Is the Brightest Galaxy behind the Bullet Cluster a Galaxy in the Making?

Omar López-Cruz*  
Coordinación de Astrofísca, Instituto Nacional de Astrofísica, Optica y Electrónica (INAOE)  
omarlx@inaoep.mx  
*Visiting Scientist, Astrophysics Group, Bristol
The Team

- Mark Birkinshaw, Malcolm Bremer, Kathy Lancaster at Bristol University, UK
- Frank Bertoldi, K. Basu, M.W. Sommer & Padeli Papadopoulos at Argelander-Institute für Astronomie, Germany
- Kathy Horellou, Daniel Johansson (PhD 2011), Sebastian Muller, and John H. Black at Chalmers University of Technology, Sweden
- Omar López-Cruz, Olga Vega, W. F. Wall, Héctor J. Ibarra-Medel and Edgar Castillo-Dominguez at INAOE
- Hernán Quintana at PUC, Chile
Science

The results to be presented in this talk come from three publications:

- López-Cruz et al. 2012 (in preparation)
The Bullet Cluster (1E 0657 -57) was discovered by Tucker et al. (1995) using *Einstein IPC*. Tucker et al. (1998) used ASCA data and derived $T= 17 \text{ keV} \ (5.2 \times 10^8 \text{ K})$, one of the hottest known cluster. Established as a cluster-cluster merger by Tucker et al. (1998a) using ROSAT. The most luminous synchrotron radio halo (Liang et al. 2000). Supersonic merger Mach=2-3 shock: $v=4000-5000 \text{ km/s}$ (Markevitch et al. 2002)
Physical Properties of the gas in the Bullet Cluster (Markevitch et al., 2002)

Fig. 4.—(a) ACIS 0.5–5 keV surface brightness profile in a 120° sector centered on the bullet and directed westward. The profile is extracted in elliptical segments parallel to the shock front; the $r$-coordinate corresponds to an average radius within a segment. Errors in this figure are 1 $\sigma$. The histogram shows the best-fit model (see text). The corresponding unprojected model density profile along the symmetry axis is shown in (b), which also includes an approximate gas pressure model using temperatures in regions B, S, and P from Fig. 2. Error bars on pressure correspond to errors in temperature.
Liang et al. (2000)
1.3 GHz ATCA observations
The APEX Telescope

Location
Llano de Chajnantor
50 km east of San Pedro de Atacama, Northern Chile

Coordinates
Latitude: 29°00'20.6" South
Longitude: 71°45'33.9" West
Altitude: 5155 m

Diameter: 12 m
Mass: 125000 kg
Main reflector: 264 aluminium panels, average panel size: 0.7m x 0.7m, 17 micron

Secondary reflector
Hyperboloidal, diameter: 0.75m

Mounting: Alt-Az
Surface: 17 micron

Technical description of LABOCA

General
LABOCA is a multi-channel bolometer array for continuum observations. It operates in the 870 μm (345 GHz) atmospheric window. The array consists of 206 channels, which are arranged in 9 concentric hexagons around a central channel. The angular resolution is 18.8" (HPBW), and the total field of view is 11.4". With a channel separation of about 36" (twice the beam size) the array is undersampled, thus special mapping techniques are used to obtain fully-sampled maps in a time-efficient manner.

The Bolometers
A bolometer is practically a thermometer. The radiation arriving at APEX from astronomical objects is absorbed by a thin metal film cooled to about 280 mK. This metal changes its temperature while absorbing the radiation, and this is measured by a heat-sensitive semiconductor. This results in a voltage change, which can be measured and amplified and is in principle proportional to the intensity of the incoming radiation.

For LABOCA, the thermal, electrical and mechanical structure of the bolometer array is based on a single silicon wafer. Free-
The 17 sources detected by APEX/LABOCA 850µm observations. The black contour shows the 2 mJy/beam level. The red inner dashed circle marks the 10 arcmin used for analysis ($<z_{\text{phot}}>$ ~1.3, Rex et al. 2010). (185 scans/8 min int.)

Table 2. List of sources extracted from the LABOCA map.

