ULIRGs are classified according to the dominance of starburst or active galactic nucleus (AGN) components. We conducted a stellar population analysis for a sample of 160 ULIRGs to study the evolution of ULIRGs. We found that the dominance of intermediate-age and old stellar populations increases along the sequence of H II-like ULIRGs, Seyfert–H II composite ULIRGs, and Seyfert 2 ULIRGs. Consequently, the typical mean stellar age and stellar mass increase along the sequence. Comparing the gas mass estimated from the CO measurements to the stellar mass estimated from the optical spectra, we found that the gas fraction is anti-correlated with stellar mass. Even so, the total masses of H II-like ULIRGs with small stellar masses and a large fraction of gas are not comparable to the small masses of Seyfert 2 ULIRGs. This indicates that H II-like ULIRGs with small stellar masses have no evolutionary connections with massive Seyfert 2 ULIRGs. Only massive ULIRGs may follow the evolution sequence toward AGNs, and massive H II-like ULIRGs are probably in an earlier stage of the sequence.

Key words: galaxies: active – galaxies: evolution – galaxies: starburst – galaxies: stellar content

Online-only material: color figures

1. INTRODUCTION

ULIRGs are classified according to the dominance of starburst or AGN components; namely, they are H II-like ULIRGs, LINER ULIRGs, Seyfert–H II composite ULIRGs, and Seyfert 2 ULIRGs. Sanders et al. (1988a, 1988b) proposed an evolutionary scenario of ULIRGs from cool ULIRGs to warm ULIRGs and finally to quasars. The cool ULIRGs have \( f_{25}/f_{60} \leq 0.2 \) and are mostly star-forming galaxies (Heckman et al. 1987), i.e., the H II-like galaxies. Here, \( f_{25} \) and \( f_{60} \) are flux densities at 25 \( \mu m \) and 60 \( \mu m \), respectively. The warm ULIRGs have \( f_{25}/f_{60} > 0.2 \) and usually host an AGN (de Grijs et al. 1985; Beichman et al. 1986). ULIRGs are important to understand the evolution of merger galaxies and the possible connections between starbursts and AGNs. Further imaging and spectroscopy studies (e.g., Surace et al. 1998; Surace & Sanders 1999; Surace et al. 2000; Lipari et al. 2003; Schweitzer et al. 2006; Netzer et al. 2007; Veilleux et al. 2009) and numerical simulations (e.g., Kormendy & Sanders 1992; Springel et al. 2005; Naab et al. 2006) support this evolutionary scenario. However, this standard evolution sequence is questioned by Colina et al. (2001), Genzel et al. (2001), Tacconi et al. (2002), and Rodríguez Zaurín et al. (2010).

If the standard evolutionary scenario is true, ULIRGs should experience continual conversion of gas components to stellar populations during their lifetimes. ULIRGs in the earlier evolutionary stage are expected to possess more gas and young stars, fewer old stellar populations, smaller stellar mass, and larger gas mass fraction compared to those of ULIRGs in a later evolutionary stage. There should be enough gas in early-stage ULIRGs to be converted into stars when they evolve to a later stage and acquire a larger stellar mass.

The stellar population analysis of ULIRGs can shed light on ULIRG evolution. Previous, similar analyses were only carried out on very small samples (e.g., Canalizo & Stockton 2000a, 2000b, 2001; Rodríguez Zaurín et al. 2007, 2008; Soto & Martin 2010). A slightly larger sample of 36 local ULIRGs was studied by Rodríguez Zaurín et al. (2009, 2010). In contrast to the standard evolutionary scenario, their stellar population analysis, based on optical spectra, exhibited no significant differences between stellar ages among the H II-like, LINER, and Seyfert 2 ULIRGs. Note that the physical parameters of ULIRGs are rather scattered (e.g., Veilleux et al. 2009); therefore, the possible evolution of ULIRGs cannot be revealed if only a small sample is analyzed.

In this work, we analyze the spectra of 160 ULIRGs available from the Sloan Digital Sky Survey (SDSS; Abazajian et al. 2009) for stellar populations. In Section 2, we introduce our ULIRG sample. The stellar population analysis of the sample is presented in Section 3. In Section 4, we discuss the inferred stellar age, mass, and gas for different types of ULIRGs. Several factors that affect our analysis are discussed in Section 5, and conclusions are given in Section 6.

