Ultra-luminous infrared galaxies (ULIRGs) are interesting objects with dramatic properties. Many efforts have been made to understand the physics of their luminous infrared emission and evolutionary stages. However, a large ULIRG sample is still needed to study the properties of their central black holes (BHs), the BH–host galaxy relation, and their evolution. We identified 308 ULIRGs from the Sloan Digital Sky Survey Data Release 6, and classified them into the NL ULIRGs (with only narrow emission lines) and the Type I ULIRGs (with broad emission lines). About 56% of ULIRGs in our total sample show interaction features, and this percentage is 79% for redshift $z < 0.2$. Optical identifications of these ULIRGs show that the active galactic nucleus percentage is at least 49%, and the percentage increases with the infrared luminosity. We found 62 Type I ULIRGs, and estimated their BH masses and velocity dispersions from their optical spectra. Together with known Type I ULIRGs in the literature, a sample of 90 Type I ULIRGs enables us to make a statistical study. We found that the BH masses of Type I ULIRGs are typically smaller than those of Palomar–Green QSOs, and most Type I ULIRGs follow the $M_{\text{BH}} - \sigma$ relation. However, some ULIRGs with a larger Eddington ratio deviate from this relation, even though the line width of the [O III] narrow-line (NL) core or the [S II] line was used as the surrogate of velocity dispersion. This implies that at least some ULIRGs are probably still in the early evolution stage toward QSOs. The anti-correlation between the mass deviation from the $M_{\text{BH}} - \sigma$ relation and the Eddington ratio supports that the evolution of Type I ULIRGs is probably followed by the building up of the $M_{\text{BH}} - \sigma$ relation and the evolution to the QSO phase.

Key words: galaxies: active – galaxies: formation – galaxies: nuclei – galaxies: starburst – infrared: galaxies

Online-only material: color figure, machine-readable tables

1. INTRODUCTION

Ultra-luminous infrared galaxies (ULIRGs) were discovered by Infrared Astronomical Satellite (IRAS) in large numbers with infrared luminosity in 8–1000 $\mu$m greater than $10^{12} L_{\odot}$. The serious intrinsic obscuration for ULIRGs in optical, UV, and even in mid-IR and X-ray bands (Condon et al. 1991b) makes it difficult to clearly probe their physical properties by observations. There are probably more ULIRGs at high redshifts than in the local universe, and even more than optically bright QSOs (Lonsdale et al. 2006). In the last two decades, multi-wavelength studies on ULIRGs have significantly improved our understanding of these dramatic objects (see the review papers of Sanders & Mirabel 1996; Lonsdale et al. 2006).

Extremely high infrared luminosity of ULIRGs is dominated by starbursts, and sometimes with additional contribution from active galactic nuclei (AGNs). Most ULIRGs are interacting systems undergoing a wide range of merger stages (e.g., Zou et al. 1991; Clements et al. 1996; Murphy et al. 1996; Surace et al. 2000; Farrah et al. 2001; Veilleux et al. 2002). ULIRGs with large luminosity or spectroscopic signatures of AGNs are most likely late-stage mergers (Veilleux et al. 2002). Observations of the molecular gas in ULIRGs (see Mirabel & Sanders 1988; Sanders et al. 1986, 1991; Gao & Solomon 2004) proved that high-density gases are reserved in a compact nuclear region. The connection between ULIRGs and AGNs was also found from optical and mid-infrared spectra (e.g., Kim et al. 1998; Veilleux et al. 1997, 1999a, 1999b). About 25% of ULIRGs present evidences of AGNs, and the percentage increases to $\sim 50\%$ when $L_{\text{IR}}$ is greater than $10^{12.3} L_{\odot}$. Less than $10\%$ ULIRGs have broad emission lines, which are the so-called Type I ULIRGs (see Clements et al. 1996; Wu et al. 1998a, 1998b; Zheng et al. 1999; Canalizo & Stockton 2001; Cui et al. 2001). ULIRGs and AGNs most probably have evolutionary connection. To understand such possible connection, Lonsdale et al. (2006) suggest that major mergers of gas-rich galaxies first form a massive cool starburst-dominated ULIRG, and then a warm ULIRG phase is followed when a central AGN turns on inside the dust cocoon and heats the surrounding dust. The central AGN will evolve into an optically bright phase when it blows away the surrounding dust cocoon. The resulting stellar system will resemble a spheroid, so that the mass of the central black hole (BH) of the AGN ($M_{\text{BH}}$) is related to the stellar velocity dispersion $\sigma$. The $M_{\text{BH}} - \sigma$ relation might build up at that time. In this scenario, ULIRGs are in a pre-QSO phase. The typical BH mass of ULIRGs should be smaller, and the galaxy bulge may not have been constructed completely, compared with those of normal QSOs.

Kawakatu et al. (2006) used a sample of eight Type I ULIRGs in the local universe with data of full width at half-maximum (FWHM) of H$\beta$ and optical continuum luminosity $L_{\beta}$(5100 Å) from Zheng et al. (2002) to estimate their BH masses and investigate the BH–bulge relation. They found that the Type I ULIRGs have systematically smaller BH masses in spite of having the comparable bulge luminosity as QSOs and elliptical galaxies. We note that the FWHM of H$\beta$ given in Zheng et al. (2002) is the FWHM of the whole emission-line profile, not the FWHM of the broad-line component, which should be used in the estimation of the BH mass. Therefore, Kawakatu et al. (2006) may underestimate the masses of BHs for these ULIRGs. Using a sample of sources mostly from Zheng et al. (2002), Hao et al. (2005) carried out a study on the Type I ULIRGs (named as...
IR QSOs in their paper), and concluded that the typical BH mass of Type I ULIRGs is smaller, and the typical Eddington ratio \( (L_{\text{bol}}/L_{\text{edd}}) \) is larger than those of Palomar–Green (PG) QSOs. At higher redshift, Borys et al. (2005) found that submillimeter galaxies have smaller BH masses than QSOs with respect to the same mass range of bulges. Alexander et al. (2008) concluded that submillimeter galaxies host BHs with a mass of \( \log(M_{\text{BH}}/M_{\odot}) \approx 7.8 \) in their sample. Because local ULIRGs and high-redshift submillimeter galaxies are similar to each other, both having bright infrared luminosity and a large amount of gas, and located in the interacting systems, the investigations on local ULIRGs could enlighten our understanding about the high-redshift submillimeter galaxies.

