A statistical study of the spectra of very luminous IRAS galaxies
I. Data

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Abstract. This paper presents the results of spectral observations for the largest complete sample of very luminous IRAS galaxies obtained to date. The sample consists of those 73 objects for which \( \log(L_{\text{IR}}/L_\odot) \geq 11.5 \) \((H_0 = 50 \text{km}^{-1} \text{Mpc}^{-1}, q_0 = 0.5) \) and \( \text{mag} \leq 15.5 \), and was extracted from the 2 Jy IRAS redshift catalog. All the spectra were obtained using 2.16m telescope of Beijing Astronomical Observatory during the years 1994-1996. A total of 123 galaxy spectra were obtained with spectral ranges of 4400˚A to 7100˚A and 3500˚A to 8100˚A at resolutions of 11.2˚A and 9.3˚A respectively. In addition to the 73 spectra for sample galaxies, we also present spectra for ten non-sample galaxies and a further 40 for the companions of sample galaxies. The data presented include nuclear spectrum and the parameters describing the emission lines, absorption lines and continua as well as DSS images and environmental parameters.

Key words: luminous infrared galaxies – spectra – environment

1. Introduction

The Infrared Astronomical Satellite(IRAS) all-sky survey provided a large database(IRAS Point Source Catalog, Version 2, 1988) of infrared galaxies. Based on recently completed redshift surveys of IRAS galaxies, statistical spectroscopic analysis of very luminous IRAS galaxy samples can now be performed. Sanders et al. (1988) have already studied the spectra of a small sample of ten ultraluminous IRAS galaxies selected from IRAS Bright Galaxy Survey (BGS) of Soifer et al.(1986). Recently Kim et al. (1995) completed a spectroscopic survey based on a large sample of luminous IRAS galaxies that was extracted from both the BGS and infrared warmed catalogs. However, the infrared luminosity range of Kim et al.’s sample is from \( 10^{10.5}L_\odot \) to \( 10^{12.5}L_\odot \) and it therefore can not represent very luminous IRAS galaxies.

This paper presents the spectroscopically data for a large complete sample of very luminous IRAS galaxies (VLIRGs), extracted from 1.936 Jy Redshift Survey of Strauss et al.(1992). The DSS images are also presented, here. A detailed analysis of the spectra and environment will be presented in paper II (Wu et al. 1997).

2. Sample selection

Strauss et al. (1990) selected 5014 objects from the IRAS database(IRAS Point Source Catalog, Version 2, 1988) according to the criteria:
1. \( f_{60} > 1.936 \text{Jy} \)
2. \( f_{60}^2 > f_{12}f_{25} \)
   a color criterion distinguishing galaxies from objects in the Galaxy
3. Galactic latitude \(|b| > 5^\circ|\)

Strauss et al.(1992) then went on to publish the redshifts of the 2658 objects which were galaxies (here after the 2Jy samples).

Our VLIRG sample is a subset of the 2Jy sample. Considering the observatory site, instruments and possible observation times, we selected galaxies according to the following criteria:
1. $\delta \geq 0^\circ$

2. $\log(L_{IR}/L_\odot) \geq 11.5$
   \hspace{1cm} ($H_0 = 50\text{km s}^{-1}\text{Mpc}^{-1}, q_0 = 0.5$)

3. $\text{mag} \leq 15.5$

Here the magnitudes are from the 2Jy catalog. These criteria guarantee S/N ratios good enough for spectroscopic classification. 73 of 2Jy-catalogue VLIRGs met these criteria.

On account of the low S/N at 12$\mu$m and 25$\mu$m for some of sources in 2 Jy sample, we used Dennefeld et al.'s (1986) formula for calculating the infrared flux, between 42.5$\mu$m and 122.5$\mu$m:

$$F_{\text{IR}} = 1.75(2.55S_{60} + 1.01S_{100})10^{-14}\text{W m}^{-2}$$ (1)

where, $S_{60}$ and $S_{100}$ are the fluxes at 60$\mu$m and 100$\mu$m respectively.