In this paper, we adopt \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \), \( \Omega_m = 0.3 \), and \( \Omega_\Lambda = 0.7 \).

2. THE ULIRG SAMPLE
and the Infrared Astronomical Satellite (IRAS) Faint Sources Catalog (Moshir et al. 1992). They are cross-checked with the NASA/IPAC Extragalactic Database (NED) and SDSS images. We found that 38 of them are incorrect identifications of ULIRGs, due to either the known redshift of a ULIRG in the NED not being consistent with the redshift from the SDSS database or an obviously large, bright galaxy nearby listed as an IRAS source but with a mismatched SDSS redshift. The spectra of 360 identified ULIRGs are then fitted and classified (Hou et al. 2009). Among them, 73 ULIRGs have broad lines and are of Type 1, and 287 objects are narrow-line ULIRGs. We will not examine Type 1 ULIRGs for stellar population studies in this paper because their spectra are dominated by strong AGN features (e.g., the power-law continuum, strong and broad emission lines, strong Fe II features).

Based on the line ratios in the Baldwin–Phillips–Terlevich (BPT) diagrams (Baldwin et al. 1981; see Figure 1; Kewley et al. 2006), 185 of 287 narrow-line ULIRGs are further classified as 32 H II-like ULIRGs, 77 Seyfert–H II composite ULIRGs, 48 Seyfert 2 ULIRGs, 6 LINER ULIRGs, and 22 ambiguous objects. We omitted the other 102 narrow-line ULIRGs from stellar population analysis because one or more lines are either redshifted outside the wavelength range or do not have a good signal-to-noise ratio for reliable line fittings, hence they cannot be classified with the BPT diagrams. We also discarded 22 ambiguous ULIRGs for our analysis because they are shown as one type in one BPT diagram but another type in the other diagram(s). Three Seyfert–H II composite ULIRGs were discarded because more than half of the pixels in their SDSS spectra were masked (bad). Therefore, we will study the stellar populations of 160 well-classified ULIRGs. Their redshift distribution is shown in Figure 2.

In Figure 3, we show the combined spectra for four types of narrow-line ULIRGs. The spectrum of every ULIRG is first normalized by the median flux in the wavelength range of 4010–4060 Å. The combined spectrum is the weighted mean of the normalized spectra according to their signal-to-noise ratio in the wavelength range of 5300–5800 Å in the rest frame. The combined spectrum clearly shows that along the sequence of H II-like, Seyfert–H II composite, Seyfert 2, and LINER ULIRGs, the normalized continuum fluxes below 4000 Å decrease and the fluxes above 4000 Å increase, which roughly indicates that the fraction of old stellar populations increases along the sequence.

3. STELLAR POPULATION ANALYSIS

Stellar population analysis is an important tool to study star formation in galaxies and the evolution of galaxies. It has been applied to various types of galaxies, e.g., H II galaxies (e.g.,
Schmitt et al. 1996; Westera et al. 2004), AGNs (e.g., Cid Fernandes et al. 2004a, 2004b), infrared galaxies (Chen et al. 2009, 2010), and ULIRGs (e.g., Rodriguez Zaurín et al. 2010; Meng et al. 2010). Here, we use it for a large ULIRG sample to study the evolution sequence of ULIRGs.

We noticed that the fiber diameter of the SDSS spectrograph is 3′′, corresponding to ~3 kpc for a galaxy at redshift z ~ 0.05 or ~18 kpc at z ~ 0.25. For any galaxies with different redshifts, the observed spectrum comes from central regions of different sizes. We use the software STARLIGHT (version 04; Cid Fernandes et al. 2005; Mateus et al. 2006; Asari et al. 2007) to analyze the stellar populations of ULIRGs in the central regions. We will discuss the aperture effect later.

