1. Observations and Data Reduction

1.1 APEX LABOCA and SABOCA observations

Observations of the galaxy cluster MACS J2135-0102 (z_{cl}=0.325) were made with the LABOCA 870μm bolometer camera[29] on the APEX telescope on 2009 May 8 for a total of 3.2hours (1200 seconds on-source) in excellent conditions (PWV=0.35—0.40mm). We used a 6 arcminute spiral pattern scan, centered at α:21:35:12.706 δ:-01:01:43.27 (J2000). For flux calibration, Mars and Uranus were both observed immediately prior to the science observations. The data were reduced using the minicrush reduction package, which includes temperature drift correction, flat-fielding, opacity correction, bad bolometer masking and de-spiking[29]. The final map appears flat, and has an r.m.s. of 3.5mJy/beam. Including systematic effects, we estimate calibration and fitting uncertainties as ~4% and 6% respectively. Visual inspection of the image shows a bright 30σ source centered at α:21:35:11.6 δ:-01:02:52.0 with an 870μm flux of 106.0±3.5mJy. Given the uncertainties in the calibration we adopt the flux of the SMG as S_{870}=106.5±7.0mJy, and derive S_{870}=24.2±7.0mJy for the counter-image.

We followed up SMMJ2135-0102 with the Submillimetre APEX Bolometer CAmera (SABOCA, Siringo et al., in prep.) on the APEX telescope on UT 2009 September 20 and 21. SABOCA is a 37 superconducting Transition Edge Sensing (TES) bolometer array with hexagonal layout and two-beam separation on sky Its filter transmission curve is optimised to cover the 350μm window, and has a central wavelength of 352μm (852 GHz) for flat spectrum sources. SABOCA operates at a temperature of 300mK and is installed in the Cassegrain cabin of APEX. We observed SMMJ2135-0102 in a 20”x20” raster of spirals with 35 seconds duration in order to obtain a fully sampled map. A total of 10 such rasters were used in the final map, corresponding to an on-source integration time of 1400 seconds (the total time, including overheads, was 2.7 hours).

Conditions during the observations were very good, with a stable atmosphere and zenith opacity of $\tau_{350\mu m}$=0.8 (PWV=0.25mm), determined every hour by skydips. The absolute flux calibration was determined using the primary calibrators Uranus and Neptune, 3 observations each, just before and after SMMJ2135-0102. We used the GILDAS/ASTRO model as a reference to calculate the expected flux, and reduced the data using minicrush. To determine the pointing corrections, we used J2253+161 as a pointing source, but the remaining data still contained some pointing drifts. We therefore reduced each scan individually in Azimuth-Elevation coordinates, which results in a 5 to 7.5σ detection used to register the source. We smoothed the combined map by the 7.5” beam size for presentation purposes, resulting in an effective beam size of 10.6”. We do not find any significant evidence for spatially resolved emission in the unsmoothed map. SMMJ2135-0102 is detected in the beam-smoothed map with $S_{352\mu m}$=530±60mJy, where the uncertainty includes factors from the opacity determination, scatter between the values from the two primary flux calibrators, and Gaussian fitting. We do not include any uncertainties in the planetary flux prediction models of ASTRO, which may add an additional 10 to 15% uncertainty.

1.2 Optical, Near- and Mid-Infrared Observations

We used existing *HST* ACS imaging of this cluster[30] to identify a faint I_{AB}=23.6±0.2, K_{AB}=19.77±0.07 galaxy, extending in a roughly East—West direction, at the position of the sub-mm source. . This cluster has also been observed extensively with the *Spitzer Space Telescope*, and we used the IRAC 3.6,4.5,5.8 & 8.0μm and MIPS 24 & 70μm[31,32] image to identify a mid-infrared counterpart.

Table 1: Optical to far-infrared photometry for SMM J2135-0102 at position α:21:35:11.6 δ:-01:02:52.0 J2000.