A large ULIRG sample is needed to study their central BHs, the BH–host galaxy relation, and galaxy evolution. The best-known samples of IRAS luminous infrared galaxies and ULIRGs are the Bright Galaxy Sample of Soifer et al. (1987), updated into the Revised Bright Galaxy Sample by Sanders et al. (2003), the complete flux-limited IRAS 1 Jy sample (Kim & Sanders 1998), the 2 Jy sample of Strauss et al. (1990), and the FIRST/IRAS sample of Stanford et al. (2000). Since the Sloan Digital Sky Survey (SDSS) covers more than a quarter of the sky, more ULIRGs with relatively high quality spectra can be found by the cross-correlation of IRAS data with the SDSS. Goto (2005) investigated the optical properties of 4248 infrared galaxies with \( L_{\text{IR}} \) of \( 10^9 \) to \( 10^{13.57} \) L_{\odot} from the cross-correlation between SDSS DR3 spectroscopic sample of galaxies and IRAS sources, and 181 of them are ULIRGs. Pasquali et al. (2005) used the SDSS DR2 data to study the optical properties of IRAS galaxies. Cao et al. (2006) identified 1207 luminous infrared galaxies and 57 ULIRGs from SDSS DR2 for a statistical study. Hwang et al. (2007) and Cao et al. (2006) identified 126 ULIRGs and high-redshift submillimeter galaxies are similar to each other, both having bright infrared luminosity and a large amount of gas, and located in the interacting systems, the investigations on local ULIRGs could enlighten our understanding about the high-redshift submillimeter galaxies.

In Section 2, we carry out a study on the BH masses and the results and discuss the NL ULIRG sample in Section 3. In Section 2.1, we first present our sample. We separate them into two subsamples, NL ULIRGs and Type I ULIRGs, and fit their SDSS spectra. We present the spectroscopic catalog of the SDSS DR6, and obtain a ULIRG sample. We compare our result with that of Hwang et al. (2007), and conclude that the typical BH mass of Type I ULIRGs is smaller, and the typical Eddington ratio \( (L_{\text{bol}}/L_{\text{edd}}) \) is larger than those of Palomar–Green (PG) QSOs. At higher redshift, Borys et al. (2005) found that submillimeter galaxies have smaller BH masses than QSOs with respect to the same mass range of bulges. Alexander et al. (2008) concluded that submillimeter galaxies host BHs with a mass of \( \log(M_{\text{BH}}/M_{\odot}) \approx 7.8 \) in their sample. Because local ULIRGs and high-redshift submillimeter galaxies are similar to each other, both having bright infrared luminosity and a large amount of gas, and located in the interacting systems, the investigations on local ULIRGs could enlighten our understanding about the high-redshift submillimeter galaxies.

In Section 2, we carry out a study on the BH masses and the results and discuss the NL ULIRG sample in Section 3. In Section 4, we carry out a study on the BH masses and the \( M_{\text{BH}}–\sigma \) relation of Type I ULIRGs. The discussions and conclusions are presented in Sections 5 and 6. In this paper, we adopt \( H_0 = 70 \) km s\(^{-1}\) Mpc\(^{-1}\), \( \Omega_m = 0.3 \), and \( \Omega_{\Lambda} = 0.7 \).

## 2. THE ULIRG SAMPLE

SDSS DR6 spectra catalog contains about 750,000 galaxies and QSOs and covers over 7425 deg\(^2\) (Adelman-McCarthy et al. 2008). IRAS Faint Source Catalog (Moshir et al. 1992, hereafter FSC92) contains 173,044 sources with IR flux in bands of \( 12, 25, 60, \) and 100 \( \mu \)m. Although the IRAS data set was published more than 17 years ago, it is still very underexplored. Only 43% of the total IRAS extragalactic FSC sources have been included in any sort of publication (Lonsdale et al. 2006).

The positional uncertainty of IRAS source (about 1–13 arcsec for the in-scan direction and 3–55 arcsec for the cross-scan direction) is much larger than that of the object in the SDSS DR6, and is described by an uncertainty ellipse. Similar to Hwang et al. (2007) and Cao et al. (2006), we used the positional uncertainty ellipse of each IRAS source to obtain their matched counterparts in the SDSS. If a galaxy of the SDSS DR6 falls into the 3\( \sigma \) uncertainty ellipse of IRAS source, we regarded them as a match. As a result, we found that 11,354 IRAS sources have only one counterpart in the SDSS DR6 and 984 have more than one counterparts. In the later case, the likelihood ratio method (see Sutherland & Saunders 1992; Hwang et al. 2007; Cao et al. 2006) is used to determine which counterpart of this IRAS source is the most probable one. After doing these, we obtained a list of 12,338 IRAS sources with SDSS DR6 optical counterparts.

### 2.1. Selection Criteria

Our selection criteria of ULIRGs are shown as follows: for the 12,338 matched IRAS sources, their 12 \( \mu \)m and 25 \( \mu \)m flux densities are mostly upper limits. Therefore, we calculated their far-infrared luminosity by using 60 \( \mu \)m and 100 \( \mu \)m fluxes with the following formulae (see Helou et al. 1988; Sanders & Mirabel 1996) and converted it to the total infrared luminosity (Calzetti et al. 2000):

\[
F_{\text{FIR}} = 1.26 \times 10^{-14} (2.58 f_{60} + f_{100}) \text{(W m}^{-2}\text{).} \tag{1}
\]

\[
L_{\text{FIR}} = 4\pi D_{\Lambda}^2 F_{\text{FIR}} (L_{\odot}). \tag{2}
\]

\[
L_{\text{IR}}(1–1000 \, \mu\text{m}) = 1.75 L_{\text{FIR}}. \tag{3}
\]

Here \( f_{60}, f_{100} \) are the IRAS flux densities in Jy at 60 and 100 \( \mu \)m, \( D_\Lambda \) is the luminosity distance, \( F_{\text{FIR}} \) is the far-infrared flux, \( L_{\text{IR}} \) is the far-infrared luminosity, and \( L_{\odot} \) is the infrared luminosity in \( L_{\odot} \). For all the matched sources, we also required that the 60 \( \mu \)m flux have high quality measurement. (In the FSC92, high quality, moderate quality, and upper limits of the flux measurements are marked as 3, 2, and 1, respectively). Because the 100 \( \mu \)m flux does not affect much on the value of \( L_{\text{IR}} \) (see Cao et al. 2006), we do not set the limit to the quality of the 100 \( \mu \)m flux density. The redshift confidence of each source should be larger than 0.65. Finally, we identified 325 ULIRG candidates with an IR luminosity greater than \( 10^{12} L_{\odot} \). When we check these 325 ULIRG candidates by using the NASA/IPAC Extragalactic Database (NED), we found 18 sources whose redshifts provided in the NED are not consistent with our results. According to the NED identifications, nine of these 18 sources have a Petrosian \( r \)-band magnitude less than 15, so they are too bright for the SDSS. If calculated their \( L_{\text{IR}} \) with the redshifts provided in the NED, we found that 17 of 18 sources are not ULIRGs. This discrepancy is probably due to the large position error of the IRAS sources and the incompleteness of the SDSS spectra. The fraction of the sources which are not excluded in the examination with the NED (307/325) is about 94.5%, which is consistent with the reliability of our sample (about 93.4%, see the next section). By excluding these 17 objects, we obtain a sample of 308 ULIRGs. Detailed information of our ULIRGs is given in Table 1.

