OPTICAL VERSUS MID-INFRARED SPECTROSCOPIC CLASSIFICATION OF ULTRALUMINOUS INFRARED GALAXIES

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ABSTRACT

The origin of the huge infrared luminosities of ultraluminous infrared galaxies (ULIGs) is still in question. Recently, Genzel and colleagues performed a mid-infrared (MIR) spectroscopic survey of a large number of ULIGs and found the major energy source in them to be massive stars formed during recent starburst activity; \( \sim 70\% \sim 80\% \) of the sample are predominantly powered by starbursts. However, previous optical spectroscopic observations classified the majority of ULIGs either as Seyferts or as LINERs. In order to reconcile this difference, we compare types of emission-line activity for a sample of ULIGs that have been observed in both optical and MIR. We confirm the results of previous studies that the majority of ULIGs classified as LINERs on the basis of optical emission-line diagnostics turn out to be starburst-dominated galaxies on the basis of MIR diagnostics. Since MIR spectroscopy can probe the more heavily reddened, inner parts of the ULIGs, and since it is quite unlikely that the inner parts are powered by starbursts while the outer parts are powered by nonstellar ionization sources, the most probable resolution of the dilemma is that the optical emission-line nebulae with LINER properties are powered predominantly by shock heating driven by superwind activity; i.e., blast waves driven by the collective effect of a large number of supernovae in the central region of galaxy mergers.

Subject headings: galaxies: active — galaxies: Seyfert — galaxies: starburst — infrared: galaxies

1. INTRODUCTION

The origin of the huge infrared luminosities of ultraluminous infrared galaxies (ULIGs) is still in question: is the major energy source starbursts or active galactic nuclei (Sanders et al. 1988a; Condon et al. 1991; Majewski et al. 1993; Smith, Lonsdale, & Lonsdale 1998; see for a review Sanders & Mirabel 1996)? Since their far-infrared luminosities, \( L_{\text{FIR}} \gtrsim 10^{12} L_{\odot} \), are comparable to those of quasars, possible starburst-AGN connections have also been discussed by many authors (Sanders et al. 1988a, 1988b; Norman & Scoville 1988; Terlevich et al. 1992; Lonsdale, Smith, & Lonsdale 1993; Lonsdale et al. 1998; see also, however, § 4 in Taniguchi 1997).

Optical spectroscopy often has been used to investigate the activity in emission-line galaxies (e.g., Veilleux & Osterbrock 1987). In fact, optical spectroscopic observations have shown that the majority of ULIGs are AGN-like objects, Seyferts, or LINERs1 (Sanders et al. 1988a; Armus, Heckman, & Miley 1989; Kim et al. 1995; Kim, Veilleux, & Sanders 1998; Veilleux et al. 1995; Veilleux 1997). Further, in order to find hidden broad emission line regions (BLRs), which provide definite evidence of AGNs, near-infrared spectroscopic programs have also been conducted (Goldader et al. 1995, 1997a, 1997b; Veilleux, Sanders, & Kim 1997). However, hidden BLRs have been found in several ULIGs. Therefore, the majority of AGN-like ULIGs are type 2 Seyferts (S2s) or LINERs, although the fraction of type 1 Seyferts (S1s) increases with increasing \( L_{\text{FIR}} \) (Kim et al. 1998). ULIGs that are optically classified as S1s or S2s are not necessarily powered by AGNs. Their classification indicates only the existence of an AGN. This AGN may not dominate the total bolometric luminosity.

