LETTER TO THE EDITOR

Herschel and SCUBA-2 imaging and spectroscopy of a bright, lensed submillimetre galaxy at z = 2.3*


(Affiliations are available in the online edition)

Received 30 March 2010 / Accepted 20 April 2010

ABSTRACT

We present a detailed analysis of the far-infrared (f-IR) properties of the bright, lensed, z = 2.3, submillimetre-selected galaxy (SMG), SMM J2135–0102 (hereafter SMM J2135), using new observations with Herschel, SCUBA-2 and the Very Large Array (VLA). These data allow us to constrain the galaxy’s spectral energy distribution (SED) and show that it has an intrinsic rest-frame $8-1000\mu$m luminosity, $L_{bol}$, of $(2.3 \pm 0.2) \times 10^{12} L_{\odot}$ and a likely star-formation rate (SFR) of $\sim 400 M_{\odot} yr^{-1}$. The galaxy sits on the f-IR/radio correlation for f-IR-selected galaxies. At $\gtrsim 70 \mu$m, the SED can be described adequately by dust components with dust temperatures, $T_d$, of $\gtrsim 30$ and $60$ K. Using SPIRE’s Fourier-transform spectrometer (FTS) we report a detection of the [CII] $158 \mu$m cooling line. If the [CII], CO and f-IR continuum arise in photo-dissociation regions (PDRs), we derive a characteristic gas density, $n \sim 10^5 cm^{-3}$, and a far-ultraviolet (-UV) radiation field, $G_{0,10^5}$, stronger than the Milky Way. $L_{[CII]}/L_{bol}$ is significantly higher than in local ultra-luminous IR galaxies (ULIRGs) but similar to the values found in local star-forming galaxies and starburst nuclei. This is consistent with SMM J2135 being powered by starburst clumps distributed across $\sim 2$ kpc, evidence that SMGs are not simply scaled-up ULIRGs. Our results show that SPIRE’s FTS has the ability to measure the redshifts of distant, obscured galaxies via the blind detection of atomic cooling lines, but it will not be competitive with ground-based CO-line searches. It will, however, allow detailed study of the integrated properties of high-redshift galaxies, as well as the chemistry of their interstellar medium (ISM), once more suitably bright candidates have been found.

Key words. galaxies: evolution – infrared: galaxies – infrared: ISM – radio continuum: galaxies – submillimeter: galaxies

1. Introduction

Submillimetre (submm) surveys have uncovered a population of intrinsically luminous, but highly obscured, galaxies at high redshift. However, even with intrinsic luminosities of $\sim 10^{13} L_{\odot}$ (e.g. Ivison et al. 1998), the brightest SMGs are still challenging targets for observational studies. In the submm and far-IR, where the bulk of their luminosity escapes, the brightest SMGs have observed flux densities of only $\sim 10$ mJy at $850 \mu$m, peaking at $\sim 50$ mJy at the wavelengths probed by Herschel. To alleviate this photon starvation, submm surveys often exploit gravitational lensing via massive, foreground galaxy clusters, thereby enhancing the apparent brightness of SMGs at all wavelengths (e.g. Smail et al. 1997; Chapman et al. 2002; Cowie et al. 2002).

