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Luminous infrared galaxies (LIRGs) and ultraluminous infrared galaxies (ULIRGs) are galaxies with infrared (IR) luminosities and space densities are both respectively. Their IR luminosities and space densities are both comparable to QSOs (Sanders & Mirabel 1996). These galaxies always show signs of tidal interaction and merger, and the interaction rate is observed to increase with IR luminosity (Zou et al. 1991; Clements et al. 1996; Murphy et al. 1996; Wu et al. 1998; Veilleux et al. 2002). Nearly all ULIRGs are strong interaction or merger systems (Kim et al. 2002).

It is widely accepted that galaxy interactions and mergers trigger extreme nuclear activity, as well as more widespread starburst (SB; Toomre & Toomre 1972; Larson & Tinsley 1978). The molecular gas concentrations of ULIRGs are in their central kiloparsec regions (Downes & Solomon 1998) and have the ability to form stars with densities comparable to those in elliptical galaxies (Tacconi et al. 2002). Kormendy & Sanders (1992) proposed that ULIRGs may evolve into elliptical galaxies through merger-induced, dissipative collapse. Structural, kinematic, and photometric properties of ULIRGs show that they originate from major mergers and they fall, on average, on the fundamental plane of moderate-mass ellipticals (stellar mass $\sim 10^{10}$–$10^{11} M_\odot$), but are well offset from giant ellipticals, suggesting that ULIRG mergers are ellipticals in formation (Genzel et al. 2001; Tacconi et al. 2002; Dasyra et al. 2006a).

Observations revealed that a large fraction of LIRGs/ULIRGs show spectral characteristics of Seyfert galaxies (Wu et al. 1998; Kewley et al. 2001). The fraction increases dramatically with IR luminosity, and among ULIRGs, the fraction is about 50% (Kim et al. 1998; Veilleux et al. 1999; Cao et al. 2006; Yuan et al. 2010; Nardini et al. 2010), or even higher ($\sim 70%$; Nardini et al. 2010). Though many of these sources are dominated by active galactic nuclei (AGNs) in their bolometric luminosity (Boller et al. 2002; Nandra & Iwasawa 2007), in most cases the predominance of SB over AGNs is proposed (Gu et al. 1997; Lutz et al. 1999; Franceschini et al. 2003); Nardini et al. (2008) proposed a fraction of $\sim 85%$.

1. INTRODUCTION

Luminous infrared galaxies (LIRGs) and ultraluminous infrared galaxies (ULIRGs) are galaxies with infrared (IR) luminosities $L_{\text{IR}} = L(8–1000 \mu m) > 10^{11} L_\odot$ and $L_{\text{IR}} > 10^{12} L_\odot$, respectively. Their IR luminosities and space densities are both comparable to QSOs (Sanders & Mirabel 1996). These galaxies always show signs of tidal interaction and merger, and the interaction rate is observed to increase with IR luminosity (Zou et al. 1991; Clements et al. 1996; Murphy et al. 1996; Wu et al. 1998; Veilleux et al. 2002). Nearly all ULIRGs are strong interaction or merger systems (Kim et al. 2002).

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Observations revealed that a large fraction of LIRGs/ULIRGs show spectral characteristics of Seyfert galaxies (Wu et al. 1998; Kewley et al. 2001). The fraction increases dramatically with IR luminosity, and among ULIRGs, the fraction is about 50% (Kim et al. 1998; Veilleux et al. 1999; Cao et al. 2006; Yuan et al. 2010; Nardini et al. 2010), or even higher ($\sim 70%$; Nardini et al. 2010). Though many of these sources are dominated by active galactic nuclei (AGNs) in their bolometric luminosity (Boller et al. 2002; Nandra & Iwasawa 2007), in most cases the predominance of SB over AGNs is proposed (Gu et al. 1997; Lutz et al. 1999; Franceschini et al. 2003); Nardini et al. (2008) proposed a fraction of $\sim 85%$.

From millimeter-wave CO observations and optical spectra analysis of 10 ULIRGs, Sanders et al. (1988) proposed that ULIRGs represent the dust-enshrouded stage of QSOs. They proposed a classical evolution scenario where two gas-rich spirals merge (or interact) first and the funneled gas toward the merger center triggers nuclear SB before the ignition of a dust-enshrouded AGN. When the dust has been consumed or swept away under the radiative pressure of AGN and supernovae, an optical quasar would appear. Canalizo & Stockton (2000, 2001) selected a sample of nine low-redshift QSOs that fall onto the intermediate position between the regions occupied by ULIRGs and QSOs in the far-infrared (FIR) color–color diagram. All these nine transition QSOs are undergoing tidal interactions and eight are major mergers. All of them also show strong recent star formation activity within 300 Myr. Canalizo & Stockton proposed a model involving a dust cocoon that initially surrounds the QSO nuclear regions, which can account for all the observed and derived properties in transition objects. This is consistent with the idea of Sanders et al. (1988), who suggested that either at least some ULIRGs evolve to become classical QSOs, or some QSOs are born under the conditions as ULIRGs and their lifetimes as QSOs last $\lesssim 300$ Myr. Most of these transition QSOs are also ULIRGs. Like Kawakatu et al. (2006), we refer to QSOs and Seyfert 1 galaxies selected from ULIRGs as type 1 ULIRGs (or IR QSOs in Zheng et al. 2002). Kawakatu et al. (2006) and Hou et al. (2009) find that type 1 ULIRGs are the early phase of black hole (BH) growth and they are QSOs in formation.