<table>
<thead>
<tr>
<th>Source</th>
<th>α(J2000)</th>
<th>δ(J2000)</th>
<th>Flux density a</th>
<th>Deboosted b flux density</th>
<th>Demagnified c flux density</th>
<th>F/ΔF d</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(h:m:s)</td>
<td>(°:′:″”)</td>
<td>(mJy)</td>
<td>(mJy)</td>
<td>(mJy)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>06:58:37.62</td>
<td>-55:57:04.8</td>
<td>48.6 ± 1.3 e</td>
<td>48.0 ± 1.3</td>
<td>0.64</td>
<td>82.8</td>
</tr>
<tr>
<td>2</td>
<td>06:58:24.47</td>
<td>-55:55:12.5</td>
<td>15.1 ± 1.0</td>
<td>14.7 ± 1.0</td>
<td>8.8</td>
<td>29.9</td>
</tr>
<tr>
<td>3</td>
<td>06:58:25.45</td>
<td>-55:56:40.1</td>
<td>6.9 ± 0.9</td>
<td>6.4 ± 1.0</td>
<td>2.2</td>
<td>17.8</td>
</tr>
<tr>
<td>4</td>
<td>06:58:19.36</td>
<td>-55:58:30.3</td>
<td>8.2 ± 0.9</td>
<td>7.7 ± 0.9</td>
<td>4.7</td>
<td>16.2</td>
</tr>
<tr>
<td>5</td>
<td>06:58:27.27</td>
<td>-56:01:16.3</td>
<td>9.0 ± 1.3</td>
<td>8.0 ± 1.3</td>
<td>6.3</td>
<td>15.9</td>
</tr>
<tr>
<td>6</td>
<td>06:58:28.94</td>
<td>-55:53:48.4</td>
<td>9.3 ± 1.2</td>
<td>8.6 ± 1.2</td>
<td>6.3</td>
<td>15.4</td>
</tr>
<tr>
<td>7</td>
<td>06:59:01.39</td>
<td>-55:52:18.1</td>
<td>11.9 ± 2.1</td>
<td>9.7 ± 2.1</td>
<td>8.4</td>
<td>14.2</td>
</tr>
<tr>
<td>8</td>
<td>06:58:24.05</td>
<td>-55:57:23.0</td>
<td>5.3 ± 0.9</td>
<td>4.7 ± 1.0</td>
<td>1.8</td>
<td>13.1</td>
</tr>
<tr>
<td>9</td>
<td>06:58:55.98</td>
<td>-55:56:51.7</td>
<td>5.4 ± 1.2</td>
<td>4.4 ± 1.3</td>
<td>3.3</td>
<td>12.8</td>
</tr>
<tr>
<td>10</td>
<td>06:58:45.60</td>
<td>-55:58:48.0</td>
<td>6.2 ± 1.1</td>
<td>5.5 ± 1.1</td>
<td>3.6</td>
<td>12.0</td>
</tr>
<tr>
<td>11</td>
<td>06:58:53.22</td>
<td>-56:00:45.0</td>
<td>7.8 ± 1.5</td>
<td>6.4 ± 1.6</td>
<td>5.2</td>
<td>11.9</td>
</tr>
<tr>
<td>12</td>
<td>06:58:52.22</td>
<td>-55:55:45.7</td>
<td>5.5 ± 1.2</td>
<td>4.5 ± 1.2</td>
<td>3.4</td>
<td>11.2</td>
</tr>
<tr>
<td>13</td>
<td>06:58:22.88</td>
<td>-56:00:40.7</td>
<td>4.8 ± 1.2</td>
<td>3.8 ± 1.3</td>
<td>2.9</td>
<td>11.0</td>
</tr>
<tr>
<td>14</td>
<td>06:58:46.68</td>
<td>-56:02:11.8</td>
<td>7.2 ± 1.9</td>
<td>4.6 ± 2.5</td>
<td>3.8</td>
<td>10.8</td>
</tr>
<tr>
<td>15</td>
<td>06:58:33.69</td>
<td>-55:54:40.8</td>
<td>4.6 ± 1.1</td>
<td>3.6 ± 1.2</td>
<td>2.5</td>
<td>10.1</td>
</tr>
<tr>
<td>16</td>
<td>06:58:12.44</td>
<td>-55:57:29.7</td>
<td>4.9 ± 1.0</td>
<td>4.2 ± 1.0</td>
<td>1.9</td>
<td>9.2</td>
</tr>
<tr>
<td>17</td>
<td>06:59:15.72</td>
<td>-56:01:07.5</td>
<td>23.6 ± 5.9</td>
<td>—</td>
<td>—</td>
<td>9.0</td>
</tr>
</tbody>
</table>

