$^{-1}$.

3.2. Size Measurement

We obtained HST-WFC3 F160W imaging of NMBS-C7447 in 2010 October (HST-GO-12167.1, see Figure 2) to measure its size by fitting a Sérsic radial surface brightness profile (Sérsic 1968), using the two-dimensional fitting program GALFIT (version 3.0.2; Peng et al. 2010). The blue object to the north was masked in the fit, as it is unclear whether it is part of the galaxy. All parameters, including the sky, were left free for GALFIT to determine, and three nearby field stars were used for the point-spread function (PSF) convolution.

In WFC3 F160W we find a mean circularized effective radius of $1.64 \pm 0.15$ kpc, a mean Sérsic $n$-parameter of 5.3 $\pm$ 0.4, and an axis ratio $b/a = 0.71 \pm 0.01$. The uncertainties reflect both sky noise and PSF uncertainties, which were simulated using different field stars. We find the same effective radius if we use the residual-corrected method as described by Szomoru et al. (2010). We also analyzed an ACS $I$-band image from the COSMOS survey (Scoville et al. 2007; Koekemoer et al. 2007). The target has an effective radius of $r_e = 1.95 \pm 0.20$ kpc with $n = 5.6 \pm 0.4$, using the same PSF stars as for WFC3.

An arclike feature is present in the residual image, to the southeast of the object (within 1.5$^\prime$, and $\sim 3$ mag fainter than the main target). This may indicate that the galaxy is undergoing a tidal interaction (see also van Dokkum & Brammer 2010).

In what follows, we will use the mean effective radius obtained with WFC3 F160W($H$), as this band coincides with rest-frame optical for our $z \sim 1.8$ galaxy.

3.3. Velocity Dispersion

We use our high-resolution spectrum, and the Penalized Pixel-Fitting method (pPXF) developed by Cappellari & Emsellem (2004) to measure an accurate stellar velocity dispersion for NMBS-C7447. Four different templates were used: the best-fit BC03 SPS model ($\sigma = 85$ km s$^{-1}$), Munari synthetic stellar library (Munari et al. 2005, $\sigma = 6.4$ km s$^{-1}$), Indo–US Library (Valdes et al. 2004, $\sigma = 38.2$ km s$^{-1}$), and the Miles library (Sánchez-Blázquez et al. 2006, $\sigma = 71.9$ km s$^{-1}$). Except for the best-fit SPS model, pPXF was used to construct an optimal template in combination with a 30th-order Legendre Polynomial. The fit was restricted to 4020 Å < $\lambda$ < 6400 Å, in order to exclude the Balmer break region and the noisier $K$ band. Figure 1 (bottom panels) shows the high-resolution spectrum with the best-fit velocity dispersion model from pPXF in red using the best-fit SPS model.

After correcting for instrumental resolution ($\sigma = 23$ km s$^{-1}$) and the spectral resolution of the templates, we find a best-fitting velocity dispersion of $\sigma_{\text{obs}} = 284 \pm 51$ km s$^{-1}$. The error was determined in the following way. We subtracted the best-fit template from the spectrum. This residual was randomly rearranged in wavelength space and added to best-fit template. We determined the velocity dispersion of 1000 simulated spectra. Our quoted error is the standard deviation of the resulting distribution of $\sigma$. When we include the Balmer
Figure 1. X-Shooter spectrum of NMBS-C7447 and the best-fit stellar population model (red line). Top panel: broad- and medium-band data (blue diamonds) in combination with low-resolution spectrum (10 Å bin$^{-1}$). The entire wavelength range from UV (0.35 μm) to NIR (2.3 μm) is covered in 2 hr integration time with unprecedented quality. The galaxy is best fit with a young stellar population ($0.40 \text{ Gyr}$, $\tau = 0.03 \text{ Gyr}$) with little star formation ($0.002 M_\odot \text{ yr}^{-1}$) and a stellar mass of $M_\star \sim 1.5 \times 10^{11} M_\odot$. Middle panel: zoom in on the rest-frame optical part of the spectrum. Gray areas indicate regions of strong skylines or atmospheric absorption. Most prominent stellar absorption features are indicated with blue dashed line. Bottom two panels: high-resolution spectrum (0.5 Å bin) of the observed features used to determine the stellar velocity dispersion. The green line is the best fit for the velocity dispersion with $4020 \ang < \lambda_{\text{rest-frame}} < 6400 \ang$ using the pPFX code (Cappellari & Emsellem 2004). The resulting stellar velocity dispersion is $\sigma_* = 294 \pm 51 \text{ km s}^{-1}$. The residual from the best fit divided by the noise is shown in the bottom panel.
break region in the fit, the formal error decreases, but the derived dispersion becomes very dependent on the chosen stellar template. Fitting the full-wavelength range gives a consistent result of $\sigma_e = 328 \pm 35$ km s$^{-1}$, but we prefer to use the method above as it is the most robust.