The case may be as Colina et al. (2001) had proposed that high-luminosity QSOs would be the end point in the merging process of massive ($> L^*$) disk galaxies, while cool ULIRGs, which would be the end product in the merging of two or more low-mass ($0.3L^*–0.5L^*$) disk galaxies, would not evolve into

IRAS F13308+5946 was observed by the IRAS, 2MASS All-Sky Extended Source Catalog Version 2.0. Flux densities at three wavebands, 12, 25, and 100 μm, are upper limits. Only the one at 60 μm, which is 0.2615 Jy, has a high-quality record (FQUAL = 3). Therefore, the IR luminosity \( L_{\text{IR}}(8–1000 \mu m) \) is calculated by (Lawrence et al. 1989; Bushouse et al. 2002; Arribas et al. 2004; Wang 2008)

\[
L_{\text{IR}}(8–1000 \mu m) \approx 2L_{60 \mu m},
\]

where \( L_{60 \mu m} \) is the luminosity at 60 μm. The derived IR luminosity is \( L_{\text{IR}}(8–1000 \mu m) = 10^{11.56} L_\odot \). For comparison, we also calculate the IR luminosity using an IR spectral energy distribution (SED) model. Since IRAS F13308+5946 is not only an SB galaxy, but also has a type 1.5 AGN (see Section 3.4), we adopt the SED model established by Siebenmorgen et al. (2004) for galaxies with both AGN and SB components. After the SED model was scaled to the observed 60 μm flux, the integrated IR luminosity is calculated to be \( L_{\text{IR}}(8–1000 \mu m) = 10^{11.55} L_\odot \), exactly the same as the one above.

We also calculate the IR luminosity in the range 1–1000 μm through 60 μm and 100 μm fluxes (Lonsdale-Persson & Helou 1987; Calzetti et al. 2000):

\[
F_{\text{FIR}}(40–120 \mu m) = 1.26 \times 10^{-14} [2.58 f_{60 \mu m} + f_{100 \mu m}] \text{[Wm}^{-2}],
\]

and

\[
F_{\text{IR}}(1–1000 \mu m) = (1.75 \pm 0.25) F_{\text{FIR}}(40–120 \mu m),
\]

\( L_{\text{IR}}(1–1000 \mu m) = 4\pi D_L^2 F_{\text{IR}}(1–1000 \mu m) L_\odot. \)

The derived IR luminosity \( L_{\text{IR}}(1–1000 \mu m) = 10^{11.18 \pm 0.07} L_\odot \) can be used as an upper limit, and it is consistent with the result if we only adopt \( f_{60 \mu m} \). Therefore, we adopt \( L_{\text{IR}}(8–1000 \mu m) = 10^{11.56} L_\odot \) as the IR luminosity throughout this paper. We do not do \( K \)-corrections on IR fluxes, because the correction factor is small (~5% adopting SB SED model from Siebenmorgen & Krügel 2007) enough to neglect, compared with the uncertainty of IR luminosity calculation and the scatter among different \( K \)-correction methods.

**2.2. Optical and Near-infrared**

IRAS F13308+5946 was also observed by SDSS imaging camera and spectrograph. The \( u, g, r, i, z \)-band images and the spectrum are from the SDSS Data Release 5 (DR5). Each band was observed with an exposure time of 53.9 s, and the pixel size is 0′.396 on the sky. The spectrum has been corrected for Galactic reddening of \( E(B - V) = 0.015 \) and redshift of \( z = 0.171 \), so the rest-frame wavelength coverage is 3258–7852 Å.

The SDSS spectrum shows a typical feature of a type 1 AGN. The \( i \)-band absolute magnitude of \( M_i = -22.564 \) satisfies the quasar criterion of \( M_i < -22.0 \) defined by Schneider et al. (2007). However, the \( B \)-band absolute magnitude is \( M_B = -21.1 \) (transferred from \( M_B = -21.8 \), which gives \( H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1} \)), and it does not satisfy the criterion for quasars of \( M_B < -22.2 \) \( (H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}) \) defined by Schmidt & Green (1983).

The larger extinction at \( B \) band could explain the inconsistency between the two bands (see also Section 3.6).

There is obvious deviation between the SDSS and IRAS positions. The IRAS 2.45σ uncertainty ellipse (corresponding to a 95% probability enclosure) with semimajor and semiminor axes of 21″ and 7″ does not embrace the optical (SDSS) position (see Figure 1). The optical source only locates within the 5σ uncertainty ellipse of IRAS position. Since there is no other bright sources within the IRAS uncertainty ellipse in either

\( \text{FIGURE 1. Source identification from IRAS and SDSS. The red ellipse is the IRAS uncertainty ellipse with 2.45σ confidence for each axis, which is plotted on the SDSS r-band image. Blue circles represent SDSS galaxies and magenta ones SDSS stars. The cyan circle marks the FIRST source in the FOV, and coincides with the galaxy IRAS F13308+5946.} \)

\footnote{The luminosity in the wavelength range 1–8 μm is estimated to be less than \( \approx 5%–10% \) of the total and negligible (Calzetti et al. 2000).}
optical and near-infrared (2MASS) bands, and IR phenomena are most related to galactic activities, we identify the object detected by IRAS, 2MASS, and SDSS as the same one. In Section 2.3, the well-known radio–FIR correlation will confirm such identification. Hereafter, we refer to the object as IRAS F13308+5946.

Figure 2 (left) gives the u-band image and the 3″ diameter fiber of the spectrograph, which covers ~10 kpc of the galaxy. Two color-map images of $u - g$ and $g - r$ are also presented. The field of view (FOV) of these images are all 25″ × 25″. These images are made after world coordinate system matching, Galactic reddening correction, and K-correction (IDL routine from Blanton et al. 2003, v4_1_4). Because the seeings at $u$, $g$, and $r$ bands are 1″, 1″, and 1″, respectively, we have to match the seeings by convolving the $r$-band image with a two-dimensional Gaussian kernel with $\sigma = 0.29$ before making the $g - r$ image. The $g - r$ image shows a color gradient indicating that the central region of the galaxy is quite blue. It could be explained by circumnuclear SB and/or AGN activity. After converting the SDSS $g - r$ color to $B - V$ color (Jester et al. 2005), we found that the $B - V$ color varies from ~0.25 at the center, to ~0.5 at the edge of the fiber aperture, and to >1 at the outskirts of the galaxy. If these variations are due to different stellar populations, the ages of the stellar populations may range from ~300 Myr to ~800 Myr (assuming solar metallicity) inside the aperture, and to >1 Gyr at the galaxy outskirt, adopting the stellar population evolution model of Bruzual & Charlot (2003), hereafter BC03). Considering local dust extinction, the $g - r$ color may be reddened, so the ages obtained above should be somewhat younger. Generally, the $u - g$ color distribution is consistent with $g - r$ color according to BC03. However, unlike $g - r$ color, the bluest region on the $u - g$ image deviates from the galaxy center. It could be attributed to the merger process.

