THE AGE–REDSHIFT RELATION FOR LUMINOUS RED GALAXIES OBTAINED FROM FULL SPECTRUM FITTING AND ITS COSMOLOGICAL IMPLICATIONS

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ABSTRACT

The relative age of galaxies at different redshifts can be used to infer the Hubble parameter and put constraints on cosmological models. We select luminous red galaxies (LRGs) from the Sloan Digital Sky Survey Data Release 7 and then cross match it with the MPA/JHU catalog of galaxies to obtain a large sample of quiescent LRGs at redshift $z \sim 0.03$–0.39. The total number of quiescent LRGs, 23,883, is divided into four sub-samples according to their velocity dispersions and each sub-sample is further divided into 12 redshift bins. The spectra of the LRGs in each redshift and velocity bin are co-added in order to obtain a combined spectrum with a relatively high signal-to-noise ratio. Adopting the GalaxEV/SteLib model, we estimate the mean ages of the LRGs from these combined spectra by using the full-spectrum fitting method. We check the reliability of the estimated age by using Monte Carlo simulations and find that the estimates are robust and reliable. Assuming that the LRGs in each sub-sample and each redshift bin were on average formed at the same time, the Hubble parameter at the present time $H_0$ is estimated from the age–redshift relation obtained for each sub-sample, which is compatible with the $H_0$ value measured by other methods. We demonstrate that a systematic bias (up to $\sim 20\%$) may be introduced to the $H_0$ estimation because of recent star formation in the LRGs due to the later major mergers at $z \lesssim 0.4$, but this bias may be negligible for those sub-samples with large velocity dispersions. Using the age–redshift relations obtained from the sub-sample with the largest velocity dispersion or the two sub-samples with high velocity dispersions, we find $H_0 = 65^{+7}_{-3}$ km s$^{-1}$ Mpc$^{-1}$ or $H_0 = 74^{+5}_{-1}$ km s$^{-1}$ Mpc$^{-1}$ by assuming a spatially flat ΛCDM cosmology. With upcoming surveys, such as the Baryon Oscillation Spectroscopic Survey, even larger samples of quiescent massive LRGs may be obtained, and thus the Hubble parameter can be measured with high accuracy using the age–redshift relation.

Key words: cosmological parameters – cosmology: theory – galaxies: abundances – galaxies: evolution – galaxies: stellar content

1. INTRODUCTION

The expansion history of the universe is presently being studied with a few observational probes, such as supernovae Type Ia, baryon acoustic oscillations (BAOs), weak-gravitational lensing, galaxy clusters, etc. Each of these probes has its pros and cons, and suffers from different systematic uncertainties (e.g., Freedman & Madore 2010). A new observational probe of the cosmic expansion history would be invaluable and can provide an additional cross check with the results obtained from the existing methods. Combining the results obtained by different means may further help to constrain the dynamical nature of the universe robustly.

Jimenez & Loeb (2002) proposed a novel approach for exploring the expansion history of the universe, which is based on the age–redshift relation of passively evolving massive galaxies. Assuming that passively evolving galaxies at different redshifts were born approximately at the same time, the age of these galaxies can then be taken as a cosmic chronometer. If the ages of such galaxies can be accurately estimated, then this age–redshift relation may be used to determine the cosmic expansion history. Even if there are some systematic errors in the absolute age measurements, it has been argued that such errors could be canceled out by the relative age of these galaxies at different redshifts, thus providing a good measurement of $H(z)$:

\[ H(z) = \frac{dz}{1 + z} = \frac{d\ln a}{dt} , \tag{1} \]

Indeed, observations show that the most massive galaxies are mainly composed of old stellar populations (OSPs) formed at redshifts $z > 1$–2; less than 1% of their present stellar mass is formed at $z < 1$ (Dunlop et al. 1996; Spinrad et al. 1997; Cowie et al. 1999; Heavens et al. 2004; Thomas et al. 2005; Cimatti et al. 2008; Thomas et al. 2010), and hence these galaxies are suitable for this approach.

Jimenez et al. (2003) applied this method to a sample of massive galaxies at low redshift by fitting their spectra with single stellar population (SSP) spectra based on the SPEED model (Jimenez et al. 2004) and obtained $H_0 = 69 \pm 12$ km s$^{-1}$ Mpc$^{-1}$. Simon et al. (2005) assembled a high-redshift data set obtained from the Gemini Deep Survey and some other archival data, and applied the same method to estimate $H(z)$ for a large redshift range ($z \sim 0.1$–1.8). These earlier works on the age–redshift relation adopted the SSP to fit each galaxy spectrum in the sample and selected the age of the oldest one in each redshift bin as the envelope of the age. However, poor signal-to-noise ratio (S/N) spectra of individual galaxies and contamination from telluric emission and absorption may lead to uncertainties in the age estimates, and the oldest galaxy envelope method draws results from a small number of galaxies at the extremes of the distribution, which may also undermine the validity of the result and makes the method hard to use.

To overcome this problem, Carson & Nichol (2010) obtained the combined spectra for those luminous red galaxies (LRGs) with similar physical properties in each redshift bin by co-adding their spectra, of which the S/N is much higher than individual
galaxies. They then estimated the age of the combined spectra by using the standard Lick absorption line indices, which may be regarded as the mean age of a large sample of galaxies. They obtained the age–redshift relation, but they did not use this relation to further constrain the Hubble parameter.

In this paper, we first select an LRG sample from the Sloan Digital Sky Survey Data Release 7 (SDSS DR7). In order to improve the S/N and remove contamination, we also use the combined spectrum rather than the single spectrum of each galaxy. However, we adopt the full spectrum fitting method, different from the standard Lick absorption line indices adopted by Carson & Nichol (2010), to estimate the mean age of the combined spectrum and then obtain the age–redshift relation. Furthermore, we also use the age–redshift relation obtained from the combined spectra to constrain the Hubble parameter $H_0$ at the present time and analyze the possible systematic bias in the estimated $H_0$. The paper is organized as follows. In Section 2, we describe the selection criteria of the LRG sample. In Section 3, we provide the details of the fitting method and the age–redshift relation estimated from the LRG sample. In Section 4, we constrain the Hubble parameter by using the obtained age–redshift relation. Discussions on the resulting age–redshift relation and the possible associated systematic bias are given in Section 5. Conclusions are summarized in Section 6.

2. SAMPLE SELECTION

In order to obtain the age–redshift relation and use it to measure the Hubble parameter, it is necessary to first select a large sample of passively evolving galaxies that contains the oldest populations with homogeneous physical properties. SDSS is currently the largest survey that provides hundreds of millions of detected objects with accurate photometric and astrometric calibrations, and some of the objects have excellent spectra (Pier et al. 2003; Hogg et al. 2001). It is generally accepted that the LRGs are passively evolving galaxies and that they host the oldest stellar populations. Therefore, we choose our sample from the LRGs of SDSS DR7 (York et al. 2000; Abazajian et al. 2009).