Band/Filter	Flux	
U_{336}	<0.1 μJy	HST U_{336}
V_{606}	0.9±0.2 μJy	HST V_{606}
I_{814}	1.4±0.4 μJy	HST I_{814}
K	36±4 μJy	UKIRT K
3.6μm	0.13±0.02 mJy	SST IRAC Ch1
4.5μm	0.21±0.02 mJy	SST IRAC Ch2
5.8μm	0.32±0.05 mJy	SST IRAC Ch3
8.0μm	0.30±0.05 mJy	SST IRAC Ch4
24μm	2.6±0.2 mJy	SST MIPS
70μm	6.0±2.6 mJy	SST MIPS
350μm	530±60 mJy	APEX/SABOCA
434μm	430±80 mJy	SMA 690GHz
870μm	106.0±7.0 mJy	APEX/LABOCA
1.2mm	25.5±4.0 mJy	SMA 1.2mm compact
2.8mm	1.4±0.3mJy	PdBI 2.8mm
8.6mm	0.13±0.04 mJy	GBT/Zpec

Notes: Observed photometry for SMM J2135-0102. To correct for lensing to find the intrinsic fluxes, divide by the amplification factor 32.4±4.5x (Δm=3.8mags). We note that 1mJy corresponds to m_{AB}=23.90. We also note that the counter-image of the galaxy is located at α:21:35:15.56, δ:-01:03:12.4 (J2000) and is ~3 magnitudes fainter.

1.3 GBT/Zpectrometer Observations

We used the Zpectrometer, a wideband spectrometer optimised for CO emission line searches with the Green Bank Telescope's Ka-band receiver, to establish the galaxy's redshift. The Zpectrometer has instantaneous frequency coverage from 25.6 to 36.1GHz with resolution 16 MHz, corresponding to z = 2.2 to 3.5 for the CO J=1-0 line and approximately 150km/s resolution[11] near the band centre. Observations were conducted on 2009 May 19 and 27 in moderate weather. The GBT's subreflector chopped between the receiver's two beams at 0.1Hz. Every 4 minutes we alternated the telescope position between the source and a nearby lensed Lyman Break Galaxy ("The Cosmic Eye" at z=3.07[30]), then differenced the spectra to eliminate residual optical offsets. Each pair was repeated 20 times for a total integration time of 5 hours, approximately equally split between the two sessions. Data reduction was performed with version D of the standard Zpectrometer GBT IDL reduction scripts. No baseline has been removed from the spectrum, and the offset from zero represents the continuum difference between the two sources. The flux and bandpass calibrator was 3C48, and we pointed and focused hourly on 2134-0153. The final spectrum is shown in Fig. 2a. We note that the spectrum is sampled at 75km/s, hence alternate points are independent.

1.4 PdBI Observations

We used the six-element IRAM Plateau de Bure Interferometer to observe the redshifted CO(3-2) line and continuum near 103.97GHz. The frequency was tuned to the CO(3–2) rotational transition at z = 2.3259, the systemic redshift of the system as derived from the CO(1-0) (see section 1.3). Observations were made in D configuration in Director's Discretionary Time (DDT) on 2009 May 29 with good atmospheric phase stability (seeing = 0.6"—1.6") and reasonable transparency (PWV = 5–15mm). We observed SMMJ2135-0102 with a total on-source observing time of 4 hrs. The spectral correlator was adjusted to detect the line with a frequency resolution of 2.5MHz across the receivers' 980MHz bandwidth. The overall flux scale for each observing epoch was set on MWC349, with observations of 2134+004 for phase and amplitude calibrations. The data were calibrated, mapped and analyzed using the GILDAS software package. Inspection of the data cube shows an extremely bright detection of CO(3–2) line emission (S/N~300) at the position of SMM J2135-0102 (Figure 2b), confirming the redshift from the CO(1-0) emission. A detailed analysis of the CO kinematics and the full CO ladder will be discussed in a future publication.

