EFFECTS OF METALLICITY AND AGN ACTIVITY ON THE MID-INFRARED DUST EMISSION OF GALAXIES

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ABSTRACT

Using a sample of the Spitzer SWIRE-field galaxies whose optical spectra are taken from Data Release 4 of the Sloan Digital Sky Survey, we study possible correlations between the mid-infrared (MIR) dust emission from these galaxies and both their metallicities and AGN activities. We find that both metallicity and AGN activity are well correlated with the following ratios: PAH-to-star, VSG-to-star, and PAH-to-VSG, which can be characterized by $\nu L_\nu [8 \mu m(dust)]/\nu L_\nu [3.6 \mu m]$, $\nu L_\nu [24 \mu m]/\nu L_\nu [3.6 \mu m]$, and $\nu L_\nu [8 \mu m(dust)]/\nu L_\nu [24 \mu m]$, respectively. We argue that our MIR-metallicity correlation could be explained by either the amount of dust (ongoing dust formation) or dust destruction (PAHs and VSGs could be destroyed by hard and intense radiation fields), and that the MIR-AGN correlation could arise due to either PAH destruction or an enhanced VSG continuum by the central AGN.

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

1. INTRODUCTION

In galaxies, the MIR bands not only contain a large number of atomic, ionic, and molecular lines, but also cover various dust features from grains of different sizes (Sturm et al. 2002). These include features related to polycyclic aromatic hydrocarbons (PAHs) and the dust continuum for very small grains (VSGs). Recent work (Calzetti et al. 2005; Wu et al. 2005; Vogler et al. 2005; Alonso-Herrero et al. 2006; Elbaz et al. 2002; Boselli et al. 2004; Förster Schreiber et al. 2004; Roussel et al. 2001) has shown that MIR dust emission is well correlated with star formation rate (SFR) indicators such as H$\alpha$, Pa$\alpha$, radio, UV, and far-infrared in either star-forming regions in galaxies or galaxies themselves as a whole. With the further advantage of having less extinction, MIR dust luminosities are ideal tracers of star formation and can be widely used to estimate the SFR.

MIR emission in galaxies could, however, be affected by many factors. For example, early observations on the ground as well as recent space observations by the Infrared Space Observatory (ISO) and the Spitzer Space Telescope (Werner et al. 2004) have shown that PAH emission is generally suppressed in low-metallicity galaxies (Roche et al. 1991; Madden 2000; Galliano et al. 2005; Madden et al. 2006; Wu et al. 2006), even missing in the most metal-poor galaxies (Houck et al. 2004b; Engelbracht et al. 2005; Thuan et al. 1999). Siebenmorgen et al. (2004) have demonstrated the absence of PAHs in the nuclei of AGN-hosting galaxies. Using the Spitzer Infrared Spectrograph (IRS; Houck et al. 2004a) spectra, Weedman et al. (2005) have confirmed that PAH emission is much weaker in AGNs. Moreover, AGN activity could also steepen the shape of the MIR VSG continuum in some active galaxies (Verma et al. 2005).

To quantitatively examine the factors that could affect MIR emission in galaxies, we need a sample of galaxies with both MIR measurements and optical spectra. The Spitzer Wide-Area Infrared Extragalactic survey (SWIRE; Lonsdale et al. 2003) and the Sloan Digital Sky Survey (SDSS; Stoughton et al. 2002) provide such opportunities. The Infrared Array Camera (IRAC; Fazio et al. 2004) 8 $\mu$m band, which just covers the main PAH features, can be used to trace the PAH emission, while the Multiband Imaging Photometer (MIPS; Rieke et al. 2004) 24 $\mu$m band, which covers the continuum, can trace the VSG emission. The SDSS spectra provide us information concerning both the metallicities and the AGN activities of galaxies. In the present paper, we mainly focus on the correlations between the MIR emission and metallicity/AGN activity.

In §2, we describe the data, the data reduction, and the sample. The spectral classification, the metallicity, and the definition of AGN activity are presented in §3. The correlation analysis between MIR and metallicity/AGN activity are shown in §4. Finally, §§5 and 6 are discussions and summary. Throughout the paper we adopt a $\Lambda$CDM cosmology with $\Omega_M = 0.3, \Omega_{\Lambda} = 0.7$, and $H_0 = 70$.