From Figures 1 and 2, we can find characteristics of later stages of a merger. Adopting 2MASS standard isophotal photometry, the H-band absolute magnitude is $M_H = -25.7$, which is four times as luminous as $L^*$ galaxies ($M_H = -24.2$; Colina et al. 2001). Therefore, the galaxy could be a merger system of massive ($\geq L^*$) galaxies.

3. SPECTRAL ANALYSIS

3.1. Spectral Synthesis with Starlight

We use the spectral synthesis code STARLIGHT (Cid Fernandes et al. 2005) to derive stellar populations of the host galaxy. STARLIGHT fits the observed spectrum $O_\lambda$ with a model spectrum $M_\lambda$, which is made up of a pre-defined set of base spectra. There is no need to give the value of the parameters’ initial guess. It carries out the fitting with a simulated annealing plus Metropolis scheme to yield the minimum $\chi^2 = \sum (O_\lambda - M_\lambda) w_\lambda \big|_2$, where $w_\lambda$ is the error in $O_\lambda$ at each wavelength. It models $M_\lambda$ by a combination

$$M_\lambda = \sum_{j=1}^{N_\lambda} \chi_{j} \gamma_{j,\lambda} O_\lambda,$$

where $\gamma_{j,\lambda} \equiv b_{\lambda,j} \otimes G_\nu$, $b_{\lambda,j} \equiv (\frac{B_{\lambda,j}}{B_{\nu,j}})$ is the normalized flux of the $j$th spectrum, $B_{\lambda,j}$ is the $j$th component of base spectrum, $B_{\nu,j}$ is the value of the $j$th base spectrum at the normalization wavelength $\lambda_0$, $G_\nu$ is the Gaussian distribution centered at velocity $\nu$, and with dispersion $\sigma$, of the line-of-sight stellar velocity, $x_j$ is the fraction of light due to component $j$ at $\nu_0$, and $r_\lambda = 10^{-0.4(A_\lambda - A_V)}$ is the global extinction term and represented by $A_V$. The nebular and AGN emission lines can be obtained by subtracting the model spectrum from the observed one as $E_\lambda = O_\lambda - M_\lambda$.

STARLIGHT uses random Markov Chains that need to be appointed an integer seed to generate random numbers during the fitting, and if it uses different seeds, it will give different results even if the parameters are configured identically. Such difference will not change the overall population distribution significantly, but the individual component $x_j$ may vary ~10% in some cases. To obtain a statistically reliable result, we carried out fittings with a set of seeds generated by Monte Carlo sampling and adopt the mean value over all seeds for every parameter.

3.2. Parameters Determination

We take simple stellar populations (SSPs) from BC03 and a power-law spectrum of AGN (if needed) $F_\lambda \propto \lambda^{\alpha}$ as our base
spectra. To minimize the parameter space and to make the result more reliable, we adopt spectral templates with 10 ages (0.005, 0.025, 0.1, 0.29, 0.5, 0.9, 1.4, 2.5, 4, and 10 Gyr) computed with the “Padova 1994” evolutionary tracks (Alongi et al. 1993; Bressan et al. 1993; Fagotto et al. 1994a, 1994b; Girardi et al. 1996) and Chabrier (2003) initial mass function.

As a type I galaxy, it is possible that the spectrum of IRAS F13308+5946 contains a power-law component, though it is not obvious in the observed spectrum. Since STARLIGHT can include a power-law spectrum in the template base, we can carry out test fittings to confirm whether it exists and find out the value of the spectral index $\alpha$. A widely adopted AGN power-law slope ($F_{\nu} \propto \nu^{\alpha}$) over the optical and UV region is $\alpha = -0.5$ (Richstone & Schmidt 1980), while other studies have given values from $-1$ to 0 (Natali et al. 1998 and references therein), corresponding to $-2 \leq \alpha \leq -1$. We carry out test fittings with $\alpha$ varying from $-3.0$ to $-0.1$ at intervals of 0.1 to search for the power-law index, as well as additional non-power-law fittings with $\alpha = 0$.

We optimize the fitting with single metallicity SSPs. To search for the best-fit metallicity, we carry out a metallicity test with the six metallicities ($Z = 0.0001, 0.0004, 0.004, 0.008, 0.02$, and 0.05) of the BC03 model for every power-law index. After that we adopt the best-fit metallicity and power-law index for the formal fitting.

Figure 3 shows the test fitting results with different power-law indices $\alpha$ and the six metallicities. We evaluate the fitting quality by the minimum $\chi^2$, which is averaged over 25 fittings with different seeds (randomly and uniformly distributed between $-100,000$ and $100,000$). In Figure 3, the minimum $\chi^2$ set reaches its bottom at $Z = 0.008$ and $\alpha = -2.0$. This is consistent with other studies that show metallicities near solar value prevail in SB galaxies (Tadhunter et al. 2005; Pellerin & Robert 2007), and also that the power-law continuum slope falls around $\alpha = -2$ (Francis 1996; Vanden Berk et al. 2001; Letawe et al. 2007). Moreover, the power-law index does not affect the metallicity very much. We learn from Figure 3 that if we fix the metallicity value, the variation of $\chi^2$ among different power-law indices is not significant. Its influence on power-law component fraction is shown in Figure 4. These data points are all from the test fits above, but only with sub-solar metallicity ($Z = 0.4 Z_\odot$). The red unfilled diamonds with a fixed power-law index represent the AGN component fraction of 25 different integer seeds at 4020 Å. We can see from the figure that in the normal range of power-law index in the literature, say, $-2 \leq \alpha \leq -1$, the average AGN fraction is kept almost constant, and the dispersion of the average AGN fraction is far less than the one from different seeds. This result indicates that the form of the AGN component does not affect the synthesis very much, and so it will not affect the stellar component significantly.