The stellar velocity dispersion is corrected to match the average dispersion as would be observed within an aperture radius of $r_e$. Our approach is similar to Cappellari et al. (2006), but taken into account the effects of a non-circular aperture, seeing, and optimized extraction. The aperture correction is only 3.5%, resulting in a velocity dispersion of $\sigma_e = 294 \pm 51$ km s$^{-1}$ (see J. van de Sande et al. 2011, in preparation).

The dynamical mass is derived using

$$M_{\text{dyn}} = \frac{\beta(n) \sigma_e^2 r_e}{G},$$

where $\beta(n)$ is an analytic expression as a function of the Sérsic index, as described by Cappellari et al. (2006). Using $n = 5.27$, we find $\beta = 5.16$, and a dynamical mass for NMBS-C7447 of $1.7 \pm 0.5 \times 10^{11} M_\odot$.

4. EVOLUTION

In this section, we compare our results to low- and high-redshift measurements, and discuss the implications for the evolution of quiescent galaxies. Figure 3 shows our results, together with other kinematical studies at $z > 1$, and galaxies from the Sloan Digital Sky Survey (SDSS) at $0.05 < z < 0.07$ (York et al. 2000). The SDSS structural parameters are from Franx et al. (2008), though we only select non-star-forming galaxies (i.e., specific SFR < 0.3/Myr; see Williams et al. 2009). For all galaxies, velocity dispersions were corrected as described in Section 3.3, and stellar masses were converted to a Chabrier (2003) IMF. All dynamical masses were derived using Equation (1).

Many high-redshift studies rely on photometric stellar masses, which suffer from large uncertainties (e.g., Conroy et al. 2009). Here, we test these stellar masses by comparing them to our dynamical measurements (Figure 3(a)). The dynamical and stellar mass for NMBS-C7447 are in agreement, and consistent with the relation for low-redshift galaxies. Given this good agreement, we should be able to predict the velocity dispersion from the size and stellar mass measurements.

We assume a constant ratio of $M_{\text{dyn}}/M_\ast = 1.68$, which is the average ratio for the SDSS sample, to account for dark matter and systematic uncertainties in the stellar mass estimate. We show the results in Figure 3(b). The predicted velocity dispersions of NMBS-C7447 and the other $z > 1.5$ galaxies are consistent with the observed velocity dispersions. This illustrates the robustness of our size and mass measurements.

In Figure 3(c), we show the velocity dispersion versus the effective radius. Similar to what has been found for other high-redshift studies, NMBS-C7447 has a clear offset from the low-redshift galaxy population. Its velocity dispersion is higher compared with $z \sim 0.06$ galaxies with similar radii. The mass–size relation is shown in Figures 3(d) and (e). The effective radius of our galaxy is smaller compared with local galaxies at similar masses, confirming other studies at high redshift. From Figure 3(f), where we show the dynamical mass versus the observed velocity dispersion, we find that NMBS-C7447 has a higher velocity dispersion than similar-mass SDSS galaxies, in agreement with other studies of high-redshift compact galaxies.

