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Mid-infrared spectroscopy of two luminous submillimeter galaxies at \( z \sim 2.8 \)

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ABSTRACT

Using the Infrared Spectrograph (IRS) on board the Spitzer Space Telescope, we have obtained rest frame mid-infrared spectroscopy of two bright submillimeter galaxies. SMMJ02399-0136 at \( z=2.81 \) shows a superposition of PAH emission features and a mid-infrared continuum, indicating significant and roughly equal contributions to its bolometric luminosity from star formation and from a Compton-thick AGN. We derive a new redshift of \( z=2.80 \) for MMJ154127+6616 from the IRS spectrum and find this object is dominated by starburst PAH emission. The rest frame mid- to far-infrared spectral energy distributions are consistent with these submillimeter galaxies being scaled up versions of local ultraluminous infrared galaxies. The mid-infrared spectra support the scenario that submillimeter galaxies are sites of extreme star formation and represent a key phase in the formation of massive galaxies.

Subject headings: galaxies: starburst, galaxies: active, galaxies: distances and redshift, infrared: galaxies

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1. Introduction

Deep submm and mm surveys using SCUBA and MAMBO have changed our view of the early universe by resolving a significant fraction of the cosmic submm background into individual sources (Smail et al. (1997); Hughes et al. (1998); see also review by Blain et al. (2002) and references therein). A detailed characterization of these luminous (sub)millimeter galaxies (SMGs) is only slowly accumulating because of their faintness at all short wavelengths and the difficulty of counterpart identification. Photometric estimates of a median redshift of 2.5-3 for the SMG population (e.g. Carilli & Yun 2000) are consistent with the recent determination of a median redshift of $z \sim 2.2$ for the $\lesssim 50\%$ of the population accessible to optical spectroscopy (Chapman et al. 2005). The detection of SMGs and the implied star formation rates and space densities immediately motivated speculation that they may trace the formation of massive spheroids. Their central role in the assembly of massive galaxies is now becoming clearer through dynamical and through gas phase metallicity studies (Genzel et al. 2003; Neri et al. 2003; Tecza et al. 2004; Swinbank et al. 2004; Greve et al. 2005). Quantifying AGN in submillimeter galaxies is of immediate relevance for determining their source of luminosity. It is of further importance in the context of understanding the evolution of the black hole mass to spheroid relation during one of the key phases of massive galaxy formation, characterized by high star formation rates and gas content.

Rest frame mid-infrared spectroscopy can further our understanding of SMGs in two ways. First, it can determine redshifts for SMGs that have up to now eluded optical redshift measurements. Mid-infrared spectral features, in particular the narrow aromatic ‘PAH’ features, if present, allow reasonably accurate redshift measurements even for targets that are extremely faint at optical wavelengths. Like the radio continuum commonly employed to locate these galaxies (e.g. Ivison et al. 2002), mid-infrared emission is closely linked to the bulk of the source luminosity that is emitted in the far-infrared, and in addition contains spectral features. The risk of erroneous redshift assignment due to misidentification is thus reduced. CO line emission shares this property, however with existing instrumentation mid-infrared spectroscopy has the advantage of larger fractional bandwidth coverage than mm spectroscopy. Second, low resolution mid-infrared spectroscopy can be used to constrain the energy sources and physical conditions of infrared-luminous galaxies, by decomposition into an AGN continuum and a starburst component that is dominated by PAH emission features. This technique has been successfully applied to the local infrared galaxy population during the ISO mission (e.g. Genzel et al. 1998; Laurent et al. 2000). With the sensitivity of IRS on the Spitzer Space Telescope it is now possible to extend this method to high redshift infrared populations such as the SMGs. Identifying the mid-infrared AGN continuum by such spectral decomposition is possible even in the presence of significant obscuration, equivalent to tens of magnitudes in the rest frame optical and more in the rest frame ultraviolet. With appropriate
signal-to-noise, relatively faint continua can be identified that do not yet strongly affect the broadband infrared colors that are another indicator of AGN. An application of the infrared methods further constraining AGN properties is in combination with rest frame hard X-ray emission at levels signalling AGN activity, in particular for cases where the X-ray photon statistics is too limited to be able to fully constrain the X-ray obscuring column and thus the intrinsic X-ray luminosity.

We are pursuing a program of Spitzer rest frame mid-infrared spectroscopy of a dozen bright and well studied SMGs. All have accurate interferometric positions that are the necessary prerequisite for such a study. In this letter, we present first results for two bright SMGs, SMMJ02399-0136, the brightest source found in the 850µm SCUBA Cluster Lens Survey (Smail et al. 1997, 2002), and MMJ154127+6616 detected near Abell 2125 in the MAMBO 1.2mm survey (Bertoldi et al. 2000). We adopt Ωₘ = 0.3, Ωₐ = 0.7 and H₀ = 70 km s⁻¹ Mpc⁻¹.

