**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)

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**ABSTRACT**

We present a detailed analysis of the far-infrared (IR) properties of the bright, lensed, submm-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-μm luminosity, L_{bol}, of (2.3 ± 0.2) × 10^{12} L_{\odot} and a likely star-formation rate (SFR) of ~400 M_{\odot} yr^{−1}. The galaxy sits on the far-IR/radio correlation for far-IR-selected galaxies. At ≥70 μm, the SED can be described adequately by dust components with dust temperatures, T_{d}, ~30 and 60 K. Using SPIRE’s Fourier-transform spectrometer (FTS) we report a detection of the [CII] 158 μm cooling line. If the [CII], CO and far-IR continuum arise in photodissociation regions (PDRs), we derive a characteristic gas density, n, ~10^{3} cm^{−3}, and a far-ultraviolet (-UV) radiation field, G_{UV}, 10^{3} 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 ~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 suitable 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 ∼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 ~10 mJy at 850 μm, peaking at ~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 – Sirigoni 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 μm} = 106 mJy. Its brightness is due to very high amplification (by 32.5 ± 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 ± 0.0001, derived from the detection of CO J = 1−0 in a blind search) and intrinsic flux (3.3 ± 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 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 λ_{obs} = 197−670 μm) on 2009 December 9, to search for [C II] 158 μm, redshifted to 524 μm. Even with the benefit of extreme amplification, SMM J2135 represents an extremely faint target in the context of the SPIRE spectrometer: the standard pipeline reduction shows significant problems with the overall flux level in both the high- and low-frequency channels (SSW, SLW). Rather than rely on the pipeline, we used a bolometer in bolometer temperature to transform the source and dark interferograms into spectra which were then subtracted and divided by a calibration spectrum of Uranus (rather than the much fainter asteroid, Vesta – see Swinyard et al. 2010). Variations in instrument temperature between the observations of the dark sky and the source can cause large relative variations in the SLW spectrum. Here, we determined the overall net flux of the source, with no subtraction or addition of flux from the variation in instrument temperature. We then inspected the SLW data and compared to the spectrum expected from the subtraction of two blackbodies at the temperatures recorded in the housekeeping data. The difference in model instrument temperatures in the dark sky and the source observation are therefore varied (by less than 1%) until a match between the overall flux level from the photometer and SSW is achieved.

New observations were also carried out with the Submillimetre Common-User Bolometer Array-2 (SCUBA-2 – Holland et al. 2006), a large-format bolometer camera for the JCMT, designed to produce simultaneous continuum images at 450 and 850 μm. These data were obtained during 2009 November 29, during early commissioning, with one 32 × 40 transition-edge sensor (TES) array at each of 450 and 850 μm, giving a field of view of ∼3’ × 3.5’ (the final commissioned instrument will have four such arrays at each wavelength). The total integration time was 3.6 ks. Pointing checks and flux calibration was achieved via observations of Neptune and Uranus, immediately before and after the science exposures. Data reduction was carried out using the SubMillimeter User Reduction Facility (SMURF), which flatfields and stacks the images, and removes atmospheric emission. Measured flux densities are listed in Table 1.

To determine the radio properties of the galaxy, observations with the VLA were obtained during late 2009. SMM J2135 was observed in the C and X bands for 10 and 5 ks, respectively. The C-band observations were taken in spectral-line mode, to search for redshifted 22-GHz water maser emission, though only

[Fig. 1. The rest-frame near-IR-radio SED of SMM J2135, with new Herschel, SCUBA-2 and VLA observations complementing existing photometry (Swinbank et al. 2010). The FTS spectrum is shown in blue. In the rest-frame optical to mid-IR regime, SMM J2135 is less luminous than Arp 220 and considerably fainter than M 82, possibly reflecting strong dust obscuration. We model the SED using a two-component dust model (solid, black line) comprising two modified blackbodies (β = +2.0) with T_d = 30 and 60 K. The solid blue line denotes a stellar fit to the rest-frame UV-near-IR photometry. Inset is a colour image, centred on SMM J2135, generated from the SPIRE 250-, 350- and 500-μm observations (N, up; E, left).]

[Fig. 2. Region around the redshifted [C II] 158 μm, the strongest atomic fine-structure line detected by our FTS spectrum of SMM J2135. Dashed line: best Gaussian fit, with θ_{FWHM} = −180 ± 150 km s⁻¹, which corresponds to strong components in the HCN, C1 and CO lines (Danielson et al., in preparation). Using the line flux and following Eq. (1) of Hailey-Dunsheath et al. (2010), we estimate a gas mass, M_{gas} = 4 × 10^{10} M_\odot, which is ∼25% of the total molecular gas mass, similar to the ratio found in local starburst galaxies (Stacey et al. 1991).]

