SPECTROSCOPIC PROPERTIES OF QSOs SELECTED FROM ULTRALUMINOUS INFRARED GALAXY SAMPLES

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ABSTRACT

We performed spectroscopic observations for a large infrared quasi-stellar object (QSO) sample with a total of 25 objects. The sample was compiled from the QDOT redshift survey, the 1 Jy ultraluminous IRAS galaxy survey, and a sample obtained by a cross-correlation study of the IRAS Point-Source Catalogue with the ROSAT All-Sky Survey Catalogue. Statistical analyses of the optical spectra show that the vast majority of infrared QSOs have narrow permitted emission lines (with FWHM of Hβ less than 4000 km s⁻¹) and more than 60% of them are luminous narrow-line Seyfert 1 galaxies. Two of the infrared QSOs are also classified as low-ionization broad absorption line (lo-BAL) QSOs. More than 70% of infrared QSOs are moderately or extremely strong Fe ii emitters. This is the highest percentage of strong Fe ii emitters in all subclasses of QSO Seyfert 1 samples. We found that the Fe ii to Hβ line ratio is significantly correlated with the [O iii] λ5007 peak and Hβ blueshift. Soft X-ray–weak infrared QSOs tend to have large blueshifts in permitted emission lines and significant Fe ii 48, 49 (5100–5400 Å) residuals relative to the Boroson & Green Fe ii template. If the blueshifts in permitted lines are caused by outflows, then they appear to be common in infrared QSOs. As the infrared-selected QSO sample includes both luminous narrow-line Seyfert 1 galaxies and lo-BAL QSOs, it could be a useful laboratory to investigate the evolutionary connection among these objects.

Key words: galaxies: Seyfert — quasars: emission lines — quasars: general

1. INTRODUCTION

Two of the most important reasons for investigating the ultraluminous IRAS galaxies (ULIRGs) are to find the evolutionary connection between circumnuclear massive starbursts and active galactic nuclei (AGNs) and to identify the evolution path from galaxy mergers to elliptical galaxies and quasi-stellar objects (QSOs; see Sanders & Mirabel 1996 for a review). In recent years, significant progress has been achieved with both space and ground-based telescopes (Surace et al. 1998; Surace, Sanders, & Evans 2000; Genzel et al. 1998; Farrah et al. 2001 and reference therein). It is now widely accepted that the vast majority (>95%) of ULIRGs are strongly interacting and merging galaxies, while some of them are postmerger galaxies. The AGN phenomenon probably appears at the final merging stage (e.g., Clements et al. 1996; Kim, Veilleux, & Sanders 1998; Zheng et al. 1999; Canalizo & Stockton 2001a; Cui et al. 2001). Spectral analyses for large samples of ULIRGs reveal that the fraction of objects with AGN spectral characteristics is about 25%–30%, while the fraction of QSO Seyfert 1 galaxies is less than 10% (Wu et al. 1998; Lawrence et al. 1999). However, the percentage of QSO Seyfert 1 galaxies increases with increasing infrared luminosity, reaching 30%–50% for L_{IR} > 10^{12.3} L_☉ (Veilleux, Kim, & Sanders 1999). As the infrared luminosity of ULIRGs is equivalent to the bolometric luminosity of optically selected QSOs (Sanders 2001), we find it convenient to refer to QSO/Seyfert 1 galaxies selected from ULIRGs as IR QSOs throughout this paper.

Previous spectroscopic studies of small and statistically incomplete IR QSO samples have uncovered some unusual properties compared with optically selected QSO/Seyfert 1 galaxies. Many IR QSOs are extremely strong Fe ii emitters (Fe ii λ4570/Hβ > 2.0), for example, PHL 1092, IRAS 07598+6508, and Mrk 231 (Lípari 1994; Lawrence et al. 1997). In fact, almost 100% of extremely strong Fe ii emitters are luminous IR QSOs (Lípari et al. 2002). More than 20 years after their discovery, the origin of such extremely strong optical Fe ii emissions in QSO/Seyfert 1 galaxies is still being debated. It has become clear, however, that the strength of the Fe ii emission cannot be explained in the framework of photoionization excitation. If strong outflows and shocks are present in strong or extremely strong Fe ii emitters, nonradiative shock heating and overabundance of iron may help to explain the strong Fe ii emission (Collin & Joly 2000). Studies of IR QSOs may therefore shed new light on the origin of the Fe ii emission.

Furthermore, the fraction of low-ionization broad absorption line QSOs (lo-BAL QSOs) is much higher in an
IR QSO sample (27%) than that in an optically selected QSO sample (1.4%) (Boroson & Meyers 1992). The lo-BAL QSOs are defined as a subclass of broad absorption line QSOs with an obvious Mg II λ2795, 2802 doublet and low-ionization line absorption troughs (Weymann et al. 1991). Some IR QSOs belong to yet another class of unusual AGNs, the luminous narrow-line Seyfert 1 galaxies (NLS1’s; Osterbrock & Pogge 1985). NLS1’s are defined by their optical emission line properties. They have narrow hydrogen Balmer lines with typical FWHM $\approx$ 500–2000 km s$^{-1}$. The [O iii] $\lambda$5007/H$\beta$ line ratio is less than 3 and most of them have strong Fe ii emissions. In the X-ray band, NLS1’s show systematically steeper power-law slopes in the continuum than normal Seyfert 1 galaxies. Some NLS1’s exhibit rapid X-ray variabilities as well (Boller, Brandt, & Fink 1996). Moran, Halpern, & Helfand (1996) pointed out that many NLS1’s are luminous in the infrared band. IR QSOs therefore offer a unique opportunity to investigate potential physical connections between IR QSOs, lo-BAL QSOs, and luminous NLS1’s (Brandt & Gallagher 2000; Canalizo & Stockton 2001b; Sanders & Mirabel 1996).

In this paper, we study the spectroscopic properties of IR QSOs, based on a large sample of 25 objects. We compare their properties with those of the Boroson & Green (1992, hereafter BG92) sample, which includes 87 optically selected QSOs. The outline of the paper is as follows. In § 2, we discuss how our IR QSO sample is compiled. The observations and data reduction are described in § 3. We present the spectra and statistical properties of our sample IR QSOs in § 4, and finally, in § 5, we discuss and summarize our results. Throughout this paper we use a Hubble constant of $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$ and $\Omega_0 = 1$ and no cosmological constant. As all our objects have redshift lower than 0.35, the adoption of a different density parameter and cosmological constant has little effect on our results.