Furthermore, since some LINER-like ULIGs show extranuclear LINER emission (Veilleux et al. 1995; Kim et al. 1998; Heckman et al. 1996; Taniguchi & Ohyama 1998), the origin of LINER-like ULIGs is controversial. This is because this emission can be attributed to shocks caused by the interaction between starburst-driven outflows and the ambient gas. It also has been observed that a number of ULIGs have intense star-forming regions in their central regions (e.g., Shaya et al. 1994; Surace et al. 1998). For example, the main energy source in Arp 220, one of the archetypical ULIGs, is thought to be an intense starburst in the central region (Shaya et al. 1994; Larkin et al. 1995; Skinner et al. 1997; Iwasawa 1998; Scoville et al. 1998; Taniguchi, Trentham, & Shioya 1998; Shioya, Taniguchi, & Trentham 1999). However, possible evidence of a hidden AGN in Arp 220 has also been discussed because of the presence of compact OH megamaser sources in its central region (Diamond et al. 1989; Lonsdale et al. 1994, 1998). This raises another important question: what powers the ULIGs on average? (Genzel et al. 1998). This is an important question, but it is difficult to answer with certainty because all ULIGs have a large amount of molecular gas and dust in their central regions (Scoville et al. 1991; Scoville, Yun, & Bryant 1997; Downes & Solomon 1998 and references therein), and thus the putative central engine could be obscured even if present. Therefore, we have to perform MIR and FIR spectroscopy of ULIGs if we wish to probe their innermost regions.

Recently, Genzel et al. (1998) made MIR spectroscopy of a large number of ULIGs. Since MIR spectroscopy can probe heavily reddened (\( A_V \sim 50 \text{ mag} \)) regions, it should be very powerful for searching for hidden AGNs in ULIGs (see also Lutz et al. 1996). However, they found that the major energy source to be massive stars formed during recent starburst activity, with \( \sim 70\% \sim 80\% \) of the sample being powered predominantly by starbursts. On the other hand, as described before, previous optical spectroscopic observations showed that the majority of ULIGs can be classified as Seyferts or LINERs. In order to reconcile this difference, in this paper we compare types of emission-line activity for...
a sample of ULIGs that have been observed in both optical and MIR and discuss a possible resolution of the dilemma.

2. A BRIEF SUMMARY OF THE MIR SPECTROSCOPY BY GENZEL ET AL. (1998)

Genzel et al. (1998) performed a MIR spectroscopic survey of 15 ULIGs using both the short-wavelength grating spectrometer (SWS) and the ISOPHOT-S spectrometer onboard the Infrared Space Observatory (ISO). They utilized either the [Ne v] 14.3 μm/[Ne ii] 12.8 μm or the [O iv] 25.9 μm/[Ne ii] 12.8 μm emission-line intensity ratio as the discriminator between starbursts and AGNs. Given the poverty of high-energy photons from massive OB stars, high-ionization lines such as [Ne v] are generally weak in starburst galaxies. On the other hand, such high-ionization lines are often strong in AGNs because of a larger number of high-ionization photons (Spinoglio & Malkan 1992; Voit 1992a). In fact, Genzel et al. (1998) obtained [Ne v] 14.3 μm/[Ne ii] 12.8 μm < 0.01 for a sample of nearby typical starburst galaxies (e.g., M82) but ~0.1–1 for a sample of nearby AGNs (e.g., NGC 4151).

Among the 15 ULIGs, Genzel et al. (1998) detected [Ne v] emission only from Mrk 273 (see Table 1). Its [Ne v]/[Ne ii] ratio, 0.27, is consistent with the observed range for AGNs. Although [O iv] was detected in IRAS 23128—5919, its [O iv]/[Ne ii] ratio, 0.037, is so small that this ULIG must be a starburst-dominated galaxy. The upper limits for the remaining objects lie in a range intermediate between the starbursts and AGNs, indicating the intermediate nature of the ULIGs. To estimate the relative contribution of starbursts to the total energy, Genzel et al. (1998) also used the 7.7 μm emission feature, which is one of the unidentified IR-emission bands, probably emitted by polycyclic aromatic hydrocarbons (PAHs). Since these features are seen only in star-forming galaxies, they are useful for estimating the star formation activity in galaxies (Moorwood & Oliva 1988; Mouri et al. 1990; Voit 1992b).

Using a diagram of the [O iv]/[Ne ii] intensity ratio vs. the relative strength of the 7.7 μm PAH feature, they concluded that 70%–80% of their ULIG sample is dominated by a starburst component.