The infrared luminosity is therefore:

$$L_{\text{IR}} = 4\pi D^2 F_{\text{IR}}$$ (2)

for each object, where $D$ is the distance from the Galactic center.

3. The sources lists and general properties

Table 1 lists the 83 target galaxies, of which 73 belong to the complete sample. Of the other ten objects in brackets, four of them have slightly lower infrared luminosities than $10^{11.5} L_\odot$ and six are fainter than our magnitude limit ( mag $> 15.5$ ). This table presents the infrared luminosities in unit of $L_\odot$, magnitudes and redshifts. All of these data were derived from the 2Jy catalog, except that in the case of IR09517+6954 (M82). We can not use redshift as a distance indicator on account of the proximity. For this reason, we adopted the distance value given by Tully (1988). These objects flagged with asterisks in column 1 are the sources which are also included in the IRAS Bright Galaxy Sample ($S_{60} > 5.24\text{Jy}$) of Kim et al.(1995). A detailed comparison between these two samples will be made in paper II.

The spatial distribution of the 73 sample galaxies on the sky is shown in Fig.1. The dotted curve is the celestial equator. The scarcity of objects near galactic declination $b \sim 0^\circ$ is due to the matching Zwicky catalog (1961-1968) which misses galaxies at low latitude.

Fig.2 shows the sample distribution as a function of redshift. The solid boxes represent our complete samples while the dotted boxes include the other ten galaxies. It is clear that the redshifts concentrate in the range 0.02 to 0.04. The median value is 0.0324 ( corresponding to a recession velocity 9700km$s^{-1}$) which is larger than the value 5900km$s^{-1}$ obtained by Kim et al.(1995) for their sample.
The infrared luminosity distribution is shown in Fig. 3. The solid and dotted boxes correspond to the same samples as in Fig. 2. The counts decrease rapidly as the infrared luminosity increases. Most of the galaxies have infrared luminosities \( \log(L_{IR}/L_\odot) \) between 11.5 and 12.0.

4. Spectroscopic observations

The spectroscopic observations were made between Apr. 15, 1994 and Feb. 15, 1996. We obtained a total of 123 galaxy spectra. All of the observations were made with a 2.16m telescope at the Xinglong Station of Beijing Astronomical Observatory using Zeiss universal spectrograph with a grating of 195 \( \text{Å/mm} \) dispersion.

Before Nov. 5, 1994, a Tek 512x512 CCD which covered a 2700 \( \text{Å} \) range from 4400 \( \text{Å} \) to 7100 \( \text{Å} \) at a resolution of 11.2 \( \text{Å} \) (2 pixels) was used. After that, a Tek 1024x1024 CCD which covered a 4600 \( \text{Å} \) range from 3500 \( \text{Å} \) to 8100 \( \text{Å} \) at a resolution of 9.3 \( \text{Å} \) (2 pixels) was employed.

In most cases, slit width of about 3” was chosen to match the typical seeing disc at Xinglong Station, but occasionally, the seeing disc was smaller than 2” or larger than 5”. Thus may affect the spectral classification. Slit position angles of 90 \( ^\circ \) than 5”. Thus may affect the spectral classification. Slit occasionally, the seeing disc was smaller than 2” or larger than 5”. Thus may affect the spectral classification. Slit position angles of 90 \( ^\circ \) than 5”.

The seeing was about 3” to 4” on most of the observation nights. In order to perform a relative flux calibration, KPNO standard stars were also observed on each night. Table 2 lists the observations by target objects. The standard IRAS name, together with one upper case letters representing the individual components (See Fig. 9 for identifications) are listed in Column 1. Column 2 to Column 10 give for each source: coordinates, observation date (Beijing Time), exposure time, airmass, slit width and position angle respectively. The sources flagged with ticks in Column 11 were observed during good weather condition.