The distributions of redshift and infrared luminosity of ULIRGs are shown in Figure 1. The redshifts of our ULIRG sample cover a range from about 0.03–0.6, with a median value of about 0.2, which is similar to that of Hwang et al. (2007).

We compared our result with that of Hwang et al. (2007), who identified 126 ULIRGs from SDSS DR4 but adopted different methods to calculate \( L_{\text{IR}} \). Our catalog recovers 122 of their 126 ULIRGs. For the rest of the four sources in their sample, F07568+4823 and F11553+4557 have IR luminosities of \( 1.19 L_{\odot} \) in our result and thus are not selected; F10200+4839
Table 1
The Parameters of Our ULIRG Sample

| IRAS Name | zSDSS | SDSS Name     | log(L_{IR}/L_{⊙}) | S_{NVSS} 1.4 GHz (mJy) | S_{FIRST} 1.4 GHz (mJy) | Note | NED | f_{Hβ} | f_{OIII}5007 | f_{Hα} | f_{NII}6583 | f_{SII} | f_{O1}6300 | Note |
|-----------|-------|---------------|-------------------|------------------------|-------------------------|------|-----|--------|-------------|--------|-------------|--------|-----------|------|
| F00090−0054 | 0.195 | J00138.79−003813.7 | 12.10            | 1.17                   |                         | I    | Yes |        |             |        |             |        |           |      |
| F01093−1002 | 0.131 | J011352.64−094559.8 | 12.00            | 6.2                    | 5.38                    | n    | Yes | 0.92  | 0.61 ± 0.04 | 6.02  | 3.54 ± 0.06 | 2.45   | 0.46 ± 0.03 | Composite |
| F01166−0844 | 0.118 | J011907.57−082909.6 | 12.09            | 2.10                   |                         | II   | Yes | 0.73  | 0.15 ± 0.03 | 3.11  | 1.67 ± 0.04 | 1.02   | 0.06 ± 0.02 | Starburst |
| F01329+1439 | 0.218 | J013537.56+145510.9 | 12.17            |                       |                         | n    | Yes | 6.14  | 13.51 ± 0.09 | 26.22 | 5.03 ± 0.06 | 6.22   | 0.87 ± 0.03 | Starburst |
| F01347+0042 | 0.198 | J013720.02+005722.3 | 12.10            | 3.3                    | 2.92                    | III  | Yes | 0.32  | 0.20 ± 0.04 | 2.92  | 2.05 ± 0.07 | 1.37   | 0.25 ± 0.04 | Composite |
| F01462+0014 | 0.280 | J014852.58+002859.9 | 12.31            | 2.8                    | 2.38                    | II   | Yes | 0.92  | 0.76 ± 0.03 | 6.70  | 3.82 ± 0.09 | 2.27   | 0.33 ± 0.05 | Composite |
| F01478+1254 | 0.147 | J015028.40+130858.4 | 12.02            |                       |                         | III  | Yes | 7.45  | 17.94 ± 0.09 | 28.73 | 6.30 ± 0.04 | 6.21   | 0.81 ± 0.03 | Starburst |
| F01572+0009 | 0.163 | J015950.25+002340.8 | 12.52            | 26.2                   | 24.08                   | I    | Yes |        |             |        |             |        |           |      |
| F02016−0108 | 0.334 | J020412.43−005351.4 | 12.63            |                       |                         | n    | Yes |        |             |        |             |        |           |      |
| F02280−0746 | 0.295 | J023028.69−073304.5 | 12.20            | 1.27                   |                         | n    | Yes | 0.53  | 0.37 ± 0.03 | 4.56  | 2.80 ± 0.06 | 2.08   | 0.19 ± 0.04 | Composite |

Notes. Column 1: IRAS name; Column 2: redshift from SDSS; Column 3: SDSS name of the object; Column 4: infrared luminosity; Columns 5 and 6: radio fluxes from NVSS and FIRST, respectively; Column 7: classes (I, II, III) for interaction features, and “n” stands for not clear; Column 8: NED identifications. “Yes”: the redshift and/or the counterpart provided in the NED is consistent with ours; “No”: the redshift is not listed in the NED; Columns 9–14: fluxes of Hβ, [OIII]5007, Hα, [NII]6583, [SII], [O1]6300, all in units of 10^{-15} erg s^{-1} cm^{-2}; Column 15: note for the type of the galaxy according to the BPT diagram.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)
and F15239+4331 are not ULIRGs, and wrong optical counterparts were identified by Hwang et al. (2007).

In order to obtain the radio properties of these ULIRGs, we also cross identified our ULIRG sample with the NVSS (Condon et al. 1998) and FIRST (Becker et al. 1995; White et al. 1997) catalogs. Note that Best et al. (2005) used a hybrid NVSS–FIRST method to identify the radio counterparts for SDSS DR2 galaxies with high reliability and completeness. We followed their method to identify radio counterparts of our ULIRG sample, and found that 140 of 308 ULIRGs have counterparts in the NVSS catalog within a typical searching radius about 15′, and 132 of these 140 sources have FIRST counterparts within 3′. Some of them are probably core-dominant radio sources, such as F08201+2801, F13408+4047, F16413+3954, F10418+1153, F09105+4108, F13451+1232, F11206+3639, and F08507+3636. For the rest of the 168 ULIRGs, 82 of them have one FIRST counterpart within 3′, and their radio flux densities are below or close to the NVSS flux limit (about 2.5 mJy). The radio information of these 222 ULIRGs is listed in our ULIRG catalog (see Table 1).

### 2.2. Reliability Estimated with the Likelihood Ratio Method

To estimate the reliability of our sample, we follow Cao et al. (2006) and Hwang et al. (2007) and adopt a likelihood ratio method (Sutherland & Saunders 1992). The likelihood ratio \( p \) is defined as

\[
p = \frac{Q(\leq m_r) \exp(-R^2/2)}{2\pi \sigma_a \sigma_b \sqrt{\pi} \sigma_a \sigma_b},
\]

where \( Q(\leq m_r) \) is the multiplicative factor measuring the probability for a true optical counterpart brighter than the flux limit exists in the association, and we set \( Q = 1 \) for simplicity. \( \sigma_a \) and \( \sigma_b \) are the standard deviations, and \( m_r \) is the SDSS \( r \)-band magnitude. Here we assume that the errors are Gaussian distributed (the error of an \( IRAS \) source is not a pure Gaussian, but in the statistical sense, the result of likelihood ratio study can still be used to evaluate the reliability), and define \( R \) as

\[
R^2 = \frac{(d_1)^2}{\sigma_{a1}^2 + \sigma_{a2}^2} + \frac{(d_2)^2}{\sigma_{b1}^2 + \sigma_{b2}^2},
\]

where \( d_1 \) and \( d_2 \) are the positional differences along the two axes of the error ellipse between each \( IRAS \) source and its SDSS counterpart, \( \sigma_{a1} \) and \( \sigma_{a2} \) are the errors of each \( IRAS \) source along the \( x \)- and \( y \)-axes, \( \sigma_{b1} \) and \( \sigma_{b2} \) are the errors of each matched SDSS source along the \( x \)- and \( y \)-axes. Because the positional error of an SDSS source is much smaller than that of an \( IRAS \) source, we only consider \( \sigma_{a1} \) and \( \sigma_{b1} \).