Therefore, we take the parameters $\alpha = -2.0$, $Z = 0.008$, and 10 SSP ages for formal fitting.

### 3.3. Formal Fitting and Stellar Populations

The formal fitting involves 100 independent fittings with different seeds. Stellar absorption lines are given the weight three times larger than the continuum to emphasize the detail of the stellar component. The recognized emission lines such as [O II] λ3726+3729, [O III] λλ3742, Ne III λ3869, Hβ+[O III] λλ4959+5007, Ha+[N II] λλ6548+6583, etc., together with the Na I D5890 ISM absorption line are all masked before fitting. The blended Fe II emission-line regions, which are assigned to be 4270–4700 Å and 5100–5600 Å, are also excluded. These masked regions are illustrated in Figure 5 and are represented by the gaps of the blue curve on the left top panel. The blue curve is the error of the observed spectrum, and the inverse of the error is the weight at each wavelength in spectral fitting. The observed spectrum $O_\lambda$ and all SSP templates are normalized at wavelength $\lambda_0 = 4020$ Å before fitting.

The outcome fraction for each stellar component varies within ~10 percentage points. Such variation is insignificant for main populations. We take the mean value for each parameter as the formal fitting result, such as $x_i$, $v_*$, $\sigma_*$, $\chi^2$, etc. All these parameters are summarized in Figure 5. The left top panel shows the observed spectrum $O_\lambda$ (green), the model $M_\lambda$ (red), and the error (blue). The left bottom panel gives the residual spectrum $E_\lambda = O_\lambda - M_\lambda$. Light-weighted stellar population fractions $x_j$ are shown in the right top panel, on which the black bar on the left represents the power-law fraction without a concrete age. Mass-weighted population fractions $\mu_j$ are shown in the right
Figure 5. Spectral synthesis of IRAS F13308+5946. Left top panel: the observed spectrum $O_\lambda$ (green), the model spectrum $M_\lambda$ (red), and the error spectrum (blue), where the gaps mean the masked regime and the thrice weighted absorption lines. Left bottom panel: the residual spectrum $E_\lambda$ (purple). Right: light (top) and mass (bottom) weighted stellar population fractions $x_j$ and $\mu_j$, respectively. The inserted panel on the right marks the ages of the stellar population templates. The flux intensities of the left two panels are normalized at 4020 Å by $4.549872 \times 10^{-16}$ erg s$^{-1}$ cm$^{-2}$.

We learn from Figure 5 that the stellar populations of the galaxy consist of two main populations: a younger one $\leq 500$ Myr (whose 500 Myr population is insignificant) and a mid-to-old $> 1$ Gyr (we define young stellar populations as those with ages $\leq 300$ Myr, old populations with ages $> 1$ Gyr, and intermediate-age populations between these). Following Cid Fernandes et al. (2005), we calculated the mean ages weighted by light,

$$\langle \log t_\star \rangle_L = \frac{\sum_{j=1}^{N_\star} x_j \log t_j}{\sum_{j=1}^{N_\star} x_j},$$

and by stellar mass,

$$\langle \log t_\star \rangle_M = \frac{\sum_{j=1}^{N_\star} \mu_j \log t_j}{\sum_{j=1}^{N_\star} \mu_j}.$$

The derived mean ages are $\langle \log t_\star \rangle_L = 8.2$ and $\langle \log t_\star \rangle_M = 9.7$. These figures demonstrate again that the galaxy mass is dominated by old populations with ages of $\sim 10^{10}$ yr, and the latest SB took place about $10^6$ yr ago and whose massive stars contribute a large fraction of luminosity. The mean velocity dispersion is $\sigma_\star = 223$ km s$^{-1}$, which is typical of giant ellipticals.

### 3.4. Emission-line Fitting

The residual spectrum $E_\lambda$ (the purple spectrum in the left bottom panel) in Figure 5 can be used to measure emission lines, since the stellar component and the AGN continuum have been removed. Fe II emission regions are not included in emission-line fitting. Emission lines are modeled by the SPECFIT task in the IRAF-STSDAS package. Thirteen components are fitted simultaneously, including the single emission line [O III], [N II] and [S II] doublets, the narrow and broad components of H$\beta$, H$\alpha$, [O III] $\lambda 4959$, and [O III] $\lambda 5007$ (represented by H$\beta_N$, H$\beta_B$, and so on). Each line, as well as the narrow and broad components, is fitted by a single Gaussian profile. The flux ratios of [O III]$_N$, [O III]$_B$, and [N II] doublets are fixed at their theoretical values. The relative positions of the [O III], [N II], and [S II] doublets are constrained by their laboratory values. FWHMs are constrained to be the same for each doublet such as [O III]$_N$, [O III]$_B$, [N II], and also for H$\beta$ and H$\alpha$ narrow and broad components. The emission-line properties without aperture or extinction correction are displayed in Table 1. The uncertainties in Columns 2 and 3 are given by the SPECFIT task. Fitting results are shown in two wavelength ranges in Figure 6. The narrow components of H$\alpha$ and H$\beta$ have FWHMs $< 1000$ km s$^{-1}$, and their broad components are $> 7000$ km s$^{-1}$. IRAS F13308+5946 can be classified as a quasar with the spectral type of a Seyfert 1.5 galaxy, for both the narrow and broad components of the two Balmer lines are significant.
Figure 6. Fits to the emission lines. Flux intensities are inherited from the residual spectrum in Figure 5. The observed line profile (green solid), the model profile (red solid), and each line and its different components (black dashed) are plotted in each panel. Left: Hβ+[O iii] region; right: Hα+[N ii]+[S ii] region.