2. DATA AND SAMPLE

The Spitzer SWIRE fields (Lonsdale et al. 2003) of ELAIS-N1, ELAIS-N2, and Lockman Hole have been imaged by both instruments, IRAC (3.6, 4.5, 5.8, and 8.0 $\mu$m; Fazio et al. 2004) and MIPS (24 $\mu$m; Rieke et al. 2004). These fields have also been completely or partly covered by the SDSS Data Release 4 (DR4; Adelman-McCarthy et al. 2006). The overlap area between the three SWIRE fields and the SDSS DR4 field used in this paper is about 15 deg$^2$. Basic Calibrated Data (BCD) images of the four IRAC bands were obtained from the Spitzer Science Center, and include flat-field corrections, dark subtraction, linearity, and flux calibrations (Fazio et al. 2004). The IRAC images (in all four IRAC bands) were mosaicked from the BCD images after point-referent, distortion correction, and cosmic-ray removal with a final pixel scale of 0.6$''$, as described by Huang et al. (2004) and Wu et al. (2005); the MIPS 24 $\mu$m images were mosaicked in a similar way but with a final pixel scale of 1.225$''$ (Wen et al. 2007; Cao & Wu 2007). The FWHMs of point-spread functions (PSFs) in mosaicked images are around 2$''$ for the four IRAC bands and 6$''$ for the MIPS 24 $\mu$m band. Matching the sources detected by the SExtractor (Bertin & Arnouts 1996) in all five bands with the 2MASS sources (Cutri et al. 2003) ensured that the astrometric uncertainties were less than 0.1$''$.

The MIR photometries were obtained by the SExtractor with an aperture of 6$''$ for the four IRAC bands and the MIPS 24 $\mu$m band. Apertures of 6$''$ were used to match the FWHM of the PSF.
of the MIPS 24 μm band, although the fiber aperture of the SDSS spectra is 3′. All these magnitudes are in the AB magnitude system (Oke & Gunn 1983). Values of −0.20, −0.17, −0.23, and −0.41 mag for the 3.6, 4.5, 5.8, and 8.0 μm bands, respectively, were adopted to correct the apertures of 6″ to 24″. Comparing the model colors between IRAC and 2MASS Ks bands (Cutri et al. 2003) with those measured for F7 dwarfs (J − Ks ≤ 0.3), as Lacy et al. (2005) did for sources in the Spitzer extragalactic First Look Survey (xFLS) field, small additional corrections were made for all the four IRAC bands. These give us the calibration errors in the four IRAC bands to better than 0.08 mag. A factor of −1.21 mag was adopted to correct the aperture from 6″ to 30″ for the 24 μm band. An additional correction of −0.196 mag was also performed for the 24 μm sources. This included a factor of 1.15 of calibration and a factor of 1.04 of color correction (J. A. Surace et al. 2005). The calibration accuracy of the 24 μm photometry is better than 10% (Rieke et al. 2004).

To build our galaxy sample, we first selected the galaxies of three SWIRE fields from the main galaxy sample of the SDSS DR4 (Adelman-Mccarthy et al. 2006) and then matched them with the MIR sources detected in the Spitzer SWIRE fields with a matching radius of 2″. Out of 1628 SDSS galaxies, 14 (about 1%) were mismatched with the MIR sources, due to the 2″ matching radius. To obtain reliable line ratios and to avoid possible contamination from the old stellar population, we only kept the sources with a reliable Hβ flux (S/N ≥ 5) and a higher Hα equivalent width (less than −5.0; the minus here means emission), where the Hα line emission flux used here was from Brzuzal & Charlot (2003) and continuum-subtracted. This gives us a sample of 600 galaxies. All of these galaxies have 8 μm fluxes, and most have 24 μm fluxes. The redshifts of the galaxies in the sample range from 0.004 to 0.18.

3. SPECTRAL CLASSIFICATION, METALLICITY, AND AGN ACTIVITY

Our spectral classification was based on the traditional line-diagnostic diagram [O iii] Hβ versus [N ii] Hα (Veilleux & Osterbrock 1987), as in Figure 1. The dotted curve in the figure is the parameterized curve by Kauffmann et al. (2003), while the dashed curve is the theoretical boundary for starbursts by Kewley et al. (2001). The galaxies below the dotted curve are H ii galaxies, galaxies between the dotted curve and dashed curve are mixture types (Wu et al. 1998) or composites (Kewley et al. 2006), and galaxies above the dashed curve are narrow-line AGNs. Altogether, there are 472 H ii galaxies, 99 composites, and 29 AGNs.

