MID-INFRARED SPECTROSCOPY OF HIGH REDSHIFT SUBMILLIMETER GALAXIES: FIRST RESULTS

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ABSTRACT

We present mid-infrared spectra of 5 submillimeter galaxies at $z = 0.65 - 2.38$ taken with the Spitzer Space Telescope. Four of these sources, at $z \lesssim 1.5$, have strong PAH features and their composite spectrum is well fitted by an M82-like spectrum with an additional power-law component consistent with that expected from AGN activity. Based on a comparison of the 7.7-µm PAH equivalent width and the PAH-to-infrared luminosity ratio of these galaxies with local templates, we conclude that these galaxies host both star-formation and AGN activity, with star-formation dominating the bolometric luminosity. The source at $z = 2.38$ displays a Mrk 231-type broad feature at restframe $\sim 8$µm that does not conform to the typical 7.7/8.6-µm PAH complex in starburst galaxies, suggesting a more substantial AGN contribution.

Subject headings: infrared; galaxies; starburst; galaxies: AGN; technique: spectroscopic

1. INTRODUCTION

Deep submillimeter-wave surveys (Smail et al. 1997; Barger, Cowie & Sanders 1999; Eales et al. 1999; Cowie et al. 2002; Scott et al. 2002; Borvás et al. 2003; Webb et al. 2003), have uncovered a population of ultra-luminous infrared (IR) galaxies (ULIRGs; $L_{IR} > 2 - 5 \times 10^{12} L_{\odot}$) at $z \sim 2$ (Blain et al. 2002). This observationally-defined population of submillimeter galaxies (SMGs) coincides with the epoch of peak global star formation and quasar activity, with a significant contribution to the global star formation rate density at $z = 2 - 3$ not traced in the UV (Chapman et al. 2005, C05). Highly obscured by their dust content, the astrophysics of SMGs and the nature of their power source remain a challenge to address at optical and near-IR wavelengths (Chapman et al. 2003, C05; Swinbank et al. 2004). Deep X-ray studies suggest that $\sim 28 - 50\%$ of SMGs host an active galactic nucleus (AGN), although at face value it appears that the AGN does not dominate the bolometric luminosity and that powerful starbursts (SB) contribute more significantly to the total energy output (Alexander et al. 2005, A05).

Less hindered by obscuration than shorter wavelengths, the mid-IR region boasts a number of spectral features, including: emission from Polycyclic Aromatic Hydrocarbons (PAHs) (e.g. restframe 6.2, 7.7, 8.6, 11.3 and 12.7 µm), associated with star formation (Helou 1999) and typically absent in powerful AGN (Voit 1992); silicate absorption at 9.7 and 18 µm, which gives a measure of the obscuration by silicate dust grains along the line of sight to a small hot dust continuum source; and a hot dust continuum ($\Lambda \lesssim 10$ µm), likely to be dominated by an AGN. The strength of these features have been used in mid-IR surveys with the Infrared Space Observatory (Genzel et al. 1998; Rigopoulou et al. 1999, Tran et al. 2001, Laurent et al. 2001) to estimate the relative contributions of SB and AGN for the brightest local galaxies (e.g. Rigopoulou et al. 1999). The spectra of the high-redshift population remained unexplored in the mid-IR, until the advent of the Spitzer Space Telescope and the unprecedented sensitivity of the Infrared Spectrograph (IRS; Houck et al. 2004, Lutz et al. 2005, Yan et al. 2005, Houck et al. 2005, Desai et al. 2006 and Weedman et al. 2006), have been among the pioneers in using IRS to study the mid-IR spectra of luminous sources at $z \sim 1 - 3$, extending to higher redshifts the analysis that was previously only accessible for nearby galaxies.