In this work, we adopt the \( 3\sigma \) error ellipse as the match justification; thus \( n(\leq m_r) \) can be obtained by using the formula:

\[
n(\leq m_r) = \frac{N(\leq m_r)}{9\pi \sigma_{a1} \sigma_{b1}},
\]

where \( n(\leq m_r) \) is the total surface density of objects brighter than the candidate, and \( N(\leq m_r) \) is the number of galaxies whose magnitude is less than or equal to \( m_r \). Under the above considerations, we obtain

\[
p = \frac{9 \exp(-R^2/2)}{2N(\leq m_r)},
\]

where we use the \( r \)-band Petrosian magnitude for galaxies of the SDSS DR6 to calculate \( p \) of each source. To obtain the reliability, we adopt the method proposed by Lonsdale et al. (1998) and Masci et al. (2001). The reliability of a source with \( p \) is given by

\[
Re(p) = 1 - \frac{N_{\text{random}}(p)}{N_{\text{true}}(p)},
\]

where \( N_{\text{true}}(p) \) represents the number of true associations, and \( N_{\text{random}}(p) \) represents the number of random associations with a \( p \), which can be derived by offsetting the positions of \( IRAS \) sources and re-calculating the associated sample. The numbers of true and random-matched sources are 12,338 and 813, then the reliability of our sample is about 93.4%. Thus we believe that our ULIRG sample is reliable enough to make a statistical study on the properties of NL ULIRGs and Type I ULIRGs. The distribution of the reliabilities for our 308 ULIRGs is shown in Figure 2.

### 2.3. The Optical Images of ULIRGs

We examine the images of these 308 ULIRGs by using the SDSS DR6 Image List Tool. Due to the limited resolution of the SDSS image, we can only mark the ULIRGs with an obvious interaction feature. ULIRGs are classified into (see Veilleux et al. 2002) class I with one nucleus but with tail features; class II have two identified nuclei and well-developed tidal tails or/and bridges; class III have two close or even overlapped nuclei, and their redshifts (almost in all cases, only one source in this system has spectral redshift measurements, and another/other have only SDSS photometric redshift data) are consistent. Examples are shown in Figure 3. About 56% of the ULIRGs in our total sample show obvious interaction features. The nearby ULIRGs

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Figure 1. Distribution of redshift (left panel) and \( L_\text{IR} \) (right panel) of our ULIRG sample.
show more clearly the interaction features, with the percentage of about 92% for \( z < 0.1 \), 84% for \( z < 0.15 \), and 79% for \( z < 0.2 \). The selection effect is obvious in the classification of interaction features of the ULIRGs, because we can see the tails and two interacting galaxies at the maximum redshift about \( z = 0.3 \). Objects at various merger stages appear in our ULIRG sample. Some of them are still widely separated, and some are advanced mergers. The minimum separation between two nuclei in our sample is about 2\( \prime \). The imaging property is classified for each source in Table 1.

Optical spectra of all 308 ULIRGs are available in the SDSS archive. This is the largest sample of ULIRGs with optical spectra.

2.4. Optical Spectra of ULIRGs

We want to identify Type I ULIRGs and NL ULIRGs from this sample. Only the spectra with signal-to-noise ratio (S/N) > 3 are considered in this study. After excluding the sources with no obvious emission lines in their spectra, we found 209 sources with emission lines, 62 of which have broad-line components and are Type I ULIRGs.

![Distribution of source matching reliabilities of our ULIRG sample.](image)

Figure 2. Distribution of source matching reliabilities of our ULIRG sample.

![Examples of SDSS images of ULIRGs with (the upper eight) or without (the lower eight) obvious interacting features in our sample. The interaction classifications are labeled for the upper eight ULIRGs.](images)

Figure 3. Examples of SDSS images of ULIRGs with (the upper eight) or without (the lower eight) obvious interacting features in our sample. The interaction classifications are labeled for the upper eight ULIRGs.

(A color version of this figure is available in the online journal.)
Figure 4. Examples of our fitted SDSS spectra for the \( \text{H} \beta \) and \( \text{H} \alpha \) regions for a NL ULIRG (two upper panels) and a Type I ULIRG (two lower panels).

SDSS spectra were processed as follows. First, we correct the Galactic extinction and redshift effects, and then subtract the Fe\( \text{ii} \) emissions from the continuum by use of the optical iron template from Boroson & Green (1992) in the wavelength range 4250 Å < \( \lambda \) < 7000 Å. Second, we fit the spectra using the Mpfit package in IDL which is based on the Levenberg–Marquardt method. The continuum emission of ULIRGs comes from central AGN and host galaxy, and is often modified by the intrinsic dust extinctions. These effects should be considered for the determination of the continuum flux. A local power law is used for fitting the continuum. After the subtraction of the fitted continuum emission from the spectra, we fit the emission lines. For NL ULIRGs, we use a single Gaussian profile to fit the \( \text{H} \alpha \), \( \text{H} \beta \), [\text{O} \text{iii}]\(4959, 5007\), [\text{N} \text{ii}]\(6548, 6583\), [\text{S} \text{ii}]\(6716, 6731\), and [\text{O} \text{i}]\(6300\) emission lines. When a single Gaussian cannot fit the profile of emission lines very well, double Gaussians are used to obtain the line flux. For Type I UIRGs, we use two Gaussian components to fit \( \text{H} \alpha \) and \( \text{H} \beta \). If the [\text{O} \text{iii}] emission lines cannot be well fitted by a single Gaussian, two Gaussian components are also used. Examples of the fitted spectra are given in Figure 4.

### 3. NL ULIRGs

The emission-line properties of 147 NL ULIRGs in our sample can be obtained and are listed in Table 1. We first classify them using the Baldwin–Phillips–Terlevich (BPT) diagram (Baldwin et al. 1981; see Figure 5).