For our purpose, it is necessary to determine the physical properties of the LRGs with relatively high accuracy by using their spectra. We select only from CUT I LRGs, considering that some physical parameters such as velocity dispersions and emission lines are available in the MPA/JHU sample only for that type (see Eisenstein et al. 2001). To obtain accurate estimates of age through the full spectrum fitting method, the selected galaxies should also have sufficiently high S/N. Our selection criteria for LRGs are similar to that described in Carson & Nichol (2010), but with an additional restriction on the S/N:

1. We select galaxies from the Catalog Archive Server (CAS) database using the TARGET\_GALAXY\_RED flag.
2. We select galaxies with $S/N > 10$ per pixel (in the continuum of the $r$-band wavelength range).
3. We select galaxies that further satisfy the restrictions:
   - $specClass$ EQ ‘SPEC\_GALAXY’, $zStat$ EQ ‘XCORR\_HIC’, $zWarning$ EQ 0, $eClass < 0$, $z < 0.4$, and $fracDev_r > 0.8$ (see Carson & Nichol 2010 for more details).

According to the criteria above, 71,971 LRGs are selected from SDSS DR7 and their redshift distribution is shown in Figure 1 (the dotted histogram). These LRGs are probably contaminated by the bulges of late-type galaxies at low redshift due to the limited fiber size (3′) of the SDSS spectrograph. Such late contaminants would, however, have new star formations, and it is well known that the [O\_ii] and H\_\alpha lines are indicators of star formation; hence, we can remove the spiral bulges from the selected sample and obtain a sample of quiescent LRGs by using the spectral line data. Here, we use the MPA/JHU spectral line data,\(^5\) which have been widely used in selecting quiescent galaxies in the literature. We select those LRGs as quiescent only if their H\_\alpha and [O\_ii] line emission are consistent with zero at the 2σ level. With this criterion, we obtain 27,208 quiescent LRGs. We note here that using other emission lines to select quiescent galaxies may result in a similar quiescent LRG sample, as Carson & Nichol (2010) pointed out that all other emission lines (such as the joint constraint of H\_\alpha and [O\_ii]) show similar zero-emission line distributions.

To estimate the Hubble expansion rate $H(z)$ by using the age–redshift relation, it is important to select samples of galaxies with homogeneous physical properties as demonstrated by Crawford et al. (2010). For this reason, the quiescent LRGs selected above are divided into four sub-samples according to their velocity dispersions, which are listed in the MPA/JHU galaxy catalog. The velocity dispersion bins for each sub-sample of the LRGs are 200 km s$^{-1}$–230 km s$^{-1}$, 230 km s$^{-1}$–260 km s$^{-1}$, 260 km s$^{-1}$–290 km s$^{-1}$, and 290 km s$^{-1}$–320 km s$^{-1}$, respectively. We denote these four sub-samples as sub-sample I, sub-sample II, sub-sample III, and sub-sample IV, respectively. In each of the velocity dispersion bins, the number of galaxies is still sufficiently large for the following co-adding spectra to reach a high S/N (>40). We do not consider galaxies with velocity dispersions larger than 320 km s$^{-1}$, as the total number of those galaxies at $z < 0.14$ is too small (<30). In addition, since the total number of galaxies with velocity dispersion less than 200 km s$^{-1}$ is 1843, much smaller than the number of galaxies in all other sub-samples, we also exclude these galaxies. The number of galaxies in each sub-sample is listed in Table 1, and and after excluding those LRGs with $\sigma_\alpha > 320$ km s$^{-1}$ or $\sigma_\alpha < 200$ km s$^{-1}$, the total number of the final sample is 23,883. The redshift distribution of these galaxies is shown in Figure 1 (the solid histogram).

3. SPECTRAL FITTING METHODS

There are three commonly adopted methods for measuring the age and metallicity of a stellar system from its spectrum: (1) the SED fitting, (2) the Lick indices fitting, and (3) the full spectrum fitting. The first method is only sensitive to the general shape of...
of the continuum, the second one focuses on using the strength or equivalent width of lines and specific spectrum features, and the third one accounts for all the information in the spectrum, including both the continuum and the lines and specific features. The full spectrum fitting method has several advantages, such as being insensitive to extinction or flux calibration errors, and it is also not limited by the physical broadening of lines since the internal kinematics is determined simultaneously with the population parameters (Koleva et al. 2008), although the method is insensitive to the element ratio effects because no models for these exist yet. On the other hand, it is more sensitive to the wavelength range of the spectrum adopted in the fitting and the resolution of the spectrum compared with those of the fitting with the Lick indices.

### 3.1. The ULySS Software

ULySS is an open-source software package developed by a group at Université de Lyon, which implements full-spectrum fitting to study physical properties of stellar populations. In ULySS, an observed spectrum is fitted with a model spectrum, adopting a linear combination of nonlinear components, optionally convolved with a line-of-sight velocity distribution and multiplied by a polynomial function. The multiplicative polynomial is adopted to absorb errors of the flux calibration, Galactic extinction, and other factors that may affect the shape of the spectrum. It minimizes the \( \chi^2 \) value with the MPFIT function when matching an observed spectrum with the model ones. The line-spread function (LSF), an analogy to the point-spread function for images, is also introduced in ULySS in order to effectively match the resolution of the model spectrum to the observations. For details about ULySS, the readers are referred to Koleva et al. (2009a). Since the full spectrum fitting method may be sensitive to the wavelength range of the spectrum adopted in the fitting, we adopt the GalexEV/SteLib (GS) model, a popular SSP synthesis model that covers the largest wavelength range, i.e., 3200 Å–9500 Å. This wavelength range includes the Ca II triplet (\( \lambda \lambda \lambda 8498, 8542, 8662 \)), which is a prominent feature produced primarily by an old population of red giants and thus it is important for determining the age of the quiescent LRGs (Díaz et al. 1989).

The GS population model is produced by the isochrone synthesis code of (Bruzual & Charlot 2003, hereafter BC03), which is widely used in SDSS data analysis. It uses the SteLib library, which contains 249 spectra, but only 187 stars have measured metallicity and can be used to compute the predicted spectra with a 3 Å spectral resolution. The GS model adopts the Padova 94 isochrones (Bertelli et al. 1994) and the Chabrier initial mass function (IMF; Chabrier 2003). In total, 696 SSPs, covering the age of 0.1 ~ 20 Gyr and the [Fe/H] of −2.3 ~ 0.4 dex, are included in the GS model. The relevant information of the GS model is provided in Table 2.

### 3.2. Model Pre-treatment

The resolution match is a key issue in the model fitting because the resolution of a model spectrum is usually different from that of the observational data. It is necessary to transform either the model spectrum or the observed spectrum to match the resolution of the other one. The spectral resolution is characterized by the instrumental broadening or the LSF. In practice, the LSF is not necessarily Gaussian and may vary with wavelength (see more details on the LSF in Koleva et al. 2008, 2009a). In ULySS, three types of calibrations (arc lamp, standard star, twilight spectrum) can be used to determine the relative LSF between the model and the observation. In this paper, we use the standard star to do the calibrations. ULySS adopts a convolution of the model with a series of LSFs, which are determined at some wavelengths, and then interpolates linearly in the wavelength range between two convolved models.