2. Observations and Data Reduction

Low resolution long slit spectra were obtained using Spitzer-IRS (Houck et al. 2004) in the staring mode. SMMJ02399-0136 was observed in the LL1 19.5–38.0µm module for 30 cycles of 120sec ramp duration. The total on-source integration time was 2 hours from addition of the independent spectra created by the telescope nod along the slit. MMJ154127+6616, without an available optical redshift, was observed in the same way in the LL1 module, and also for 15 cycles of 120sec ramp duration in the LL2 14.0–21.3µm module. We replaced deviant pixels in the individual differences of the two nod positions of the pipeline 11.0.2 basic calibrated data frames by values representative of their spectral neighborhoods, and averaged the set of resulting 2-dimensional frames clipping deviant values for the individual pixel fluxes. After subtracting residual background emission, we used the SMART package (Higdon et al. 2004) to extract calibrated 1-dimensional spectra for the positive and negative beams; these were averaged into the final spectra. Figs. 1 and 2 show the extracted LL1 spectra of SMMJ02399-0136 and MMJ154127+6616 as well as parts of the corresponding 2-dimensional frames. The shorter wavelength LL2 spectrum of MMJ154127+6616 does not show significant continuum or feature emission at the target position, consistent with the tentative photometric fluxes of 0.05mJy and 0.07mJy at 16µm and 22µm reported by Charmandarlis et al. (2004).
3. Spectral Classification and Redshifts

The spectrum of SMMJ02399-0136 shows well detected 6.2\(\mu\)m and 7.7\(\mu\)m aromatic ‘PAH’ emission features superposed on a strong continuum. It is well fitted by the superposition of a scaled and redshifted starburst spectrum (M82, Sturm et al. 2000) and a linearly rising, unabsorbed or little-absorbed continuum (Fig. 1). This spectrum is similar to those of local universe infrared luminous galaxies having significant contributions from both star formation and powerful AGN to their bolometric luminosities (e.g. Mrk 273, Genzel et al. 1998). The global fit shown in Fig. 1 corresponds to a redshift of 2.83. The 6.2\(\mu\)m feature is intrinsically narrower and in a less complex part of the mid-infrared spectrum than the broader 7.7/8.6\(\mu\)m complex. Fitting just this feature and comparing to similar fits to local universe ISO-SWS PAH spectra we obtain a redshift of 2.829 with a formal fit uncertainty of 0.013. Both values are in better than 1% agreement with the accurate CO-based redshift of 2.8076 for SMMJ02399-0136 (Frayer et al. 1998; Genzel et al. 2003).

The spectrum of the fainter MMJ154127+6616 is dominated by a broad peak near 30\(\mu\)m observed wavelength, with very weak emission at shorter and longer wavelengths. We identify this feature with the 7.7\(\mu\)m PAH feature, based on the fit obtained to a redshifted starburst spectrum (Fig. 2). We have also investigated fits with the obscured continuum spectrum of IRAS F00183-7111 (Tran et al. 2001; Spoon et al. 2004). Such spectra have a maximum near 8\(\mu\)m rest wavelength, at the onset of the silicate absorption feature, and have to be considered as alternative fit to peaked mid-infrared spectra of infrared galaxies. While resulting in comparable redshifts, the fits with an F00183-like spectrum do not reproduce the weakness or absence of short wavelength continuum emission (see insert of Fig. 2). This is corroborated by a factor 1.5 increase in reduced \(\chi^2\) of the 82 degree of freedom fit over this spectral range when changing from an M82 to an F00183 template. We suggest that the spectrum of MMJ154127+6616 is PAH dominated, consistent with the presence of a marginally significant maximum at the position of the 6.2\(\mu\)m feature.

To our knowledge, no redshift more accurate than the uncertain radio/submm estimates has been reported for MMJ154127+6616. Using their SCUBA 850\(\mu\)m flux in addition to the MAMBO 1.2mm and radio data, Eales et al. (2003, Object A2125-MM27 in their list) estimate \(z=2.45^{+0.67}_{-0.67}\) from the radio/submm relation and \(z<1\) from the technically difficult 1200\(\mu\)m to 850\(\mu\)m ratio. Aretxaga et al. (2003) estimate \(z=2.8^{+1.7}_{-0.3}\) with slight variations for different adopted models. From the fit in Fig. 2, we derive \(z=2.80\) with an uncertainty of \(\Delta z=0.1\) estimated from the global fit. This uncertainty is likely an upper limit given the indications for 6.2\(\mu\)m PAH emission. As for SMMJ02399-0136, this is somewhat larger than the median redshift for the part of the SMG population for which redshifts have been obtained in the optical (Chapman et al. 2005). These results demonstrate the power of IRS
to derive redshifts not only for 24\,\mu m selected sources (Houck et al. 2005), but also for the those bright SMG sources where the redshifted mid-infrared features lie shortwards of the noisy $\lambda \gtrsim 35\mu m$ region of the IRS low resolution spectra.