The STARLIGHT program fits an observed galaxy spectrum \( O(\lambda) \) to a combination of \( N \) simple stellar populations (SSPs). The intrinsic extinction due to the foreground dust in the host galaxy is considered and parameterized by the \( V \)-band extinction \( A_V \). The line-of-sight stellar motions are modeled by a Gaussian distribution, \( G(v_0, \sigma_v) \), centered at the velocity \( v_0 \) and with the dispersion \( \sigma_v \). The modeled spectrum \( M(\lambda) \) is described as

\[
M(\lambda) = M_{\lambda_0} + \sum_{j=1}^{N} x_j b_j(\lambda) \otimes G(v_0, \sigma_v) r(\lambda),
\]

where \( M_{\lambda_0} \) is the synthetic flux normalized at \( \lambda_0 \), \( x_j \) is the fractional contribution of the \( j \)th SSP to the model flux at \( \lambda_0 \), \( b_j(\lambda) \) is the normalized spectrum of the \( j \)th SSP, and \( r(\lambda) = 10^{-0.4(A(\lambda) - A_{\lambda_0})} \) is the reddening term. The best fitting is to search for the minimum of \( \chi^2 = \sum j [(O(\lambda) - M(\lambda)) \cdot w(\lambda))^2] \), where \( w(\lambda) \) is the weight factor and \( w(\lambda)^{-1} \) is the uncertainty of observed spectrum \( O(\lambda) \) given in the SDSS database. We used a base of \( N = 45 \) SSPs, with different ages and metallicities, from the evolution synthesis models of Bruzual & Charlot (2003), and adopted the initial mass function from Chabrier (2003), the Padova 1994 evolutionary tracks (Alongi et al. 1993; Bressan et al. 1993; Fagotto et al. 1994; Girardi et al. 1996), and the STELIB library (Le Borgne et al. 2003). The base comprises a star population with 15 different ages between 1 Myr and 13 Gyr at each of the three metallicities: 0.2, 1, and 2.5 \( Z_\odot \). Here, \( Z_\odot \) is the metallicity of the Sun. The reddening law of Calzetti et al. (1994) is adopted in the fitting.

We obtained the spectra of 160 ULIRGs with uncertainties from SDSS. We corrected the Galactic reddening effect and converted each spectrum to the rest frame. The STARLIGHT was used to fit the continuum and absorption features. The emission lines and sky lines are discarded in the mask file of STARLIGHT. The spectrum pixels without error measurements or with negative flux values are excluded. In addition, the Na D doublet, 5870–5905 Å, and the other three bands, 6845–6945 Å, 7550–7725 Å, and 7165–7210 Å, are also masked due to the bugs in the SSP model (Le Borgne et al. 2003) or the large fitting residual in some regions (Mateus et al. 2006). Considering the redshift coverage of our sample, we restricted the fitting in the wavelength range 3400–6700 Å for each spectrum. A power-law component, \( F(\lambda) \propto \lambda^{\alpha} \), is used in the STARLIGHT to account for the AGN contribution to the observed continuum (Cid Fernandes et al. 2004a, 2005), and \( \alpha = -1.5 \) (Richstone & Schmidt 1980; Cid Fernandes et al. 2004a) is adopted. The random Markov Chains method was used in the STARLIGHT, which needs an integer seed input. Different seeds slightly affect the fitting results. Following Meng et al. (2010), we fit each spectrum 100 times with different seeds. The final fitted parameters are the mean values from 100 runs. One example of the spectrum fitting is shown in Figure 4.

The stellar populations in a galaxy can be described by the fractions of young stars of \( t_j < 10^8 \) yr, intermediate-age stars of \( 10^8 \) yr \( \leq t_j \leq 10^9 \) yr, and old stars of \( t_j > 10^9 \) yr (Cid Fernandes et al. 2005). Here, \( t_j \) is the age of the \( j \)th SSP. We obtain the fractional contributions of these three stellar populations of different ages and the power-law contribution to the model spectrum flux at 4020 Å. For each type of ULIRG, we obtain the mean, given in Table 1. Because there are only a small number (only six) of LINER ULIRGs, we will not discuss their stellar population below.

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**Figure 4.** One example of spectrum fitting. We show the normalized observed spectrum \( F_\lambda / F_{\lambda_0,020} \) (black) and the modeled spectrum (green) in the upper-left panel and the residual in the lower-left panel. The key parameters from the fitting are: \( \chi^2 \), mean stellar age, stellar mass, and extinction, which are given on the right side. The fractional contribution to the model flux \( x_j \) and the stellar mass \( \mu_j \) of the \( j \)th SSP are plotted on the right.