We parameterize the mass–size relation by (Shen et al. 2003; van der Wel et al. 2008)

$$r_e = r_e^0 \left( \frac{M_{\text{dyn}}}{10^{11} M_\odot} \right)^{b}.$$

Using a least-squares fit to the low-redshift galaxy sample, we find $r_e^0 = 3.32$ kpc and $b = 0.50$. When comparing NMBS-C7447 to local galaxies at fixed dynamical mass, we find that the effective radius is a factor $\sim 2.5$ smaller. We use a similar approach for the velocity dispersion as a function of dynamical mass (Figure 3(f)):

$$\sigma_\ast = \sigma_e \left( \frac{M_{\text{dyn}}}{10^{11} M_\odot} \right)^{b},$$

with $\sigma_e = 145$ km s$^{-1}$ and $b = 0.26$. NMBS-C7447 has a higher velocity dispersion by a factor $\sim 1.8$ compared to the low-redshift relation.

Figure 4 shows the evolution of the sizes and velocity dispersions of the galaxies, normalized to a standard dynamical mass using Equations (2) and (3). We add the sample by van der Wel et al. (2008) for a more complete redshift coverage, with stellar masses derived from the FIRES (Förster Schreiber et al. 2006) and FIREWORKS catalog (Wuyts et al. 2008). We use a simple power-law fit $r_e \propto (1 + z)^{\alpha}$ for galaxies with $M_{\text{dyn}} > 3 \times 10^{10} M_\odot$ and find $\alpha = -0.98 \pm 0.09$. This is in
agreement with van der Wel et al. (2008), but slightly higher than Newman et al. (2010). Our results imply a growth in size at fixed mass by a factor of \(\sim 2.5\) from \(z \sim 1.8\) to the present day. When assuming a similar power law for the velocity dispersion \((\sigma_\star \propto (1 + z)^{0.51 \pm 0.07})\), we find a decrease in velocity dispersion by a factor of \(\sim 1.5\) from \(z \sim 1.8\) to the present day at fixed mass.

Figures 4(a) and (b) show that the scatter in the relation in the normalized size and velocity dispersion is large at fixed redshift. At \(z > 1.5\), three galaxies have been observed with a range in normalized dispersions of a factor of \(\sim 2.5\). This may lead to the conclusion that the measurements have large unidentified errors and cannot be trusted yet. On the other hand, intrinsic scatter in the galaxy properties may cause this rather large observed scatter. We can test this directly by using the deviations of the galaxies in the mass–size relation.

If the scatter is due to variations in the intrinsic properties, we expect that the deviations of the galaxies in the
We only select galaxies with $M_{\text{obs}} > 3 \times 10^{10} M_\odot$. Symbols are as described in Figure 3, with the addition of data from van der Wel et al. 2008 (purple circles). The gray filled circle at $z \sim 0.06$ shows the median from the SDSS, with the error indicating the 1σ and 2σ scatter. The solid lines show a simple best fit to the data of $(1 + z)^{-0.98 \pm 0.09}$ for the evolution in effective radius, and $(1 + z)^{0.51 \pm 0.07}$ for the velocity dispersion. (c) Scatter in the $M_{\text{dyn}}-r_e$ relation vs. the scatter in the $M_{\text{dyn}}-\sigma_{\text{obs}}$ relations, together with the 1σ and 2σ contours of the SDSS galaxies, all corrected for evolution. The discrepancy between the different measurements is expected based on the intrinsic scatter in the low-redshift relations.

mass–size relation correlate with the deviations of the galaxies in the mass–dispersion relation. If the scatter is observational, there is no expected correlation. In Figure 4(c), we compare the deviation from the $M_{\text{dyn}}-r_e$ relation to the deviations in the $M_{\text{dyn}}-\sigma_{\text{obs}}$ relation. The deviation of the $M_{\text{dyn}}-r_e$ and $M_{\text{dyn}}-\sigma_{\text{obs}}$ relations were derived using the evolution of these relations at fixed mass as shown in Figures 4(a) and (b).