The metallicities of H ii galaxies were from the metallicity catalog of SDSS DR4 (Tremonti et al. 2004). Here we adopted the median of the likelihood distribution for 12 + log(O/H). A total of 329 H ii galaxies, which have measured metallicities in the Tremonti et al. (2004) catalog, were selected for the following analysis. Of these, 297 have 24 μm fluxes. We defined dwarf galaxies as the galaxies whose absolute B magnitudes were greater than −18. Here the B magnitudes were calculated from the SDSS g and r magnitudes (Smith et al. 2002). The dwarf galaxies are marked with plus symbols in Figure 1.

Figure 2 shows the metallicities of H ii galaxies as a function of internal reddening. The internal reddening (characterized by E(B − V)) was derived from the Balmer decrement Hα/Hβ (Calzetti 2001). The figure suggests that dusty galaxies tend to be metal-rich.

To quantify AGN activity, we define a distance dAGN in dex (see the red dotted line in Fig. 1 as an example) to represent AGN activity in the traditional line-diagnostic diagram [O iii] Hβ versus [N ii] Hα. This is quite similar to the star-forming distance defined by Kewley et al. (2006) in the diagnostic diagram [O iii] Hβ versus [O ii] Hα or [S ii] Hα. Considering that the composites could be dominated by star formation and that this would weaken possible contributions from the central AGN, the dAGN is defined as the distance of an AGN from its position (x0, y0) to the Kewley et al. (2006) line in the [O iii] Hβ versus [N ii] Hα plane.

4 J. A. Surace, et al. 2005, The SWIRE Data Release 2: Image Atlases and Source Catalogs for ELAIS-N1, ELAIS-N2, XMM-LSS, and the Lockman Hole, available at http://ssc.spitzer.caltech.edu/legacy/swirehistory.html.

5 MPA emission line catalog, which is available at http://www.mpa-garching.mpg.de/SDSS/DR4/oh_catalogue.html.

6 Available at http://www.mpa-garching.mpg.de/SDSS/DR4/Data/oh_catalogue.html.
et al. (2001) curve along the parallel of the best linear fitting of all AGNs (solid line) in Figure 1, and can be formulized as

\[ d_{\text{AGN}} = 0.507(5.8x_p + y_p - 3.196 + A), \]

where \( x = \log [\text{N}\,\text{II}]/\text{H}\alpha \) and \( y = \log [\text{O}\,\text{III}]/\text{H}\beta \). Larger distances correspond to stronger AGN activities. After removing the two most deviated AGNs, 27 AGNs between the two dash-dotted lines were selected for the following analysis. Three of them do not have 24 \( \mu \)m fluxes.

4. ANALYSIS

4.1. MIR Ratios Versus Metallicity

To correct the redshift effect, we adopted the spectral energy distribution of the normal H II galaxy NGC 3351 from IRS observations in the Spitzer Legacy program SINGS (Kennicutt et al. 2003) as the template for the \( K \)-corrections for our sample galaxies in both the 24 and 8 \( \mu \)m bands (Wu et al. 2005). In order to avoid the strong PAH emission, we used the 3.6 \( \mu \)m band to estimate the stellar contribution in the 8.0 \( \mu \)m band. A factor of 0.26 (Wu et al. 2005) was used to scale the stellar continuum of 3.6 \( \mu \)m to that of 8 \( \mu \)m. After subtracting the corresponding stellar continuum contribution, we obtained the flux of 8 \( \mu \)m dust emission, denoted by 8 \( \mu \)m(dust), as in Wu et al. (2005). The 8 \( \mu \)m(dust) includes the dust emission from both the PAHs and VSGs. Considering that the contribution of the stellar continuum in the 24 \( \mu \)m band is quite small and negligible, we have not removed the stellar continuum from the 24 \( \mu \)m band flux.