(A color version of this figure is available in the online journal.)
Figure 5. Fraction distributions of stellar populations for different types of ULIRGs from top to bottom.

| Type          | Young (<10^8 yr) | Intermediate Age (10^8–10^9 yr) | Old (>10^9 yr) | Power Law |
|---------------|------------------|----------------------------------|----------------|-----------|
| H II-like     | 0.622            | 0.261                            | 0.117          |           |
| Composite     | 0.355            | 0.408                            | 0.138          | 0.099     |
| Seyfert 2     | 0.177            | 0.500                            | 0.198          | 0.125     |
| LINER         | 0.112            | 0.579                            | 0.261          | 0.048     |

The fractional contributions (i.e., \(x_j\) in Equation (1)) of these stellar populations to the modeled total stellar emission are shown in Figure 5. We found that they are very different for different types of ULIRGs. The young stellar population is more dominant for the H II-like ULIRGs than the composite and Seyfert 2 ULIRGs. The stellar populations of intermediate-age and old stars are more dominant in the Seyfert 2 ULIRGs than in the H II-like and composite ULIRGs. The older stellar populations and the significant power-law component in Seyfert 2 ULIRGs suggest that they are at a more evolved stage in the evolution track toward AGNs. The fractional distribution of stellar populations of composite ULIRGs suggests that they are at the transitional stage between H II-like and Seyfert 2 ULIRGs.

4. PHYSICAL PARAMETERS OF DIFFERENT TYPES OF ULIRGs

The results of the stellar population analysis of ULIRGs suggest the possible evolution sequence from H II-like to composite to Seyfert 2 ULIRGs. The H II-like ULIRGs are at an earlier evolutionary stage, the composite ULIRGs are at a transitional stage, and the Seyfert 2 ULIRGs are at a more evolved stage. In this section, we discuss the physical parameters of ULIRG galaxies, namely, the mean stellar age, stellar mass, and gas mass, which may be related to the possible evolutionary sequence.

4.1. Mean Stellar Age

Based on the results of the stellar population analysis, we can get the light-weighted mean stellar age (Cid Fernandes et al. 2005):

\[
\langle \log t_* \rangle_L = \sum_{j=1}^{N} x_j \log t_j, \tag{2}
\]

which is an indicator of star formation history. The other such indicator is \(D_n(4000)\), obtained by the MPA/JHU group, which is defined as the average flux density ratio for the bands 3850–3950 Å and 4000–4100 Å (Bruzual 1983; Balogh et al. 1999). We compared them (Figure 6) and found that they are well correlated, with a Spearman rank-order correlation coefficient of \(r_s = 0.90\). The best fitting is

\[
D_n(4000) = -(0.24 \pm 0.06) + (0.18 \pm 0.01)\langle \log t_* \rangle_L. \tag{3}
\]
The distributions of \( \langle \log t_{\mathrm{dyn}} \rangle \) for \( \text{H}\alpha\)-like, composite, and Seyfert 2 ULIRGs are shown in the right panels of Figure 6. The mean values of \( \langle \log t_{\mathrm{dyn}} \rangle \) for three types of ULIRGs—\( \text{H}\alpha\)-like, composite, and Seyfert 2—are 7.6, 8.0, and 8.4, with standard deviations of 0.4, 0.5, and 0.4, respectively. The increase in these mean values is consistent with the evolutionary sequence from \( \text{H}\alpha\)-like ULIRGs and composite ULIRGs to Seyfert 2 ULIRGs. The young stellar population \( (t_j < 10^8 \text{ yr}) \) is always present in ULIRGs (see Figure 6) due to the enhanced star formation in the galaxy-merging process. The large deviations of \( \langle \log t_{\mathrm{dyn}} \rangle \) for these types of ULIRGs are probably caused by the complex dynamical process and star formation history of merger systems. Therefore, both \( \langle \log t_{\mathrm{dyn}} \rangle \) and \( D_{\odot}(4000) \) are only a rough age indicator of ULIRGs.