We follow the steps described in Koleva et al. (2009a) and Du et al. (2010) to match the resolution of the spectra for galaxies in our sample with that from the GS model. We use the spectrum of SDSS standard star, which is already contained in the ULySS package, as a representative of the SDSS observations. For the GS model spectrum, the relative LSF is obtained in ULySS by comparing the spectrum of the observed spectrum of the SDSS standard stars with the GS model spectrum of the stars with the same physical properties. We then adopt this relative LSF to generate the resolution-matched GS model spectrum by the LSF convolution function in the ULySS package. Below, when we mention the GS model spectrum, we are actually referring to such resolution-matched ones.

### 3.3. Spectrum Fitting

We adopt the SSPs given by ULySS to fit the combined spectrum or the spectrum of each galaxy in our sample but do not consider the detailed star formation history (SFH) of each galaxy, as the sample is almost homogeneous and the galaxies in it are passively evolving. We defer the discussion of the effect due to the difference in the SFH of each galaxy to Section 5.

#### 3.3.1. Combined Spectrum

High S/N spectra are essential for obtaining accurate estimates of the age of galaxies. We have tested the effect of the S/N on the age uncertainty. We found that the uncertainties in age estimates are about 20% and 10% for galaxy spectra with S/N = 20 and 40, respectively. In order to apply the age–redshift relation effectively, the uncertainties in age estimates need to be smaller than 10%. For the majority of galaxies in our sample, however, their SDSS spectra have S/N ≲ 20.

### Table 1

**The Total Number of Galaxies in Each Sub-sample**

| Sample     | Velocity Dispersion Range | Number |
|------------|---------------------------|--------|
| Sub-sample I | 200 km s\(^{-1}\) | 4756   |
| Sub-sample II | 230 km s\(^{-1}\) | 8748   |
| Sub-sample III | 260 km s\(^{-1}\) | 7149   |
| Sub-sample IV | 290 km s\(^{-1}\) | 3230   |
| Total       | 200 km s\(^{-1}\) | 23,883 |

### Table 2

**The Settings in the GS Model**

| Model | Library | Resolution (Å) | Wavelength (Å) | Age (Gyr) | Z (dex) | IMF     | Track       |
|-------|---------|----------------|----------------|-----------|---------|---------|-------------|
| GS    | SteLib  | 3              | 3200–9500      | 0.1–20    | −2.3–0.4| Chabrier| Padova 94   |
Levenberg–Marquardt routine to search the parameter space to δz of bins from 0. We thus obtained 12 combined spectra over redshift 03 to 0.39 for each sub-sample.

To do this, we first correct the foreground Galactic extinction by using the reddening maps of Schlegel et al. (1998) for each galaxy. As the number of galaxies at z < 0.03 is too small in all of the sub-samples, these galaxies are neglected in the following analysis. The galaxies in each sub-sample are then divided into 12 redshift bins from z = 0.03 to z = 0.39 with a redshift step of δz = 0.03. A combined spectrum is then obtained for each redshift and velocity dispersion bin by co-adding the rest-frame spectra of all the galaxies in that bin through the IRAF SCOMBINE. We thus obtained 12 combined spectra over redshift bins from 0.03 to 0.39 for each sub-sample.

The combined spectra are then fitted by ULySS. ULySS uses Levenberg–Marquardt routine to search the parameter space to get the minimization of χ². Therefore, it needs some initial estimated value to begin searching the parameter space. In this paper, we set the initial estimate for the age to 8 Gyr and for metallicity to solar metallicity since the LRGs are expected to be old and metal rich. We do not set any limit on the allowed age and the abundance of metallicities of the model spectra. The fitting is performed in the whole wavelength range covered by the combined spectra. The estimates on the age, metallicity, and velocity dispersion of the model galaxies and the associated errors are then obtained for the best-fit model to the combined spectrum. For illustration, Figure 2 shows the combined spectrum in the first redshift bin of the sub-sample II, and the best-fit model spectrum by the GS model and its residues. The fitting results for sub-sample II are listed in Table 3.

Figure 3 illustrates the best-fit result obtained by adopting the GS model. The top, middle, and bottom panels in the figure show the velocity dispersions, metallicities, and ages for each redshift bin in each of the four sub-samples, respectively. As seen from the top panel of Figure 3, the fitting results of the velocity dispersions are consistent with the ones given in the MPA/JHU catalog, which are shown in Figure 3 as open squares, triangles, diamonds, and circles, respectively. The middle panel shows that the ages in each sub-sample have similar metallicities, confirming that our samples are almost homogeneous, though of course subtle differences remain. From the bottom panel, it is clear that the mean age (tage) decreases with redshift from 0.03 to 0.39. Apparently, the age of the galaxies with higher

Table 3

| Redshift Interval | SSP-equivalent Age (Gyr) | SSP-equivalent [Fe/H] (dex) | Velocity Dispersion (km s⁻¹) |
|------------------|--------------------------|-----------------------------|-------------------------------|
| 0.03 < z ≤ 0.06 | 7.13 ± 0.53              | 0.17 ± 0.01                 | 243.5 ± 4.0                  |
| 0.06 < z ≤ 0.09 | 6.52 ± 0.43              | 0.17 ± 0.01                 | 239.2 ± 3.7                  |
| 0.09 < z ≤ 0.12 | 6.31 ± 0.40              | 0.16 ± 0.01                 | 236.0 ± 3.7                  |
| 0.12 < z ≤ 0.15 | 6.01 ± 0.40              | 0.17 ± 0.01                 | 239.0 ± 3.7                  |
| 0.15 < z ≤ 0.18 | 6.11 ± 0.45              | 0.15 ± 0.01                 | 240.7 ± 3.9                  |
| 0.18 < z ≤ 0.21 | 5.49 ± 0.24              | 0.18 ± 0.01                 | 242.4 ± 3.8                  |
| 0.21 < z ≤ 0.24 | 5.37 ± 0.22              | 0.17 ± 0.01                 | 243.0 ± 3.5                  |
| 0.24 < z ≤ 0.27 | 4.98 ± 0.22              | 0.15 ± 0.01                 | 242.7 ± 3.5                  |
| 0.27 < z ≤ 0.30 | 4.96 ± 0.19              | 0.14 ± 0.01                 | 247.6 ± 3.3                  |
| 0.30 < z ≤ 0.33 | 4.78 ± 0.16              | 0.12 ± 0.01                 | 247.4 ± 3.4                  |
| 0.33 < z ≤ 0.36 | 3.82 ± 0.24              | 0.16 ± 0.02                 | 243.7 ± 3.5                  |
| 0.36 < z ≤ 0.39 | 3.64 ± 0.19              | 0.17 ± 0.02                 | 248.9 ± 3.2                  |

Notes. Column 1 shows the redshift interval, Columns 2, 3, and 4 show the SSP-equivalent age in unit of Gyr, the [Fe/H] in unit of dex, and the velocity dispersion in unit of km s⁻¹ and their associated errors, respectively.

which leads to >20% uncertainties in age estimates. To overcome this problem, we choose to co-add the spectra of galaxies in each sub-sample (and each redshift bin) to obtain a combined spectrum with significantly higher S/N (>40).