It is well known that the mass of a galaxy is well related to its metallicity (Pagel & Edmunds 1981). To avoid possible effects caused by different mass variations, we used the MIR ratios

\[ \nu L_{\nu}[8\mu m(dust)]/\nu L_{\nu}[3.6\mu m] \]

and

\[ \nu L_{\nu}[24\mu m]/\nu L_{\nu}[3.6\mu m] \]

to estimate the stellar contribution in the log-log space. We plotted the mean values (diamonds) and the 1 \( \sigma \) standard deviation bars with a metallicity bin of 0.2. The plus symbols represent the dwarf galaxies. We can see that the MIR ratios and metallicity are correlated. Both \( \nu L_{\nu}[8\mu m(dust)]/\nu L_{\nu}[3.6\mu m] \) and \( \nu L_{\nu}[24\mu m]/\nu L_{\nu}[3.6\mu m] \) ratios show nearly linear correlations with metallicity in the log-log space, and the Spearman correlations are tight with the probabilities of null hypothesis being \( 2.7 \times 10^{-17} \) and \( 5.2 \times 10^{-7} \), respectively. Almost all the dwarf galaxies here obey the same correlation as the normal galaxies do, except Mrk 1434, which has the lowest metallicity in our sample. Although the MIR ratio

\[ \nu L_{\nu}[8\mu m(dust)]/\nu L_{\nu}[24\mu m] \]

correlates with metallicity, this correlation only exists for galaxies with metallicities lower than
8.7. For galaxies with higher metallicities, the $\nu L_\nu[8 \mu m(dust)]/\nu L_\nu[24 \mu m]$ ratios remain almost constant. Compared with the above two correlations, the Spearman correlation between $\nu L_\nu[8 \mu m(dust)]/\nu L_\nu[24 \mu m]$ and metallicity is much weaker, with the probability of null hypothesis being 0.02.

4.2. MIR Ratios Versus AGN Distance $d_{AGN}$

Figure 4 shows the MIR ratios as functions of AGN activity. Here we used the distance $d_{AGN}$ as defined in § 3 to characterize AGN activity. The MIR ratio $\nu L_\nu[8 \mu m(dust)]/\nu L_\nu[3.6 \mu m]$ seems to mildly increase with the distance $d_{AGN}$. The probability of null hypothesis for the Spearman correlation is 0.3, indicating that the correlation is poor. The ratio $\nu L_\nu[24 \mu m]/\nu L_\nu[3.6 \mu m]$ is well correlated with $d_{AGN}$. The probability of null hypothesis for such a correlation is $3.6 \times 10^{-4}$, indicating that the 24 $\mu m$ emission in mass units tends to be stronger with the level of AGN activity. On the contrary, the MIR ratio $\nu L_\nu[8 \mu m(dust)]/\nu L_\nu[24 \mu m]$ is anti-correlated with $d_{AGN}$. The probability of null hypothesis is $1.7 \times 10^{-5}$. The correlation between $\nu L_\nu[8 \mu m(dust)]/\nu L_\nu[24 \mu m]$ and $d_{AGN}$ is the tightest among the three. Even the most discrepant point in Figures 4a and 4b follows such a correlation.

4.3. MIR Ratios Versus Internal Reddening

To explore the possible influence of internal reddening on MIR emission, the MIR ratios were also plotted against $E(B - V)$ in Figure 5. For H II galaxies, both ratios, $\nu L_\nu[8 \mu m(dust)]/\nu L_\nu[3.6 \mu m]$ and $\nu L_\nu[24 \mu m]/\nu L_\nu[3.6 \mu m]$, show tight correlations with $E(B - V)$. The probabilities of a null hypothesis of the Spearman correlation are $3.1 \times 10^{-22}$ and $3.4 \times 10^{-10}$, respectively. Both correlations indicate that the dusty galaxies have relatively strong 8 or 24 $\mu m$ dust emission. Such correlations can also be expected in Figure 3, since the metallicities of H II galaxies are also correlated with their internal reddening (Fig. 2). However, $\nu L_\nu[8 \mu m(dust)]/\nu L_\nu[24 \mu m]$ does not show any correlation with $E(B - V)$. The probability of null hypothesis is 0.16. Therefore, this ratio does not depend on the internal reddening.

For AGNs, none of the three MIR ratios correlate with reddening. The Spearman correlations show that the probabilities of null hypothesis are 1.00, 0.16, and 0.09 respectively, indicating that the internal reddening does not affect any of the three MIR ratios of AGNs.

5. DISCUSSIONS

5.1. Aperture Effect

Since the galaxies in our sample cover a redshift range from 0.004 to 0.17, the 6$^\prime$ aperture corresponds to a physical size from several hundred parsecs to several tens of kiloparsecs. Will the aperture affect the correlations we obtained? We examined this by grouping the galaxies into several redshift bins, as shown in Figures 3 and 4. We find that either the H II galaxies (Fig. 3) or the AGNs (Fig. 4) with different redshifts follow the same correlations.