Recently, Swinbank et al. (2010) exploited the cluster lensing technique using the Large Apex BOLometer Camera (LABOCA – Siringo et al. 2009) on the 12-m Atacama Pathfinder Experiment (APEX) telescope to map the cluster, MACS J2135–01 ($z = 0.325$), and thereby discovered SMM J2135, an SMG with $S_{870 \mu m} = 106$ mJy. Its brightness is due to very high amplification (by $32.5 \pm 4.5$) by the foreground cluster (similarly bright sources may have recently been unearthed by the South Pole Telescope – Vieira et al. 2010). The lens model for SMM J2135 is well constrained and its redshift ($z = 2.3259 \pm 0.0001$, derived from the detection of CO $J = 1-0$ in a blind search) and intrinsic flux ($3.3 \pm 0.5$ mJy) are typical of SMGs found close to the confusion limit in submm surveys. SMM J2135 thus presents an opportunity to study a member of this important population at high signal-to-noise and with the spatial and spectral resolution necessary to determine the detailed far-IR spectral properties of SMGs. Due to the high magnification, it is feasible to apply some of the observational tools used on local star-forming galaxies to understand the processes of star formation at high redshift. Indeed, we can employ diagnostics capable of determining the flux of ionising radiation and the SFR, thus determining the state of the overwhelming majority of the atomic and molecular gas in this galaxy (Wolfire et al. 1990; Hollenbach & Tielens 1999; Kaufman et al. 1999). In this paper we present spectroscopic and photometric far-IR/submm measurements of SMM J2135 made using Herschel (Pilbratt et al. 2010). We also include new observations with
the James Clerk Maxwell Telescope (JCMT) and VLA. We use these observations to constrain the SED of SMM J2135 and measure or set firm limits for the line fluxes from the main atomic cooling lines.

2. Observations

To complement the existing submm photometry of SMM J2135, observations at 250, 350 and 500 μm were obtained with SPIRE (Griffin et al. 2010). The field was observed first using the “small-map mode”, where orthogonal scans produce a useful cross-linked area of ∼16 arcmin². We used four repetitions, giving an on-source integration time of ∼200 s. Processing relied on the SPIRE scan map pipeline (Griffin et al. 2008), which deglitches, flux calibrates and performs various corrections. After removal of a linear baseline, images were made using the standard naive mapper within the Herschel interactive pipeline environment (HIPE v2.0). From the final maps, we identify a ∼100-σ source at the position of SMM J2135 in all bands; its flux densities are listed in Table 1.

SMM J2135 was also observed for 7 ks using the central pixels of SPIRE’s FTS (covering λtral pixels of SPIRE’s FTS (covering 100-μm bands; its flux densities are listed in Table 1)

...
Table 1. Photometry.

<table>
<thead>
<tr>
<th>Wavelength (μm)</th>
<th>Flux (mJy)</th>
<th>Observatory/Instrument</th>
</tr>
</thead>
<tbody>
<tr>
<td>250 μm</td>
<td>366 ± 55</td>
<td>Herschel/SPIRE</td>
</tr>
<tr>
<td>350 μm</td>
<td>429 ± 64</td>
<td>Herschel/SPIRE</td>
</tr>
<tr>
<td>352 μm</td>
<td>520 ± 70</td>
<td>APEX/SABAOC (^b)</td>
</tr>
<tr>
<td>434 μm</td>
<td>430 ± 40</td>
<td>SMA (^b)</td>
</tr>
<tr>
<td>450 μm</td>
<td>480 ± 54</td>
<td>SCUBA-2</td>
</tr>
<tr>
<td>500 μm</td>
<td>325 ± 49</td>
<td>Herschel/SPIRE</td>
</tr>
<tr>
<td>850 μm</td>
<td>115 ± 13</td>
<td>SCUBA-2</td>
</tr>
<tr>
<td>870 μm</td>
<td>106 ± 12</td>
<td>APEX/LABOCA (^b)</td>
</tr>
<tr>
<td>1.2 mm</td>
<td>26 ± 4</td>
<td>SMA (^b)</td>
</tr>
<tr>
<td>2.17 mm</td>
<td>2.0 ± 0.25</td>
<td>PdBI (^b)</td>
</tr>
<tr>
<td>2.80 mm</td>
<td>1.4 ± 0.25</td>
<td>PdBI (^b)</td>
</tr>
<tr>
<td>8.57 mm</td>
<td>0.13 ± 0.05</td>
<td>GBT/Zpectrometer (^b)</td>
</tr>
<tr>
<td>3.55 cm</td>
<td>0.240 ± 0.030</td>
<td>VLA/X</td>
</tr>
<tr>
<td>4.49 cm</td>
<td>0.240 ± 0.055</td>
<td>VLA/C</td>
</tr>
</tbody>
</table>