The Balmer decrement method is often used to evaluate the intrinsic reddening effect. In previous works (e.g., Kewley et al. 2006; Veilleux et al. 1999a, 1999b), \( \text{H}_\alpha / \text{H}_\beta = 2.85 \) was used for galaxies whose emissions are dominated by star formation, and \( \text{H}_\gamma / \text{H}_\beta = 3.1 \) is used for galaxies dominated by the AGN. But before we classify the object through the BPT diagrams, we cannot assess which source is dominated by the star formation or the AGN. In this work, we adopt the intrinsic ratio \( \text{H}_\alpha / \text{H}_\beta = 3.1 \), and the reddening curve of Cardelli et al. (1989, hereafter CCM89), and also assume \( R_v = A_v/E(B−V) = 3.1 \) to do the optical classification. In order to examine the influence of the intrinsic ratio of \( \text{H}_\gamma / \text{H}_\beta \), we also used \( \text{H}_\alpha / \text{H}_\beta = 2.85 \) to do the classification again, and found that the classification of only one source (F09444+1019) is not consistent with the case of assuming \( \text{H}_\gamma / \text{H}_\beta = 3.1 \).

The intrinsic flux at wavelength \( \lambda \) can be expressed as

\[
I(\lambda) = F(\lambda) \times 10^{c(f(H_\alpha)−f(H_\beta))}.
\] (9)

The relation between the intrinsic and observed line ratio of \( \text{H}_\alpha \) and \( \text{H}_\beta \) is

\[
I(\text{H}_\alpha) / I(\text{H}_\beta) = 10^{c(f(\text{H}_\alpha)−f(\text{H}_\beta))} \times F(\text{H}_\alpha)/F(\text{H}_\beta),
\] (10)

where \( f(\lambda) \) is related to the generalized CCM89 reddening curve, \( I(\lambda) \) is the intrinsic flux, \( F(\lambda) \) is the observed flux, and \( c \) is the value of the Balmer extinction. We estimated \( c \) from the observed line ratio and the reddening curve, after the intrinsic line ratio is assumed. We use the new classification scheme made by Kewley et al. (2006) for the classification.

The 147 NL ULIRGs are classified as five types: 29 star-forming galaxies, 62 composite galaxies (which are likely to contain metal-rich stellar populations, plus AGN, see Kewley et al. 2006), 34 Seyfert galaxies, 6 LINERs, and 16 ambiguous galaxies, which are classified as one type in one or two diagrams but another type in the other diagram(s). Together with the
62 Type I ULIRGs, the percentage for AGNs is about 78% if we regard that the composite galaxies also contain AGNs. The AGN percentage becomes 49% if we only consider the Seyfert galaxies, LINERs, and Type I ULIRGs. The AGN percentage becomes 49% if we only consider the Seyfert galaxies, LINERs, and Type I ULIRGs as AGNs, either Type I ULIRGs, or Seyfert galaxies. Therefore, the radio–FIR relation originates from the starburst-related non-thermal radiation, and the radio excess objects are due to the AGN-related radio emission (Roy & Norris 1997).

4. TYPE I ULIRGs

In our ULIRG sample, there are 62 Type I ULIRGs. We can explore their properties of central BHs. Examples of their SDSS spectra are shown in Figure 8. The parameters of these Type I ULIRGs are listed in Table 2.

4.1. Black Hole Masses of Type I ULIRGs

We assume that the motion of the gas moving around the central BH is dominated by the gravitation force and that the gas of broad emission line region (hereafter BLR) is virialized (e.g., Peterson & Wandel 1999, 2000). The BH mass can then be expressed as $M_{\text{BH}} = \frac{R_{\text{BLR}} v_{\text{FWHM}}^2}{G}$, and the realistic formula given by Kaspi et al. (2000) is

$$\frac{M_{\text{BH}}}{M_\odot} = 1.464 \times 10^5 \left( \frac{R_{\text{BLR}}}{\text{ly} - \text{days}} \right) \left( \frac{v_{\text{FWHM}}}{10^3 \text{ km s}^{-1}} \right)^2,$$

(14)

where $v_{\text{FWHM}}$ is the FWHM of the broad emission line, and $R_{\text{BLR}}$ is the radius of the BLR. For our objects, the $v_{\text{FWHM}}$ is taken as the FWHM of the broad component of the H$_\alpha$ emission line, and the $R_{\text{BLR}}$ can be estimated from the Fe ii and the Galactic-extinction-corrected continuum luminosity at 5100 Å, using

$\frac{R_{\text{BLR}}}{\text{ly} - \text{days}} = (26.4 \pm 4.4) \left( \frac{\lambda L_\lambda(5100 \, \text{Å})}{10^{44} \text{ erg s}^{-1}} \right)^{0.6(1 \pm 0.1)}.$

(15)

The relation between $R_{\text{BLR}}$ and $L_\lambda(5100 \, \text{Å})$ was first found by Kaspi et al. (2000), and their data were refitted by McLure & Jarvis (2002) in the same cosmology as we adopted. Here we assume that the central AGN dominates the continuum emission at 5100 Å, and the contribution from stellar emission and the intrinsic reddening effect can be neglected. Kawakatu et al. (2006) argued that, for Type I

### Table 2

| Parameter | Value |
|-----------|-------|
| $M_{\text{BH}}$ (10$^6$ $M_\odot$) | $1.464 \times 10^5$ |
| $R_{\text{BLR}}$ (ly - days) | $26.4 \pm 4.4$ |
| $v_{\text{FWHM}}$ (10$^3$ km s$^{-1}$) | $1.464 \times 10^5$ |

Notes: Column 1: IRAS name; Column 2: redshift; Column 3: continuum flux at 5100 Å corrected by the use of $F_{\lambda}(5100 \, \text{Å})_{\text{rest}} = (1 + z)F_{\lambda}(1 + z)(5100 \, \text{Å})_{\text{rest}}$; Columns 4–7: FWHM of the broad component of H$_\alpha$, the FWHM of the [O iii]5007 Å profile, and the [O ii]6300 Å core, as well as the [S ii] profile, if available; Column 8: derived BH mass; Column 9: Eddington ratio; Column 10: infrared luminosity; Column 11: the quality of [O iii] FWHM; “1”: the fitting result is reliable. “2”: the FWHM cannot be well fitted due to the low quality of the spectra or suffer serious absorptions around the emission lines.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)
ULIRGs, the central AGN dominance of the 5100 Å emission is reasonable.