To further explore the aperture effect, we plotted the MIR ratios as functions of redshift in Figure 6. The mean MIR ratios (except for dwarf galaxies) and the corresponding standard deviations with a redshift bin of 0.02 were also plotted. There is only a small variation of the mean MIR ratios (less than 0.2 dex) with redshift.

Meanwhile, we “virtually” placed a template galaxy (e.g., the SINGS galaxy NGC 3351) in different redshifts. The 6$^\prime$ aperture corresponds to different physical sizes at different redshifts. Therefore, we did the aperture photometry for the MIR images of the SINGS galaxy NGC 3351 with a set of apertures whose physical sizes are equal to those of the 6$^\prime$ aperture at different redshifts. As a result, we can obtain the MIR ratios of NGC 3351 as a function of redshift or aperture, which are plotted as the dotted curves in Figure 6. Here we only give the MIR ratios of NGC 3351 at the rest frame and do not consider the $K$-correction. From the figure, all three MIR ratios of the template NGC 3351 only vary by about 0.1–0.2 dex with redshift.

Both the sample statistics and template modeling show that the aperture effect on MIR ratios is weaker than the correlations shown in Figure 3. Therefore, we believe that the aperture effect would not significantly affect our correlations obtained from Figures 3 and 4.

5.2. Metallicity and Dust Emission

Although the VSG continuum also contributes to the Spitzer 8 $\mu m$ band (Smith et al. 2007b), in H II galaxies the strongest 7.7 $\mu m$ PAH features still dominate the emission in this band. However, the VSG continuum dominates the Spitzer MIPS 24 $\mu m$ band. Therefore, the correlations between MIR ratios and metallicity in Figure 3 reveal the relationships between the ratios of PAH-to-star, VSG-to-star, and PAH-to-VSG, with metallicity. Here, the 3.6 $\mu m$ luminosity can approximately represent the stellar mass (Smith et al. 2007a; Hancock et al. 2007). All these ratios increase with metallicity, although the details are different (e.g., different slopes). Apparently, the dust properties in the H II galaxies seem to depend on metallicity. However, the metallicity itself is often related to many other factors, such as mass (the mass-metallicity...
relation, i.e., lower mass dwarf galaxies often have lower metallicities and radiation field (in a low-metallicity environment, the radiation field is often hard). Hence, it is necessary to explore the underlying mechanisms.

In fact, all of these MIR behaviors mainly depend on two main factors: local radiation field and dust. The properties of the radiation field include hardness, which can be characterized by the MIR [Ne iii]/[Ne ii] (Thornley et al. 2000; Wu et al. 2006; Madden et al. 2006), and intensity, which can be characterized by either MIR luminosity density (Engelbracht et al. 2005; Wu et al. 2006) or star formation rate (Rosenberg et al. 2006). The very hard and intense radiation field could destroy the PAHs (Galliano et al. 2005), and even the VSGs (Contursi et al. 2000).

The dust properties include the amount of dust and the fractions and spatial distributions of PAHs and VSGs. Galaxies with lower or negligible PAH or VSG emission could contain less dust, possibly because they have low metallicities and lack material to form dust, they have masses too low to retain dust against radiation pressure and winds, or they are too young to have formed PAHs (Hogg et al. 2005; Madden et al. 2006; Draine et al. 2007). Different fractions and distributions of PAHs and VSGs could result in different PAH-to-VSG ratios.

The positive correlations between the PAH-to-star and VSG-to-star ratios and the metallicity obtained from Figure 3 could be explained by the amount of dust. It could be expected from the relations between reddening and metallicity (Fig. 2) or the PAH-to-star and VSG-to-star ratios (Figs. 5a and 5b). In fact, the internal reddening is directly related to the amount of dust if assuming a constant dust-to-gas ratio, due to the tight correlation between $E(B - V)$ and H column density (Bohlin et al. 1978; Draine 2003). Therefore, the low PAH-to-star and VSG-to-star ratio of lower metallicity galaxies could not be due to the fact that their masses are too low to retain the amount of dust, because some of the normal galaxies also follow the same correlation as lower metallicity galaxies do in Figure 3. It could be that they are so young that a large amount of dust has not had enough time to be released. This is supported by Figure 2.