2. SAMPLE SELECTION

Our IR QSO sample is compiled mainly from three sources.

1. The QDOT redshift survey is a survey of the IRAS galaxies sparse-sampled at a rate of 1 in 6. It includes 2387 IRAS galaxies, complete down to a 60 $\mu$m flux density limit of 0.6 Jy. Lawrence et al. (1999) gave a table of 97 ULIRGs (for $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$ and $\Omega_0 = 1$) with the criterion that the 60 $\mu$m luminosity is greater than $10^{12}$ $L_\odot$. The optical spectral features and classifications are given in their ULIRG table. There are eight objects in the table identified as IR QSOs.

2. Kim & Sanders (1998) selected 118 ULIRGs [infrared luminosities $L(8–1000 \mu m) > 10^{12}$ $L_\odot$ for $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$ and $\Omega_0 = 0$] from the criterion of 60 $\mu$m flux density greater than 1 Jy in the sky region with $\delta > -40^\circ$ and $|b| > 30^\circ$. Veilleux et al. (1999) gave the spectroscopic features and classification of 108 out of these 118 ULIRGs. There are 10 IR QSOs among these 108 ULIRGs.

3. Moran et al. (1996) presented spectroscopic classifications for a catalog of IRAS galaxies selected from the cross-correlation of the IRAS Point-Source Catalogue with the ROSAT All-Sky Survey by Boller et al. (1992). This catalog consists of 241 objects and 80 of them are identified as QSO Seyfert 1 galaxies. Eleven of these objects are IR QSOs.

Because of the constraint of the observatory site and instrumental capability, we selected our targets by requiring the IR QSOs to be in the northern sky ($\delta > -30^\circ$) and $z < 0.35$ with $L(8–1000 \mu m) > 10^{12}$ $L_\odot$ for $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$ and $\Omega_0 = 1$. In addition, we included F09427+1929 (Zheng et al. 1999). Taking into account the overlapping sources, the sample consists of 25 IR QSOs. Table 1 lists the basic parameters. Note that all the infrared luminosities have been converted using $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$ and $\Omega_0 = 1$.

While the sample size is still moderate, it is interesting to put this number in the context of the total expected number of IR QSOs in the local universe. The PSCz catalog provides a complete redshift survey of 15411 IRAS galaxies (Sanders et al. 2000). About 900 ULIRGs were found, which implies that the percentage of ULIRGs in the IRAS galaxy catalog is about 6%. The percentage of IR QSOs among ULIRGs is approximately 10%, as there are eight IR QSOs among 97 ULIRGs in the QDOT catalog and 10 IR QSOs among 108 ULIRGs in the 1 Jy sample. So the fraction of IR QSOs in the complete PSCz catalog is of the order of 0.6%, i.e., the total IR QSOs in the PSCz catalog may be less than 100. Our sample therefore includes roughly one quarter of IR QSOs in the local universe. Statistical results based on this quite large IR QSO sample should be representative.

3. OBSERVATIONS AND DATA REDUCTION

Long-slit optical spectroscopic observations were carried out on the 2.16 m telescope at the Xinglong station of the National Astronomical Observatories. The observations were mostly performed between 1998 October and 1999 November by using an OMR spectrograph, while some preliminary studies were conducted before 1998. For our 1998 and 1999 observations, a Tektronix 1024 $\times$ 1024 CCD was used, giving a wavelength coverage of 4000 to 9000 Å with a grating of 200 Å/mm. The spectral resolution was 9.7 Å (2 pixels). The slit width varied from 1.5 to 3.5 to match the seeing at the Xinglong station. For the pre-1998 observations, the instrument setup was slightly different. For these observations, a grating of 195 Å/mm$^{-1}$ was used and the coverage was from 3500 to 8100 Å with a resolution of 9.3 Å. For F01572+0009, the spectrum coverage was in the range 3800 to 6300 Å with a resolution of 4.9 Å. The observation log is given in Table 2, listing observation epochs, exposure times, approximate seeings, and adopted slit widths.

Data reduction was performed using IRAF software. CCD reductions included bias subtraction, flat-field correction, and cosmic-ray removal. Sky light subtractions were accomplished during the extraction procedure. Wavelength calibrations were carried out using a HeAr lamp. The resulting wavelength accuracy is better than 1 Å. KPNO standard stars were observed for flux calibrations. The telluric O$_2$ absorption bands near 6870 and 7620 Å were removed using the spectra of the standard stars.

The IRAF package SPECTFIT was developed and is kindly provided by Gerard A. Kriss.
models. We model the emission lines with Gaussian profiles and the local continuum as a power law.

Since the intrinsic extinction of ULIRGs is significant, the Galactic extinction is ignored in our analysis. The extinction correction is calculated approximately according to Veilleux & Osterbrock (1987), and the intrinsic broad-line Hα/Hβ ratio is taken to be 3.1 (Baker 1997). The Hβ/Hγ ratio is used to estimate the extinction when Hα is out of the spectral coverage (Osterbrock 1989). The measured fluxes of Balmer lines are the sum of the narrow and broad components. It is noted that the intrinsic broad Balmer line ratios may be larger than the adopted values (e.g., MacAlpine 1985) and the extinction corrections may have large uncertainties. Fortunately, the emission-line ratios adopted in our analyses, e.g., Fe ii λ4570/Hβ and [O iii] λλ5007/Hβ, are almost independent of extinction, because of the proximity of the involved lines. For the Fe ii residual measurement, the uncertainty from the extinction correction will be discussed in §4.3. In general, the uncertainty for the flux measurement introduced by the extinction correction is less than 20%.

As the Fe ii emission is moderately or extremely strong for most of our sample galaxies, Fe ii multiplets seriously blend with the Hβ and [O iii] λλ4959, 5007 lines and contaminate the continuum. We carefully remove the Fe ii multiplets following Bg92. Their method uses an Fe ii template derived empirically from high-quality data of I Zw 1, a typical NLS1 galaxy. We then measure the flux for all emission lines based on the Fe ii–subtracted continuum. On the other hand, the emission lines for a quite large fraction of our sample IR QSOs show a remarkable asymmetric profile. In such cases, double Gaussian profiles are needed to fit them. The asymmetry and blueshift can then be measured from the fitting. In the following subsections we describe in more detail the Fe ii multiplets removal method and the measurement of the line asymmetry and blueshift.