Notes. (\(^a\)) Errors include uncertainty in absolute flux calibration; (\(^b\)) see Swinbank et al. (2010), also for \(\lambda_{obs} < 250 \text{ μm}\).

dust-reprocessed UV light and provides a measure of its instantaneous SFR. Correcting for lensing amplification, we find \(L_{bol} = (2.3 ± 0.2) \times 10^{12} L_{\odot}\), indicating a SFR of ~400 \(M_{\odot} \text{ yr}^{-1}\) (Kennicutt 1998). \(L_{bol}\) is thus comparable to that of Arp 220 and rather higher than that quoted by Swinbank et al. (2010) who integrated the best modified blackbody fit to the 350-, 434- and 870-μm emission, missing much of the energy at rest-frame ~8–100 μm.

If we parameterise the far-IR SED of SMMJ2135 using a modified blackbody spectrum, a single component model with \(T_{BB} = 34 \text{ K}\) underestimates \(S_{350 \text{ μm}}\) by ~100×. A two-component model with \(T_{BB} = 30\) and 60 K provides a significantly improved fit (Fig. 1). The mass of dust associated with the warm and cool components are \(M_{dust,warm} = 10^6\) and \(M_{dust,cool} = 4 \times 10^6 M_{\odot}\) (adopting the parameters used by Dunne et al. 2000). Given the cold molecular gas mass derived from the CO(1−0) emission (\(M_{gas} = (16 ± 1) \times 10^9 M_{\odot}\), Swinbank et al. 2010), this suggests a gas-to-dust ratio of \(M_{dust}/M_{gas} ∼ 40\), rather lower than that of the Milky Way, 120, and Lyman-break galaxies (~100; e.g. Coppin et al. 2007) but consistent with typical SMGs (~60; e.g. Coppin et al. 2008) given that the uncertainties are considerable.

3.2. Radio properties

If the radio spectrum of SMMJ2135 follows a \(S_{\nu} ∝ \nu^{-0.7}\) power law, which is consistent with the data but by no means certain (Fig. 1; Table 1), then its radio luminosity is \(L_{1.4 \text{ GHz}} = 9 \times 10^{23} \text{ W Hz}^{-1}\) so that \(q_{IR} = 2.42 ± 0.06\), entirely consistent with the far-IR/radio correlation for 250-μm-selected galaxies ((\(q_{IR}\) = 2.40 – Ivison et al. 2010a).

3.3. Spectral properties

The full FTS spectrum (Fig. 1) covers the major fine-structure cooling lines and we detect one strong emission line, \([\text{CII}] 1158 \text{ μm}\), at the 4.3-σ level (Fig. 2). Table 2 presents the best-fit flux with the width constrained to the instrumental resolution. The flux is not sensitive to the fit parameters, for example returning values well within 1σ for a line fixed at \(v_{lsr} = 0 \text{ km s}^{-1}\). The FTS spectrum covers several other lines and although we see hints of emission associated with \([\text{O} I]\) 1455 μm and \([\text{N} II]\) 122 μm, we have chosen to report conservative upper limits (best-fit flux plus 3σ) on these and other lines in Table 2.

[C II] is one of the brightest emission lines in star-forming galaxies, typically accounting for 0.1–1% of \(L_{bol}\). It arises from the warm and dense PDRs that form on the UV-illuminated surfaces of molecular clouds, though the [C II] flux from diffuse HII regions or from diffuse PDRs can be considerable (e.g. Madden et al. 1993; Lord et al. 1996). In local star-forming galaxies, \(L_{\text{CII}}/L_{bol}\) and \(L_{\text{CII}}/L_{\text{CO(1-0)}}\) provide a sensitive test of the physical conditions within the ISM. For SMMJ2135 we find \(L_{\text{CII}}/L_{bol} = (2.4 ± 0.6) \times 10^{-4}\) and \(L_{\text{CII}}/L_{\text{CO(1-0)}} = (3.5 ± 0.5) \times 10^{-7}\) and compare these to measurements of local galaxy populations in Fig. 3. We see that \(L_{\text{CII}}/L_{\text{CO(1-0)}}\) in SMMJ2135 is similar to local ULIRGs, but that \(L_{\text{CII}}/L_{bol}\) is consistent with the ratios found in more typical star-forming galaxies and nuclei.