As for the PAH-to-VSG ratio, assuming that the AGB stars are the dominant carbon reservoir to form PAHs (Dwek 1998) with an age of star formation less than 500 Myr when the 4 $M_\odot$ star has entered the AGB stage (Madden et al. 2006), the PAH-to-VSG ratio could increase with time. After that, the ratio could approach a constant. This seems to be consistent with Figure 3c, in which the value of $\nu L_\nu [8 \mu m(dust)]/\nu L_\nu [24 \mu m]$ increases with metallicity and then remains constant beyond solar metallicity. Such an explanation is quite similar to the explanation of the low dust-to-gas ratios for low-metallicity SINGS galaxies by Draine et al. (2007).

In addition, the behavior of the PAH-to-VSG ratio with time can be well described by Figure 4 of the recent work by Galliano (2006) on chemical evolution modeling of carbon and silicate grains.

Another explanation could be that the hard and intense radiation field from young stars in lower metallicity galaxies can destroy not only the PAHs but also the VSGs. Since the PAHs are much more sensitive to the hard radiation field than the VSGs are, the slope of the PAH-metallicity relation is much steeper than that of the VSGs. This results in a decreasing PAH-to-VSG ratio in the lower metallicity galaxies (Fig. 3). Such a destruction effect is further supported by Figure 7, which shows the anticorrelation between $\nu L_\nu [8 \mu m(dust)]/\nu L_\nu [24 \mu m]$ and the 24 $\mu m$ intensity for the sample of H ii galaxies, although such an anticorrelation is not as steep as that for AGNs. The 24 $\mu m$ intensity is obtained from the ratio of 24 $\mu m$ luminosity to physical area in an aperture of 6″.

We thus conclude that both dust formation and destruction can explain the correlations between the MIR ratios and metallicity. This is consistent with the conclusions for PAHs by Wu et al. (2006) and Draine & Li (2007).
5.3. AGN Activity and Dust Emission

The MIR spectra of AGNs were already noted to be void of PAH features (Roche & Aitken 1985; Roche et al. 1991; Aitken & Roche 1985; Genzel & Cesarsky 2000; Laurent et al. 2000; Siebenmorgen et al. 2004). This could be explained by the destruction of PAHs due to the hard radiation field of the central source (Madden et al. 2006). It is also supported by recent Spitzer results given by Dale et al. (2006) and Armus et al. (2007), who used [O iii]/[Ne ii] as the indicator of the hardness of the radiation field. However, Figure 4a shows that the PAH-to-star ratio apparently does not have any tendency to decrease, but rather increases with AGN activity. Draine et al. (2007) explained the SINGS AGNs as low-luminosity AGNs which have little effect on the 8 μm dust emission, so they show no evidence of PAH suppression. This is, however, not the case for our sample of AGNs, since all of them have higher Hα equivalent widths according to our selection in § 2. The amount of dust cannot account for that, since the internal reddening does not correlate with any of the three MIR ratios (Fig. 5). We suggest that the AGNs can not only destroy the PAHs in the central regions, but could also possibly excite the PAH emission in the outer regions (Smith et al. 2007b).

Another explanation is that the central AGN raises the level of the VSG continuum in the 8 μm band. Similarly, the sharp increase of the VSG-to-star ratio with AGN activity in Figure 4b may also be due to the enhancement of the 24 μm VSG continuum by the powerful AGN. Although the outer PAH emission could be excited by the central AGN, both the destruction of PAHs and the enhancement of the 24 μm VSG continuum by the AGN would result in the tight anticorrelation between the PAH-to-VSG ratio and AGN activity.

5.4. Radiation Field and Dust Emission

One of the important factors in explaining the correlations between the MIR ratios and metallicity or AGN activity is the radiation field, which could be provided either by young stars or by AGNs. Hogg et al. (2005) suggested that [O iii]/Hβ could be an indicator of radiation field hardness.

Figure 8 shows the three MIR ratios as functions of [O iii]/Hβ. For AGNs, the correlations between the MIR ratios and [O iii]/Hβ are similar to those between the MIR ratios and d_{AGN}. So, the AGN distance d_{AGN} is directly related to the radiation field. For H II galaxies, all these MIR ratios show the anticorrelation with [O iii]/Hβ. With [O iii]/Hβ increasing, the PAH-to-star and VSG-to-star ratios of the H II galaxies and AGNs show different features. Hence, the PAH-to-star and VSG-to-star ratios seem to depend not only on the radiation field, but also on some other important factor as well. As discussed above, in the H II galaxies the amount of dust would play an important role. However, the PAH-to-VSG ratio, which describes the fraction of two different dust components, does not depend on the amount of dust but rather the radiation field. So, the PAH-to-VSG ratio of the H II galaxies and AGNs would present similar behaviors along [O iii]/Hβ, as shown in Figure 8c.