### 3.1. Fe ii Multiplets Removal

To estimate the Fe ii strength and measure the line fluxes reliably, we adopt the BG92 method, which relies on an Fe ii template. The template and observed spectra are both transformed into the rest frame. The template is broadened by convolving with a Gaussian of various line widths and scaled by multiplying by a factor indicating the line strength. The best match is then searched for in the two-dimensional parameter space of the line width and line strength. A good Fe ii subtraction is found when the parts of the continuum between the Hγ and Hβ and between 5100 and 5400 Å (which covers the Fe ii multiplets 48, 49) are flat. The best-fit Fe ii template emission lines are then subtracted from the observed spectrum. The Fe ii flux is then determined from the best-fitting Fe ii template between the rest wavelengths 4434 and 4685 Å. The procedure of Fe ii subtraction is illustrated in Figure 1. In each panel of Figure 1, the top curve is the dereddened spectrum, the bottom curve

### TABLE 1

**SAMPLE OF IR QSOs SELECTED FROM ULIRGS**

| IRAS (1) | R.A. (2) | Decl. (3) | \( \log \left( \frac{L_{\text{FIR}}}{L_{\odot}} \right) \) (4) | \( \log \left( \frac{L_{\text{IR}}}{L_{\odot}} \right) \) (5) | \( \log \left( \frac{L_X}{L_{\text{FIR}}} \right) \) (6) | Redshift (7) | Reference (8) |
|---------|---------|----------|-----------------|-----------------|-----------------|------------|-------------|
| F00275-2859 | 00 30 04.2 | –28 42 24.6 | 12.64 | 12.90 | –2.89 | 0.279 | 1 |
| F01572+0009 | 01 50 52.0 | +00 23 42.2 | 12.65 | 12.85 | –1.72 | 0.163 | 2 |
| F02054+0835 | 02 08 06.8 | +08 50 05.2 | 12.97 | 13.29 | < –2.17 | 0.345 | 1 |
| F02065+4705 | 02 09 45.8 | +47 19 43.2 | 12.27 | 12.45 | < –2.47 | 0.132 | 1 |
| F04415+1215 | 04 44 28.8 | +12 21 13.1 | 12.41 | 12.53 | –1.67 | 0.089 | 3 |
| IR 06269-0543 | 06 29 24.7 | –05 45 26.0 | 12.49 | 12.74 | –1.11 | 0.117 | 3 |
| F07599+6508 | 08 04 30.4 | +64 59 53.3 | 12.45 | 12.77 | < –3.02 | 0.148 | 2 |
| F09427+1929 | 09 45 27.6 | +19 15 42.1 | 12.61 | 12.90 | < –1.99 | 0.284 | 4 |
| F10106+4547 | 10 05 41.8 | +43 32 41.6 | 12.20 | 12.54 | –0.46 | 0.178 | 1 |
| F11119+3257 | 11 14 38.8 | +32 41 34.7 | 12.64 | 12.88 | < –2.40 | 0.189 | 2 |
| Z11586-0112 | 12 02 26.6 | –01 29 15.3 | 11.91 | 12.43 | –1.72 | 0.151 | 2, 3 |
| F12134+5459 | 12 15 49.3 | +54 42 24.6 | 12.17 | 12.36 | –1.67 | 0.150 | 3 |
| F12265+0219 | 12 29 06.6 | +02 03 09.0 | 12.65 | 13.04 | –0.03 | 0.158 | 2, 3 |
| F12540+5708 | 12 56 13.9 | +56 52 24.6 | 12.60 | 12.82 | –3.95 | 0.042 | 1, 2 |
| F133218+0552 | 13 34 21.9 | +05 37 04.6 | 12.53 | 12.94 | < –2.23 | 0.205 | 2 |
| F13342+3932 | 13 36 24.0 | +39 17 32.2 | 12.49 | 12.72 | < –2.30 | 0.179 | 2 |
| F15069+1808 | 15 09 13.7 | +17 57 11.0 | 12.24 | 12.47 | –1.47 | 0.171 | 3 |
| F15462-0450 | 15 48 56.8 | –04 59 33.5 | 12.35 | 12.50 | < –2.68 | 0.101 | 2 |
| F16136+6550 | 16 13 57.1 | +65 43 11.0 | 11.92 | 12.24 | –0.21 | 0.129 | 3 |
| F18216+6419 | 18 21 57.1 | +64 20 37.4 | 13.02 | 13.34 | –0.73 | 0.297 | 3 |
| F20036-1547 | 20 06 31.9 | –15 39 05.8 | 12.70 | 12.89 | < –2.44 | 0.193 | 1 |
| F20520-2329 | 20 54 57.3 | –23 18 24.8 | 12.52 | 12.77 | –1.48 | 0.206 | 3 |
| F21219-1757 | 21 24 41.6 | –17 44 45.3 | 12.02 | 12.39 | –2.18 | 0.113 | 2 |
| F22454-1744 | 22 48 04.1 | –17 28 28.5 | 11.94 | 12.37 | –1.03 | 0.117 | 3 |
| F23411+0228 | 23 43 39.7 | +02 45 05.7 | 12.14 | 12.34 | –1.98 | 0.091 | 3 |

**Note.** — The prefix of the object name indicates the origin of IRAS fluxes. “F” refers to the IRAS Faint Source Catalogue, and “Z” means the Faint Source Reject File (see Moshir et al. 1992). For IR 06269-0543, the IRAS fluxes come from the IRAS Point-Source Catalogue. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds (J2000.0). Col. (4)–(5): far-infrared and infrared luminosity, calculated following Sanders & Mirabel (1996); col. (6): soft X-ray luminosity (0.2–2.4 keV) normalized to far-infrared luminosity; col. (7): redshift, taken from the references.