5. Data reduction

All of the data reductions were performed using IRAF 2. The IRAF packages CCDRED, TWODSPEC and ONEDSPEC were used to reduce the long-slit spectral data. The CCD reductions included bias subtraction, flat-field correction and cosmic-ray removal. The dark counts were so low that their subtraction was not performed. We adopted Horne’s (1986) avariance weighed algorithm in order to extract the spectra. As for the aperture size, we adopted similar method to that of Kim et al. (1995) to minimize the aperture-related effects on the nuclear spectra. The apertures were varied according to the redshift of the objects so that they approached diameters of 2 kpc (\( H_0 = 50 \text{km s}^{-1}\text{Mpc}^{-1} \)) for galaxies with \( z < 0.034 \), but were fixed at 4” for objects at larger redshifts as the seeing was typically 3” to 4” and the pixel sizes was 1.3”.

The only two exceptions were for IR12323+1549A and IR09517+6954 (M82) which are quite nearby and a 2 kpc aperture was too large for them.

An Fe-He-Ar lamp was used for the wavelength calibrations. More than 20 lines were used to establish the wavelength scale by fitting a first-order spline3 function. The accuracy of the wavelength calibration was better than 1 \( \text{Å} \).

On most nights, more than two KPNO standard stars were used to perform the relative flux calibration. Atmospheric extinction was corrected using the mean extinction coefficients for the Xinglong station, that were measured out by BATC multi-color survey (Yan, 1995).

The telluric \( \text{O}_2 \) absorption bands at 6870 \( \text{Å} \) and 7620 \( \text{Å} \) did heavier effect on those emission lines at the similar observed wavelength. We therefore constructed an artificial – the spectrum of standard stars setting every wavelength to unity except these wavelength corresponding to the \( \text{O}_2 \) bands. Division by the artificial spectrum could therefore removed telluric absorption bands. In most cases, this technique worked well, especially for the band near 6870 \( \text{Å} \). However in some cases, this correction seems not to have been very satisfactory and affected the measurement of the emission lines at 7620 \( \text{Å} \).

6. Spectra obtained

Optical spectra are presented for all program objects in Fig. 4. They have all been corrected for telluric absorption, though some of corrections were not as good as we would have thought.

![Example of Gaussian fit for Hα + \([\text{NII}]\)λ6584 + λ6548 emission. Three narrow Gaussian components are used. The pluses are observed data.](image)

The measurements of emission line, absorption line and continuum strengths were performed within the IRAF environment using tasks (SPLOT and SPECFIT). For
isolated emission lines such as $[\text{OIII}] \lambda 5007$, $[\text{OII}] \lambda 3727$ and $[\text{OI}] \lambda 6300$, both Gaussian fitting and direct integral methods were used. For the blended lines such as $\text{H}\alpha$, $[\text{NII}] \lambda 6548, \lambda 6584$, and $[\text{SII}] \lambda 6716, \lambda 6731$ double lines, we employed a multi-Gaussian component method using task SPECFIT, to deblend them. There are three parameters for each Gaussian component: the central wavelength, the total flux and width of the emission line; and two parameters for each continuum component: the flux and the slope. In order to speed up the convergence, some limit conditions were adopted. For example, we fixed the center wavelengths of several components relate to one another. In Fig.5, for example, we used the simplex algorithm for the fitting and obtained the result via a chi-square minimization process. As for the spectra with obvious $\text{H}\beta$ absorption indicating an underlying stellar population, a similar method was used. Because of the coexistence of $\text{H}\beta$ emission and absorption, one emission and one absorption component were used for the $\text{H}\beta$ fitting. The wide absorption wings due to stellar populations often cause the absorption to be overestimated if Gaussian model is adopted. To solve this problem, we adopted the Lorentz model as shown in Fig.6, and the results seem better. Some of our sample galaxies are Seyfert-like, and their spectra could not fitted well with only single Gaussian component for each of $\text{H}\alpha$, $\text{H}\beta$. In those case, we combined one narrow ($<1000\text{km s}^{-1}$) and one broad ($>1000\text{km s}^{-1}$) Gaussian component as shown in Fig.7.