### 4.2. Stellar Mass

ULIRGs experience the continual conversion of gas to stars. The stellar masses in ULIRGs are mostly contributed by intermediate-age and old stars (see \( \mu_j \) distribution in Figure 4), and thus are a possible indicator of ULIRG evolution.

The stellar mass of a ULIRG in the central 3\( " \) of the SDSS fiber spectrograph, \( M_{\text{fiber}} \), in units of \( M_\odot \), can be estimated from the stellar mass parameter \( M_{\text{cor, tot}} \) given by STARLIGHT\(^6\):

\[
M_{\text{fiber}} = M_{\text{cor, tot}} \times 10^{-17} \times 4\pi d^2 \times (3.826 \times 10^{33})^{-1},
\]

where \( d \) is the luminosity distance in cm. The aperture effect must be corrected by using the SDSS Petrosian magnitude (Blanton et al. 2001), \( m_{\text{Petro}} \), and fiber magnitude, \( m_{\text{fiber}} \), so that the estimated mass can be a constant fraction of the total mass of galaxies, independent of their positions and redshifts. The aperture correction factor for each SDSS photometric band is roughly given by (Hopkins et al. 2003)

\[
A = 10^{-0.4(m_{\text{Petro}} - m_{\text{fiber}})}.
\]

The spectra of ULIRGs fitted for the stellar population analysis roughly cover the \( u, g, r, i, \) and \( z \) bands. We take the average of the correction factors of these bands, weighted by the uncertainty \( \delta A_j \):

\[
\bar{A} = \sum_{j=u,g,r,i,z} \frac{A_j}{\delta A_j} / \sum_{j=u,g,r,i,z} 1 / \delta A_j ,
\]

to correct the aperture effect for each ULIRG. The corrected stellar mass, \( M_* \), in units of \( M_\odot \), which is a constant fraction of the total stellar mass in a ULIRG, then can be estimated by

\[
\log(M_*) = \log(M_{\text{fiber}}) + \log(\bar{A}).
\]

We obtained \( M_* \) for the ULIRGs in our sample. To show the uncertainty of such corrected mass estimates from the fiber spectrum of the central part of ULIRGs, we compared them to the total stellar masses of whole galaxies estimated by the MPA/JHU group from the SDSS photometric data of \( u, g, r, i, \) and \( z \) bands (see footnote 5 for their Web site; Salim et al. 2007). We found that they are well correlated (see Figure 7) with the Spearman rank-order correlation coefficient, \( r_s = 0.80 \), which means that the aperture-corrected stellar masses calculated from the STARLIGHT parameters are statistically consistent with those estimated masses of the whole galaxies. The data scatter in Figure 7 roughly indicates the uncertainty of the mass estimates.\(^7\)

The most important feature in Figure 7 is the obviously different distributions of \( \log M_* \) for \( \text{H}\alpha\)-like, composite, and Seyfert 2 ULIRGs, from the masses estimated from spectral and photometric analyses. The means of the \( \log M_* \) distribution for the mass from the spectral analysis for three types of ULIRGs, \( \text{H}\alpha\)-like, composite, and Seyfert 2, are 10.70, 11.17, and 11.40, with standard deviations of 0.45, 0.38, and 0.25, respectively. Seyfert 2 ULIRGs always have \( M_* \lesssim 10^{10.6} M_\odot \), larger than the masses in \( \text{H}\alpha\)-like and composite ULIRGs (see Figure 7). The increase in stellar masses along the sequence from \( \text{H}\alpha\)-like to composite to Seyfert 2 ULIRGs is consistent with the standard evolutionary scenario of ULIRGs.