**References.** — (1) Lawrence et al. 1999; (2) Kim & Sanders 1998; (3) Moran et al. 1996; (4) Zheng et al. 1999.
TABLE 2  
JOURNAL OF OBSERVATIONS

| IRAS Name          | Date      | Exp. Time (s) | Slit (arcsec) | Seeing (arcsec) |
|-------------------|-----------|---------------|---------------|-----------------|
| F00275-2859       | 1999 Nov 7 | 3600          | 3.0           | 3.0             |
| F01572 +0009      | 1996 Nov 17 | 3600          | 3.0           | 3.0             |
| F02054 +0835      | 1998 Oct 22 | 2700          | 3.0           | 2.1             |
| F02065 +4705      | 1999 Feb 20 | 1800          | 2.2           | 1.5             |
| F04415 +1215      | 1998 Oct 18 | 3600          | 3.0           | 3.5             |
| IR 06269-0543     | 1998 Oct 23 | 1800          | 3.0           | 2.1             |
| F07599 +6508      | 1997 Mar 16 | 3600          | 3.0           | 1.5             |
| F09427 +1929      | 1998 Dec 20 | 3600          | 2.5           | 1.5             |
| F10026 +4347      | 1999 Feb 22 | 3600          | 2.2           | 1.5             |
| F11119 +3257      | 1999 Feb 21 | 2400          | 2.2           | 1.5             |
| Z11598-0112       | 1997 Mar 12 | 5400          | 3.0           | 3.0             |
| F12134 +5459      | 1999 Feb 22 | 2700          | 2.2           | 1.5             |
| F12265 +0219      | 1995 Mar 13 | 600           | 3.0           | 3.0             |
| F12540 +5708      | 1997 Mar 16 | 1200          | 3.0           | 1.5             |
| F13218 +0552      | 1999 Feb 21 | 3600          | 2.2           | 2.0             |
| F13342 +3932      | 1999 Feb 22 | 1500          | 2.2           | 1.5             |
| F15069 +1808      | 1999 Feb 22 | 2700          | 2.2           | 1.5             |
| F15462 +0450      | 1997 Apr 11 | 3600          | 3.0           | 2.0             |
| F16136 +6550      | 1998 Oct 20 | 1800          | 3.0           | 2.1             |
| F18216 +6419      | 1998 Oct 17 | 2700          | 2.5           | 3.5             |
| F20036 +1547      | 1998 Oct 23 | 1800          | 2.5           | 3.5             |
| F20502 +2329      | 1998 Oct 22 | 2700          | 3.0           | 2.1             |
| F21219 -1757      | 1998 Oct 20 | 2700          | 3.0           | 2.1             |
| F22454 -1744      | 1998 Oct 20 | 2700          | 3.0           | 2.1             |
| F23411 +0228      | 1997 Oct 4  | 4800          | 2.5           | 3.5             |

is the Fe II template, and the middle curve shows the Fe II-subtracted spectrum. Note that the Fe II-subtracted spectra have been shifted downward for clarity.

In the BG92 method, it is assumed that the relative strengths of the Fe II lines (within each multiplet and among multiplets) are the same for different objects. For half our spectra, the Fe II emission can be subtracted very well by the Fe II template. However, for F00275-2859, IRAS 07598+6508, F09427+1929, Mrk 231 (i.e., F12540+5708), and F20036-1547, the Fe II multiplets 48, 49 (5100–5400 Å) are stronger than the Fe II multiplets 37, 38 relative to the BG92 template. The spectra for these objects, significant Fe II residuals can be seen in their Fe II-subtracted spectra. The extreme case is Z11598-0112, for which nearly half the Fe II 4570 (i.e., Fe II multiplets 37 and 38) is left after the multiplets 48, 49 are subtracted. Figure 2 shows two examples of such remarkable Fe II emission residuals in the Fe II multiplets 48, 49 (top) and 37, 38 (bottom). Compared with the optical QSO sample of BG92, the IR QSO sample contains more objects showing large deviations from the Fe II template. The spectra for F13218+0552 and F23411+0228 are too noisy to detect the Fe II lines reliably, so we take the Fe II strength for F13218+0552 from Remillard et al. (1993) and ignore F23411+0228 in our statistical analysis concerning the Fe II strength.

3.2. Emission-Line Fitting and Measurement

As a first step, we use a single Gaussian profile to fit each emission line for all target galaxies. It works well for most emission lines. However, a single Gaussian profile cannot fit some lines, e.g., those with asymmetric profiles. In such cases, two Gaussian components are used to fit the emission lines, namely, one narrow component and one centroid-shifted broad component. The blueshift (or redshift) is defined as the shift of the broad component relative to the narrow component in kilometers per second. Figure 3 illustrates the two-Gaussian component fitting for the permitted line Hβ (top) and forbidden line [O III] λ5007 (bottom). In Figure 3, the observed and fitted profiles are shown by the solid and dashed lines, respectively, while the dot-dashed line is for the Gaussian components, and the dotted line represents the fitting residual. As one can see, for F01572+0009 the blueshift of the permitted emission-line Hβ of F00275-2859 is 750 km s⁻¹, while the blueshift of [O III] λ5007 is 510 km s⁻¹.

Moreover, there is no correlation between the FWHM of the narrow Gaussian component of the permitted line Hβ and that of the forbidden line [O III] λ5007. It implies that the narrow Gaussian component of the permitted emission lines is different from the narrow lines (such as [O III] λ5007) from the narrow-line region. Efforts were also made to separate the narrow Gaussian component contributed by the narrow-line region. However, the contribution from the narrow-line region is usually less than 3%, so we ignore this component in our discussions.

We also measure the asymmetry parameter

\[ \text{asy} = \frac{\lambda_3(3/4) - \lambda_1(1/4)}{\Delta \lambda(1/2)} \]  

defined by de Robertis (1985), where \( \lambda_1(1/4) \) and \( \lambda_3(3/4) \) are the wavelength centers at 1/4 and 3/4 of the maximum,
respectively, and $\Delta \lambda(1/2)$ is the FWHM. The asymmetry parameter is positive (negative) if there is excess light in the blue (red) wing.

Based on the Fe ii–subtracted spectra and Gaussian fitting of emission lines, we measured the flux, FWHM, and equivalent width (EW) for each strong emission line for all our objects. The fluxes of broad lines or asymmetric lines refer to the sum of double components. For most targets, the uncertainty of flux measurement of emission lines is about 10%, but for low cases of low signal-to-noise ratio
(S/N) it could be up to 20%. The uncertainty of the blueshift measurement is within 150 km s$^{-1}$. However, for three sources (F02054+2835, F13218+0552, and F23411+0228), the fluxes of emission lines have large uncertainties due to the poor S/N, and hence they are less reliable.