For our adopted cosmology, a dust temperature of 45K and an emissivity index $\beta = 1.5$ (consistent with the SMMJ02399-0136 studies of Ivison et al. (1998) and Genzel et al. (2003)) the intrinsic 8-1000\mu m luminosity is $L_{IR} \sim 1.2 \times 10^{13}L_{\odot}$ for SMMJ02399-0136, after correcting for the lensing amplification of 2.45. We estimate $L_{IR} \sim 1.9 \times 10^{13}L_{\odot}$ for MMJ154127+6616 scaling with the intrinsic 850\mu m fluxes.

4. **ULIRG-like rest frame mid- to far-infrared SEDs**

The rest frame mid- to far-infrared SEDs provide clues about properties, energy sources, and radiation fields of SMGs but are presently insufficiently constrained by direct observations. Constraints on their far-infrared peaks are currently indirect using the observed submm and radio fluxes and the assumption of the radio/far-infrared correlation for star forming galaxies (Chapman et al. 2003, 2005). In view of the variations observed in local galaxy SEDs, we have added another constraint by comparing the ratio of PAH features and SCUBA 850\mu m continua (rest frame $\sim 222\mu m$ for our two objects). We adopt SCUBA fluxes of 23mJy for SMMJ02399-0136 (Smail et al. 2002) and 14.6mJy for MMJ154127+6616 (A2125-MM27 in Eales et al. 2003). In Fig. 3 the ratio of peak flux density of the 7.7\mu m PAH feature after continuum subtraction to the continuum flux density at rest frame 222\mu m for our two SMGs is compared to the same measure for 11 local ultraluminous infrared galaxies (ULIRGs) with PAH emission, where the PAH data have been taken from ISOPHOT-S observations (e.g. Rigopoulou et al. 1999) and the continua from slight extrapolations of the far-infrared photometry of Klaas et al. (2001), which reaches out to 200\mu m observed wavelength. The PAH to far-infrared ratios of the two SMGs are fully consistent with that of the local ULIRG population. These SED properties are in agreement with the finding from spatially resolved mm interferometry that SMGs are scaled up versions of the compact star formation events in local ULIRGs (Tacconi et al. 2005).

5. **AGN content**

With both strong AGN continuum and PAH features, at a feature-to-continuum ratio $\sim 1$, SMMJ02399-0136 is at the transition between predominantly starburst powered and predominantly AGN powered according to the mid-infrared diagnostic of Genzel et al. (1998).
AGN signatures are also seen in the optical spectrum (Ivison et al. 1998). The combination of mid-infrared spectroscopy and the Chandra X-ray data of Bautz et al. (2000) can constrain the properties of this AGN. Bautz et al. (2000) clearly detect relatively hard X-ray emission from SMMJ02399-0136, with an observed luminosity in the rest frame 2-10keV band of $0.18 \times 10^{44}$ erg s$^{-1}$ (corrected to our adopted cosmological parameters). Because of limited photon statistics, their data cannot discriminate between seeing the direct AGN emission, although absorbed by a significant column of $N_H \sim 10^{24}$ cm$^{-2}$ (with the intrinsic emission $\sim 15$ times brighter), and a fully Compton thick AGN seen in reflection, with the intrinsic emission brighter by the inverse of their adopted reflection efficiency of 0.022. For two related reasons, the Compton thick case appears more consistent with our infrared observations. First, the ratio of rest frame hard X-rays and mid-infrared AGN continuum $\log(L_{2-10keV}/\nu L_{\nu}(6\mu m))$ is -0.54 for the reflected case. This ratio is at the center of the equivalent distribution of mid-infrared to intrinsic hard X-ray ratios for local AGN, studied by Lutz et al. (2004), while the lower ratio for the direct emission case would be at the lower end of this distribution. Second, correcting from intrinsic hard X-rays to AGN bolometric luminosity assuming $L_{2-10keV}/L_{bol} \sim 0.09$ for AGN (Elvis et al. 1994), the reflected case with $L_{bol,AGN} \approx 2 \times 10^{12} L_\odot$ is closer to the roughly similar contributions of AGN and star formation that are suggested by the infrared spectroscopy. In summary, we conclude that SMMJ02399-0136 is powered by roughly equal contributions of star formation and a Compton-thick AGN.