We have an IRS program to study the range of mid-IR properties of a sample of 24 high-$z$ SMGs with $S_{24\mu m} \gtrsim 0.4$ mJy, using the radio-identified sample with spectroscopic redshifts, compiled by C05. Here we present IRS spectra of the first five targets observed (SMM J221733 +001120, SMM J163659 +405728, SMM J030228 +000654, SMM J163639 +405636, and SMM J163650 +405735): four are at lower-$z$, with $z = 0.65 - 1.5$, and one is at $z = 2.38$. The low-$z$ targets cover wavelengths longwards of 10 µm and give insight into the longer mid-IR emission from SMGs; the full sample is more focused on $z \sim 2$ SMGs and hence probes shorter restframe wavelengths. This preliminary sample is otherwise representative of the SMG population, in terms of bolometric luminosity, dust temperature and submillimeter-to-radio flux ratio (C05).

2. OBSERVATIONS AND REDUCTION

We observed each target using the low resolution Long-Low (LL) observing mode of IRS ($R \sim 57 - 126$) at two different nod positions for 30 cycles of 120s each. We cover restframe emission longwards of 6 µm to probe for PAH emission at 6.2, 7.7, 8.6 and 11.3 µm and for silicate absorption centered at 9.7 µm. The data were obtained...
between December 2005 and March 2006.

The data were processed using the Spitzer IRS S13 pipeline\(^8\), which includes saturation flagging, dark subtraction, linearity correction, ramp correction and flat-fielding. With a slit size of \(\sim 10.5 \times 168''\), IRS does not resolve the SMGs spatially, and the targets were treated as point sources throughout the data reduction and analysis. We performed additional reduction of the 2D spectra using IRSCLEAN\(^9\) to remove rogue pixels, and relied on differing between the nod positions to subtract the residual background. We used the Spitzer IRS Custom Extraction (SPICE)\(^{10}\) software to optimally extract flux-calibrated 1D spectra, by taking a weighted average of profile-normalized flux at each wavelength to increase the S/N of these faint sources.

3. RESULTS AND DISCUSSION

The mid-IR spectra of SMM J221733, SMM J163659, SMM J030228 and SMM J163639 show moderate to strong PAH features (see Fig. 1), and we refer to these targets collectively as the PAH sample. Detection of PAH emission is assumed to indicate the presence of SB activity. At most a very shallow dip is present around 9.7 \(\mu\)m in the spectra, indicating little silicate absorption.

Our highest-\(z\) source, SMM J163650, is somewhat different to the other targets, with a broad feature at restframe \(\sim 8 \mu\)m, unlike the typical blended PAH complex of the 7.7- and 8.6-\(\mu\)m features found in SB galaxies. It is more reminiscent of the spectrum of Mrk 231 (Armus et al. 2006), which features an unabsorbed continuum between absorption from silicates at longer wavelengths and hydrocarbons at shorter ones.

8 http://ssc.spitzer.caltech.edu/irs/db/
9 http://ssc.spitzer.caltech.edu/archanaly/contributed/irsclean
10 http://ssc.spitzer.caltech.edu/postbcd/spice.html

\(\text{Fig. 1.} \) 1D Spitzer IRS spectra for 5 SMGs and the composite spectrum of the PAH sample. For the 5 individual spectra, the lower curve represents the unsmoothed spectrum, with the first order (LL1: \(\lambda_{\text{obs}} = 19.5 - 38 \mu m\)) and second order (LL2: \(\lambda_{\text{obs}} = 14 - 21.3 \mu m\)) of the low-resolution mode shown in dotted and dashed lines, respectively. The upper curve shows the spectrum smoothed by 3 pixels and offset in flux for clarity. The various wavelengths of PAH emission features are indicated. We show the smoothed version of the composite spectrum for the PAH sample, together with the ISO SWS spectra of M82 (dashed line), smoothed to the resolution of IRS and normalized to the 7.7-\(\mu\)m PAH feature. The excess in the SMG composite, when fitted by M82, is consistent with an additional power-law component emission from an AGN (dotted line; see Sect. 3.1.)