The dereddened and Fe II–subtracted spectrum for each sample IR QSO is shown in Figure 1. Table 3 lists the FWHM, blueshifts and asymmetry parameters for H$\beta$ and [O iii] $\lambda$5007. The intrinsic FWHM values are obtained from the subtraction, in quadrature, of the observed FWHM and
that of the instrumental profile, measured from the comparison lamp lines. Note that only the significant \([\text{O} \text{ III}] \lambda 5007\) blueshifts (the \([\text{O} \text{ III}] \lambda 5007\) blueshift > 500 km s\(^{-1}\)) are listed. In Table 4, the color excess \(E(B-V)\), the equivalent widths of the emission lines, and various line ratios are listed.

4. STATISTICAL RESULTS

As discussed in the introduction, our sample is a unique one to investigate the physical connection among IR QSOs, luminous NLS1’s, and lo-BAL QSOs. We therefore performed statistical studies similar to those in BG92 for their optical sample, which includes 87 QSOs from the Bright Quasar Survey Catalogue with redshift less than 0.5 (Schmidt & Green 1983). The results for these two samples will be compared to understand any possible evolutionary connection between IR QSOs and classical QSOs.

4.1. Percentage of NLS1’s and Strong Fe II Emitters

It is obvious from Table 3 that for all our IR QSOs except F16136+6550 and F18216+6419 the H\(\beta\) FWHM is less than 4000 km s\(^{-1}\). This differentiates IR QSOs from classical QSOs as the main characteristic of classical QSOs is the presence of broad permitted emission lines with typical FWHM between 4000 and 10,000 km s\(^{-1}\) (Rodríguez-Ardila, Pastoriza, & Donzelli 2000). To make it clear, Figure 4 shows the distribution of the H\(\beta\) FWHM for our sample (top) and the BG92 sample (bottom). A Kolmogorov-Smirnov (K-S) test indicates a probability of 9.5 \(\times\) 10\(^{-3}\) for the two distributions being the same. From Table 3 and Figure 4, the percentage of IR QSOs with H\(\beta\) FWHM less than 2000 km s\(^{-1}\) in our sample is 60% (15/25). In comparison, only 23% of BG92 QSOs have FWHM H\(\beta\) less than 2000 km s\(^{-1}\), and 1/3 of BG92 QSOs are classical QSOs with H\(\beta\) FWHM larger than 4000 km s\(^{-1}\).

As part of our IR QSOs are selected from the IRAS ROSAT cross-correlation catalog, our sample may be biased to include more NLS1’s (Stephens 1989). To check this, we performed statistics for the subsample of 15 objects selected from two purely IR-selected samples (the QDOT redshift survey and 1 Jy ULIRG sample). Out of these 15 objects, eight are identified as NLS1’s (53%). Therefore, there is no clear difference in the fraction of NLS1’s between the whole sample and the purely IR-selected subsample.

We also carefully investigated whether the H\(\beta\) blueshift could influence the H\(\beta\) FWHM and concluded that this possibility is unlikely. Therefore the percentage of NLS1’s seems genuinely high in our IR QSO sample.

Figure 5 shows the histograms of the Fe II \(\lambda 4570/H\beta\) ratio for the IR QSO and BG92 samples. We can see from
Figure 5 that the Fe II λ4570/Hβ ratio distributions for the two samples are quite different. A K-S test reveals that the probability for these two distributions being the same is 3.0 × 10⁻⁶. Table 4 shows that 25% (6 in 24) and 46% (11 in 24) of IR QSOs, respectively, are extremely strong (Fe II λ4570/Hβ > 2.0) and moderately strong (1.0 < Fe II λ4570/Hβ < 2.0) Fe II emitters (Joly 1991; Véron-Cetty, Véron, & Concâlves 2001). In contrast, for the BG92 sample, only 15 out of 87 (17%) QSOs are moderately strong Fe II emitters, and there are no extremely strong Fe II emitters present. The high percentage of strong Fe II emitters in our sample can also be seen by comparing with that of the overall AGN population. Véron-Cetty et al. (2001) found that moderately strong Fe II emission occurs in only about 5% of AGNs and only a few AGNs are extremely strong Fe II emitters. Furthermore, the two weakest Fe II emitters (with Fe II λ4570/Hβ < 0.5) in our sample (F16136+6550 and F18216+6419) have broad permitted emission lines, with FWHM larger than 4000 km s⁻¹ and hence are classical QSOs.

4.2. Correlations

In this subsection, we study the correlations between various emission lines and continua for our sample IR QSOs. For this purpose, we performed Spearman rank-order (S-R) correlation analyses among various quantities and investigate the implications of these correlations. As mentioned above, most of our sample IR QSOs are moderately or extremely strong Fe II emitters, and the origin of the Fe II emission is still not understood. Hence our analysis focuses on the correlations of the Fe II strength with other parameters. Throughout this paper, the correlations are characterized by the probability P that the null hypothesis of no correlation is true.

Figure 6 shows the Fe II λ4570/Hβ line ratio versus the [O iii] λ5007 peak, defined as the peak height of the [O iii] λ5007 line relative to that of Hβ, as in PG92. These two parameters are anticorrelated with a correlation coefficient of 0.71 at a very high significance level (P = 6.1 × 10⁻⁶). This result is consistent with BG92 although the correlation between these two parameters is stronger than the one reported by BG92 for optically selected QSOs. The Fe II λ4570/Hβ ratio is also well correlated with the [O iii] λ5007/Hβ ratio with P = 9.8 × 10⁻³. Note that six IR QSOs in our sample have very weak [O iii] λ5007 emission...
Section 5.1.2: The correlation coefficient between $\lambda 5007$ and $\lambda 4570$ is 0.76, which is highly significant, with $\lambda 4570/\lambda 5007$ ratio versus the H$\beta$ FWHM for 24 of our objects (F23411+0228 is excluded because of its low S/N). If the two classical QSOs with H$\beta$ FWHM larger than 4000 km s$^{-1}$ are excluded, then the S-R correlation coefficient between these two parameters is 0.47 with $P = 2.8 \times 10^{-2}$. If we further exclude the three objects with H$\beta$ FWHM larger than 3000 km s$^{-1}$ (but smaller than 4000 km s$^{-1}$), the correlation becomes somewhat stronger, with an S-R correlation coefficient of 0.58, corresponding to $P = 9.9 \times 10^{-3}$. We caution, however, that if we include the two objects with H$\beta$ FWHM larger than 4000 km s$^{-1}$, the Fe $\Pi$ $\lambda 4570/\lambda 4959, 5007$ profile. The S-R correlation coefficient is 0.46 with $P = 2.8 \times 10^{-2}$. Our result is broadly consistent with BG92, although the H$\beta$ asymmetry parameter for our sample IR QSOs seem to be much larger than those for the BG92 sample. Quantitatively, just 13% of BG92 QSOs have the asymmetry parameter larger than 0.1, while in our sample 48% (26%) of IR QSOs have the H$\beta$ asymmetry value larger than 0.1 (0.2).