Greene & Ho (2005) found a tight correlation between Balmer emission-line luminosities and AGN optical continuum luminosity (minimal host galaxy contamination) at 5100 Å ($L_{5100} = \lambda L_\lambda$ at $\lambda = 5100$ Å). We use this correlation to examine whether our spectral decomposition is successful. We measure $L_{5100}$ from the power-law spectrum which is obtained from spectral synthesis. The model AGN spectrum gives $L_{5100} = 10^{49.04} L_\odot$. The observed Hα and Hβ luminosities are $L_{\text{H}\alpha} = 10^{50.73} L_\odot$ and $L_{\text{H}\beta} = 10^{50.07} L_\odot$. Using Greene & Ho’s correlations, $L_{5100}$ is calculated to be $10^{49.47} L_\odot$ and $10^{50.97} L_\odot$. They are both consistent with the 5100 Å luminosity we modeled, so the spectral decomposition of the AGN and host galaxy is reasonable.

### 3.5. Aperture Correction

We have shown in Figure 2 that the observed spectrum is the flux from the 3″ diameter fiber of the SDSS spectrograph. Precise calculations must include the flux coming from the entire galaxy. Table 2 lists the Galactic reddening corrected fiber magnitude (fiberMag, measured within the aperture of a fiber), Petroian magnitude (petroMag, measured by the modified form of the Petroian system), and $K$-correction factor for each band. The aperture effect is significant since the difference between fiberMag and petroMag can be larger than 1 mag at some bands. Since there is no larger aperture spectrum of the galaxy available at present, aperture correction is necessary in this work. A rough estimate of the aperture effect can be derived via

$$A = \frac{L_{\text{Petro}}}{L_{\text{fiber}}} = 10^{-0.4(m_{\text{Petro}}-m_{\text{fiber}})}$$

(Hopkins et al. 2003). The correction factors for the $u$, $g$, $r$, $i$, $z$ bands are 1.68, 2.2, 2.58, 2.60, and 2.57, respectively. At the $u$ band, the aperture effect is the least, but it is still a factor of $A = 1.68$. From the spectral synthesis in Section 3.3, it is known that the luminosity of the galaxy is dominated by young stellar populations and the AGN, which can both be better traced by the $u$ band rather than the other four bands, and so we carry out aperture correction using the $u$-band’s factor.

The spectral synthesis method provides an opportunity for improving the aperture correction method above. Having decomposed the observed spectrum into the AGN power-law and stellar component, we can convert their fluxes at a given band to apparent magnitudes. In combination with $m_{\text{fiber}}$ and $m_{\text{Petro}}$, we give a new method for purely stellar component aperture correction. The derived formula is

$$A = \frac{L_{\text{Petro}}}{L_{\text{fiber}}} = \frac{10^{-0.4(m_{\text{Petro}}-m_{\text{AGN}})} - 1}{10^{-0.4(m_{\text{fiber}}-m_{\text{AGN}})} - 1},$$

where $L_{\text{Petro}}$ and $L_{\text{fiber}}$ are fluxes of stars at a given band within the Petroian and fiber aperture, respectively; $m_{\text{AGN}}$ is the apparent magnitude of the AGN at a given band converted from the flux density of the power-law spectrum.
3.6. Extinction Curve

Large extinction happens in ULIRGs/LIRGs and re-emits UV-to-optical emission to FIR. The proper dust extinction law that we use here is the one given by Calzetti et al. (2000) and Leitherer et al. (2002). The Calzetti curve is only applicable to wavelengths longer than 1200 Å. Leitherer et al. (2002) extended the curve to 970 Å. At even shorter wavelengths, the extinction curve has larger systematic uncertainties, but we extrapolate it a little to 912 Å to cover the Lyman series limit. Their curves are identical at 1500 Å, and the differences at shortward wavelengths are minor. We adopt Leitherer et al.’s curve for 912 Å ≤ λ ≤ 1800 Å, and adopt Calzetti’s curve for 1800 Å < λ ≤ 9000 Å.

The intrinsic emission \( F_i(\lambda) \) can be recovered through the extinction curve \( k(\lambda) \) via

\[
F_i(\lambda) = F_o(\lambda)10^{0.4(E_{B-V}^i(\lambda)-E_{B-V}^o(\lambda))},
\]

where \( F_o(\lambda) \) is the observed spectrum, \( E_{B-V}^i(\lambda) \) is the color excess for the stellar and AGN continuum spectrum, and \( 10^{0.4(E_{B-V}^i(\lambda)-E_{B-V}^o(\lambda))} \) corresponds to the global extinction term \( r_2 \) in Equation (5). \( E_{B-V}^o(\lambda) \) is calculated from \( A_V \) obtained from the spectral synthesis (\( A_V = 0.62 \)), and it is \( E_{B-V}^i(\lambda) = 0.15 \). The color excess for nebular gas emission lines is denoted by \( E_{\beta}(B-V) \) and is directly estimated through the Balmer decrement. The line ratio \( H_\alpha/H_\beta = 6.13 \), whose intrinsic flux ratio is \( (H_\alpha/H_\beta)_0 = 2.87 \) assuming temperature \( T = 10,000 \) K and case B recombination (Osterbrock 1989).

When applying the Calzetti curve to the \( B \) band, the extinction correction factor is \( \sim 4 \), which is 1.5 mag brighter, such that the corrected absolute magnitude is \( M_B = -22.6 \), which satisfies the quasar criterion \( M_B < -22.2 \).

4. SFR AND BLACK HOLE MASS

We can compare the observed IR luminosity to the current SFR. Because the H\( \alpha \) line contains emission from the AGN, we use [O \( \text{II} \)] \( \lambda 3727 \) to estimate the SFR. We take the color excess \( E_{\beta}(B-V) = 0.71 \) for gas reddening and the Calzetti curve for spectral line extinction correction. The current SFR is calculated from (Kewley et al. 2004)

\[
\text{SFR}([\text{O} \text{II}]) (M_\odot \text{ yr}^{-1}) = (6.58 \pm 1.65) \times 10^{-42} L_{[\text{O} \text{II}]} \text{(erg s}^{-1})
\]

where \( L_{[\text{O} \text{II}]} \) is the extinction-corrected (a factor of 45.6) luminosity of [O \( \text{II} \)] \( \lambda 3727 \). The derived SFR is 43.8 ± 11.0 \( M_\odot \) yr\(^{-1}\). We do not use aperture correction here, because we have learned that the SB takes place mainly at the central region of the galaxy (see Section 2.2), which the fiber aperture covers. Considering the star-forming region can also be found outside the aperture, we take such SFR as a lower limit and the \( u \)-band aperture corrected SFR, which is 73.5 ± 18.4 \( M_\odot \) yr\(^{-1}\), as an upper limit. For SB galaxies, SFR can be also estimated through IR luminosity (Kennicutt 1998 and references therein). As for IRAS F13308+5946, since it contains both SB and AGN components, the total IR luminosity \( 10^{11.50} L_\odot \) only suggests an upper limit of the SFR, which is 62.9 \( M_\odot \) yr\(^{-1}\). The spectral synthesis has given the SB fraction of the galaxy, so the SFR can be estimated only by the IR luminosity from the SB. Such calculations will be given in Section 5.