1.5 SMA Observations and Reduction

345GHz (870μm) observations of the galaxy were carried out with the SMA in its very extended configuration (baselines up to 500m) with 8 antennae, on 2009 July 13 in Directors Discretionary Time (DDT). The galaxy was observed over 9 hours in 10 minutes cuts using quasars 2148+069 and 2225-049 as the gain calibrators. The weather over the first 2 hours was only moderate (and subsequently flagged) but then improved significantly, with the humidity dropping to 10% and τ_{225GHz}~0.1 for the remaining time. These atmospheric conditions resulted in excellent phase stability and reasonable sensitivity (T_{sys} at transit was ~300K). 3C454.3 and Uranus were used as bandpass and flux calibrators, respectively, selecting only the shortest baseline for Uranus, where the emission was not resolved out. The r.m.s. noise in the final map is σ=2.1mJy and the synthesis beam is 0.33”x0.21” at a position angle of 15° East of North. Further 690GHz (434μm) observations were carried out in sub-compact configuration on 2009 September 09 in DDT time. The weather conditions were excellent throughout the 8 hour observation with τ_{225GHz}<0.08. Both Neptune and Callisto, which were within 15 degrees of the target on the observation date, were used as gain calibrators. Observations of nearby bright quasars were interspersed with the source to check the robustness of the gain solution. Neptune, Callisto, Mars and Uranus were used to calibrate both the bandpass and flux. We estimate the absolute flux scale for the 345GHz and 690GHz observations is accurate to 10% and 25%, respectively. The r.m.s. noise in the final 690GHz map is 80mJy and in this configuration, the synthesized beam is 2.9x2.3” at a PA of -15° East of North.

The data were calibrated using the MIR IDL package, adapted for SMA (http://www.cfa.harvard.edu/~cqi/mircook.html). In the 345GHz observations, a more accurate, post-observation baseline solution was applied to improve the delays before doing the standard calibration procedure. The data were then exported to MIRIAD to be imaged and cleaned. A first order polynomial was fit to the channels expected to be line-free (ie. those offset by >1000km/s from the CO(9-8) line in the upper sideband) and subtracted from the visibilities to produce separate line and continuum images.

2. Gravitational Lens Modeling

With spectroscopic confirmation that this galaxy is a lensed, multiply-imaged, background galaxy we searched for and identified a counter-image in the multi-wavelength imaging at α:21:35:15.56, δ:-01:03:12.4. This source is ~3 magnitudes fainter, as expected, and has almost identical colours as SMMJ2135-0102 (the 850μm flux of the counterpart is S_{870}=24.2±7.0mJy). We constructed a gravitational lens model for the galaxy cluster which strongly constrained the total mass in the region responsible for lensing SMMJ2135-0102. A striking multiply imaged blue galaxy at α:21:35:11.51 δ:-01:03:33.8 (J2000), is approximately 37" due south of the brightest cluster galaxy (BCG); its multiple images were key for constraining the lens model. We obtained its redshift with three 1.2ks exposures using VLT/FORS in MXU mode on 2006 November 13 as part of program 078.A-0420 in 1" seeing and clear conditions. All three images of the multiply imaged blue galaxy were placed on FORS slits, each yielding continuum with a S/N>5. From the resulting spectrum, a redshift of z=2.320+/-0.001 was measured for each of the three images from the features of SiIIλλ1526.7,1533.4; FeIIλ1608, CIVλ1549 and AlIλ1670.8. This triple image, together with the spectroscopically confirmed z=2.3259 lensed SMG, were used as primary constraints in the lens modelling for the massive cluster at z=0.325. We note that the multiply imaged blue galaxy is within ~500km/s of the z=2.3259 SMG (and 200kpc in projection in the source plane), suggesting that the SMG resides in a small group of high redshift[33]galaxies at.

We used LENSTOOL[34,35] to construct a parametric model of the mass distribution reproducing the triply imaged systems[37] (LENSTOOL optimizes the model by minimizing the location of each image in the source plane). We used a simple model with a single cluster-scale mass component, as well as individual galaxy-scale mass components centered on each cluster member (selected from their *HST V-I* colors). Each component was described by a double Pseudo Isothermal Elliptical (dPIE) mass distribution[36,37] and we assumed that the cluster galaxies follow a scaling relation with constant mass-to-light ratio according to an $L*$ cluster galaxy. We obtained a very good fit using this model, with an r.m.s. of 0.2" between the predicted and observed position of the multiple images. The cluster-scale component is centered 9.7kpc East and 10.2kpc South of the BCG, with an ellipticity of 0.25 and a position angle of -9.7 degrees (East of North). The enclosed mass within an aperture of 250kpc is M=3.3±0.3x10$^{14}M_{\odot}$ with an Einstein radius of θ_e=34.5±2.0" at z=2.32 (Richard et al. 2010 in prep). The best-fit parameters of the dPIE profile are given in Table 3.