To investigate the BH masses of Type I ULIRGs systematically, a large sample is absolutely needed. Kawakatu et al. (2006) used eight ULIRGs from the Type I ULIRG sample of Zheng et al. (2002) to investigate this problem, and concluded that the BH masses of Type I ULIRGs are typically smaller than those of PG QSOs. The FWHM $H_β$ they used is not the broad component of $H_β$, which leads to an underestimation of the BH mass. Hao et al. (2005) carried out a study on Type I ULIRGs, with a sample mainly from Zheng et al. (2002), but added several PG QSOs. The FWHM of the $H_β$ broad component they used was estimated in the same way as that in Boroson & Green (1992), who used double components to fit the $H_β$ line. Hao et al. (2005) used the cosmology of $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $Ω_m = 0.3$, and $Ω_{\Lambda} = 0.7$, the same as ours. We noted that three of our 62 Type I ULIRGs were listed in their sample: for F01572+0009, the BH mass in our work ($\log(M_{BH}/M_\odot) \sim 8.0$) is consistent with their result ($\log(M_{BH}/M_\odot) \sim 7.7$). For F10026+4347, the same BH mass ($\log(M_{BH}/M_\odot) \sim 7.8$) is given in Hao et al. (2005) and our work. But for the other source F13342+3932, the BH mass we obtained ($\log(M_{BH}/M_\odot) \sim 8.4$) is larger than theirs ($\log(M_{BH}/M_\odot) \sim 7.4$), mainly because we use the much more broad component of $H_β$ from SDSS spectra.

We combine the sample of Hao et al. (2005) with ours, and obtain a large sample of 90 Type I ULIRGs. The distribution
Figure 8. Examples of SDSS spectra of Type I ULIRGs in our sample. In each panel, the top curve is the extinction and redshift-corrected spectra. The middle curve is the spectra after the subtraction of the Fe\text{II} emissions, which was shifted downward. The bottom curve is the model for Fe\text{II} emissions.

Figure 9. BH mass distribution. The solid line represents the BH mass distribution of our sample and the Type I ULIRGs from Hao et al. (2005), while the dot-dashed line is for that of the PG QSOs obtained from Hao et al. (2005).

The bolometric luminosity $L_{\text{bol}}$ measures the total luminosity associated with the AGN. We estimate the bolometric luminosity using the formula in Kaspi et al. (2000): $L_{\text{bol}} \approx 9\lambda L_\lambda(5100 \text{ Å})$. For those ULIRGs from Hao et al. (2005), we directly use their data because they used the same method to calculate the BH mass and $L_{\text{bol}}$. The distribution of the Eddington ratio of this sample is shown in Figure 10, and the mean value is about 0.92 for these 90 Type I ULIRGs, and 0.55 for our 62 Type I ULIRGs, larger than that of PG QSOs (the mean value of the Eddington ratio for them is about 0.2).

The intrinsic reddening effect in Type I ULIRGs is still poorly known, and it probably affects the estimation of the optical luminosity. The Balmer decrement method is often used to estimate the reddening effect for narrow emission galaxies, but is seldom used for broad emission-line galaxies. In principle, the observations in the X-ray band can be used to estimate the absorption column density and then the absorption. But for our 62 Type I ULIRGs, only several have been observed in the X-ray band. More work is still needed to understand the intrinsic reddening effect in Type I ULIRGs.
4.2. The $M_{\text{BH}}$–$\sigma$ Relation for Type I ULIRGs

The $M_{\text{BH}}$–$\sigma$ relation for ULIRGs was seldom discussed in the past, mainly due to the poor understanding of BH masses and the limitation of the sample size. Dasyra et al. (2006b) measured the velocity dispersions of 54 ULIRGs, and carried out a simulation to study the reasonableness of using the $M_{\text{BH}}$–$\sigma$ relation to estimate their BH masses. They concluded that if the efficiency of gas accretion onto the BH from its surroundings remains constant with time, this relation can be used. For Type I ULIRGs, we can estimate their BH masses and velocity dispersions by use of their optical spectra, thus it is possible to test the $M_{\text{BH}}$–$\sigma$ relation for ULIRGs by observation. Here we investigate the $M_{\text{BH}}$–$\sigma$ relation for our Type I ULIRG sample.

When the stellar velocity dispersions have measured data in the literature, we adopt them directly, otherwise, the line width is used to estimate $\sigma$, which were usually adopted in the studies on different types of AGNs (e.g., Nelson 2000; Boroson 2003; Grupe & Mathur 2004; Salviander et al. 2007; Komossa & Xu 2007). For six sources, F01572+0009, F12540+5708, F15462–0450, F21219–1757, F13451+1232(w), and PG 0050+124, their velocity dispersions have been measured in Dasyra et al. (2006a, 2006b, 2007) and are directly adopted here. BH mass uncertainty is estimated from the uncertainty of the formula Equation (15) and the errors of the $L_\lambda$($5100$ Å) and FWHM$_{\text{H}_\alpha}$. The uncertainty of $\sigma$ is estimated from the fitting error of FWHM of emission lines, and the instrumental resolution for SDSS spectra is about 7 km s$^{-1}$. To make a comparison, we also use the value of seven QSOs from Dasyra et al. (2007), who measured the $\sigma$ for 11 QSOs. Among these 11 QSOs, PG0050+124 is identified as a Type I ULIRG and PG1404+226 as a NL Seyfert 1 galaxy in Hao et al. (2005). PG1426+015 is an interacting system. The BH mass of LBQS0307–0101 is unavailable. Thus only seven of 11 QSOs are used. The instrumental resolution for their measured velocity dispersion is about 30 km s$^{-1}$.

We show the $M_{\text{BH}}$–$\sigma$ relation of our sample by using these surrogates of $\sigma$ in Figure 11, where $\sigma = \text{FWHM}_{\text{lines}}/2.35$. Because the outflow may influence the profile of [O iii], there are some problems when using the FWHM of [O iii] profile as the surrogate of $\sigma$. Thus we do not adopt the FWHM of the [O iii] profile as the surrogate of $\sigma$. In the upper panel, the FWHM of the [O iii] NL core is used to estimate $\sigma$. Komossa & Xu (2007) used [S ii] as the surrogate of $\sigma$ and found that NL Seyfert 1s do follow the $M_{\text{BH}}$–$\sigma$ relation. In the middle panel, we use the FWHM of [S ii] for $\sigma$ of some ULIRGs. Some ULIRGs do not follow the $M_{\text{BH}}$–$\sigma$ relation. The larger deviations from this relation are, i.e., F11394+0108 and F17234+6228, whose FWHMs of [S ii] are broader than those of the [O iii] profile. The FWHM of the [O iii] NL core is used to estimate $\sigma$ for these ULIRGs and the result is shown in the lower panel of Figure 11. Considering the error bars, we found that most ULIRGs follow the $M_{\text{BH}}$–$\sigma$ relation, but several sources have relatively larger deviations compared with those seven QSOs. This can be seen even from those six ULIRGs with measured velocity dispersions. Therefore most Type I ULIRGs follow the $M_{\text{BH}}$–$\sigma$ relation and probably are at a late evolutionary stage, though several ULIRGs do not follow this relation, which probably hints that AGN phase appears in the late evolutionary stage of ULIRGs, and the $M_{\text{BH}}$–$\sigma$ relation of most Type I ULIRGs has already built up. According to the popular evolutionary picture of ULIRGs, during the evolution phase of ULIRGs to QSO, their BHs are growing, and the $M_{\text{BH}}$–$\sigma$…