3. OPTICAL VERSUS MIR CLASSIFICATIONS OF ULIGS

We compare optical emission-line classifications with MIR classifications for a sample of ULIGs that are observed in both optical and MIR. Our sample consists of the 12 ULIGs given in Table 1. There we have compiled the following important MIR and optical emission-line ratios:

1. MIR (Genzel et al. 1998)
   a. [Ne v] 14.3 μm/[Ne ii] 12.8 μm
   b. [O iv] 25.9 μm/[Ne ii] 12.8 μm

2. Optical (Sanders et al. 1988a; Armus et al. 1989; Veilleux et al. 1995; Duc, Mirabel, & Mazu 1997; Kim et al. 1998)
   a. [O iii] λ5007/Hβ
   b. [N ii] λ6583/Hα
   c. [S ii] λλ 6716, 6731/Hα
   d. [O i] λ6300/Hα

### Table 1

| ID | Name     | [Oiv]/[Neii] | [Nev]/[Neii] | Type   | [Oiii]/Hβ | [Nii]/Hα | Optical S   | [O i]/Hα | Type  |
|----|----------|--------------|--------------|--------|-----------|----------|-------------|----------|-------|
| a  | UGC 5101 | -0.77        | -0.22        | H      | 0.36      | 0.12     | -0.45       | -0.95    | L     |
| b  | 12112+0305| -0.52        | -0.57        | H      | 0.37      | -0.41    | -0.43       | -1.01    | L     |
| c  | M 231    | -0.22        | -0.48        | A      | ...       | ...      | ...         | ...      | ...   |
| d  | Mrk 273  | -0.07        | -0.57        | A      | 0.64      | -0.06    | -0.29       | -0.90    | S2    |
| e  | 14348—1447| -0.68        | -0.39        | H      | 0.43      | -0.25    | -0.42       | -1.09    | L     |
| f  | Arp 220  | -1.51        | -1.22        | H      | 0.20      | 0.36     | -0.13       | -0.79    | L     |
| g  | NGC 6240 | -0.80        | -1.20        | H      | 0.07      | 0.09     | 0.04        | -0.43    | L     |
| h  | IRAS 17208—0014 | -0.85 | -0.72    | H      | -0.14     | -0.41    | -0.64       | -1.30    | H     |
| i  | IRAS 20100—4156 | -0.21 | -0.11    | H      | 0.17      | -0.36    | -0.77       | -1.21    | H     |
| j  | IRAS 20551—4250 | -0.92 | -0.74    | H      | 0.03      | -0.40    | -0.41       | -1.13    | H     |
| k  | IRAS 22491—1808 | -0.35 | -0.49    | H      | -0.19     | -0.37    | -0.62       | -1.24    | H     |
| l  | IRAS 23128—5919 | -1.43 | -1.15    | H      | 0.43      | -0.37    | -0.34       | -1.03    | L     |

a This ID is used to show each galaxy in Fig. 1.

b Logarithmic MIR emission-line ratios.

c Logarithmic optical emission-line ratios.

d A = AGN or AGN-like, S1 = Seyfert 1, S2 = Seyfert 2, L = LINER, and H = H ii or starburst galaxies.

2 Genzel et al. (1998) note that the [S ii] 33.5 μm line can also be used instead of [Ne ii] 12.8 μm whenever the [Ne ii] line data are not available, because the [S ii] emission arises from nearly the same ionization-condition region as that of the [Ne ii] emission.

This table shows the comparison between optical and MIR classifications of ULIGs. It includes the emission-line ratios and the type of classification for each galaxy.
As shown in Table 1, it is difficult to classify ULIGs unambiguously solely on the basis of MIR line ratios, since most of them are upper-limit data. Therefore, following Genzel et al. (1998), we use a diagram of the \([\text{O} \, \text{iv}]/[\text{Ne} \, \text{ii}]\) intensity ratio and the relative strength of the 7.7 \(\mu\)m PAH feature (see Fig. 5 in Genzel et al. 1998). This diagram shows that only two ULIGs, Mrk 231 and Mrk 273, are classified as AGNs (i.e., more than 50% of their energy comes from AGNs). The optical classification is made with the criteria given in Figure 5 in Veilleux et al. (1995; see also Veilleux & Osterbrock 1987).