The relative emission-line fluxes are listed in Table 3 for all objects. The typical uncertainty in these measurement is about 10%. Colons (:) and semicolons (;) indicate values with relative uncertainties at about 30% and 50% respectively. For the line $[\text{OII}] \lambda 3727$, we could not obtain a value with an uncertainty of less than 20%, because it was at the blue end of the spectra, which can be affected by the low Q.E., lower S/N and poor flux calibration. In some cases, $[\text{OI}] \lambda 6300$ lines were heavily affected by the nearby emission lines $[\text{SIII}] \lambda 6312$ which could increase the uncertainty. The telluric absorption bands 6870Å and 7620Å was also enlarge the uncertainty in the measurement of lines near them, despite the corrections performed. The double lines $[\text{SII}] \lambda 6716, \lambda 6733$, could sometimes be separated, but when this was not possible, only the combined values are given.

The measured redshifts, observed $\text{H}\alpha$ fluxes, equivalence widths of $\text{H}\alpha$ emission lines, NaID absorption lines and $\text{H}\beta$ absorption lines, and two continuum fluxes (at 4861Å and 6563Å) are listed in Table 4. The typical uncertainty in the measured $\text{H}\alpha$ fluxes was 15%, as the $\text{H}\alpha$ lines often had to be deblended from an overlapping $[\text{NII}]$ emission line.

Finally, we compare our measured redshifts with those of corresponding sources in the 2Jy redshift sample. The distribution of redshift differences is plotted in Fig.8. The mean redshift difference is 0.000054 and scatter is 0.00038.
This means that our measurements agree well with those of the 2Jy catalogue.

7. DSS images

In order to be able to study the relationship between nuclear activity and degree of interaction of VLIRG in a future paper in this series, we extracted the optical images for all our objects from the CD-ROM version of Digital Sky Survey. The contour maps using IRAF tasks, we presented in Fig.9.

8. Summary

We have presented the observation data of optical nuclear spectra and DSS images of a sample of very luminous IRAS galaxies from 2Jy catalog. In the following paper (Wu et al., 1997, Paper II), we will give the results of spectral analysis and environmental study, in the same time, address the possible model and evolutionary sequence of very luminous IRAS galaxies.

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DSS CD-ROM is provided by 2.16m Telescope, Xinglong Station, Beijing Astronomical Observatory.
Table 1 VLIRGs from IRAS 2Jy Catalog