![Figure 11. $M_{\text{BH}}$–$\sigma$ diagrams for Type I ULIRGs. The filled triangles represent the six sources with measured $\sigma$ in Dasyra et al. (2006a, 2006b, 2007), open triangles represent the seven QSOs with measured $\sigma$ in Dasyra et al. (2007), filled circles indicate the ULIRGs whose parameters are estimated in this work. If $\sigma$ is unavailable in reference, it was estimated by several methods: in the upper panel, the $\sigma$ is estimated from the FWHM of the [O iii] NL core; in the middle panel, the $\sigma$ is estimated from the FWHM of the [S ii] profile; in the lower panel, the same as the middle panel, except that for some sources, i.e. F11394+0108 and F17234+6228, their velocity dispersions are estimated from the FWHM of the [O iii] NL core because the FWHM of the [S ii] profile is smaller than that of the [S ii] profile. The dashed line is the $M_{\text{BH}}$–$\sigma$ relation from Tremaine et al. (2002).](image-url)
relation is building up step by step. The scatter in the $M_{\text{BH}}-\sigma$ diagram probably reflects the fact that ULIRGs are in different evolutionary stages and the central BHs of some ULIRGs are still rapidly growing. Therefore, the interaction properties of these Type I ULIRGs may be the hint in understanding this problem.

In our sample, F13451+3932 is an interaction system with two bright nuclei; BH mass and velocity dispersion of the west nucleus can be obtained. F10531+5531 and F11559+4545 are interaction systems. F14394+5332 interacts with a companion galaxy. Some sources show that tidal tail/plume features interact with a much smaller galaxy, such as F01572+0009, F09591+2045, F11162+6020, F07548+4227, F11134+0225, F14026+4341, F14315+2955, F14390+6209, F11206+3639, F11394+0108, F13342+3932, F15320+0325, F15437+4647, F16122+1531, F17234+6228. Some Type I ULIRGs are probably interacting systems but not certain because of the lower image resolution and the lack of redshift data of their companions, such as F11553−0259, F110015−0018, F114402+0108. Other ULIRGs do not show obvious interaction features at least from their SDSS images. We compare those ULIRGs with or without interaction features in the $M_{\text{BH}}-\sigma$ diagram. The result is shown in Figure 12. It seems that the ULIRGs with interaction features have slightly larger deviations, but the difference is not significant. Even for those ULIRGs with interaction features, some of them are close to the $M_{\text{BH}}-\sigma$ line, and others have larger deviations, which implies that the $M_{\text{BH}}-\sigma$ relation for some Type I ULIRGs is not fully built up. The sources in our sample do not show large deviations from the $M_{\text{BH}}-\sigma$ line, probably because the AGN phase appears in the late stage of mergers and the interaction between central BH and its host galaxy already starts before the ULIRGs present broad emission lines in the optical band. More observations are needed to verify the interaction properties and merger stages of all these Type I ULIRGs.

4.3. Dependence on the Eddington Ratio

We show the log($M_{\text{BH}}/M_{\text{BH}}$) versus log($L_{\text{bol}}/L_{\text{Edd}}$) diagram in Figure 13, where $M_{\text{BH}}$ is the BH mass calculated from the $M_{\text{BH}}-\sigma$ relation of Tremaine et al. (2002). Here log($M_{\text{BH}}/M_{\text{BH}}$) represents the deviation of the BH mass from the $M_{\text{BH}}-\sigma$ relation. The Eddington ratio log($L_{\text{bol}}/L_{\text{Edd}}$) usually measures the accretion rate of the BH. The uncertainty of log($M_{\text{BH}}/M_{\text{BH}}$) is estimated from the uncertainties of $M_{\text{BH}}$, the $M_{\text{BH}}-\sigma$ relation of Tremaine et al. (2002), and $\sigma$. The uncertainty of log($L_{\text{bol}}/L_{\text{Edd}}$) is estimated from the errors of $M_{\text{BH}}$ and $f_{5100}$ Å. An anti-correlation trend appears in this plot even using different methods to estimate $\sigma$. For the sources with larger deviations from the $M_{\text{BH}}-\sigma$ relation, they tend to have larger Eddington ratios and smaller BH masses, implying that their BHs grow faster. For the sources that are close to the $M_{\text{BH}}-\sigma$ relation, they have relatively smaller Eddington ratios and larger BH masses, and their central BHs grow slowly. These results imply that different kinds of ULIRGs probably exist (i.e., some are close to the $M_{\text{BH}}-\sigma$ relation and with a relatively smaller Eddington ratio, some with larger deviations to the $M_{\text{BH}}-\sigma$ relation and a relatively larger Eddington ratio), and they may have evolutionary connection. One possible explanation of this trend is that the merger of gas-rich galaxies will first form a non-regular host galaxy with a larger deviation from the $M_{\text{BH}}-\sigma$ relation. The interaction between central BH and its host galaxy will slowly make it close to the $M_{\text{BH}}-\sigma$ relation, since the Eddington ratio becomes smaller, the central BH becomes larger and the stars around the central region form a more regular spheroid step by step. In Figure 12, we also plot the log($M_{\text{BH}}/M_{\text{BH}}$) versus log($L_{\text{bol}}/L_{\text{Edd}}$) relation for ULIRGs with or without obvious interaction features.

To estimate $M_{\text{BH}}$ and $L_{\text{bol}}/L_{\text{Edd}}$, the continuum flux at 5100 Å was used. One may worry that the trend appeared in the log($M_{\text{BH}}/M_{\text{BH}}$) versus log($L_{\text{bol}}/L_{\text{Edd}}$) plot is due to the common dependence of these two quantities on the continuum flux at 5100 Å. Because log($M_{\text{BH}}/M_{\text{BH}}$) is proportional to log($L_{5100}^{0.61}$ Å) (we used the R–L relation of Kaspi et al. 2000), and log($L_{\text{bol}}/L_{\text{Edd}}$) is proportional to log($L_{5100}^{0.39}$ Å). If the relation depends on the methods of estimating $M_{\text{BH}}$ and $L_{\text{bol}}/L_{\text{Edd}}$, log($M_{\text{BH}}/M_{\text{BH}}$) should increase as log($L_{\text{bol}}/L_{\text{Edd}}$) increases. However, this is not the case in our plot. Therefore, we believe that the anti-correlation trend between log($M_{\text{BH}}/M_{\text{BH}}$) and log($L_{\text{bol}}/L_{\text{Edd}}$) is real.