The BH virial mass is calculated by means of \( H_\alpha \) via

\[
M_{\text{BH}} = (2.0^{+4.8}_{-0.3}) \times 10^6 \left( \frac{L_{\text{H}\alpha}}{10^{42} \text{ erg s}^{-1}} \right)^{0.55 \pm 0.02} \times \left( \frac{\text{FWHM}_{H_\alpha}}{10^3 \text{ km s}^{-1}} \right)^{2.06 \pm 0.06} M_\odot
\]

(Greene & Ho 2005), where \( L_{\text{H}\alpha} \) is the observed \( H_\alpha \) luminosity. We do not carry out aperture correction on \( L_{\text{H}\alpha} \) because the 3\( \text{'} \) fiber aperture covers ~10 kpc, definitely including the broadline region. The derived BH mass is \( M_{\text{BH}} = 1.8 \times 10^8 M_\odot \). The Eddington ratio \( L_{\text{bol}} / L_{\text{Edd}} \) is calculated by adopting the bolometric luminosity \( L_{\text{bol}} \approx 9 \times L_{\text{H}\alpha} (5100 \text{ Å}) \) (Kaspi et al. 2000), where \( L_{\text{H}\alpha} (5100 \text{ Å}) \) is the AGN optical continuum luminosity at 5100 Å. The inferred Eddington ratio is \( L_{\text{bol}} / L_{\text{Edd}} = 0.12 \), which is typical of Palomar–Green (PG) QSOs (median value 0.24; Hao et al. 2005, hereafter Hao05), far less than the one of IR QSOs (1.73) and NLS1s (1.27). These results indicate that the supermassive black hole (SMBH) is at a late stage of growth. If the SMBH grew from a single seed, the duration of the growth can be estimated by the \( \epsilon \)-folding timescale (Haiman & Loeb 2001),

\[
t_{\text{acc}} \equiv \frac{M_{\text{BH}}}{M} = 4 \times 10^7 \left( \frac{\epsilon}{0.1} \right) \eta^{-1} \text{ yr},
\]

where \( \epsilon = L_{\text{bol}} / M c^2 \) is the mass-to-radiation conversion efficiency and \( \eta = L_{\text{bol}} / L_{\text{Edd}} \) is the Eddington ratio. For efficient energy production, \( \epsilon \sim 0.1 \), and the \( \epsilon \)-folding timescale is \( t_{\text{acc}} = 3.5 \times 10^8 \) yr. It is close to the duration of the SB phase. This means that before the SB activity took place, the BH mass was less by a factor of \( \sim 2.7 \), which was still massive enough to support a broad-line region. Therefore, the galaxy probably harbored a type 1 AGN during the SB phase.

5. FIR LUMINOSITY IN THE PAST

We have little information to determine the origin of the BH, that is, whether it grew from a single seed or from BH mergers when galaxies merged. Therefore, the AGN emission in the past is hard to estimate. Compared with the uncertainty of the AGN, we have better defined stellar evolution models (Kurucz 1992; Lejeune et al. 1997, 1998; BC03). Combining with the SFH, we are able to trace back to the past and calculate the luminosity of the stellar component at a given epoch. Then, we could estimate the IR luminosity by calculating the UV-to-optical flux absorbed by dust. Because there is no UV observation data available for this galaxy and the shortward end of the rest-frame spectrum is only limited to 3258 Å, we use the model spectrum of the UV band for such calculation.

To test the feasibility of our method, we first calculate the present FIR luminosity by reconstructing the UV-to-optical spectrum. Because BC03 SSP templates are in units of solar luminosity per angstrom per solar mass, we can accurately convert the present stellar mass \( M_{\text{cor}} \) to a spectrum by means of the mass-weighted fraction \( \mu_j \). We reconstruct the model spectrum \( F_\beta(\lambda, \mu_j) \) covering the whole UV-to-optical wavelengths in our calculation (from 912 Å to 9000 Å) through

\[
F_\beta(\lambda, \mu_j) \equiv M_{\text{cor}} \sum_{j=1}^{N} \mu_j B_{\beta,j,\lambda} + F_\beta(\lambda) \times 10^{-0.4(A_\lambda - A_V)},
\]

where we do not use aperture correction here, because we have learned that the SB takes place mainly at the central region of the galaxy (see Section 2.2), which the fiber aperture covers.
where $t_0$ is the present time, $M_{\text{cor}}_{\text{tot}}$ is the present stellar mass obtained from spectral synthesis and derived to be $5.5 \times 10^{10} M_\odot$ after aperture correction through Equation (9) (does not need extinction correction), $B_{\lambda,j,t}$ are BC03 SSP templates without normalization, and $F_\lambda(\lambda)$ is a double power-law spectrum of the AGN. The spectral indices of power-law that we use here are given by Hatziminaoglou et al. (2008) with $\alpha = -1$ for $\lambda < 1250$ Å and $\alpha = -2$ for $\lambda \geq 1250$ Å. Figure 7 shows the reconstructed model spectrum (red solid) superimposed by the observed one (green solid). This model spectrum is used as $F_\lambda(\lambda)$ in Equation (10).