This similarity suggests that SMM J163650 has more substantial AGN-activity than the SMGs in the PAH sample, as expected from the presence of a strong CIV \((\lambda 1549)\) feature at restframe UV (C05) and a broad H\(\alpha\) component \((\sim 1753 \pm 238 \text{ km s}^{-1};\) Swinbank et al. 2004), both revealing the unambiguous presence of an AGN. We discuss the properties of this source in more detail in a subsequent paper discussing the full sample (Menéndez-Delmestre et al. in prep.) and concentrate here on the median properties of the SMGs with clear PAH emission.

To get an insight into the physics inherent to SMGs in our PAH sample, we compare their spectra with extensively studied local templates: the AGNs Mrk 231 (A06b) and NGC 1068 (Sturm et al. 2000), the SB M82 (Förster Schreiber et al. 2003) and the ULIRGs Arp 220 (A06b) and NGC 6240 (Armus et al. 2006a, A06a). Arp 220 has been a favorite template for high-redshift SMGs (Pope et al. 2006, Kovács et al. 2006): it has strong PAH features, indicative of SB activity, and a steep mid-IR continuum due to a heavily obscured nuclear component inferred to be responsible for the bulk of the IR luminosity (S04). AGNs have been identified in both merging components of NGC 6240 but SB dominates the total IR luminosity (Komossa et al. 2003).

A qualitative comparison of the spectra of our PAH sample with these templates rules out Mrk 231, NGC 1068 and Arp 220 as good matches, but the spectra are similar to those of M82 and NGC 6240. Similar results were found by L05, who detected strong PAH features in the spectra of two luminous SMGs at \(z \sim 2.8\) that were well fitted by an M82-type spectrum.

3.1. The Composite SMG spectrum

We take advantage of the similarity between the spectra in the PAH sample and of our precisely known red-
shifts (C05) to double our S/N constructing a composite spectrum by averaging the individual spectra (Fig. 1). We use the composite spectrum to make a preliminary assessment of the independent contributions of SB and AGN activity in our PAH sample. Normalizing the local templates to the 7.7-$\mu$m peak in the composite spectrum, we find that the composite spectrum is well fitted at $\lambda \lesssim 9\mu$m by the NGC6240 and M82 spectra (Fig. 1). However, neither template provides a good fit to the composite spectrum at $\lambda \gtrsim 9\mu$m: the continuum emission of NGC6240 exceeds that of the composite spectrum at $\lambda \gtrsim 12\mu$m, while the spectrum of M82 falls below it. No physically reasonable additional AGN component can be added to the NGC6240 spectrum to produce a good fit to the composite spectrum at longer wavelengths. On the other hand, an M82-type spectrum plus a power-law continuum provides a good fit to the composite SMG data at all wavelengths.

3.1.1. Starburst Component

The 7.7-$\mu$m PAH feature is generally the most prominent in the mid-IR spectra of SB galaxies. Its strength relative to the continuum, measured by the equivalent width (EW), can be used to evaluate the fractional SB contribution to the total bolometric output, as the hot mid-IR continuum is enhanced significantly in the presence of an AGN. SB-dominated objects, such as M82 and NGC6240, are characterized by larger PAH EWs than objects with a prominent AGN, such as Mrk231.

EWs are sensitive to how the continuum is defined. We define a linear continuum by interpolating between two points clear of PAH emission, at 6.8-$\mu$m and 13.7-$\mu$m, or at 9-$\mu$m when the spectrum does not include one of these points. In Fig. 2 we plot the 7.7-$\mu$m restframe EWs and PAH-to-IR luminosity ratios for the SMGs in the PAH sample with 7.7-$\mu$m coverage and for the composite spectrum. The error in $L_{7.7\mu m}/L_{IR}$ for our SMG sample is dominated by a $\sim 20\%$ uncertainty in the IR luminosities (C05). We compare a number of low- and high-$z$ sources, including 2 ULIRGs at $z \sim 2$ with clear PAH detections from the Y05 sample with $S_{24\mu m} \gtrsim 0.9$ mJy, and 2 SMGs (SMM J02399–0136 with $S_{850\mu m} = 23$ mJy and MM J154127+6616 with $S_{850\mu m} = 14.6$ mJy) at $z \sim 2.8$ (L05).