The combined spectra are then fitted by ULySS. ULySS uses Levenberg–Marquardt routine to search the parameter space to get the minimization of χ². Therefore, it needs some initial estimated value to begin searching the parameter space. In this paper, we set the initial estimate for the age to 8 Gyr and for metallicity to solar metallicity since the LRGs are expected to be old and metal rich. We do not set any limit on the age.
obtained directly from the MPA

t line strength of 4097 red-sequence galaxies in 93 low-redshift
et al. 2005). Nelan et al. (2005) investigated the spectroscopic
samples, 200 km s⁻¹ mean luminosity-weighted ages, and mean formation time of the LRGs obtained through their combined spectra in each redshift bin for each of the four sub-
correlates with σv

more massive galaxies were formed earlier, while the small
galactic velocity dispersions tend to be somewhat older than those with
lower velocity dispersion, which is consistent with the well-
known “downsizing” formation of galaxies, i.e., the bigger and
more massive galaxies were formed earlier, while the small
galaxies formed later (Cowie et al. 1996). Assuming that the
τage−σv relation follows a power law, i.e., τage ∝ σv γ , we fit
the relationship for each redshift bin and obtain the slope γ.
The mean value of γ for all redshift bins (and its standard
deviation) is γ = 0.77 ± 0.25. We also first obtain the mean τage for
each sub-sample and then fit the mean τage−σv relationship and
find γ ≃ 0.79 ± 0.24.

A number of studies have obtained the relationship between
the age (τage) and velocity dispersion (σv) of early-type galaxies
or LRGs and have shown that the τage depends on σv. For
case, Caldwell et al. (2003) analyzed the integrated spectra
of 175 nearby early-type galaxies by using higher-order Balmer
lines as the age indicators and found that early-type galaxies
with lower σv have smaller luminosity-weighted mean ages.
The data obtained by Caldwell et al. (2003) suggest that the
slope of the τage−σv relation is roughly 0.8–1.2 (Nelan et al.
2005). Thomas et al. (2005) studied the spectra of 124 early-
type galaxies in both high- and low-density environments by
using the absorption line indices, and they also found that τage correlates with σv. Adopting the data in Thomas et al. (2005),
the slope of the τage−σv relation is found to be 0.78±0.23 (Nelan
et al. 2005). Nelan et al. (2005) investigated the spectroscopic
line strength of 4097 red-sequence galaxies in 93 low-redshift
galaxy clusters and found τage ∝ σv 0.59±0.13. Smith et al. (2009)
studied the spectra of 232 quiescent galaxies in the Shapley
supercluster and found τage ∝ σv 0.40. As discussed in Nelan
et al. (2005), the differences in sample selection criteria and
emission treatment may account for the differences in the τage−σ
scaling relation. Considering these differences, our results are
very consistent with those obtained by previous works.

3.3.2. Reliability of the Fitting Results

The fitting results may be dependent on the particular syn-
thesis technique adopted in this paper, i.e., ULySS, and may
be affected by the existence of multiple solutions in the fitting
due to degeneracies among the model parameters. In this
sub-section, we check the reliability of the fitting results.

Koleva et al. (2008) analyzed the spectra of Galactic clusters
using ULySS, and they found that stellar populations of these
clusters obtained from the model are very consistent with that
obtained from the color–magnitude diagrams. Koleva et al.
(2009b) further analyzed the detailed SFH of 16 dwarf galaxies
by using either ULySS or STECKMAP, and they found that the
two programs give remarkably consistent results. In addition,
Michielsen et al. (2007) adopted two different techniques, i.e.,
the Lick/IDS index system and the full spectrum fitting method,
to test the reliability of the estimates of the ages and metallicities
of 16 dwarf elliptical galaxies, and they found that these two
techniques give consistent results on the age and the metallicity,
with an rms error of 1.63 Gyr in age and 0.09 dex in \([Z/H]\). Du et al. (2010) synthesized the star formation histories and evolution of 35 brightest E+A galaxies from SDSS DR5, and demonstrated the robustness of the ULySS technique in measuring the age and metallicity of stellar systems. These studies show that the fitting results with different synthesis techniques are consistent with each other, and the results of our ULySS fitting should be robust.

We perform Monte Carlo simulations to visualize the degeneracies and validate the errors by simulating the effect of the noise. For each combined spectrum, we perform 1000 simulations. In each of the simulations, a random Gaussian noise is added to the combined spectrum and the amplitude of the added noise is set to the estimated noise associated with the combined spectrum. We then get the corresponding mean values of the age, abundance of metallicity and velocity dispersion, and their standard deviations. Figure 4 shows the results of the 1000 Monte Carlo simulations (open symbols) and the original best fit is shown in Figure 3 (filled symbols). According to Figure 4, we conclude that in most of the cases, the values of mean velocity desperation and mean age for every bin of the 1000 Monte Carlo simulations lead to the best-fitting solutions, although there are still some deviations especially for sub-sample IV, which may be caused by the relatively small number of galaxies used to obtain the combined spectrum. Since we only need to model the age–redshift relation, the diversity of metallicity between the best-fitting value and the value of the Monte Carlo simulations does not affect our conclusion.

The general agreement of the above series of tests suggests that the ULySS technique is robust in determining the age, metallicity, and velocity dispersion of stellar systems, and that the fitting results on the physical properties of galaxies obtained from the full spectrum fitting are also secure.

4. CONSTRAINTS ON THE HUBBLE PARAMETER

The age–redshift relation obtained from observations can be directly fitted by

\[ t_{\text{age}} = t_U - t_{\text{form}}, \tag{2} \]

where \(t_{\text{age}}\) is the mean age obtained from the combined spectrum, \(t_{\text{form}}\) is the mean formation time of the quiescent galaxies and assumed to be a constant for each sub-sample, and \(t_U\) is the age of the universe. According to the \(\Lambda\)CDM cosmology, \(t_U\) at redshift \(z\) is given by

\[ t_U = \frac{1}{H_0} \int_z^\infty \frac{dz}{(1+z)\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}}, \tag{3} \]

which depends not only on the value of \(H_0\) but also on the composition of the universe, i.e., \(\Omega_m\) and \(\Omega_\Lambda\).