The [C II] transition is a primary PDR coolant and is a sensitive probe of both the physical conditions of the photodissociated gas and the intensity of the ambient stellar radiation field (Hollenbach & Tielens 1999). Hence using the PDR models of Kaufman et al. (1999) we can determine an acceptable range of temperature, \(T\), and gas density, \(n\), in SMMJ2135, from our measurements of [C II], CO(1-0) and \(L_{bol}\). In these models, \(L_{\text{CII}}/L_{\text{CO(1-0)}}\) is most sensitive to \(n\) whilst \(L_{\text{CII}}/L_{bol}\) is sensitive to the incident far-UV field strength, \(G_0\), and hence \(T\). Figure 3

---

Table 2. Spectral-line and bolometric luminosities.

<table>
<thead>
<tr>
<th>Line</th>
<th>(L_{bol}) (μm)</th>
<th>Flux ((×10^{-17} \text{ W m}^{-2}))</th>
<th>Luminosity ((L_{\odot}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>([\text{O} I])</td>
<td>63.18</td>
<td>3σ &lt; 4.5</td>
<td>3σ &lt; 14.9 \times 10^9</td>
</tr>
<tr>
<td>([\text{O} III])</td>
<td>88.36</td>
<td>3σ &lt; 2.4</td>
<td>3σ &lt; 8.0 \times 10^9</td>
</tr>
<tr>
<td>([\text{N} II])</td>
<td>122.10</td>
<td>3σ &lt; 1.4</td>
<td>3σ &lt; 4.7 \times 10^9</td>
</tr>
<tr>
<td>([\text{O} I])</td>
<td>145.53</td>
<td>3σ &lt; 2.5</td>
<td>3σ &lt; 8.5 \times 10^9</td>
</tr>
<tr>
<td>([\text{C} II])</td>
<td>157.74</td>
<td>1.7 ± 0.4</td>
<td>(5.5 ± 1.3) \times 10^8</td>
</tr>
<tr>
<td>CO(1−0)</td>
<td>2602.6</td>
<td>2.14 ± 1.2σ</td>
<td>(8.0 ± 0.4) \times 10^10</td>
</tr>
</tbody>
</table>

Notes. \(^a\) Upper limits on line-to-bolometric luminosity ratios.

---

Fig. 3. \(L_{\text{CII}}/L_{bol}\) versus \(L_{\text{CO(1-0)}}/L_{bol}\) for SMMJ2135 compared to star-forming regions, star-forming galaxies and ULIRGs in the local Universe. This figure is adapted from Hailey-Dunsheath et al. (2010) and shows the ratios for powerful, high-redshift QSOs as well as the SMG, MIPS J1428+35. Tracks for PDR models of gas density, \(n\), and far-UV field strength, \(G_0\), are taken from Kaufman et al. (1999). We see that the gas in SMMJ2135 experiences a far-UV field similar to that seen in local ULIRGs, but is at much lower densities than the typical material in such systems.
shows $L_{\text{HII}}/L_{\text{bol}}$ versus $L_{\text{CO}}/L_{\text{bol}}$ and suggests a best-fit density, $n \sim 3 \times 10^3 \text{ cm}^{-3}$, with $T \sim 400 \text{ K}$ and $G_0 \sim 10^2$ (Kaufman et al. 1999). $G_0$ is measured in multiples of the local interstellar value, so the far-UV radiation field illuminating the PDRs is $\sim 10^3 \times$ more intense than that in the Milky Way, but comparable to that found in local ULIRGs and the $z = 1.3$ SMG, MIPSJ1428 (Hailey-Dunneheath et al. 2010), while the densities in SMMJ2135 ($n \sim 10^3$) are most similar to those found in normal star-forming galaxies, 10–100x lower than those seen in local ULIRGs.