In a hard radiation field environment ([O iii]/Hβ > 1), the PAH-to-VSG ratio decreases sharply with increasing [O iii]/Hβ, whether in H II galaxies or in AGNs. However, the PAH-to-VSG ratio remains constant in a weak radiation field environment ([O iii]/Hβ < 1). We conclude that the hard radiation field, rather than metallicity or AGN activity, is the most direct factor to determine the PAH-to-VSG ratio.

6. SUMMARY

We have constructed a sample of galaxies from both the SDSS Data Release 4 and the Spitzer SWIRE fields to study possible effects of both metallicity and AGN activity on the MIR dust emission. Based on this sample we have found that:

1. The MIR ratios, PAH-to-star, VSG-to-star, and PAH-to-VSG, which can be characterized respectively by \( \nu L_\nu \langle [\text{8 μm dust}] \rangle / \nu L_\nu \langle [3.6 \mu m] \rangle \), \( \nu L_\nu \langle [24 \mu m] \rangle / \nu L_\nu \langle [3.6 \mu m] \rangle \), and \( \nu L_\nu \langle [24 \mu m] \rangle / \nu L_\nu \langle [24 \mu m] \rangle \), are found to be positively correlated with the metallicities of galaxies. The above correlations could be explained by either the amount of dust (ongoing dust formation) or dust destruction (either the PAHs or VSGs could be destroyed by the hard and strong radiation field).

2. The VSG-to-star and PAH-to-VSG ratios are strongly correlated or anticorrelated with AGN activity. However, the PAH-to-star ratio poorly depends on AGN activity. This may be due to the PAH destruction or enhanced VSG continuum by the central AGN.