In order to obtain a model-independent measurement of \(H_0\), however, we first simply assume \(H(z) = H_0 + H'z\) (but it may be a good approximation only at low redshift); then, the age of the universe is given by

\[ t_U = \int_z^\infty \frac{dz}{(1+z)(H_0 + H'z)}. \tag{4} \]

Using the standard \(\chi^2\) minimization, we fit the age–redshift relation obtained from each sub-sample to get the best fit of \(H_0\) and \(t_{\text{form}}\), and the uncertainty of \(H_0\) by marginalizing over \(H'\) and \(t_{\text{form}}\) (and the uncertainty of \(t_{\text{form}}\) by marginalizing over \(H'\) and \(H_0\)). Figure 5 shows the best fit of the age–redshift relation for...
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Figure 5. Best fits to the age–redshift relations obtained from each sub-sample (points with error bars) by assuming $H(z) = H_0 + H'z$ (dashed lines) and a spatially flat ΛCDM model (solid lines), respectively. The dashed lines almost overlap the solid lines.

Table 4

| Sample                  | $H(z) = H_0 + H'z$ | Flat ΛCDM |
|-------------------------|--------------------|-----------|
|                         | $H_0$             | $\chi^2$ | $H_0$ | $\chi^2$ |
| Sub-sample I            | 84^{+7}_{-9}      | 1.47      | 89^{+7}_{-9} | 1.43     |
| Sub-sample II           | 77^{+9}_{-7}      | 1.26      | 83^{+9}_{-7} | 1.21     |
| Sub-sample III          | 68^{+5}_{-7}      | 0.72      | 72^{+5}_{-7} | 0.66     |
| Sub-sample IV           | 63^{+7}_{-4}      | 0.86      | 65^{+7}_{-3} | 0.86     |
| Sub-sample III+IV       | 68^{+4}_{-5}      | 0.82      | 74^{+5}_{-4} | 0.78     |
| All sub-samples         | 73^{+4}_{-3}      | 1.14      | 80^{+4}_{-4} | 1.08     |

Notes. Here, $H_0$ is in units of km s$^{-1}$ Mpc$^{-1}$; $\chi^2$ is the reduced $\chi^2$. Columns 2 and 3 list the best-fit value of $H_0$, its 1σ error, and the reduced $\chi^2$, by assuming $H(z) = H_0 + H'z$, while Columns 4 and 5 list the best-fit value of $H_0$, its 1σ error, and the reduced $\chi^2$ by assuming a spatially flat ΛCDM model.

formation time of the galaxies in each sub-sample, denoted as $t_{\text{form1}}$, $t_{\text{form2}}$, $t_{\text{form3}}$, and $t_{\text{form4}}$, respectively, since $H_0$ and $H'$ are the same for each of the age–redshift relations. By marginalizing over parameters $H$, $t_{\text{form1}}$, $t_{\text{form2}}$, $t_{\text{form3}}$, and $t_{\text{form4}}$, we obtain the best fit of $H_0 = 73^{+4}_{-3}$ km s$^{-1}$ Mpc$^{-1}$ (see the left panels of Figure 6).

Assuming spatial flatness for simplicity, we further adopt Equations (2) and (3) (given by the standard ΛCDM model) to fit the age–redshift relation obtained from each sub-sample, separately. The best fit of $H_0$ is obtained by marginalizing over $\Omega_m$ and $t_{\text{form}}$ and it ranges from 89^{+7}_{-5} km s$^{-1}$ Mpc$^{-1}$, 83^{+5}_{-8} km s$^{-1}$ Mpc$^{-1}$, 72^{+5}_{-6} km s$^{-1}$ Mpc$^{-1}$ to 65^{+7}_{-3} km s$^{-1}$ Mpc$^{-1}$ for the four sub-sample velocity dispersions from low to high, respectively (see Figure 5 and Table 4). We also obtain $H_0$ by fitting the age-relations obtained from each of the four sub-samples simultaneously by marginalizing over $\Omega_m$, and the mean formation time of those galaxies, and the best fit of $H_0$ is 80^{+4}_{-4} km s$^{-1}$ Mpc$^{-1}$ (see the right panels of Figure 6).

And the best fit of $\Omega_m$ is 0.09 and it ranges from 0.08 to 0.25, which cannot be constrained with high accuracy. By marginalizing over other parameters, we obtain the best fits of $t_{\text{form1}}$, $t_{\text{form2}}$, $t_{\text{form3}}$, or $t_{\text{form4}}$, which are $9.7^{+0.3}_{-0.7}$ Gyr, $9.2^{+0.4}_{-0.3}$ Gyr, $8.8^{+0.2}_{-0.3}$ Gyr, or $8.4^{+0.2}_{-0.2}$ Gyr, respectively. These values of $t_{\text{form}}$ seem to be much larger than expected from the standard ΛCDM cosmology for LRGs, which are mainly caused by the poorly constrained $\Omega_m$ (=0.09). By assuming a flat universe with
\( \Omega_m = 0.27 \) (the concordant cosmological model) and refitting the age–redshift relations for the four velocity dispersion bins simultaneously, the best fit gives \( H_0 = 73 \, \text{km s}^{-1} \, \text{Mpc}^{-1} \), \( t_{\text{form1}} = 5.9 \, \text{Gyr} \), \( t_{\text{form2}} = 5.4 \, \text{Gyr} \), \( t_{\text{form3}} = 5.0 \, \text{Gyr} \), and \( t_{\text{form4}} = 4.6 \, \text{Gyr} \), respectively. Clearly, the mean formation time of those less massive galaxies is smaller than that of those more massive galaxies, which is fully consistent with the “downsizing” evolution nature of galaxy formation. One may also directly obtain the formation time from the age–redshift relations by adopting the concordant cosmological model, i.e., fixing the Hubble constant to be \( H_0 = 71 \, \text{km s}^{-1} \, \text{Mpc}^{-1} \), the matter density to be \( \Omega_m = 0.27 \), and dark energy density to be \( \Omega_\Lambda = 0.73 \); the formation time from the age–redshift relations is \( t_{\text{form1}} = 6.2 \, \text{Gyr} \), \( t_{\text{form2}} = 5.7 \, \text{Gyr} \), \( t_{\text{form3}} = 5.3 \, \text{Gyr} \), and \( t_{\text{form4}} = 4.9 \, \text{Gyr} \), respectively. The mean galaxy formation time is about 5.5 Gyr for the four velocity dispersion bins, which is adopted in Figure 3 (represented by the dashed line). Note that the obtained \( t_{\text{form}} \) is the average age of a population of galaxies but neither the age of individual galaxies nor the oldest population of stars in those galaxies. Note also that there is strong degeneracy between \( t_{\text{form}} \) and \((H_0, \Omega_m)\) obtained from the fitting, which introduces a large uncertainty in the estimation of \( t_{\text{form}} \).