| IRAS*  | Log($L_{IR}/L_{\odot}$) | $z$  | IRAS*  | Log($L_{IR}/L_{\odot}$) | $z$  |
|-------|-------------------------|------|-------|-------------------------|------|
| (1)   | (2)                     | (3)  | (4)   | (5)                     | (6)  |
| 00189+3748 | 11.572                 | 0.0364 | 13136+6223* | 11.937 | 0.0311 |
| 00267+3016 | 11.966                 | 0.0504 | 13183+3423* | 11.863 | 0.0230 |
| 00509+1225 | 11.772                 | 0.0604 | 13299+1121 | 11.516 | 0.0317 |
| 01173+1405* | 11.868                | 0.0312 | 13362+4831* | 11.706 | 0.0275 |
| 01324+2138 | 11.629                 | 0.0472 | 13373+0105* | 11.701 | 0.0225 |
| 01484+2290* | 11.851                | 0.0324 | 13428+5608* | 12.392 | 0.0373 |
| 01572+0009 | 12.665                 | 0.1630 | 13458+1540 | 11.821 | 0.0570 |
| 02071+3857 | 11.546                 | 0.0179 | 13496+0221 | 11.752 | 0.0328 |
| 02203+3315 | 11.837                 | 0.0338 | 13536+1836 | 11.611 | 0.0497 |
| 02222+2159 | 11.652                 | 0.0338 | 14151+2705 | 11.565 | 0.0365 |
| 02248+2621 | 11.519                 | 0.0327 | 14178+4927* | 11.541 | 0.0256 |
| 02435+1253* | 11.501                | 0.0216 | 14547+2448* | 11.897 | 0.0339 |
| 02512+1446* | 11.780                | 0.0312 | 14568+4504 | 11.501 | 0.0357 |
| 03117+4151 | 11.562                 | 0.0235 | 15107+0724* | 11.525 | 0.0131 |
| (05084+7936) | 12.170                | 0.0543 | 15163+4255* | 12.072 | 0.0402 |
| (05414+5840) | 11.505                | 0.0148 | 15327+2340* | 12.464 | 0.182 |
| (06538+4628) | 11.490                | 0.0214 | 15425+4114 | 11.515 | 0.0317 |
| (07062+2041) | 11.550                | 0.0174 | 15426+4116 | 11.546 | 0.0319 |
| (07063+2043) | 11.570                | 0.0173 | 16104+5235* | 11.687 | 0.0294 |
| (07256+3355*) | 11.467              | 0.0135 | 16180+3753 | 11.592 | 0.0307 |
| 08354+2555* | 11.781                | 0.0184 | 16284+0411* | 11.582 | 0.0246 |
| 08507+3520 | 11.811                 | 0.0559 | 16504+0228* | 12.028 | 0.0243 |
| (09047+1838) | 11.490                | 0.0291 | 16577+5900* | 11.582 | 0.0187 |
| 09126+4432* | 11.913                | 0.0393 | 16589+0521 | 11.637 | 0.0502 |
| 09168+3308 | 11.725                 | 0.0499 | 17366+8646 | 11.544 | 0.0264 |
| 09320+6134* | 12.220                | 0.0392 | 17392+3845 | 11.554 | 0.0410 |
| 09333+4811* | 11.523                | 0.0259 | 17501+6825 | 11.829 | 0.0512 |
| (09517+6954) | 10.833                | 0.0009 | 18525+5518 | 11.683 | 0.0484 |
| 10203+5235 | 11.620                 | 0.0322 | 18595+5048 | 11.501 | 0.0271 |
| (10311+3507) | 12.096                | 0.0710 | 19120+7320 | 11.624 | 0.0250 |
| (10565+2448*) | 12.245               | 0.0431 | 20550+1565* | 12.074 | 0.0364 |
| 11231+1456* | 11.809                | 0.0341 | 22388+3359* | 11.531 | 0.0214 |
| 11254+1126 | 11.800                 | 0.0410 | 22501+2427 | 11.723 | 0.0421 |
| 11257+8580 | 12.040                 | 0.0104 | 23007+0836* | 11.734 | 0.0162 |
| 11543+0124 | 11.716                 | 0.0397 | 23024+1916* | 11.573 | 0.0248 |
| (12112+0305) | 12.531                | 0.0724 | 23135+2516* | 11.730 | 0.0273 |
| 12120+6388 | 12.029                 | 0.0608 | 23254+0830* | 11.568 | 0.0290 |
| 12251+4026 | 11.660                 | 0.0371 | 23488+1949* | 11.528 | 0.0142 |
| 12265+0219 | 12.663                 | 0.1583 | 23488+2018* | 11.609 | 0.0179 |
| 12323+1549 | 11.767                 | 0.0461 | 23532+2513 | 11.795 | 0.0571 |
| 12540+5708* | 12.636                | 0.0418 | 23594+3622 | 11.586 | 0.0321 |
| 12592+0436 | 11.787                 | 0.0371 |                  |        |      |

* The sources marked * in column (1) were also observed by Kim et al.(1995)