Table 2. Gravitational Lens model parameters

	ΔRA (")	ΔDec (")	ε	θ (deg)	r_{core} (kpc)	r_{cut} (kpc)	v_{disp} (km/s)
DM halo	2.1±0.5	-2.2±0.5	0.25±0.02	-9.7±3	99±5	[1000]	1294±45
BCG	[0]	[0]	[0.15]	[148]	[0.2]	152±8	268±4
L* galaxies	-	-	-	-	[0.15]	[45]	192±10

Note: Numbers in square brackets are note allowed to vary in the fit. Position angles are clockwise from North. For a complete description on the choice of these parameters, see Richard et al. (2009).

Table 3. Amplification (μ) and source-plane properties of the star-forming regions within SMMJ2135-0102.

Component	S_{870} (mJy) (image plane)	μ	S_{870} (mJy) (source plane)	*FWHM* (pc) (source plane)
A1	13.2±2.1	9.3±1.2	1.42±0.22	328±40 x 2050±150
B1	14.4±2.1	12.9±1.6	1.12±0.16	229±33 x 1880±150

C1	14.5±2.1	22.0±2.0	0.66±0.10	205±24 x 2460±100
D1	8.2±2.1	31.0±3.9	0.30±0.07	90±20 x 2000±200
D2	6.4±2.1	19.9±2.5	0.34±0.11	98±28 x 2600±160
C2	14.9±2.1	15.5±2.5	0.96±0.13	180±28 x 2800±150
B2	6.6±2.1	5.3±0.7	1.25±0.39	352±50 x 2700±200
A2	8.3±2.1	4.7±0.6	1.77±0.45	452±50 x 2700±200

In Fig. 1a we show the true colour *HST* ACS/WFPC2 *VI*-band image of the cluster core, and overlay the contours from the APEX/LABOCA map (contours start at 5σ and are spaced in 5σ intervals up to 30σ). We also overlay the *z*=2.3259 tangential (outer) and radial (inner) critical curves, clearly showing that the brightest sub-mm source is formed from a pair of radial images. Fig. 1b contains a true colour IRAC 3.6, 4.5, 8.0μm image around the lensed galaxy with the 350μm contours from SABOCA in overlay. Using the mapping between the image and source-plane, we derive a total amplification factor of 32.5±4.5x, although this varies from ~5x to ~30x across the galaxy image (Table 2).

3 Spectral Energy Distribution Analysis

3.1 Stellar Mass

We used the extensive multi-wavelength imaging to estimate the stellar mass by fitting the latest stellar population synthesis models to the observed SED based on the photometry in Table 1[38]. We used a Salpeter 1955 initial mass function (IMF)[39], and considered both a solar and sub-solar ($0.2Z_{\odot}$) metallicity, and both constant star-formation histories and exponentially decaying (τ) models with *e*-folding decay times of up to 100 Myr. We considered the effects of dust in the modelling by adopting the Calzetti et al. (1994) reddening law[40]. For SMM J2135-0102 the best fit SEDs have a range of ages from 10—30Myr with significant dust extinction, E(B-V)=1.0±0.1, and a stellar mass (corrected for lensing) of M_{stars}=3±2x10^{10}$M_{\odot}$ (although we caution that there are systematic uncertainties in this estimate due to the unknown star-formation history of the galaxy and the strong dust extinction).