Another important issue is the identification reliability of our Type I ULIRG sample. For 41 of 62 Type I ULIRGs, their counterparts and redshifts listed in the NED are consistent with our results. For other 21 ULIRGs, no counterparts and redshifts are available in the NED. As discussed in Section 2.3 (also see Figure 2), 18 of these 21 ULIRGs have their reliability...
Type I ULIRGs are above the trend which was defined by the PG QSOs and NL Seyfert 1 galaxies. If this correlation can be explained as both the infrared and optical continuum emissions of PG QSOs and NL Seyfert 1 being mainly associated with the AGN, the deviation to this correlation may imply an additional contribution to the $L_{\text{IR}}$ besides the AGN in Type I ULIRGs, i.e., the contribution from starbursts.

5. DISCUSSIONS

The intrinsic extinction of ULIRGs is significant. Kawakatu et al. (2006) estimated the optical extinction of three Type I ULIRGs using the X-ray data, and concluded that the optical extinction $A_V$ is probably less than 1. While the typical optical extinction estimated from the Balmer decrement method for the NL ULIRGs is about 3 (see the $E(B-V)$ values provided in Veilleux et al. 1999a, under the assumption $R = A_V/E(B-V) = 3.1$). This result proves that the optical extinction of Type I ULIRGs is typically smaller than that of NL ULIRGs. We compared the optical extinction obtained from the X-ray method and the Balmer decrement method for these three Type I ULIRGs. For F11598-0112, the optical extinctions derived by these two methods are consistent with each other, both being about 0.03. For F01572+0009, these two methods give smaller values of the optical extinction. For the remaining one, F11119+3257, the extinctions derived by these two methods have a large difference. The extinction effect in different evolutionary stages may have a large difference.

Recently, Dong et al. (2008) carried out a study on the broad-line Balmer decrement in Seyfert 1 galaxies and QSOs, and concluded that the Balmer decrement is a good indicator for dust extinction. We use the Balmer decrement method to test the influence of extinction on our results. After such a correction, the mean BH mass of our Type I ULIRGs sample becomes $\log(M_{\text{BH}}/M_\odot) \approx 8.1$, which is larger than $\log(M_{\text{BH}}/M_\odot) \approx 7.8$ obtained without this correction, and is still typically smaller than that of PG QSOs ($\log(M_{\text{BH}}/M_\odot) \approx 8.4$). The anticorrelation trend appeared in the $\log(M_{\text{BH}}/M_\odot)$ versus $\log(L_{\text{bol}}/L_{\text{Ed}})$ plot still exists. Therefore, we believe that the optical extinction does not affect our main results significantly.

In Figures 11 and 13, we note that the sources which are close to the $M_{\text{BH}}-\sigma$ relation tend to have relatively smaller Eddington ratios and larger BH masses. The distributions of their BH masses and Eddington ratios are similar with those of PG QSOs (see the upper panel in Figure 13). For the ULIRGs with larger deviations from the $M_{\text{BH}}-\sigma$ line, they tend to have larger Eddington ratios and smaller BH masses. An evolutionary connection may exist between them. When the BH activity in ULIRGs is active enough, the central BH can blow away a large fraction of the surrounding gases, and the ULIRGs appear like optically bright QSOs. Thus the evolution of Type I ULIRGs is probably followed by the building up of the $M_{\text{BH}}-\sigma$ relation and evolving toward the QSO phase.

Cao et al. (2008) compared the mid-infrared spectroscopic properties of 19 local Type I ULIRGs (named IR QSOs in their work) with that of QSOs and ULIRGs. They concluded that the MIR spectra slopes, the polycyclic aromatic hydrocarbon (PAH) emission strengths, and [Ne II] 12.81 $\mu$m luminosities of Type I
Figure 14. Two examples about the same results in Figures 11 and 13, but only the data that have been confirmed in previous works were used.

Figure 15. \( L_{IR} \) vs. \( \lambda L_{\lambda} (5100 \text{ Å}) \). The open circles indicate the PG QSOs, the open triangles represent the NL Seyfert 1 galaxies, and the crosses denote the Type I ULIRGs. The data are taken from Hao et al. (2005). The filled circles are new data of the Type I ULIRGs in our sample.

ULIRGs differ from those of PG QSOs but are comparable with ULIRGs. Their results support that Type I ULIRGs are at a transitional stage from ULIRGs to classical QSOs, which are consistent with ours. Therefore, Type I ULIRGs are important for the understanding of co-evolution of the central BH and its host galaxy.

6. CONCLUSIONS

We identified 308 ULIRGs from the SDSS DR6 spectroscopy catalog and the IRAS Faint Source Catalog. This is, to date, the largest ULIRG sample with optical spectra in the local universe. About 56% of them show obvious interaction features, and this percentage increases for objects with smaller redshifts, probably due to the selection effect. After excluding the ULIRGs without obvious emission lines (with \( S/N < 3 \) or suffer serious absorptions around the emission lines), we obtained 147 NL ULIRGs (with only narrow emission lines in their spectra) and 62 Type I ULIRGs (with broad emission lines) in this sample. At least 49% of these 209 ULIRGs contain AGNs, and this percentage increases with \( L_{IR} \). The ULIRGs near the radio–FIR relation mainly have the starburst related emissions, and the radio excess in some objects is due to the AGN related radio emissions.

In combination with previous data, a large sample of 90 Type I ULIRGs is used to study their BH masses and BH–host galaxy relation. We found that their BH masses are systematically smaller than those of PG QSOs, even though the optical extinction effects were corrected through the Balmer decrement method. Their Eddington ratios are systematically larger than those of PG QSOs. Most Type I ULIRGs in our sample follow the \( M_{BH}–\sigma \) relation, but some do not, even the FWHM of [O II] NL core or [S II] NL was used as the surrogate of velocity dispersion, which implies that some Type I ULIRGs are in the early stage of galaxy evolution and their \( M_{BH}–\sigma \) relation is still building up. We found an anti-correlation trend between \( \log(M_{BH}/M_{BH}) \) and \( \log(L_{bol}/L_{Edd}) \), where \( M_{BH} \) is the BH mass derived from the \( M_{BH}–\sigma \) relation of Tremaine et al. (2002). The Type I ULIRGs with larger deviations from the \( M_{BH}–\sigma \) relation tend to have larger Eddington ratios and smaller BH masses, and the ULIRGs which are close to the \( M_{BH}–\sigma \) relation tend to have smaller Eddington ratios and larger BH masses. This anti-correlation trend implies that the evolution of Type I ULIRGs is probably followed by the building up of the \( M_{BH}–\sigma \) relation and evolving toward the QSO phase. Different types of ULIRGs are probably at different evolution stages.

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