We can predict, using the virial theorem, how the points would lie if the scatter is intrinsic, i.e., due to variations in the galaxy structure. This line is shown in Figure 4(c), and we see that the galaxies lie very close to this line. In addition, we show the area which is covered by the SDSS galaxies in the same diagram (1σ and 2σ contours). Almost all data points lie within these contours. Hence we conclude that the scatter is mostly intrinsic, and not observational. A direct measure of the average offset of the sizes and dispersions can be obtained by increasing the number of observed galaxies to about 30, which would reduce the error by a factor of $\sim 3$. Alternatively, the average mass–size relation can be used to determine the average offset at $z = 1.5–2$. Thus, we conclude that the difference between our results and those by van Dokkum et al. (2009a) and Onodera et al. (2010) are due to intrinsic scatter in galaxy properties.

5. CONCLUSIONS

In this Letter, we have presented the first high-S/N, high-resolution spectrum of a compact massive quiescent galaxy at $z = 1.80$ observed with X-Shooter. Using this spectrum we have determined the stellar mass and velocity dispersion: $M_* \sim 1.5 \times 10^{11} M_\odot$, $\sigma_{\text{obs}} = 294 \pm 51$ km s$^{-1}$. From HST-WFC3 imaging we find that $r_e = 1.64 \pm 0.15$ kpc. The stellar mass and dynamical mass agree well ($M_{\text{dyn}} = (1.7 \pm 0.5) \times 10^{11} M_\odot$) and are consistent with the local SDSS relation. Our results suggest that stellar masses at high redshift are robust, and thus supports the claim that massive, quiescent galaxies with high stellar mass densities at $z \sim 2$ exist.

When comparing this galaxy to low-redshift early-type galaxies, we find that it is structurally different. At fixed dynamical mass, NMBS-C7447 is smaller by a factor $\sim 2.5$, and has a higher velocity dispersion by a factor of $\sim 1.8$.

Despite the high accuracy of our derived stellar parameters, our study is still limited to a single high-redshift galaxy, and it brings the total number of stellar kinematic measurements for individual galaxies at $z > 1.5$ to three. We have shown that the differences between the three measurements can be explained by the scatter in the mass–size relation. A larger sample of compact massive quiescent galaxies at high redshift is needed to accurately measure the structural evolution of these galaxies with cosmic time.

We thank the anonymous referee for his comments, Johan Fynbo and Joanna Holt on the reduction of the UVB and VIS X-Shooter data, and the NMBS team for their contribution. This research was supported by grants from the Netherlands Foundation for Research (NWO), the Leids Kerkhoven-Bosscha Fonds. Support for program HST-GO-12167.1 was provided by NASA through a grant from the Space Telescope Science Institute.

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Figure 4. Evolution in effective radius and velocity dispersion at fixed dynamical mass, thus corrected for the $M_{\text{dyn}}-r_e$ and $M_{\text{dyn}}-\sigma_{\text{obs}}$ relations from Figures 3(e) and (f). The only select galaxies with $M_{\text{obs}} > 3 \times 10^{10} M_\odot$. Symbols are as described in Figure 3, with the addition of data from van der Wel et al. 2008 (purple circles). The gray filled circle at $z \sim 0.06$ shows the median from the SDSS, with the error indicating the 1σ and 2σ scatter. The solid lines show a simple best fit to the data of $(1 + z)^{-0.98 \pm 0.09}$ for the evolution in effective radius, and $(1 + z)^{0.51 \pm 0.07}$ for the velocity dispersion. (c) Scatter in the $M_{\text{dyn}}-r_e$ relation vs. the scatter in the $M_{\text{dyn}}-\sigma_{\text{obs}}$ relations, together with the 1σ and 2σ contours of the SDSS galaxies, all corrected for evolution. The discrepancy between the different measurements is expected based on the intrinsic scatter in the low-redshift relations.