According to the line-to-continuum ($l/c$) diagnostic presented by Genzel et al. (1998), systems with $l/c_{7.7\mu m} \gtrsim 1$ are classified as SB-dominated and those with $l/c_{7.7\mu m} < 1$, as AGN-dominated. With $l/c_{7.7\mu m} \gtrsim 1$, SBs appear to dominate the Y05, L05 and our PAH sample. However, the distribution in 7.7-$\mu$m EW and PAH-to-IR luminosity ratio in Fig. 2 may suggest a distinction in the relative SB-to-AGN contributions, with lower values of these parameters indicating a stronger AGN contribution. We distinguish three regions in Fig. 2: (1) a region with low PAH-to-IR luminosity ratios, occupied by Mrk1014 (Armus et al. 2004) and the 24-$\mu$m-bright sample of Y05; (2) an intermediate PAH-to-IR luminosity region where NGC6240 and the bulk of the SMGs in our sample are located; and (3) a region with the highest PAH-to-IR luminosity ratios, occupied by M82 and the two SMGs in L05.

At $z \sim 2$, 24-$\mu$m flux traces 8-$\mu$m restframe continuum; a stronger hot mid-IR continuum (produced by an AGN) dilutes the strength of PAH features, leading to lower $L_{7.7\mu m}/L_{IR}$. The location of the Y05 sample in the plot could follow from the selection of 24-$\mu$m-bright targets ($S_{24\mu m} \gtrsim 0.9$ mJy) at this redshift, which would select objects with lower SB-to-AGN ratios. SMGs in our sample have higher $L_{7.7\mu m}/L_{IR}$ ratios, similar to NGC6240, which we interpret as an indication of a markedly stronger SB contribution to the total luminosity than the Y05 sample. With similar IR-luminosities, the location of the L05 SMG pair in this plot indicates that the 7.7-$\mu$m PAH feature is very strong. With large values for both the EW and the PAH-to-IR luminosity ratio, MM J154127 has been suggested to be dominated by SB-activity (L05). The large PAH-to-IR luminosity ratio for SMM J02399 suggests strong SB-activity; however, the relatively low EW value, together with the evident strong mid-IR continuum (see Fig. 1, L05) is consistent with this source having roughly equal AGN and SB contributions.

The SMGs in our PAH sample have values of $EW_{7.7\mu m}$ and $L_{7.7\mu m}/L_{IR}$ that place their SB-to-AGN ratio between that of the AGN-dominated ULIRG Mrk1014 and the SB M82. This is qualitatively similar to NGC6240, which has both SB and AGN components. As a caveat, we note that even though the 7.7-$\mu$m PAH-to-IR luminosity ratio is associated to the SB-to-AGN ratio, it is also sensitive to details of the spectral energy distribution of the system, such as the presence of multiple dust components at different temperatures and the amount of extinction (e.g., Arp 220; S04). This may explain the particularly high 7.7-$\mu$m PAH-to-IR luminosity ratio for SMM J02399.

3.1.2. The AGN Component

\footnote{Kovács et al. (2006) show that SMGs fall below the local FIR-radio relation and thus the C05-derived $L_{IR}$ values, which rely on this relation, are in average overestimated by a factor of $\sim 2$.}

\footnote{For our sample, (l/c) $\sim 1$ corresponds to EQW $\sim 0.5\mu$m}
Mid-IR line diagnostics suggest that SMGs are SB-like. The spectra of the SB-dominated galaxies M82 and NGC 6240 provide a good fit to the composite spectrum at $\lambda \lesssim 9 \mu$m; however, only an M82-type spectrum with an additional power-law AGN component gives a good fit to the composite spectrum at all wavelengths. The power-law component is defined as $S_\nu \sim \nu^{-2.9}$, consistent with the range of IR spectral indices for 3C quasars in Simpson & Rawlings (2000).