The light in UV-to-optical (912–9000 Å) absorbed by dust and re-emitted to IR is approximately calculated by

$$L_{\text{IR}}(\lambda,t) = \sum_{j=1}^{n} f_\star_{\lambda,j,t} B_{\lambda,j,t} \int_{\lambda_0}^{\lambda} F_\lambda(\lambda,t) - F_\lambda(\lambda,t_0)] d\lambda,$$

(15)

where $F_\lambda(\lambda,t)$ and $F_\lambda(\lambda,t_0)$ have similar meaning as $F_\lambda(\lambda)$ and $F_\lambda(\lambda)$ in Equation (10), but they represent the spectra at lookback time $t$. After the $u$-band aperture correction, the derived IR luminosity is $L_{\text{IR},0} = 10^{11.43} L_\odot$. It is approximately equal to the observed $L_{\text{IR}} = 10^{11.56} L_\odot$. It demonstrates that our method is feasible in recovering the present FIR luminosity, and so we can apply the method to the past. Meanwhile, it is convenient to calculate the contribution fractions from the SB and AGN. We only need to calculate IR luminosities from the two components separately. The SB and AGN contribute $L_{\text{star,IR}} = 10^{11.28} L_\odot$ and $L_{\text{AGN,IR}} = 10^{10.90} L_\odot$, respectively. The SB contributes $\sim 70\%$ of the FIR luminosity. However, both components are important.

As in Section 5 the current SFR can be also estimated through the IR luminosity $L_{\text{FIR}}(8–1000 \mu m)$ from the host galaxy. Since the host galaxy contributes $\sim 70\%$ of the FIR luminosity, we obtain SFR $= 43.3 M_\odot \text{yr}^{-1}$. It is consistent with the one from [O II] luminosity inside the aperture. Therefore, the derived stellar populations and AGN spectra, the dust extinction, and the observed emission-line fluxes are concordant with each other.

The estimation of the past IR luminosity is carried out in a similar way. We just need to supplement the stellar mass loss of each population at a given look-back time $t$. Because the AGN emission in the past is unknown, we just estimate the stellar component contribution. The stellar spectrum (i.e., the host galaxy) in the past without extinction is produced through

$$F_\lambda(\lambda,t) = M_{\text{cor}}_{\text{tot}} \sum_{j=1}^{n} \frac{\mu_j}{f_\star_{\lambda,j,t}} f_\star_{\lambda,j,t} B_{\lambda,j,t},$$

(16)

where $f_{\star_{\lambda,j,t}}$ is the present $(t_0)$ fraction of the remaining stellar mass to the initial mass of population $j$, $f_{\star_{\lambda,j,t}}$ is such fraction at a given time $t$, and $f_{\star_{\lambda,j,t}}$ and $f_{\star_{\lambda,j,t}}$ are in the range $0 < f_{\star_{\lambda,j,t}} < 1$. Since the recent SB happened in the past 500 Myr, we estimate the IR luminosity of the past 25, 100, 290, and 500 Myr separately.

Take 25 Myr ago as an example. When the 25 Myr old population was just newly born, it was assigned an age of 1 Myr and the parameter $f_{\star_{\lambda,j,t}}$ is equal to 1. The 100 Myr old population was 75 Myr old with $f_{\star_{\lambda,j,t}} = 0.7226$. Other populations are also configured in the same way. Here, the reconstructed spectrum through Equation (16) is used as the intrinsic spectrum $F_\lambda(\lambda)$ in Equation (10). The extinction term $A_\lambda$ is assigned to the present. The attenuated spectrum through $F_\lambda(\lambda,t) 10^{-0.4A_\lambda}$ is used as $F_\lambda(\lambda)$ in Equation (10). Because dust extinction increases from optical to UV, we adopt the aperture correction at the $u$ band derived from Equation (9). Calculated through Equations (10) and (15), the IR luminosity transferred from 912–9000 Å to IR at 25 Myr ago was $L_{\text{IR,25M}} = 10^{12.18} L_\odot$, which is the ULIRG luminosity. If we consider the AGN’s contribution, the IR luminosity should be higher. When applied to 100, 290, and 500 Myr ago, the estimated IR luminosities from the host galaxy were $L_{\text{IR,100M}} = 10^{12.10} L_\odot$, $L_{\text{IR,290M}} = 10^{12.11} L_\odot$, and $L_{\text{IR,500M}} = 10^{11.45} L_\odot$. These IR luminosities, which can be seen as a luminosity history of the galaxy, are shown in Figure 8. As has been demonstrated in Section 4, the galaxy probably harbored a type I AGN during SB. Therefore, a type I ULIRG might have appeared during the SB phase and lasted for $\sim 300$ Myr.

6. DISCUSSION

6.1. Fe II Pseudo-continuum

Many IR QSOs are extremely strong Fe II emitters (Zheng et al. 2002; Lipari et al. 2003). In the IRAS F13308+5946 spectrum, we also find Fe II pseudo-continuum emission in the
wavelength regions 4270–4700 Å and 5100–5600 Å. We have masked these two wavelength regions before spectral synthesis. Actually, we have attempted to subtract Fe \( \text{ii} \) before fitting. However, as in the case of IRAS Z11598–0112, IRAS F02065+4705, etc. (Zheng et al. 2002), Fe \( \text{ii} \) multiplets 37, 38 (4500–4680 Å) are relatively stronger than Fe \( \text{ii} \) multiplets 48, 49 (5100–5400 Å) when compared with the Boroson & Green (1992, hereafter BG92) Fe \( \text{ii} \) template, and also the Véron-Cetty et al. (2004) template. Thus, the Fe \( \text{ii} \) multiplets 37, 38 are left when multiplets 48, 49 are removed. We have also attempted to remove Fe \( \text{ii} \) lines from the residual spectrum, but the result was not improved. Furthermore, including Fe \( \text{ii} \) template as a component to fit \( O_\lambda \) does not bring any improvement at all. Therefore, we masked the Fe \( \text{ii} \) pseudo-continuum regions before spectral synthesis, as mentioned in Section 3.4.