The optical line ratios show that only four galaxies are classified as H\(\text{ii}\)-region (i.e., starburst) galaxies. Mrk 231 and Mrk 273 are S1 and S2, respectively. The remaining six ULIGs are LINERs. In Table 2, we compare activity types based on the MIR classification with those based on the optical one. Both the MIR and optical classifications identify two galaxies, Mrk 231 and Mrk 273, as AGNs and four galaxies, IRAS 17208—0014, IRAS 20100—4156, IRAS 20551—4250, and IRAS 22491—1808, as starbursts (although IRAS 20551—4250 is suspected of having LINER-like properties [Johansson 1991; Duc et al. 1997]). Since MIR observations can probe the heavily reddened, inner part of the nuclear region, we expected that MIR spectroscopy would reveal hidden AGNs in some of the ULIGs that have been classified as starburst galaxies on the basis of optical observations. However, no such case was found. On the contrary, six ULIGs that had been classified as LINER-like on the basis of optical observations turn out, based on the MIR spectroscopy, to be starburst-dominated galaxies. This suggests strongly that these ULIGs, which are optically classified as LINERs, are not genuine AGNs but shock-heated galaxies. If this is the case, we can conclude that both the MIR and optical classifications give the same activity types for all the ULIGs analyzed in this study.

We note the following difference between MIR and optical classification schemes. Since optical emission lines arise mostly from low-ionization ions, optical classification uses low-ionization emission-line ratios (Veilleux & Osterbrock 1987; Veilleux et al. 1995). On the other hand, Genzel et al. (1998) adopted high-ionization lines such as \([\text{O} \, \text{iv}]\) and [Ne v] in order to obtain firmer evidence that the central engine is an AGN. Therefore, if we wish to identify LINERs in future MIR spectroscopy, we will have to use low-ionization MIR emission lines such as \([\text{O} \, \text{i}]\) 63 \(\mu\)m, \([\text{O} \, \text{ii}]\) 145 \(\mu\)m, and \([\text{C} \, \text{ii}]\) 158 \(\mu\)m (Spinoglio & Malkan 1992; Luhman et al. 1998).

4 We do not discuss LINERs associated with the nuclei of ordinary galaxies in this paper. Those who are interested in this issue are recommended to see Ho, Filippenko, & Sargent (1997), Maoz et al. (1998), and Barth et al. (1998).

### TABLE 2

**MIR vs. Optical Classification of ULIGs**

| MIR              | Optical   | ULIGs          |
|------------------|-----------|----------------|
| AGN              | Seyfert   | Mrk 231, Mrk 273 |
| AGN              | LINER     | ...            |
| AGN              | H \(\pi\)  | ...            |
| H \(\pi\)        | Seyfert   | ...            |
| H \(\pi\)        | LINER     | Arp 220, NGC 6240, UGC 5101, IRAS 12112+0305, IRAS 14348—1447, IRAS 23128—5919 |
| H \(\pi\)        | H \(\pi\)  | IRAS 17208—0014, IRAS 20100—4156, IRAS 20551—4250, IRAS 22491—1808 |

3 The optical spectrum of Mrk 231 is dominated by very strong Fe \(\pi\) emission features, which are one of important characteristics of type 1 AGNs (e.g., Boroson & Green 1992). Further, the presence of the broad Balmer emission lines provides evidence for AGNs in this galaxy (Boksenberg et al. 1977; Lipari, Colina, & Macchetto 1994 and references therein).