From the power-law component flux at $10.5 \mu$m we estimate the X-ray luminosity ($L_X$) using the correlation between $S_{10.5 \mu m}$ and $S_{2-10 keV}$ presented by Krabbe et al. (2001). This yields $L_X \sim 10^{44}$ erg s$^{-1}$ for an AGN at the average redshift for the SMGs presented in this paper, $z \sim 1.4$, in reasonable agreement with the X-ray luminosities found for the SMGs in A05. Following A05's approach, we compare the average X-ray-to-far-IR ratio of the SMGs in the PAH sample with the typical ratio for quasars and find that the residual flux is consistent with an underlying AGN contributing in the order $\sim 10\%$ to the total far-IR emission. This agrees with the A05 result that AGN activity is often present in SMGs but does not dominate the energetics. Since the $10.5-\mu$m excess is dominated by lower redshift sources, further SMGs at $z \lesssim 2$, included in Menéndez-Delmestre et al. (in prep), will better constrain this excess.

4. CONCLUSIONS

We present first results of a Spitzer program to characterize the mid-IR spectra of high redshift SMGs. We compare the spectra to well-studied local templates and find that SMGs have starburst mid-IR spectra more like M82 than the often quoted local analog Arp 220. The composite spectrum of the SMGs in the PAH sample is well fitted by an M82-like starburst-component with a power-law continuum most likely representing a fainter underlying AGN. This similarity to the M82 spectrum suggests that the chemistry of the interstellar medium and radiation fields in these systems may be understood by looking at local galaxies in detail. Analysis of the $7.7-\mu$m equivalent widths and PAH-to-IR luminosity ratios show that SMGs are markedly different from 24 $\mu$m-selected samples, such as the $z \sim 2$ sample of Y05, which show stronger AGN contributions. This work provides further evidence that SMGs host both star-formation and AGN activity, but that star-formation dominates the bolometric luminosity, reiterating the role of SMGs as the build-up sites for a significant fraction of the stellar content we see today.

By probing the lower-redshift end of the C05 SMG sample distribution, this sample provides rest-frame wavelength coverage longwards of 9 $\mu$m to assess the AGN contribution. The SMG at $z = 2.38$, with a redshift closer to that of a typical C05 SMG, displays a potentially more AGN-dominated Mrk 231-type broad feature at restframe $\sim 8 \mu$m. The difference in AGN contributions within our preliminary sample suggests an increasing relative AGN activity in SMGs at higher redshifts, potentially due to the $24 \mu$m flux limit applied to the sample. The full sample, with a more extended redshift distribution, will provide us with additional valuable information concerning the typical SMG population.

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REFERENCES

Alexander, D. M., Bauer, F. E., Chapman, S., Smail, I., Blain, A., Brandt, W. N., Ivison, R. 2005, ApJ, 632, 736 (A05)
Armus, L. et al. 2004, ApJS, 154, 178
Armus, L. et al. 2006, ApJ, 640, 204 (A06a)
Armus, L. et al. 2006, ApJ, in press, astro-ph/0610218 (A06b)
Barger, A. J., Cowie, L. L., & Sanders, D. B. 1999, ApJ, 518, L5
Blain, A., Smail, I., Ivison, R., Kneib, J.-P., Frayer, D. T. 2002, Phys. Rep., 369, 111B
Borys, C., Chapman, S., Halpern, M., & Scott, D. 2003, MNRAS, 344, 385
Brandl, B. R. et al. 2006, ApJ, astro-ph/0609024
Chapman, S., Blain, A., Ivison, R., Smail, I. 2003, Nature, 422, 695
Chapman, S., Blain, A., Smail, I., Ivison, R. 2005, ApJ, 622, 772 (C05)
Cowie, L. L., Barger, A. J., & Kneib, J.-P. 2002, AJ, 123, 2197
Desai, V. et al. 2006, ApJ, 641, 133
Eales, S., Lilly, S., Gear, W., Dunne, L., Bond, J.R., Hammer, F., Le Fèvre, O., & Crampton, D. 1999, ApJ, 510, 518
Förster Schreiber, N. M., Sauvage, M., Charmandaris, V., Laurent, O., Gallais, P., Mirabel, I. F., Vigroux, L. 2003, A&A, 399, 833
Frayer, D. T., Ivison, R., Scoville, N. Z., Yun, M., Evans, A. S., Smail, I., Blain, A., Kneib, J.-P. 1998, ApJ, 506, L7
Genzel, R. et al. 1998, ApJ, 498, 579
Helou, G. 1999, "The Universe as Seen by ISO". Eds. P. Cox & M. F. Kessler. ESA-SP 427, 797
Houck, J. R. et al. 2004 ApJS, 154, 18
Houck, J. R. et al. 2005 ApJ, 622, 105