As described in § 3.2, the H$\beta$ blueshift value is determined by the blueshift of the broad Gaussian component relative to the narrow Gaussian component in permitted emission lines. The blueshifted broad Gaussian component may be connected with the outflow of clouds in the broad-line region (Leighly 2001). Outflows with a velocity of several
Such shocks may be an important ingredient for understanding the strong correlation seen between the Fe II $\lambda 4570/\text{H} \beta$ ratio and the H$\beta$ blueshift.

### 4.3. Soft X-Ray Properties

We collected all the X-ray information from Moran et al. (1996) and Xia et al. (2001) based on ROSAT archive data. Table 1 lists the ratio of the soft X-ray luminosity to the far-infrared luminosity, $L_X/L_{\text{FIR}}$, where “FIR” indicates far-infrared. This is an important quantity as nearly all the luminosity of a ULIRG is emitted in the far-infrared band (Surace et al. 2000). We can see from Table 1 that 17 of our IR QSOs were detected by either the ROSAT All-Sky Survey (13/17) or pointing observations (4/17). The ratio of the soft X-ray luminosity to the far-infrared luminosity spans about 4 orders of magnitude. Not surprisingly, the four objects (IRAS 07598+6508, Mrk 231, F00275-2859, and F21219-1757) detected only by ROSAT pointings have the lowest $L_X/L_{\text{FIR}} < 0.01$ values compared with the other 14 objects detected by the ROSAT All-Sky Survey. For the nondetections, we calculated their upper limits of the soft X-ray luminosity as follows. We assume a detection limit of 6 source photons (as in the ROSAT All-Sky Survey Faint Source Catalogue; Voges et al. 2000) and an average exposure time of 400 s for each source. The spectrum of each source is taken to be a power law with a photon index of 2.3 (appropriate for AGNs), and Galactic neutral hydrogen column density is adopted. The estimated $L_X/L_{\text{FIR}}$ upper limits are also given in Table 1. As might be expected, they all satisfy $L_X/L_{\text{FIR}} < 0.01$.

Figure 10 shows the H$\beta$ blueshift versus the ratio of soft X-ray luminosity to far-infrared luminosity for 14 objects detected by the ROSAT All-Sky Survey and ROSAT pointings. In this statistic and also in the following statistics concerning $L_X/L_{\text{FIR}}$, we excluded F16136+6550 and F18216+6419 because they have broad emission lines and their S-R correlation coefficients are $< 0.61$, corresponding to $P = 2.0 \times 10^{-2}$. In Figure 10, we also labeled the two potential low-BAL QSOs (F09427+1929 and F20036-1547; see § 5.2) by using their soft X-ray luminosity upper limits. These two objects strengthen the trend described above.

During our data reduction, we noticed that the Fe II emission cannot be subtracted very well by the Fe II template of...
BG92 for 1/3 of our targets; i.e., there are large residuals of \( \text{Fe}^{\text{II}} \) multiplets 48, 49 (5100–5400 Å) or \( \text{Fe}^{\text{II}} \) multiplets 37, 38 (4500–4680 Å) in the \( \text{Fe}^{\text{II}} \)-subtracted spectra. We define the residual of \( \text{Fe}^{\text{II}} \) multiplets 37, 38 (or \( \text{Fe}^{\text{II}} \) 48, 49) as the excess of \( \text{Fe}^{\text{II}} \) 37, 38 (or \( \text{Fe}^{\text{II}} \) 48, 49) relative to its strength in the best-fit \( \text{Fe}^{\text{II}} \) template. A positive residual means that there is an excess in the \( \text{Fe}^{\text{II}} \) 37, 38, while a negative value signals an \( \text{Fe}^{\text{II}} \) 48, 49 excess.

The \( \text{Fe}^{\text{II}} \) residual is somewhat uncertain because of the extinction correction. Since the blue light suffers more extinction than the red light, an overcorrection in the extinction would lead to an overestimate of the \( \text{Fe}^{\text{II}} \) multiplets 37, 38 and hence increase the value of the \( \text{Fe}^{\text{II}} \) residual in this multiplet. This overall trend also establishes that the excess of \( \text{Fe}^{\text{II}} \) multiplets 48, 49 relative to multiplets 37, 38 cannot be an artifact. For example, for F00275-2859, we have adopted \( E(B-V) = 0.41 \), which results in a negative \( \text{Fe}^{\text{II}} \) residual (i.e., there is an excess in the \( \text{Fe}^{\text{II}} \) multiplets 48, 49). If no extinction is adopted, then the value of the \( \text{Fe}^{\text{II}} \) residual in the multiplets 48, 49 would further increase by 30%. We note that while BG92 have described such residuals, they are not as remarkable as those in our IR QSO sample.

We list the measurements of significant \( \text{Fe}^{\text{II}} \) residuals in Table 4. We have examined the correlation of the residuals with other parameters. A correlation was found between the residuals of \( \text{Fe}^{\text{II}} \) multiplets and the soft X-ray luminosity. This is interesting because it ties in with the long-standing puzzle of why some NLS1’s with extremely strong \( \text{Fe}^{\text{II}} \) emission are X-ray–luminous, while others with similar

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**Fig. 4.**—Histograms of the Hβ FWHM for IR QSOs (top) and for the Boroson & Green sample (bottom), which includes 87 optically selected bright QSOs.