3. Analysis and discussion

3.1. Far-infrared SED

The new observations clearly identify a turnover in the SED of SMM J2135 at ∼350 μm (Fig. 1). We use the far-IR photometry (Table 1 and Swinbank et al. 2010) to calculate its rest-frame 8−1000-μm luminosity directly, which is due largely to
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/SABOCA 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 ± 0.03</td>
<td>VLA/X</td>
</tr>
<tr>
<td>4.49 cm</td>
<td>0.240 ± 0.05</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 λabs < 250 μm.

3.2. Radio properties

If the radio spectrum of SMM J2135 follows a $S_v \propto \nu^{-0.7}$ power law, which is consistent with the data but by no means certain (Fig. 1; Table 1), then its radio luminosity is $L_{1.4 \text{GHz}} = 9 \times 10^{23}$ W Hz$^{-1}$ so that $q_{\text{IR}} = 2.42 \pm 0.06$, entirely consistent with the far-IR/radio correlation for 250-μm-selected galaxies $(q_{\text{IR}} = 2.40 - \text{Ivison et al. 2010a)}$.

3.3. Spectral properties

The full FTS spectrum (Fig. 1) covers the major fine-structure cooling lines and we detect one strong emission line, [C II] 158 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 $v_{\text{tot}} = 0$ km s$^{-1}$. The FTS spectrum covers several other lines and although we see hints of emission associated with [O I] 1145 μm and [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.

Note: [C II] is one of the brightest emission lines in star-forming galaxies, typically accounting for 0.1–1% of $L_{\text{bol}}$. 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 H II regions or from diffuse PDRs can be considerable (e.g. Madden et al. 1993; Lord et al. 1996). In local star-forming galaxies, $L_{\text{CII}}/L_{\text{bol}}$ and $L_{\text{CII}}/L_{\text{CO}(1-0)}$ provide a sensitive test of the physical conditions within the ISM. For SMM J2135 we find $L_{\text{CII}}/L_{\text{bol}} = (2.4 \pm 0.6) \times 10^{-2}$ and $L_{\text{CII}}/L_{\text{CO}(1-0)} = (3.5 \pm 0.5) \times 10^{-7}$ and compare these to measurements of local galaxy populations in Fig. 3. We see that $L_{\text{CII}}/L_{\text{CO}(1-0)}$ in SMM J2135 is similar to local ULIRGs, but that $L_{\text{CII}}/L_{\text{bol}}$ 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 SMM J2135, from our measurements of [C II], CO(1-0) and $L_{\text{bol}}$. In these models, $L_{\text{CII}}/L_{\text{CO}(1-0)}$ is most sensitive to $n$ whilst $L_{\text{CII}}/L_{\text{bol}}$ is sensitive to the incident far-UV field strength, $G_0$, and hence $T$. Figure 3
shows $L_{\text{CRI}}/L_{\text{bol}}$ versus $L_{\text{CO}}$ and suggests a best-fit density, $n \sim 10^3$ cm$^{-3}$, with $T \sim 400$ K and $G_0 \sim 10^5$ (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 $\sim 10^5 \times$ more intense than that in the Milky Way, but comparable to that found in local ULIRGs and the $z = 1.3$ SMG, MIPS J1428 (Hailey-Duncombe et al. 2010), while the densities in SMM J2135 ($n \sim 10^3$) are most similar to those found in normal star-forming galaxies, 10–100× 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. 103 cm$^{-3}$ (Swinbank et al. 2010) and previous suggestions of extended star ULIRGs, but distributed over a larger volume. This is consistent that SMM J2135 has a SFR intensity similar to that seen in local star-forming galaxies (e.g. Biggs et al. 2008). Measurem ets have been made. Together these results suggest that SMM J2135 has a SFR intensity similar to that seen in local ULIRGs and the $z = 1.3$ SMG, MIPS J1428 (Hailey-Duncombe et al. 2010), while the densities in SMM J2135 ($n \sim 10^3$) are most similar to those found in normal star-forming galaxies, 10–100× lower than those seen in local ULIRGs.

The line luminosity suggests that the mass of SMM J2135 is $\sim 25\%$ 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 $\sim 10^5 \times$ higher than that in the Milky Way, but comparable to those found in ULIRGs. In contrast, we find a characteristic density, $n \sim 10^3$ 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 SMM J2135 has a SFR intensity similar to that seen in local ULIRGs, but distributed over a larger volume. This is consistent with the $\sim 2$-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 SMM J2135 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.

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