Komossa, S., Burwitz, V., Hasinger, G., Predehl, P., Kaastra, J. S., Icke, Y. 2003 ApJ, 582, 15
Kovács, A., Chapman, S., Dowell, C. D., Blain, A., Ivison, R., Smail, I., Phillips, T. G. 2006, ApJ, 650, 592
Krabbe, A., Böker, T., Maiolino, R. 2001 ApJ, 557, 626
Laurent, O., Mirabel, I. F., Charmandaris, V., Gallais, P., Madden, S. C., Sauvage, M., Vigroux, L., Cesarsky, C. 2000, å, 359, 887
Lutz, D., Valiante, E., Sturm, E., Genzel, R., Tacconi, L., Lehner, M., Sternberg, A., Baker, A. 2005 ApJ, 625, 83 (L05)
Pope, A. et al. 2006, MNRAS, 370, 1185
Rigopoulou, D., Spoon, H. W. W., Genzel, R., Lutz, D., Moorwood, A. F. M., Tran, Q. D. 1999, AJ, 118, 2625
Scott, S. et al. 2002 MNRAS, 331, 817
Simpson, C., Rawlings, S. 2000, MNRAS, 317, 1023
Smail, I., Ivison, R., Blain, A.1997, ApJ, 490L, 5S

A05

Smał, I., Phillips, T. G. 2006, ApJ, 650, 592
Krabbe, A., Böker, T., Maiolino, R. 2001 ApJ, 557, 626
Laurent, O., Mirabel, I. F., Charmandaris, V., Gallais, P., Madden, S. C., Sauvage, M., Vigroux, L., Cesarsky, C. 2000, å, 359, 887
Lutz, D., Valiante, E., Sturm, E., Genzel, R., Tacconi, L., Lehner, M., Sternberg, A., Baker, A. 2005 ApJ, 625, 83 (L05)

Pope, A. et al. 2006, MNRAS, 370, 1185
Rigopoulou, D., Spoon, H. W. W., Genzel, R., Lutz, D., Moorwood, A. F. M., Tran, Q. D. 1999, AJ, 118, 2625
Scott, S. et al. 2002 MNRAS, 331, 817
Simpson, C., Rawlings, S. 2000, MNRAS, 317, 1023
Smail, I., Ivison, R., Blain, A.1997, ApJ, 490L, 5S
Spoon, H. W. W., Moorwood, A. F. M., Lutz, D., Tielens, A. G. G. M., Siebenmorgen, R., Keane, J. V. 2004, A&A, 414, 873 (S04)
Sturm, E., Lutz, D., Tran, D., Feuchtgruber, H., Genzel, R., Kunze, D., Moorwood, A. F. M., Thornley, M. D. 2000, A&A, 358, 481
Swinbank, A. M., Smail, I., Chapman, S., Blain, A., Ivison, R., Keel, W. C. 2004, ApJ, 617, 64
Tian, Q. D. et al. 2001, ApJ, 552, 527
Voit, G. M. 1992, MNRAS, 258, 841
Webb, T. M. A., Lilly, S., Clements, D. L., Eales, S., Yun, M., Brodwin, M., Dunne, L., & Gear, W. 2003b, ApJ, 597, 680
Weedman, D. W., Le Floc’h, E., Higdon, S. J. U., Higdon, J. L., Houck, J. R. 2006, ApJ, 638, 613
Yan, L. et al. 2005, ApJ, 628, 604 (Y05)