### 4.3. Gas in ULIRGs

We noticed that Seyfert 2 ULIRGs mostly have \( M_* > 10^{10.6} M_\odot \) (see Figure 7). However, many \( \text{H}\alpha\)-like ULIRGs or composite ULIRGs have much smaller stellar mass, \( M_* < \)

\(^6\) http://www.starlight.ufsc.br/papers/Manual_StCv04.pdf

\(^7\) In our sample, the total dynamical masses of four ULIRGs, F09039+0503, F13428+5608, F15250+3609, and F15327+2340, can be calculated from the central velocity dispersion (Dasarya et al. 2006). As suggested by the referee, we got \( M_{\text{dyn}}(M_*) \) of 10.9, 11.1, 10.9, and 11.2 and plotted them in Figure 7 for comparison with the total stellar masses derived from the stellar population analysis. Considering the typical gas content of ULIRGs of \(~ 10^{10} M_\odot \) (see Section 4.3), we think that different kinds of mass estimates are consistent with each other.
The gas mass from the CO measurements (the upper panel of Figure 8) and the gas fraction of total mass (the lower panel of Figure 8) seem to be anti-correlated with the stellar masses of the ULIRGs ($r_s = -0.60$ and $r_s = -0.88$), if we do not consider the outlier F08572+3915. The anti-correlation is only marginally significant because of the small sample of data available. The possible anti-correlation is preserved for the gas fraction and stellar mass estimated from photometric analysis.

H ii-like ULIRGs with a gas fraction $> 10\%$ follow the anti-correlation. Gas in ULIRGs may be converted eventually to stars. About half of H ii-like ULIRGs have a stellar mass less than $10^{10.6} M_\odot$ (see Figure 7). H ii-like ULIRGs in Figure 8 have a gas mass less than $<10^{10} M_\odot$ and a gas fraction less than $<15\%$. For those less massive H ii-like ULIRGs, there is not enough gas to form stars, and they are not massive enough in total to evolve to Seyfert 2 ULIRGs ($M_* > 10^{11} M_\odot$). Only massive H ii-like ULIRGs ($M_* > 10^{10.6} M_\odot$) may follow the standard evolutionary scenario of ULIRGs.

5. DISCUSSION

Stellar population analysis for narrow-line ULIRGs shows the systematic changes in stellar age and mass along the sequence from H ii-like to composite to Seyfert 2 ULIRGs. Here, we discuss several factors that may affect the results of stellar population analysis.

5.1. Power-law AGN Contribution to the Spectral Continuum

During the stellar population analysis via STARLIGHT, we used a power-law component, $F(\lambda) \propto \lambda^\alpha$, with a fixed $\alpha = -1.5$ to represent the AGN contribution to the continuum spectrum (Cid Fernandes et al. 2004a, 2005). The AGN contribution is significant for composite, Seyfert 2, and LINER ULIRGs, but not for H ii-like ULIRGs. However, the index for the power-law contribution, $\alpha$, could be -2.0 to -1.0 (see Natali et al. 1998). To evaluate the influence of the power-law index $\alpha$ in the stellar population analysis, we re-do the fittings to all spectra of all 160 ULIRGs with different values of $\alpha$, -1.0, -1.25, -1.5, -1.75, and -2.0, 10 times each with different random seeds. We found that the change of $\chi^2$ by different $\alpha$ values is less than $\sim 1\%$, which is not adequate to use $\chi^2$ to judge the best $\alpha$ for fitting. Changes in the stellar mass and mean stellar age caused by different $\alpha$ are always less than 10%. Therefore, the adopted power-law index of $\alpha = -1.5$ is suitable for the stellar population analysis.

5.2. Different Bases of Simple Stellar Populations

The evolutionary population synthesis method is mainly based on the stellar evolution model. We used a base of 45 SSPs for the stellar population analysis. The different bases of SSPs may affect the fitting results. Following the same procedures described in Section 3, we re-do the fittings to the spectra for 160 ULIRGs with a base of 150 SSPs (25 ages and six metallicities) and a base of 15 SSPs (15 ages and one metallicity) extracted from Bruzual & Charlot (2003). Although the fractional contribution of each stellar population component does not remain the same and may vary by about 20%, the mean stellar age and stellar mass do not change significantly—less than $\sim 10\%$. Their distributions are consistent with those shown in Section 4 for different types of ULIRGs.
5.3. The Aperture Effect

We conducted a stellar population analysis for the SDSS spectrum of the central 3′ region. The aperture effect has been corrected for the mass estimates, but not for the mean stellar age. To evaluate the aperture effect, we divided the ULIRG sample into several redshift bins and re-did the analysis. In each redshift bin, the linear size of the aperture is almost the same for all ULIRGs, and the aperture effect is likewise almost the same. Here, we take the redshift bin of 0.20 < z < 0.24 as the example; it has the largest number of ULIRGs in the bin. As shown in Figure 9, the correlation between $D_e$ and $(\log t_\lambda)_L$ stays the same as the entire sample of ULIRGs. The distributions of $(\log t_\lambda)_L$ for H II-like, composite, and Seyfert 2 ULIRGs in the right-hand panel of Figure 9 also show similar offsets to the entire sample shown in Figure 6. The same behaviour is found for other redshift bins. Therefore, we believe that the aperture effect does not influence our results.