**Fig. 5.**—Histograms of the \( \text{Fe}^{\text{II}} \) λ4570/Hβ ratio for IR QSOs (top) and the BG92 sample (bottom).

**Fig. 6.**—\( \text{Fe}^{\text{II}} \) λ4570/Hβ vs. the ratio of the peak height of [O III] λ5007 to that of Hβ. Upper limits for the nondetections are indicated by arrows. For the detected objects, the Spearman rank-order correlation coefficient is \(-0.78 \) with \( P = 6.1 \times 10^{-4} \); i.e., the probability that the null hypothesis of no correlation between these two parameters is true is \( 6.1 \times 10^{-4} \).
optical spectra are X-ray–weak. Figure 11 shows the residuals of Fe\n\text{ii} multiplets versus the \(L_X/L_{\text{FIR}}\) ratio for 14 objects with concrete X-ray detections. We can see from Figure 11 that as the residual of Fe\n\text{ii} multiplets increases from negative to positive, the soft X-ray luminosities of IR QSOs also increase (the S-R correlation coefficient is 0.44 with the correlation significant \(P = 0.117\)). The most interesting result from Figure 11 is that objects with larger Fe\n\text{ii} multiplets residuals are all X-ray–weak. To check the validity of this result, we measured or estimated the Fe\n\text{ii} multiplets residual for another two low-redshift lo-BAL QSOs, namely, PG 1700+518 and IRAS 14026+4341. The

![Fig. 7.—Fe \(\lambda 4570/\text{H}\beta\) vs. the H\(\beta\) blueshift, which is defined as the blueshift of the H\(\beta\) broad component relative to the H\(\beta\) narrow component in kilometers per second. A negative value indicates a redshift. For 23 objects, the correlation coefficient is 0.76 with \(P = 2.7 \times 10^{-5}\).](image1)

![Fig. 8.—Fe \(\lambda 4570/\text{H}\beta\) vs. H\(\beta\) FWHM, showing the 22 objects with H\(\beta\) FWHM less than 4000 km s\(^{-1}\) (filled squares) and the two objects with H\(\beta\) FWHM greater than 4000 km s\(^{-1}\) (open squares). The Spearman rank-order correlation coefficient for the objects with FWHM smaller than 3000 km s\(^{-1}\) (4000 km s\(^{-1}\) is 0.47 (0.58), corresponding to \(P = 2.8 \times 10^{-5}\) (\(P = 9.9 \times 10^{-5}\)). No correlation is apparent if we include all objects. Note that F23411+0228 is excluded because of its low S/N spectrum.](image2)

![Fig. 9.—Fe \(\lambda 4570/\text{H}\beta\) vs. the H\(\beta\) asymmetry index defined by de Robertis (1985; see eq. [1]). The correlation coefficient is 0.46, corresponding to \(P = 3.9 \times 10^{-2}\).](image3)

![Fig. 10.—H\(\beta\) blueshift vs. soft X-ray luminosity for 14 objects (squares) detected by the \textit{ROSAT} All-Sky Survey or pointings. The correlation coefficient for the detected objects is \(-0.61\) with \(P = 2.0 \times 10^{-2}\). Additionally, two potential lo-BAL QSOs are marked by arrows with their upper limits of X-ray luminosity (see text). Typical error bars are indicated at lower left.](image4)
Fe II multiplets 48, 49 residuals are 0.19 and 0.1, respectively. These two objects are shown in Figure 11 as well by using their upper limits of the soft X-ray luminosity (the soft X-ray information of PG 1700+518 is from Wang, Brinkmann, & Bergeron 1996). In the same figure, we also indicated the locations of two potential lo-BAL QSOs, F09427+1929 and IRAS 20036–1547, as they have significant Fe II multiplets 48, 49 residuals and extremely weak [O III] $\lambda5007$. It is interesting that all four low-redshift lo-BAL QSOs and the two potential low-BAL IR QSOs are located in the bottom left of Figure 11. Furthermore, we also measured the Fe II multiplets residual for soft X-ray–weak QSOs (Brandt, Laor, & Wills 2000) with available spectral data. None of them have positive Fe II multiplets residuals. It appears that the Fe II multiplets residual may be a good criterion to select X-ray–weak QSOs or lo-BAL QSOs.

4.4. Infrared Properties

The infrared color-color diagram has been used as an important tool to discriminate starbursts and AGN activities in the nuclear or circumnuclear regions of galaxies (de Grijs et al. 1985; Lipari 1994). In our sample, there are 20 IR QSOs securely detected in three far-infrared bands (25, 60, and 100 $\mu$m). Figure 12 shows the location of these objects in the infrared color-color diagram, $\alpha(60, 25) \pm \log(L_{\text{FIR}})$ versus $\alpha(100, 60)$, where the wavelengths are in microns. In the same diagram, the power-law and blackbody lines are also indicated.

It is clear from Figure 12 that almost all IR QSOs except F13218+0552 are located between the blackbody and power-law lines. Moreover, a group of IR QSOs is clearly located close to the blackbody line. This group includes F01572+0009, IR 06269-0543, F11119+3257, F13218+0552, F15462-0450, F23411+0228, and Mrk 231.

We find that they have either significant [O III] $\lambda5007$ blueshifts (see Table 3) or significant [O III] $\lambda3727$ blueshifts (Mrk 231; see Lipari et al. 2002). The objects close to the power-law line are F18216+6419, F16136+6550, F12265+0219 (3C 273), F10026+4347, F22454-1744, and three additional objects in the bottom left of the figure. The first two objects are the only classical QSOs in our sample, while the remaining objects are all moderate or extremely strong Fe II emitters with bright soft X-ray emission (see Table 4).

5. SUMMARY AND DISCUSSION

We studied an IR QSO sample with a total of 25 objects. The sample is compiled from the QDOT redshift survey, the 1 Jy ULIRG survey, and a cross-correlation study of the IRAS Point-Source Catalogue with the ROSAT All-Sky Survey Catalogue. Using the observed optical spectra and archive data in the infrared and soft X-ray, we investigated the correlations of the Fe II $\lambda4570$/H$\beta$ ratio with the [O III] $\lambda5007$ peak, H$\beta$ FWHM, and the H$\beta$ FWHM. All these parameters are correlated. We found that soft X-ray–weak QSOs, especially lo-BAL QSOs, tend to have significant Fe II multiplet 48, 49 (5100–5400 $\AA$) residuals (see Fig. 11). The correlation between the Fe II $\lambda4570$/H$\beta$ residuals and the $L_{x}/L_{\text{FIR}}$ ratio, shown in Figure 11, although somewhat weak, may be a useful clue for understanding why some strong or extremely strong Fe II emitters are X-ray–luminous, while others are X-ray–weak.