Notes. Statistical uncertainties on the listed positions are 1–2″, which is smaller than the pointing uncertainty. a Flux density as extracted from the map. b Flux density corrected for boosting due to confusion noise. c Flux density corrected for lensing. d Significance of the detection in the Gaussian-matched-filtered map. e Source #1 is extended relative to the 22″ beam: it has an apparent size of 29.2″ × 23.3″. f Source #17 lies in the outer part of the map where the noise level is high and the method used to deboost the flux densities fails.
Figure 1: Figure 1a (upper left): Gaussian filtered map generated from APEX+LABOCA observations at 870 μm. This map shows Source #1 with eleven further sources within the central 10-arcmin region of constant noise in the analysis of Johansson et al. (2010). Figure 1b (upper right): Smaller region near Source #1, from an unsmoothed map generated from APEX+LABOCA observations at 870 μm, the faint extended Sunyaev-Zel’dovich effect signal is also visible (green). The resolution of 19.1 arcsec in this image is insufficient to resolve components A and B of Source #1. However, the elongation of the contours is consistent with the positions of source A and B. Figure 1c (lower center): Preliminary modeling of the rest-frame SED of Source #1 using GRASIL (Silva et al. 1998), with a renormalized flux density scale. Data points are taken from Gonzalez et al. (2009), Rex et al. (2009), Johansson et al. (2010); and the revised measurement by Wilson et al (2009). The full data set cannot be modeled as a typical ULIRG.
The bullet has the most lensed galaxies

Clusters observed with APEX/LABOCA by Johansson, Sigurdarson and Horellou (2011)

Fig. 1. Signal-to-noise maps of the five cluster fields. White circles represent the significant sources in the map and black contours show the noise maps of each cluster map at levels of 2.4 and 8 mJy/beam". The signal-to-noise representation causes the appearance of the increasing noise towards the edge of each map to be suppressed.

<table>
<thead>
<tr>
<th>Target</th>
<th>$\alpha$ [J2000]</th>
<th>$\delta$ [J2000]</th>
<th>$z$</th>
<th>rms$^5$ [mJy/beam&quot;]</th>
<th>$\Omega^2$ [arcmin$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abell 2163</td>
<td>16 15 45.1</td>
<td>-06 08 31</td>
<td>0.203</td>
<td>2.2</td>
<td>150</td>
</tr>
<tr>
<td>Bullet Cluster$^1$</td>
<td>06 58 29.2</td>
<td>-55 56 45</td>
<td>0.296</td>
<td>1.2</td>
<td>220</td>
</tr>
<tr>
<td>Abell 2744$^2$</td>
<td>00 14 15.0</td>
<td>-30 22 60</td>
<td>0.308</td>
<td>1.5</td>
<td>220</td>
</tr>
<tr>
<td>AC 114$^3$</td>
<td>22 58 52.3</td>
<td>-34 46 55</td>
<td>0.312</td>
<td>1.2</td>
<td>130</td>
</tr>
<tr>
<td>MS 1054-03$^4$</td>
<td>10 57 00.2</td>
<td>-03 37 27</td>
<td>0.823</td>
<td>1.6</td>
<td>200</td>
</tr>
</tbody>
</table>
Why the Bullet Cluster (1E0657-56)?

- Known bright, multiple-image, lensed submillimeter galaxy in the background ($z=2.8$; Bradac+06, Gonzalez+09, Rex+09)

- Recent collision of two clusters at $z=0.3$ (Markevitch+02,04)
  - Sub-cluster conveniently travelling perpendicular to our line of sight ($<8^\circ$ from sky plane)
  - Analysis of X-ray emission shows a supersonic bow shock proceeding the gas
  - Weak lensing maps indicate the X-ray gas lags behind the cluster galaxies due to ram pressure

- Abundant ancillary data:
  - multi-wavelength imaging
  - 930 spec-zs
    (mostly in cluster / foreground)
  - weak/strong lensing maps