3.2 Bolometric Luminosity

We also parameterised the far-infrared SED (including *Spitzer*/MIPS 70μm, SABOCA 350μm, SMA 434μm & 870μm, SMA 1.2mm & PdBI 2.8mm photometry; Table 1) of the galaxy using a modified blackbody spectrum[3] (Fig 3). A single modified black-body fit suggestted a characteristic emission temperature of T_d=34±4K, but under-predicted the 70μm flux by a factor >100. To improve the fit, we therefore parameterised the SED using two dust component models, fixing T_d=30 and 60K. Integrating the SED we derive a bolometric luminosity (corrected for lensing) of $L_{bol}=1.2\pm0.2\times10^{12}L_\odot$, suggesting a star-formation rate of $SFR=210\pm50M_\odot/yr$[16].

4 Size and Luminosity of star-forming regions

To construct the comparison samples in the size and luminosities of local star-forming regions, we exploited a number of IRAS and millimetre studies. To ensure a fair comparison is made between the star-forming regions at z~2 and z=0, we restricted the comparison samples wherever possible to dust continuum observations where extrapolations to rest-frame 260μm luminosity can be reasonably made (rest-frame 260μm corresponds to observed 870μm at z=2.32).

First, we exploited IRAS studies of galactic GMCs. For these following comparison samples, we corrected the rest-frame 100μm luminosities to 260μm by fitting a modified black-body to the 100μm luminosity at the known temperature (which is derived from L_{60}/L_{100} in each case). We note that, since for a temperature of 30K a black-body peaks at ~170μm, the correction is typically small, with a median L_{260}/L_{100}=1.5±0.4. First, Scoville et al. (1989)[20] derived far-infrared sizes and luminosities of giant molecular clouds in the first galactic quadrant. In this sample, the clouds have a median diameter of 50±10pc and a median rest-frame 260μm luminosities of 4×10^{19}W/Hz. Turning to the outer galaxy, Snell et al. (2002)[22] presented far-infrared sizes and luminosities for molecular clouds with typical sizes 1—4pc and luminosities 1×10^{17}W/Hz. We also included two IRAS studies of molecular clouds in the Large Magellanic Cloud (LMC) from Caldwell et al. (2002)[23] and Livanou et al. (2006)[24] who investigated the properties of 73 GMCs with sizes 4—150pc and 260μm luminosities $L_{260\mu m}=10^{20-24}$W/Hz.

We also exploited millimetre observations of the dense cores of galactic GMCs from Hill et al. (2005)[25] (applying the same procedure as above to correct to rest-frame 260μm luminosity). This sample comprises a survey of 131 star-forming complexes suspected of undergoing massive star-formation. From this parent sample, we extracted 53 star-forming regions where reliable sizes, luminosities and temperatures are available (see Table 4 and 6 of Hill et al. 2005). Finally, we also show the sizes and luminosities of young, dense HII regions in Henize 2—10[41] and M82[43]. In both of these samples, we have extrapolated the VLA 7mm luminosities to rest-frame 260μm using the same technique as above, but we estimate that there is an order of magnitude uncertainty in this correction due to the extrapolation from 7mm and 260μm.

Since the galaxy the we detected is a ULIRG at z=2.3259, we also compare the properties of the star-forming regions to the "extreme" starburst observed in the local ULIRGs Arp220, using the sub-compact 690GHz (434μm) SMA observations of the source[42]. In this configuration, the synthesised beam was 1.2"x0.9", corresponding to 470 x 350pc at 79.9Mpc. At these wavelengths, Arp220 comprises two prominent components ($S_{435\mu m}$=1.28±0.38Jy and 0.96±0.29Jy for the western and eastern structures respectively), both of which are unresolved in the SMA map. We corrected the corresponding luminosities to rest-frame 260μm using their predicted temperatures ($T_{d,west}$~100K and $T_{d,east}$~60K) and derived L_{260}/L_{435}=4.6 and L_{260}/L_{435}=7.2 for the western and eastern components respectively, resulting in $L_{260,west}=4.5\pm2.0\times10^{24}$ W/Hz and $L_{260,east}=5.5\pm2.0\times10^{24}$ W/Hz. Although these components are unresolved at 434μm, higher resolution (0.2") SMA observations at 870μm have resolved the structures on ~50pc scales[28]. In Fig. 4 we therefore show the sizes as resolved at 870μm, but caution that this assumes that there is no significant size difference between 434μm and 850μm.

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