5.1. Outflows

One of the striking features of the emission lines for IR QSOs is the blueshift of permitted emission lines or the forbidden [O III] $\lambda5007$ line. As we have carefully removed the Fe II multiplets surrounding the H$\beta$ and [O III] $\lambda\lambda4959, 5007$, there should not be much Fe II multiplet contaminations.
tion to the H\(\beta\) and [O iii] \(\lambda 4959, 5007\) emission lines. Moreover, the blueshifts measured from H\(\beta\) and H\(\alpha\) are similar, as are the blueshifts measured from the [O iii] \(\lambda 5007\) and [O iii] \(\lambda 4959\) lines (see Fig. 3). The asymmetries of the H\(\beta\) and [O iii] \(\lambda 5007\) lines cannot be attributed to contaminations from other emission lines. Outflows give a plausible explanation for the emission-line blueshift (for alternative explanations, see Brandt et al. 2000). Such emission-line outflows have been found and discussed extensively for some NLS1’s (Leighly 2000; Christophoulou et al. 1997), radio galaxies (Tadhunter et al. 2001), and IR QSOs (Lipari et al. 2002).

From the strong correlation between the Fe ii FWHM and the H\(\beta\) FWHM, BG92 suggested that the Fe ii line and permitted emission lines share a common emission region. If the H\(\beta\) blueshifts are due to cloud outflows in the broad-line region, shocks are likely to be produced in outflows. Such shocks may be responsible for the Fe ii emission, as the pure photoionization model fails to explain the strong Fe ii emission (Collin & Joly 2000). The tight correlation between the H\(\beta\) blueshift and the Fe ii \(\lambda 4570/H\beta\) ratio can be understood as these are physically connected through shocks associated with outflows. Analogously, the [O iii] \(\lambda 5007\) blueshifts could probe the outflows in narrow-line emission regions. It is interesting to see that all objects with large [O iii] \(\lambda 5007\) blueshifts are located close to the blackbody line in the infrared color-color diagram. Hence the locations of IR QSOs in the infrared color-color diagram can be related to outflows in the [O iii] \(\lambda 5007\) emission-line region. We caution, however, that there are other explanations concerning the strong Fe ii emission, especially in NLS1 galaxies (see Sulentic, Marziani, & Dultzin-Hacyan 2000a for a review).

If the emission-line blueshifts can be attributed to outflows, then our sample indicates such outflows are common for IR QSOs. Our statistics, however, do not clarify which mechanism (central AGN radiative pressure, starbursts, or both) drives these outflows. High-resolution observations and investigations in the UV, soft X-ray, and optical bands are needed to further explore this unique sample.

5.2. Connection of IR QSOs with Luminous NLS1’s and Low-ionization BAL QSOs

Of our IR QSOs, 60% satisfy the strict criteria of NLS1’s. For the remaining objects, most are moderately strong or extremely strong Fe ii emitters. However, 71% (5/7) of the extremely strong Fe ii emitters in the IR QSO sample fail to meet the strict criterion of NLS1’s. Similarly, a large fraction (44%) of extremely strong Fe ii emitters in the sample of Véron-Cetty et al. (2001) also have H\(\beta\) FWHM larger than 2000 km s\(^{-1}\). As Véron-Cetty et al. (2001) pointed out, there should be a continuous distribution of optical line widths for QSO Seyfert 1 galaxies and hence the separation between the broad-line Seyfert 1 galaxies and NLS1’s at 2000 km s\(^{-1}\) could be arbitrary (see also Sulentic et al. 2000b). Our results seem to support the above statement and hint that the strength of the optical Fe ii emission line, rather than the H\(\beta\) FWHM, may be the most important characteristic of nonclassical QSOs.

Much attention has been paid to lo-BAL QSOs recently. Canalizo & Stockton (2001b) studied four lo-BAL QSOs currently known at \(z < 0.4\) and found that all four are ULIRGs that reside in dusty starbursts or poststarbursts. Two of these, Mrk 231 and IRAS 07598+6508, are in our IR QSO sample. The main characteristics of lo-BAL QSOs are strong Fe ii emissions, very weak [O iii] \(\lambda 5007\) emissions, and low X-ray luminosity. They are immediately located between the power-law and blackbody lines in the infrared color-color diagram (see Fig. 12). A recent Chandra survey for BAL QSOs also revealed that all these four lo-BAL QSOs have high column densities and are unusually faint in both soft and hard X-ray bands (Gallagher et al. 2002). These properties are shared by some other IR QSOs in our sample in addition to Mrk 231 and IRAS 07598+6508. For example, F00275-2859, F09427+1299, and F20036-1517 have all the properties of lo-BAL QSOs as described above. We identify them as potential or more evolved lo-BAL QSOs. If UV observations establish that they are real lo-BAL QSOs, the percentage of lo-BAL QSOs in our sample will be 20%, similar to the fraction found by Boroson & Meyers (1992) for a much smaller IR QSO sample.

Brandt & Gallagher (2000) argued that the potential physical connection between luminous NLS1’s and lo-BAL QSOs is their high accretion rate relative to the Eddington accretion rate. IR QSOs tend to appear in the final merging phase with their central AGN activity recently triggered or rejuvenated by the merging activity (Sanders & Mirabel 1996; Zheng et al. 1999; Canalizo & Stockton 2001a and reference therein). Numerical simulations show that a large amount of gas flows toward the center during mergers (e.g., Barnes & Hernquist 1991), so it seems plausible that IR QSOs may all have high accretion rates. Such systems may have a greater ability to drive radiative outflows. The correlations we presented in § 4.2 suggest that the outflow velocity and the physical condition in the outflow region (inferred from the H\(\beta\) and [O iii] \(\lambda 5007\) emission-line blueshifts) influence the Fe ii, infrared, and soft X-ray emission properties. In short, IR QSOs, luminous NLS1’s, and lo-BAL QSOs may have some common physical conditions. The difference between them may be from different viewing angles or from different evolution phases. A careful study of IR QSOs may be important for understanding the evolution and formation of classical QSOs.

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