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REFERENCES

Adelman-McCarthy, J. K., et al. 2006, ApJS, 162, 38
Aitken, D. K., & Roche, P. F. 1985, MNRAS, 213, 777
Alonso-Herrero, A., Rieke, G. H., Rieke, M. J., Colina, L., Pérez-González, P. G., & Ryder, S. D. 2006, ApJ, 650, 835
Arima, L., et al. 2007, ApJ, 656, 148
Bertin, E., & Arnouts, S. 1996, A&AS, 117, 393
Bohlin, R. C., Savage, B. D., & Drake, J. F. 1978, ApJ, 224, 132
Boselli, A., Lequeux, J., & Gavazzi, G. 2004, A&A, 428, 409
Bruzual, G., & Charlton, S. 2003, MNRAS, 344, 1000
Calzetti, D. 2001, PASP, 113, 1449
Calzetti, D., et al. 2005, ApJ, 633, 871
Cao, C., & Wu, H. 2007, AJ, 133, 1710
Contursi, A., et al. 2000, A&A, 362, 310
Cutri, R. M., et al. 2003, The IRSA 2MASS All-Sky Point Source Catalog (Pasadena: NASA/IPAC)
Dale, D. A., et al. 2006, ApJ, 646, 161
Draine, B. T. 2003, ARA&A, 41, 241
Draine, B. T., & Li, A. 2007, ApJ, 657, 810
Draine, B. T., et al. 2007, ApJ, 663, 866
Dwek, E. 1998, ApJ, 501, 643
Elbaz, D., Cesarsky, C. J., Chanial, P., Aussel, H., Franceschini, A., Fadda, D., & Chary, R. R. 2002, A&A, 384, 848
Engelbracht, C. W., Gordon, K. D., Rieke, G. H., Werner, M. W., Dale, D. A., & Latter, W. B. 2005, ApJ, 628, L29
Fazio, G. G., et al. 2004, ApJS, 154, 10
Förster Schreiber, N. M., Roussel, H., Sauvage, M., & Charmandaris, V. 2004, A&A, 419, 501
Galliano, F. 2006, preprint (astro-ph/0610852)
Galliano, F., Madden, S. C., Jones, A. P., Wilson, C. D., & Bernard, J.-P. 2005, A&A, 434, 867
Genzel, R., & Cesarsky, C. J. 2000, ARA&A, 38, 761
Hancock, M., Smith, B. J., Struck, C., Giroux, M. L., Appleton, P. N., Charmandaris, V., & Reach, W. T. 2007, AJ, 133, 671
Hogg, D. W., Tremonti, C. A., Blanton, M. R., Finkbeiner, D. P., Padmanabhan, N., Quintero, A. D., Schlegel, D. J., & Wherry, N. 2005, ApJ, 624, 162
Houck, J. R., et al. 2004a, ApJS, 154, 18
−. 2004b, ApJS, 154, 211
Huang, J.-S., et al. 2004, ApJS, 154, 44
Kauffmann, G., et al. 2003, MNRAS, 346, 1055
Kennicutt, R. C., Jr., et al. 2003, PASP, 115, 928
Kewley, L. J., Dopita, M. A., Sutherland, R. S., Heisler, C. A., & Trevena, J. 2001, ApJ, 556, 121
Kewley, L. J., Groves, B., Kauffmann, G., & Heckman, T. 2006, MNRAS, 372, 961
Kewley, L. J., Groves, B., Heidt, C., Smail, I., Schawinski, K., Alexander, D., Jaffe, T., & Canada, M. 2006, MNRAS, 370, 931
Lacy, M., et al. 2005, ApJS, 161, 41
Laurent, O., Mirabel, I. F., Charmandaris, V., Gallais, P., Madden, S. C., Sauvage, M., Vigroux, L., & Cesarsky, C. 2000, A&A, 359, 887
Lonsdale, C. J., et al. 2003, PASP, 115, 897
Madden, S. C. 2000, NewA, 5, 249
Madden, S. C., Galliano, F., Jones, A. P., & Sauvage, M. 2006, A&A, 446, 877
Oke, J. B., & Gunn, J. E. 1983, ApJ, 266, 713
Pagel, B. E. J., & Edmunds, M. G. 1981, ARA&A, 19, 77
Rieke, G. H., et al. 2004, ApJS, 154, 25
Roche, P. F., & Aitken, D. K. 1985, MNRAS, 213, 789
Roche, P. F., Aitken, D. K., Smith, C. H., & Ward, M. J. 1991, MNRAS, 248, 606
Rosenberg, J. L., Ashby, M. L. N., Salzer, J. J., & Huang-J., S. 2006, ApJ, 636, 742
Roussel, H., Sauvage, M., Vigroux, L., & Bosma, A. 2001, A&A, 372, 427
Siemiginowska, R., Kriigel, E., & Spoon, H. W. W. 2004, A&A, 414, 123
Smith, B. J., Struck, C., Hancock, M., Appleton, P. N., Charmandaris, V., & Reach, W. T. 2007a, AJ, 133, 791
Smith, J. A., et al. 2002, AJ, 123, 2121
Smith, J. D. T., et al. 2007b, ApJ, 656, 770
Stoughton, C., et al. 2002, AJ, 123, 485
Sturm, E., Lutz, D., Verma, A., Netzer, H., Sternberg, A., Moorwood, A. F. M., Oliva, E., & Genzel, R. 2002, A&A, 393, 821
Thornley, M. D., Schreiber, N. M. F., Lutz, D., Genzel, R., Spoon, H. W. W., Kunze, D., & Stemberg, A. 2000, ApJ, 539, 641
Thuan, T. X., Sauvage, M., & Madden, S. 1999, ApJ, 516, 783
Tremonti, C. A., et al. 2004, ApJ, 613, 898
Veilleux, S., & Osterbrock, D. E. 1987, ApJS, 63, 295
Verma, A., Charmandaris, V., Klaas, U., Lutz, D., & Haas, M. 2005, Science, 309, 119
Vogler, A., Madden, S. C., Beck, R., Lundgren, A. A., Sauvage, M., Vigroux, L., & Ehle, M. 2005, A&A, 441, 491
Ward, M. J., et al. 2005, ApJ, 633, 706
Wen, X. Q., Wu, H., Cao, C., & Xia, X. Y. 2007, Chinese J. Astron. Astrophys., 7, 187
Werner, M. W., et al. 2004, ApJS, 154, 1
Wu, H., Cao, C., Hao, C.-N., Liu, F.-S., Wang, J.-L., Xia, X.-Y., Deng, Z.-G., & Young, C. K.-S. 2005, ApJ, 632, L79
Wu, H., Zou, Z. L., Xia, X. Y., & Deng, Z. G. 1998, A&AS, 132, 181
Wu, Y., Charmandaris, V., Hao, L., Brandl, B. R., Bernard-Salas, J., Spoon, H. W. W., & Houck, J. R. 2006, ApJ, 639, 157