The Fe \( \text{ii} \) \( \lambda 4570 \) (4434–4684 Å) flux is measured during the procedures above and the line ratio Fe \( \text{ii} \) \( \lambda 4570/\lambda H\beta \) is 0.81. This ratio is typical of optical selected QSOs (BG92). We find that the Fe \( \text{ii} \) continuum extension to \( [\text{O}\,\text{ii}] \lambda 3727, \lambda H\beta \), etc., lines is hard to detect, and so we measure these lines fluxes directly.

### 6.2. Extinction Curve

In this paper, we do not adopt Cardelli et al.’s (1989) extinction curve, because it is for cases which are similar to Milky Way and not applicable to SB galaxies. We use the Calzetti curve and Leitherer et al.’s (2002) extension form because they are derived from star-forming regions and SB galaxies.

Dust in different components and stellar populations vary in temperature, ingredient, amount, geometry, etc., and so different attenuation for each component should be adopted if we could distinguish them. However, as the spectra from the host galaxy and central AGN are coupled, and there is also only one extinction term in STARLIGHT, the extinction obtained from spectral synthesis is a combined value from both regions. Also, some optically thick star formation regions may exist, which may not be detected even by optical or near-infrared, but may still contribute to IR flux. In this case, the actual extinction could be underestimated.

From the Balmer decrement, the line ratio \( H\alpha/H\beta \), the derived color excess of the stellar continuum is \( E_c(B-V) = 0.3115 \), which is twice the one obtained from spectral fitting. This indicates differential attenuation between the dusty SB region and older populations.

### 6.3. IRAS F13308+5946: A Possible Evolutionary Link Between (Type I) ULIRGs and QSOs

The spectral synthesis gives a 500 Myr SB history, which implies that a triggering mechanism took place during such epoch. Galaxy interactions and mergers have timescales of a few \( 10^8 \) yr (Binney & Tremaine 1987). The similar timescales imply that the SB was possibly triggered by galaxy mergers.

In Sections 4 and 5, we demonstrated that IRAS F13308+5946 has possibly been experiencing an IR QSO phase since \( \sim 300 \) Myr ago. Following Hao05, we plot IRAS F13308+5946 on the diagram that shows the relation between IR luminosity and the bolometric luminosity measurement (represented by \( \lambda L_{\lambda} \) (5100 Å); Kaspi et al. 2000) in Figure 9. IRAS F13308+5946 is located at a transitional position between IR QSOs and PG QSOs. The tight correlation followed by PG QSOs and NLS1s suggests their IR luminosities are associated with the optical through central AGNs, while IR QSOs have IR excess powered by other mechanisms rather than AGN. As for IRAS F13308+5946, we attribute the IR excess to ongoing star formation. In Figure 10, which shows the IR spectral index \( \alpha(60, 25) \) (defined as \( \alpha = \frac{\log(\lambda F(\lambda 60)/\lambda F(\lambda 25))}{\log(\lambda 60/\lambda 25)} \) versus the IR excess \( L_{\text{IR}}/L_{5000} \), it is also located between IR QSOs and PG QSOs. The IR excess increases as the dust temperature decreases, suggesting that star formation activities become more and more important in powering IR luminosity of IR QSOs and ULIRGs because the temperature of dust heated by stars is lower than that heated by AGN.

On the other hand, Hao05 give the statistical median \( M_{\text{BH}} \) values of IR QSOs and PG QSOs, which are \( 4.9 \times 10^7 \) \( M_\odot \) and \( 2.1 \times 10^7 \) \( M_\odot \), respectively. Thus, IRAS F13308+5946 has both BH mass and Eddington ratio similar to those of PG QSOs. Furthermore, as a type 1.5 galaxy, the featureless continuum and emission lines from the AGN may be partially attenuated by the dusty torus, and the AGN itself may be powering a classical QSO, for the galaxy is an \( i \)-band quasar.
Therefore, IRAS F13308+5946 may evolve into an optical QSO when SB ceases and the nuclear dust is dissipated by the radiative pressure of the AGN. In Figures 9 and 10, the positional arrangement of ULIRGs, IR QSOs, and classical QSOs implies an evolutionary sequence: ULIRGs → type I ULIRGs/IR QSOs → (IRAS F13308+5946) → PG QSOs. As the H-band luminosity is ~4L*, it supports the evolutionary scenario proposed by Colina et al. (2001) that ULIRGs generated by two or more massive (> L*) galaxies would evolve into QSOs (also supported by Sanders et al. 1988 and Lutz et al. 1999).

Finally, through r-band surface photometry, we find that the outskirt surface brightness profile follows the de Vaucouleurs law and the central region follows a point-spread function. It is consistent with other studies that show that some (maybe even higher fraction) ULIRGs may undergo QSO phase in their evolutionary history before they settle down as ellipticals (Zheng et al. 1999; Arribas et al. 2004; Dasyra et al. 2006).

7. SUMMARY

We carry out a study based on stellar population synthesis result of a type I ULIRG, IRAS F13308+5946. Our findings are as follows.

1. The cross-identification from IRAS, 2MASS, SDSS, and FIRST, combined with the radio–FIR correlation, confirms that the LIRG IRAS F13308+5946 is the optical quasar from SDSS observation.

2. With sub-solar metallicity Z = 0.008 and power-law index α = −2.0, stellar population synthesis shows that the host galaxy since 500 Myr ago has a history of SB.

3. We estimate the past IR luminosity during the SB epoch. We find that it has probably experienced a type I ULIRG phase from ~300 Myr ago. When the star formation activity weakened recently, the IR luminosity decreases to the present level (10^{11.56} L_⊙) as an LIRG. Nuclear SB and AGN activity both contribute to the IR luminosity budget, with ~70% from SB.

4. The SMBH mass M_{BH} = 1.8 \times 10^8 M_⊙ and the Eddington ratio L_{bol}/L_{Edd} = 0.12 are both consistent with PG QSOs, suggesting a potential classical QSO.

5. IRAS F13308+5946 is located at the transitional position between IR QSOs and PG QSOs on the L_{IR} versus L_{5100}/L_{5100} plots. Combining the results above, we conclude that IRAS F13308+5946 is probably an evolutionary transition object from a type I ULIRG to a PG QSO.

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