No strong AGN continuum is present in MMJ154127+6616 (Fig. 2), in particular below $\sim 6.5\mu m$ rest wavelength where it would be most easily detectable in the presence of PAHs. This is further supported by the weakness of the tentative 16 and 22$\mu m$ photometric detections of Charmandaris et al. (2004), at levels below 0.1mJy. As is the case for local ULIRGs, it is appropriate to caution that our conclusion of dominance of star formation does not exclude in any way the presence of an AGN that is a very minor contributor to the bolometric luminosity. A significant number of minor AGN in SMGs is suggested by the deepest Chandra observations (Alexander et al. 2003, 2005).

6. Discussion

We have presented Spitzer mid-infrared spectroscopy of two of the brightest known submillimeter galaxies, SMMJ02399-0136 and MMJ154127+6616. Our unambiguous detections of PAH spectral features and mid-infrared continua allows us to constrain the energy sources in these objects, and to determine the previously unknown redshift for one of them (MMJ154127+6616). We find that the luminosity of the first galaxy is generated by ap-
proximately equal contributions from star-formation and an AGN. The second galaxy is dominated by star formation.

The existence of star formation dominated systems at infrared luminosities in excess of $10^{13}L_\odot$ is unique to the high redshift universe. In our previous ISO studies of ULIRGs in the local universe, using the same mid-infrared methods, we have found star formation dominated systems only up to a luminosity of $10^{12.65}L_\odot$ (Rigopoulou et al. 1999; Tran et al. 2001). Similar conclusions have been reached from optical spectroscopy of local ULIRGs (Veilleux et al. 1999). The existence of higher luminosity starbursts in SMGs may be related to their higher gas fractions (Greve et al. 2005; Tacconi et al. 2005). Star formation proceeding at these extreme rates in high redshift objects ($\gtrsim 1000M_\odot/yr$ for $L_{IR} > 10^{13}L_\odot$) naturally fits into the evolving understanding of the formation of massive galaxies at high redshift, however. Such extreme events can trace the formation of the $10^{11}M_\odot$ galaxies already fully assembled at redshifts $z=1.6$ to 1.9 (Cimatti et al. 2004). Rapid star-formation may also meet the constraint on rapid formation of massive ellipticals inferred from measurements of the $\alpha$/Fe element abundance ratios (Thomas et al. 2005).

Spectroscopy with IRS can play a central role in elucidating the relationships amongst various infrared selected high redshift galaxy populations. Houck et al. (2005) have recently obtained IRS spectra of 24$\mu$m bright (>0.75mJy) but optically faint (R>24) galaxies selected from a large area Spitzer survey. Submillimeter galaxies at $z\sim 2$ with an Arp220-like SED but still more luminous than a typical SMG from the current SCUBA/MAMBO surveys could meet the basic brightness and obscuration constraint of this sample. The preponderance of heavily obscured continua in the Houck et al. (2005) spectra, however, unlike the PAH and PAH plus continuum spectra of our two SMGs, argues for a small overlap between the two populations, and that the population of R-band faint but 24$\mu$m bright sources may be dominated by obscured AGN.

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Fig. 1.— Spitzer IRS low resolution spectrum of SMMJ02399-0136 (top) along with the 2-dimensional long slit spectrum from which it was extracted (bottom). Note the increase of noise at long wavelengths. The thin dotted lines indicate the fit of the spectrum by the sum of the scaled and redshifted ISO-SWS spectrum of the starburst M82, and a linearly sloped and unabsorbed AGN continuum.
Fig. 2.— Spitzer IRS low resolution spectrum of MMJ154127+6616. The thin dotted line indicates the fit by the scaled and redshifted spectrum of M82. The small insert repeats the spectrum together with the lower quality fit by the obscured galaxy IRAS F00183-7111. The bright line at the bottom of the 2-dimensional spectrum is a serendipitous source found in the slit.
Fig. 3.— Histogram showing the ratio of PAH 7.7$\mu$m peak flux density and rest frame 222$\mu$m continuum flux density for eleven local ULIRGs. In this measure of the mid- to far-infrared SED, the two SMGs are very similar to the local ULIRG population. However, both show a lower value than the low luminosity starburst M82. The M82 point is based on the PAH data of Förster Schreiber et al. (2003) and the far-infrared continuum of Colbert et al. (1999), obtained in large and similar apertures.