Taken together, this suggests that the molecular emission does not reside in a single, compact region, illuminated by an intense UV radiation field, but that the material is more extended, does not reside in a single, compact region, illuminated by an in-local ULIRGs.

8 $10^3 \text{ cm}$ (Swinbank et al. 2010) and previous suggestions of extended star formation in SMGs (e.g. Biggs & Ivison 2008), as well as a small number of high-redshift systems where similar results show that facilities such as Herschel and SCUBA-2 will allow detailed study of the integrated properties of high-redshift galaxies (through SED modelling), as well as the chemistry of their ISM.

Acknowledgements. We thank Steve Hailey-Dunneheath for useful discussion. We thank Fred Lo for granting DDT observations, and Wayne Holland for observing SMMJ2135 during SCUBA-2 commissioning. SPIRE has been developed by a consortium of institutes led by Cardiff Univ. (UK) and including Univ. Leibniz (Germany); IAC (Spain); Stockholm Observatory (Sweden); Imperial College London, RAL, UCL/MSSL, UKATC, Univ. Sussex (UK); Caltech, JPL, NHSC, Univ. Colorado (USA). This development has been supported by national funding agencies: CSA (Canada); NAOC (China); CEA, CNES, CNRS (France); ASI (Italy); MCINN (Spain); SNSB (Sweden); STFC (UK); and NASA (USA). SCUBA-2 is funded by STFC, the JCT Development Fund and the Canadian Foundation for Innovation.

References
Holland, W., MacInnes, M., Fairley, A., et al. 2006, in SPIE Conf. Ser., 6275

4. Discussion and conclusions
We have delineated the far-IR SED of a highly magnified (but intrinsically typical) SMG, SMMJ2135, at $z = 2.3$. Its rest-frame 8–1000-\mu m and 1.4-GHz luminosities are $2.3 \times 10^{12} L_\odot$ and $9 \times 10^{22} \text{ W Hz}^{-1}$, with $SFR \sim 400 M_\odot \text{ yr}^{-1}$, and it sits on the far-IR/radio correlation for starburst galaxies.

Herschel FTS spectroscopy detects the redshifted [CII] 158 \mu m emission line, allowing us to investigate the properties of its ISM. The line luminosity suggests that the mass of [CII] is ~25% of the molecular gas, similar to the ratio found in local starbursts.

We use CO(1–0), [CII] and $L_{\text{bol}}$ to investigate the ISM’s physical conditions. From a comparison with PDR models, we derive a far-UV radiation field, $G_0$, which is $\sim 10^3 \times$ higher than that in the Milky Way, but comparable to those found in ULIRGs. In contrast, we find a characteristic density, $n \sim 3 \times 10^3 \text{ cm}^{-3}$, which is lower than seen in ULIRGs, but comparable to values seen in local star-forming galaxies and nuclei, as well as a small number of high-redshift systems where similar measurements have been made. Together these results suggest that SMMJ2135 has a SFR intensity similar to that seen in local ULIRGs, but distributed over a larger volume. This is consistent with the ~2-kpc distribution of star formation across this galaxy (Swinbank et al. 2010) and previous suggestions of extended star formation in SMGs (e.g. Biggs & Ivison 2008).

Our results show that SPIRE’s FTS has the ability to measure the redshifts of suitably bright and distant, obscured galaxies via detection of atomic cooling lines such as [CII]. However, we estimate that $\gtrsim 10$ h integrations will be required and this is not competitive with blind, ground-based CO-line searches (e.g. Weiß et al. 2009), as evidenced by the ease with which the redshift of SMMJ2135 was determined using Zpectrometer on the Green Bank Telescope (Swinbank et al. 2010). Nevertheless, our results show that facilities such as Herschel and SCUBA-2 will allow detailed study of the integrated properties of high-redshift galaxies (through SED modelling), as well as the chemistry of their ISM.

Acknowledgements. We thank Steve Hailey-Dunneheath for useful discussion.