According to the above fittings, obviously a strong constraint on \( H_0 \) can still be obtained by either assuming a simple model-independent form of the evolution of \( H(z) \) or a flat universe, i.e., \( \Omega_m + \Omega_\Lambda = 1 \), although the age–redshift relations are obtained in a limited redshift range and the uncertainties in the age estimates may be substantial. The \( H_0 \) estimated from the sub-sample with lower velocity dispersion tends to be higher than that from the sub-sample with higher velocity dispersion (more massive and luminous LRGs), which may be due to some bias introduced by the systematical difference in the assembly history of less massive galaxies and massive galaxies. Brown et al. (2007) pointed out that the evolution of galaxies in the red sequence is heavily dependent on luminosity, i.e., the lower the luminosity of the galaxies, the more significant the population of new stars formed since \( z = 1 \). So the contamination from the population of stars formed at low redshift (e.g., \( z \lesssim 0.4 \)) is probably more significant in sub-sample I and sub-sample II than that for sub-sample III and sub-sample IV. Also, the age–redshift relation estimated from the lower velocity dispersion sub-sample tends to be shallower than that from the higher velocity dispersion sub-sample, which may lead to an overestimation of the Hubble parameter of up to \( \sim 20\% \) (see discussions in Section 5.3).

As the possible systematic bias may be not significant for the two sub-samples with high velocity dispersions, we also fit the age–redshift relations obtained from the two sub-samples simultaneously by assuming either a spatially flat \( \Lambda \)CDM model or \( H(z) = H_0 + H'z \). The best fit of \( H_0 \) is either \( 74^{+5}_{-5} \, \text{km s}^{-1} \, \text{Mpc}^{-1} \) or \( 68^{+2}_{-1} \, \text{km s}^{-1} \, \text{Mpc}^{-1} \). Also, the best fit of \( \Omega_m \) is \( 0.07^{+0.08}_{-0.01} \) if assuming a spatially flat \( \Lambda \)CDM model.

Considerable progress has been made in determining the Hubble parameter over the past two decades by using many different techniques (e.g., Freedman & Madore 2010). For example, the Hubble parameter is estimated to be \( H_0 = 73 \pm 5 \, \text{km s}^{-1} \, \text{Mpc}^{-1} \).
by using the tip of the red giant branch as an alternate calibration to the Cepheid distance scale (Mould & Sakai 2008), 72 ± 4 (random) ± 11 (systematic) km s⁻¹ Mpc⁻¹ by using the surface brightness fluctuation to determine cosmic distances (Blakeslee et al. 2002), 74.3 ± 3.6 km s⁻¹ Mpc⁻¹ by using Type Ia supernovae (Riess et al. 2009), 76.9 ± 0.3 ± 0.6 km s⁻¹ Mpc⁻¹ by using the Sunyaev–Zel’dovich effect (Bonamente et al. 2006), and 68 ± 2 km s⁻¹ Mpc⁻¹ by using the BAO signature in the matter power spectrum (Percival et al. 2010). The Hubble Space Telescope key project yielded a consistent value of $H_0 = 72 ± 3$ (random) ± 7 (systematic) km s⁻¹ Mpc⁻¹ by combining the data obtained from different techniques (Freedman & Madore 2010). Komatsu et al. (2009) also obtained a value of $H_0 = 70.5 ± 1.3$ km s⁻¹ Mpc⁻¹ by combining the WMAP5 data with the SN Ia and BAO data, while Tammann et al. (2008) found consistently low values of $H_0$, from several different tracers they obtain a mean value of $H_0 = 62.3 ± 1.3$ km s⁻¹ Mpc⁻¹. Considering the possible systematic error in the $H_0$ estimation by using the age–redshift relation, our estimates of $H_0$ are fully consistent with those listed above.

5. DISCUSSION

In this paper, we have obtained the mean age, metallicity, and velocity dispersion for a sample of quiescent galaxies selected from SDSS DR7 in different redshift bins. The age–redshift relation derived from those quiescent galaxies is consistent with the expectation from the ΛCDM cosmology and may provide a good estimate of the Hubble parameter ($H_0$). However, the estimate of $H_0$ is valid only if those quiescent galaxies are passively evolving and the galaxies in different redshift bins represent the same population formed more or less at the same time. In order to check whether these requirements are satisfied for the quiescent galaxy sample selected in this paper, we perform some tests below to investigate the evolution effects due to different SFH or galaxy mergers, and illustrate that those quiescent galaxies indeed are formed more or less at the same epoch using the evolution of their average colors.

5.1. Star Formation History

According to the selection criteria, most galaxies in our sample should be quiescent galaxies and are supposed to be passively evolving. However, the SFH of those galaxies may not be a single burst. To test whether there are significant younger stellar populations in the galaxies, we redo the full spectrum fitting for each combined spectrum by adopting two stellar components, one young stellar population (YSP) and one OSP. The age of the YSP is assumed to be in the range from 0.1 Gyr to 1 Gyr, while for the old population it is assumed to be in the range from 1 Gyr to 15 Gyr. For both populations, the metallicity is a free parameter without restrictions. According to the fitting results, we note here that the fitting age of the YSP always reaches the edge of its limits (the age of YSP is always either 0.1 Gyr or 1 Gyr), which means that a YSP with an age in the given range cannot be found. Furthermore, even if a YSP exists, the light fraction is very small (2.8% on average) so that it can be neglected. Therefore, we conclude that the YSP (the age of which <1 Gyr) is negligible and not required in the fitting. We also test the cases by setting a larger upper limit on the age of the YSP, e.g., 2 Gyr, 3 Gyr, or even 4 Gyr (or alternatively a lower limit on the age of the OSP, i.e., 4 Gyr to 6 Gyr), and also find that no significant YSP is required by the fitting. All these tests suggest that most of the quiescent LRGs may be passively evolving and may not experience significant recent (<2 Gyr) star formation. For those galaxies at low-redshift bins, however, we find there YSP’s may exist with age ~3 Gyr, possibly due to the later major mergers (see discussions in Section 5.3).

To close this sub-section, we note here that Tojeiro & Percival (2010) find bright LRGs to be consistent with pure passive evolution, whereas faint LRGs slightly deviate from pure passive evolution as revealed by the evolution of the number and luminosity density of LRGs as well as that of their clustering. The lower passiveness of LRGs with smaller velocity dispersion does not seem able to be directly revealed by the combined spectra of LRGs studied in this paper, which might be due to the signature of YSPs (probably with quite different ages) in (some of) the LRGs being diluted or smoothed due to the co-adding of a large number of LRG spectra in our analysis. High S/N spectra of individual LRGs may be helpful to clarify the low passiveness of small LRGs; however, the S/N of most LRGs in our sample is only slightly larger than 10 and is not sufficiently high to clarify this problem.

5.2. Combined Spectrum versus Single Spectrum

The combined spectrum in each redshift and velocity bin may only represent the mean spectrum of galaxies in that bin. Does the physical properties derived from the model fitting of this combined spectrum represent the mean properties of all galaxies in that bin? In order to test this, we fit each single spectrum for all of the galaxies in each velocity dispersion bin and redshift bin with ULySS. The initial settings are the same as that in Section 3.3.1. After obtaining the best fit of the age for each single spectrum, we calculate the mean of the ages of those galaxies that belong to the same velocity dispersion and redshift bin and its standard deviation. Figure 7 shows the mean age–redshift relation for every single spectrum. As seen from Figure 7, the mean age–redshift relation obtained from the combined spectra is still consistent with that obtained from the single spectra but with much larger errors.