5.4. Extinction

In the stellar population synthesis model of STARLIGHT (Cid Fernandes et al. 2005; Mateus et al. 2006), extinction was considered as a foreground screen and fitted by one parameter, the V-band extinction $A_V$. But the young, intermediate, and old stellar populations have different extinctions in a galaxy. Particularly, the young stellar population was more extinguished than the others, being in places that were very obscured by dust. Different $A_V$ values should be assumed for the different populations. However, this cannot be achieved in the model.

From the stellar population analysis of ULIRGs, the distributions of extinction parameter $A_V$ given by the STARLIGHT model for H II-like ULIRGs, composite ULIRGs, and Seyfert 2 ULIRGs are very similar, as shown in Figure 10. The means of $A_V$ for three types of ULIRGs are 0.91, 1.09, and 0.92, with standard deviations of 0.28, 0.39, and 0.36, respectively. The $A_V$ extinction parameters of H II-like and Seyfert 2 ULIRGs on average are slightly smaller than those of composite ULIRGs, consistent with Vieilleux et al. (2009).

The distributions of the mean stellar age for different ULIRGs discussed in Section 4 are probably not influenced by the simplified treatment of extinction in the model. The mean stellar age given by the stellar population synthesis model is well correlated with results of $D_e$ (see Figure 6), which verifies the mean age. On the other hand, in ULIRGs, the stellar mass is dominated by old stellar populations (see the right-hand panels of Figure 4), which are expected to suffer less from extinction than young stellar populations. Therefore, the simplified extinction in the model probably does not affect our conclusions about ULIRGs.

6. CONCLUSIONS

We analyzed the stellar populations for a sample of 160 narrow-line ULIRGs. They are optically classified as 32 H II-like ULIRGs, 74 Seyfert–H II composite ULIRGs, and 6 LINER ULIRGs, and 48 Seyfert 2 ULIRGs. We found that along the sequence of H II-like, composite, and Seyfert 2 ULIRGs, both the mean stellar age and the aperture-corrected stellar mass increase. This supports the standard evolutionary scenario of ULIRGs in which the Seyfert 2 ULIRGs are in a late stage of ULIRG evolution, with an old mean stellar age and large stellar mass ($\sim 10^{11} M_\odot$), while H II-like ULIRGs are in an early stage, with a young mean stellar age and a small stellar mass.

Do H II-like ULIRGs have enough gas for starbursts, so that they can evolve to Seyfert 2 ULIRGs? We collected CO measurements from 10 ULIRGs that have the SDSS spectra for the stellar population analysis. The gas mass fractions seem to be anti-correlated with the stellar masses of massive ULIRGs. All ULIRGs in our sample with CO measurements have a gas mass less than $\sim 10^{10} M_\odot$. H II-like ULIRGs with a small stellar mass ($M_* < 10^{10.4} M_\odot$) do not possess enough gas for starbursts, and therefore have no evolutionary connections with massive Seyfert 2 ULIRGs. We conclude that only massive H II-like ULIRGs and composite ULIRGs may follow the evolutionary sequence toward AGNs.

We thank the referee for helpful comments and Drs. XiaoYan Chen, XianMin Meng, and Ran Wang for discussions and suggestions. The authors are supported by the National Natural Science Foundation of China (10821061, 10833003, and 11033001) and the National Key Basic Research Science Foundation of China (2007CB815403 and 2007CB815405). The STARLIGHT project is supported by the Brazilian agencies CNPq, CAPES, and FAPESP and by the France–Brazil CAPES/Cofecub program. Funding for the SDSS has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, the Max Planck Society, and the Higher Education Funding Council for England. The SDSS Web site is http://www.sdss.org.

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