4 The most important implication of the MIR spectroscopy is that the majority of ULIGs present little evidence for AGNs with high-ionization emission lines. This raises a serious problem. Are low-ionization AGNs that have been classified on the basis of optical spectroscopy really AGNs? Since the discovery of LINERs (Heckman 1980), this question has been addressed many times (Heckman 1986; Ho 1998 and references therein). Here we consider the case for ULIGs. Three alternative explanations of the LINER-like spectra in the optical have been proposed: (1) genuine AGNs with low-ionization conditions (e.g., Ferland & Netzer 1983; Halpern & Steiner 1983); (2) dense gas clouds photoionized by hot O stars \(T_{\text{eff}} \gtrsim 45,000\) K (Filippenko & Terlevich 1992; Shields 1992); and (3) shock heating (Johansson & Bergvall 1985, 1988; Johansson 1991; Veilleux et al. 1995, 1997; Kim et al. 1998; see also Heckman 1980; Dopita & Sutherland 1995). Since the MIR classification made by Genzel et al. (1998) deals only with high-ionization lines, it is impossible to probe genuine LINERs in the ULIGs. However, the most important point clarified by Genzel et al. (1998) is that massive stars are the major energy source in the ULIGs. This suggests strongly that optical emission-line nebulae cannot be attributed mainly to photoionization by the central engine of an AGN. Therefore, we discuss the latter two possibilities.

We discuss the second possibility first, because intense starbursts are actually occurring in the heart of ULIGs (Armus et al. 1989; Shaya et al. 1994; Scoville et al. 1998; Taniguchi et al. 1998), and further, the gas densities in ULIGs are generally higher than those typical in the star-forming regions of galaxies (Taniguchi & Shioya 1998). Although LINERs are often regarded as low-luminosity extensions of typical luminous AGNs, dense gas clouds photoionized by hot O stars \(T_{\text{eff}} \gtrsim 45,000\) K also show LINER-like optical spectra (Filippenko & Terlevich 1992; Shields 1992). One of the important characteristics of such O star LINERs is that the \([\text{O} \, \text{i}] \lambda 6300\) emission is significantly weak with respect to the H\(\alpha\) emission \(([\text{O} \, \text{i}]/\text{H}\alpha < 1/\sqrt{2})\). We note that all the ULIGs except NGC 6240 satisfy this condition (see Table 1). Although there is no firm evidence for hot O stars in the ULIGs, the presence of Wolf-Rayet stars has been reported for some luminous infrared galaxies, e.g., IRAS 01003—2238 (Armus, Heckman, & Miley 1988) and NGC 1614 (Conti 1991). If these high-temperature descendants of massive stars dominate the photoionization of ULIGs, they would lead to LINER-like spectra. In Figure 1 we compare the optical emission-line...
ratios with the hot O star photoionization models of both Filippenko & Terlevich (1992), and Shields (1992). The comparison shows that neither model can explain the data points of the LINER-like ULIGs. Although these models may explain the excitation properties of some starburst-dominated ULIGs, we conclude that hot O stars are not the major ionization source in the LINER-like ULIGs studied here.

We consider the possibility of shock heating. It is naturally expected that some ULIGs are dominated by shock heating, because they show evidence of superwind activity; i.e., a blast wave driven by the collective effect of a large number of supernovae in the central region of a galaxy merger (Heckman, Armus, & Miley 1987, 1990; Veilleux et al. 1995; Heckman et al. 1996; Ohyama, Taniguchi, & Terlevich 1997; Kim et al. 1998). Further, Lutz et al. (1998) recently detected faint [O IV] 25.9 μm emission in a number of nearby starburst galaxies such as M82. This provides strong evidence for shock heating in starburst galaxies because they showed that the fast shock models by Dopita & Sutherland (1995) consistently explain both the optical and MIR spectroscopic properties of M82. In order to examine whether the shock heating models by Dopita & Sutherland (1995) can explain the optical emission-line properties of the ULIGs studied here, in Figure 1 we compare the observed optical emission-line ratios with results of their shock models. The figure shows that the majority of the ULIGs can be explained by shock heating models with shock velocity between 100 km s\(^{-1}\) and 500 km s\(^{-1}\) (see also Taniguchi & Ohyama 1998).

In summary, comparing the MIR and optical classifications for the sample of ULIGs, we have confirmed that the LINER-like ULIGs are not genuine AGNs but shock-heated galaxies, as suggested by Veilleux et al. (1995) and Kim et al. (1998). This suggests that both the optical and MIR classifications should be used rather than a single method alone. Finally, we should note that our discussion is applicable only to infrared-selected emission-line galaxies, as optically selected LINERs may be powered by another energy source, e.g., an AGN (see Ho 1998 and references therein).

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