5.3. Major Mergers of Quiescent Galaxies

The differences among the model spectra become small if the ages of the stellar populations are larger than 4 Gyr. Therefore,
the uncertainties in the estimates of the ages and metallicities of galaxies with low S/N spectra are substantial. For this reason, we have combined the spectra of galaxies in each redshift and velocity dispersion bin together to improve the S/N. However, the age difference obtained by modeling the combined spectra can represent the age difference of the universe only if those galaxies at different redshifts are of the same population and were formed more or less in the same epoch. There is a potential caveat to this approach, i.e., if a significant fraction of quiescent galaxies experience major mergers and thus some star formation at low redshift $z \lesssim 0.4$, then some quiescent galaxies in the redshift bin 0.03–0.06 were formed at $z < 0.4$ and they were not represented by those galaxies in the redshift bin 0.36–0.39. It is important to check the effect of the major merger of galaxies on the age–redshift relation.

The major merger rate of galaxies is defined as the number of mergers per galaxy with mass larger than a threshold ($M_*$) per unit time and denoted as $dN_{\text{mrg}}/dt$, and it can be roughly estimated by the fitting formula given by Hopkins et al. (2010), i.e.,

$$
\frac{dN_{\text{mrg}}}{dt} = A(M_{\text{min}}) (1 + \frac{z}{\beta(M_{\text{min}})}) \text{[per galaxy],}
$$

where the normalization is

$$
A(M_{\text{min}})_{\text{major}} \approx 0.02 [1 + (M_{\text{min}}/M_0)^{0.5}] \text{Gyr}^{-1},
$$

the redshift evolution is

$$
\beta(M_{\text{min}})_{\text{major}} \approx 1.65 - 0.15 \log(M_{\text{min}}/M_0),
$$

and $M_0 \equiv 2 \times 10^{10} M_\odot$. For the galaxies in our sample, they are generally brighter than $3L^*$ (Eisenstein et al. 2001) and have stellar masses in the range from $10^{11} M_\odot$ to a few times $10^{12} M_\odot$ according to Tal et al. (2012). Assuming that the minimum mass of those galaxies is $M_{\text{min}} = 10^{11} M_\odot$, the average number of major mergers experienced by a galaxy at redshift $z$ since $z = 0.40$ is

$$
N_{\text{mrg}}(z) = \int_z^{0.40} \frac{dN_{\text{mrg}}}{dt} \left| \frac{dt}{dz} \right| dz,
$$

where $dt/dz$ is given by Equation (1). The fraction of galaxies in a redshift bin $z \pm dz$ that experienced major mergers since $z = 0.4$ is $N_{\text{mrg}}(z)$, and $N_{\text{mrg}}(z) \approx 0.33, 0.26,$ and 0.01 at $z = 0.03, 0.11,$ and 0.39 for our sample, respectively. Note that almost all the major mergers are dry mergers for massive galaxies with mass $>10^{11} M_\odot$ similar to that in our sample (Hopkins et al. 2010). These dry mergers may also lead to new star formation or star burst in the galactic centers, and thus introduce a systematic bias to the age–redshift relation because the mean age obtained from the combined spectra by the GS model at low-redshift bins may be systematically underestimated due to the additional population of stars formed later.

We check the effect of these major mergers on the age–redshift relation as follows. First, we assume an underlying age–redshift relation according to the ΛCDM, i.e., the age of the galaxy at redshift $z$ is $t_0(z) - t_{\text{form}}$, and $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.27$, and $t_{\text{form}} = 5.5$ Gyr are assumed. Here, $t_{\text{form}} = 5.5$ Gyr is adopted according to the average formation time obtained by fitting the age–redshift relation for four velocity dispersion bins (see Section 4 for details). However, Thomas et al. (2005) found that vigorous star formation episodes in massive galaxies often occur at $z \sim 2–5$, corresponding to a cosmic age of less than 3.3 Gyr. The $t_{\text{form}}$ obtained from the age–redshift relations for the quiescent LRGs in this paper is larger than that obtained by Thomas et al. (2005), which needs further investigation. As the galaxies in our sample are all LRGs, the age of the newly formed stellar population by major mergers, if significant, is at least 1 Gyr, which corresponds to $\delta_z \sim 0.1$, since the migration of galaxies driven by mergers from blue cloud to red sequence may last $\sim 1$ Gyr (see Schawinski et al. 2010). If a galaxy at redshift $z$ is the remnant of a major merger, then the age of the younger stellar population in it is approximately $\frac{1}{2}[t_0(z) - t_{\text{form}}] + 1$ Gyr. Then, a “forged” combined spectrum of galaxies at redshift bin can be approximately generated by two stellar populations, i.e., an OSP with age $t_0(z) - t_{\text{form}}$ and a YSP with age $\sim 1/2[t_0(z) - t_{\text{form}}] + 1$ Gyr. The fraction of major mergers is

$$
N_{\text{mrg}}(z + \delta_z) = \int_z^{0.40+\delta_z} \frac{dN_{\text{mrg}}}{dt} \left| \frac{dt}{dz} \right| dz.
$$

Hopkins et al. (2010) have shown that the fraction of the young population generated by major mergers is $\sim 0.05–0.10$ in galaxies with $>10^{11} M_\odot$ (see their Figure 14). Here, we assume it to be $\sim 0.07$. Note that this fraction may be an upper limit as the LRGs studied here are quiescent ones in which the star formation generated by major mergers might be even less. Therefore, the fraction of the young population contributing to the combined spectrum is $\sim 0.07 \times N_{\text{mrg}}(z)$, and the fraction of the old population is $1 - 0.07 \times N_{\text{mrg}}(z)$. We fit these spectra obtained for each redshift using the same method as that used in Section 3.3.1 and obtain the age for these combined spectra. Similar to Section 4, we obtain the best fit of $H_0 = 86^{+2}_4 \text{km s}^{-1} \text{Mpc}^{-1}$ by fixing $\Omega_m = 0.27$.

From the above calculation, we conclude that $H_0$ may be systematically overestimated by up to $\sim 20\%$ if using the age–redshift relation obtained from the combined spectra. Considering this systematic bias, the $H_0$ estimated from the age–redshift relation in this paper is consistent with those estimated by other techniques. Note also that the systematic bias introduced to the $H_0$ estimate appears insignificant for the two sub-samples with the highest velocity dispersions, which might mean that those very massive LRGs are really quiescent and have approximately zero star formation at redshift $z \lesssim 0.4$. Tojeiro & Percival (2010) have pointed out that the brightest galaxies show the smallest departure from pure passive evolution. Therefore, the most massive LRGs with velocity dispersion $\gtrsim 300 \text{km s}^{-1}$ may be efficient tools for constraining the cosmological parameters such as $H_0$ through the age–redshift relations extracted from their spectra.

We also check whether the $g - r$ color of the galaxies having the combined spectra in each redshift bin is consistent with that of the model galaxies that have the same spectrum as the combined spectrum in the highest redshift bin. To do this, we extract a model spectrum from the GS model grid whose age and metallicity are the best-fitting results with ULySS for redshift bin 0.36–0.39, and then we let this spectrum evolve toward low redshift. That is, if the age and metallicity of the combined spectrum are $t$ and $Z_{\text{Fe/H}}$ at $z = 0.375$, then at a low redshift $z$ we extract a spectrum from model grid whose age is $t + \delta t$ and let the metallicity be fixed to $Z_{\text{Fe/H}}$, where $\delta t = t_0(z) - t_0(z = 0.375)$. We repeat this process until $z = 0.045$ and denote the spectra obtained from the above processes as the “forged spectra.” For each combined spectrum, there is also a model spectrum to fit
it. We denote this spectrum as the “model spectrum.” Then, we calculate the \( g - r \) color with the SDSS filter of those “forged spectra” and “model spectra” with the IRAF task SYNPHOT. We find that the \( g - r \) color of the “model spectra” are almost the same as of the that “forged spectra,” which means the merger effect is not significant for our sample. Furthermore, we pick out those spectrum whose S/N > 30 from our sample as a sub-sample to derive their physical property with full spectrum fitting. This sub-sample has 1386 galaxies, and these are almost all concentrated in the redshift range from 0.02 to 0.2. We fit these galaxies with SSPs. The initial settings are the same as in Section 3.3.1. Similarly, we extract the corresponding spectrum from the GS model according to the best fit. Then, we calculate the \( g - r \) color and find that dispersion of the \( g - r \) color is very small compared with that of the combined spectrum, which means that the results of the single spectrum are consistent with those of the combined spectrum.

5.4. Model Dependence

In this paper, we use the GS model to fit the combined spectra, as its wavelength coverage is wider compared with the other models provided by the ULYSS package. For completeness, we also test the Pegase-HR/Elodie3.1 model and the Vazdekis/Miles model, and find there to be some model dependence. The model dependence may be caused by the limitation of wavelength coverage as the Pegase-HR/Elodie3.1 model covers the wavelength from 3900 Å to 6800 Å, and for the Vazdekis/Miles model it is 3540 Å–7409 Å. This result is consistent with that of Verkhodanov et al. (2005), in which they analyzed the photometric data of a large sample of elliptical galaxies and found that \( H_0 = 72 \pm 10 \text{ km s}^{-1} \text{ Mpc}^{-1} \) and \( 53 \pm 10 \text{ km s}^{-1} \text{ Mpc}^{-1} \) for two different stellar population synthesis models, i.e., PEGASE and GISSEL, respectively. The main ingredients of those models are the stellar evolution tracks, the stellar library, the IMF, the grids of ages and metallicities, and the Szhfs, etc. Each model may have different settings in one or more of those ingredients. As demonstrated by Chen et al. (2010), at present there are still some differences in the output between these different models. The model dependence may be avoidable if carefully choosing a compatible stellar population synthesis model for the problem to be studied. We note here that it is also interesting to test the model given by Maraston & Stromback (2011), which is based on the fuel consumption theorem and quite different from the other models. However, it is not easy to test this model because it is not yet included in the ULYSS code.

From the above tests, we conclude that the age-redshift relation obtained from the combined spectra of a large sample of quiescent LRGs can be used to constrain the Hubble parameter \( H_0 \) (and possibly other cosmological parameters if combining with other data sets). If a large sample of very massive quiescent LRGs can be obtained by future surveys, such as the Baryon Oscillation Spectroscopic Survey (BOSS), which is less affected by systematic bias due to new star formation at low redshift, then the \( H_0 \) may be able to be determined with substantial accuracy.

6. CONCLUSIONS

In this paper, we selected 23,883 quiescent LRGs from SDSS DR7 in the redshift range from 0.03 to 0.39 by setting a threshold of zero emission (at a 2σ-level) of the H\( \alpha \) and [O\text{II}] lines directly obtained from the MPA/JHU catalog. The quiescent LRG sample is divided into four sub-samples according to galaxy velocity dispersions. For each sub-sample, the spectra of galaxies in each of the 12 redshift bins (from \( z = 0.03 \) to 0.39 with a step of \( \delta z = 0.03 \)) are combined together to obtain a high S/N combined spectrum. Using the full spectrum fitting method, the luminosity-weighted physical properties, such as the velocity dispersion, the metallicity, and the age, of those quiescent LRGs are obtained from the combined spectra by adopting a single population synthesis model, i.e., the GS model. Using Monte Carlo simulations, we find that the model results are robust and reliable. We argue that the age-redshift relation estimated from the LRG sample could be systematically biased because of contamination from a possible younger stellar population formed at \( z \lesssim 0.4 \) as a consequence of major mergers. This bias is most significant for LRGs with smaller velocity dispersions, but is insignificant for the most massive LRGs. Considering this systematic bias, the age-redshift relation obtained from the model fittings is fully consistent with the expectations from the ΛCDM cosmology.

The Hubble parameter \( H_0 \) is first estimated by using the age-redshift relation obtained from each sub-sample, and its value ranges from \( 89^{+9}_{-7} \text{ km s}^{-1} \text{ Mpc}^{-1} \), \( 83^{+8}_{-9} \text{ km s}^{-1} \text{ Mpc}^{-1} \), and \( 74^{+5}_{-7} \text{ km s}^{-1} \text{ Mpc}^{-1} \) to \( 65^{+8}_{-7} \text{ km s}^{-1} \text{ Mpc}^{-1} \) for the four sub-samples with velocity dispersions from low to high, respectively. The large value of the \( H_0 \) estimated from the sub-samples with low velocity dispersion is probably due to systematic bias, which can be as high as \(~\sim 20\%)\). Using the age-redshift relations obtained from the two sub-samples with high velocity dispersions or the sub-sample with the largest velocity dispersion, we find \( H_0 = 74^{+5}_{-7} \text{ km s}^{-1} \text{ Mpc}^{-1} \) or \( H_0 = 65^{+8}_{-7} \text{ km s}^{-1} \text{ Mpc}^{-1} \) if assuming a spatially flat ΛCDM cosmology, which may be less affected by the systematic bias, close to the true \( H_0 \), and are very consistent with the best estimates using other techniques. However, it needs to be tested further whether those most massive galaxies are truly passively evolving or not.

In summary, we have demonstrated that the age-redshift relation of quiescent galaxies can be reliably estimated by using the full spectral fitting method if the S/N of their spectra is sufficiently high. We conclude that some cosmological parameters, such as the Hubble parameter, can be constrained with considerable accuracy through the age-redshift relation obtained from the most massive LRGs, which is totally independent of other methods. With future surveys like BOSS, the Hubble parameter may be tightly constrained by the age-redshift relation obtained from the most massive quiescent LRGs.

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