Clowe et al. (2004)
Rex et al. (2009)
Figure 1. Top: 8 μm image showing the location of image C relative to images A and B. In this image the galaxy between images A and B has been subtracted for clarity. The field of view (FOV) is 65'' × 50''. Bottom: F850LP cutouts of the regions surrounding lensed images A and B (left) and image C (right). The crosses denote the locations of each image; the solid curve in the left panel is the critical curve from the z = 2.7 magnification map. The objects detected in the F850LP image that lie closest to the IRAC coordinates for images A and B are numbered 1–4. Object 1 is a cluster elliptical galaxy and object 2 is a star. The two fainter galaxies (3 and 4) are offset from the IRAC detections by 0'78 and 1'75, whereas the relative astrometry is good to 0'25, and can thus be excluded as optical counterparts to the lenses. The FOV is 17'' × 12'' in both panels. For all images north is up and east is to the left.

Figure 2. Reconstructed surface mass density $\kappa$ of the cluster for a fiducial source at infinite redshift, $z_s \to \infty$.

Bradac et al., 2009

Gonzalez et al. 2009
F435W - V - F814W (subcluster) color composite of the 1E0657 - 56. The ACS images are inset.
Bullet Cluster

X-ray luminous cluster merger at $z = 0.3$

Special thanks...

Doug Clowe (Magellan/IMACS images)

Jean-Gabriel Cuby (VLT/HAWKI images)

Anthony Gonzalez, Sun Mi Chung (Magellan/IMACS redshifts)

Dario Fadda, Phil Appleton (CTIO Hydra redshifts)

Cathy Horellou, Daniel Johansson and LABOCA team

David Hughes, Itziar Aretxaga and AzTEC team

Egami et al. (2010)
IR/submm SED of $z=2.8$ LIRG ($5 \times 10^{11} \, L_\odot$)

Magnification factor 50x ($\to 100x$ including unquantified local lensing)

- Observed flux densities: 7.0, 24.5, 65.3, 98.6, 101.4 mJy
- Corrected for lensing (x75): 0.09, 0.3, 0.9, 1.3, 1.4 mJy

Impossible to observe without lensing

Rex et al. (2010)
CO redshifts for SMG

Schematic and now dated sub-mm spectrum of a molecular cloud showing fine structure & molecular emission lines (only the lowest rotational transition is shown).

Not all of the suggested species have been detected.
M82 reconstructed apodized spectrum

![Graph showing the spectrum with various CO transitions and [NII] emissions.](image)

- P. Panuzzo et al. - Herschel/SPIRE FTS View of M82
Gonzalez et al. 2010 PAH redshift, $z=2.791 \pm 0.007$

$\text{CO}(3-2) \rightarrow 91.23 \text{ GHz}; \text{CO}(1-0) \rightarrow 30.41 \text{ GHz}$
ATNF Facilities: ATCA 6 x 22m
Table 1. Some ATCA properties. — See the ATCA Users Guide (Table 1.1) for more details and up-to-date information.

<table>
<thead>
<tr>
<th>ATCA observing bands</th>
<th>16-cm*</th>
<th>6-cm</th>
<th>3-cm</th>
<th>15-mm</th>
<th>7-mm</th>
<th>3-mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>(L/S)</td>
<td>1.1 – 3.1</td>
<td>4.4 – 6.7</td>
<td>7.5 – 10.5</td>
<td>15 – 25</td>
<td>30 – 50</td>
<td>85 – 105</td>
</tr>
<tr>
<td>(C)</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>number of antennas</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>primary beam FWHM</td>
<td>44’ – 16’</td>
<td>10’7 – 7’4</td>
<td>6’3 – 5’1</td>
<td>~2’</td>
<td>~70”</td>
<td>~30”</td>
</tr>
</tbody>
</table>

Notes: ATCA observing information can be found at www.narrabri.atnf.csiro.au/observing, including a link to the CABB Sensitivity Calculator which is highly recommended to obtain observing characteristics (e.g., $T_{sys}$) at specific frequencies and correlator settings (see also Fig. 3). The ATCA primary beam size (in arcmin) can be approximated by $50/\nu$ where $\nu$ is the observing frequency in GHz; the MIRIAD task PBPLTT provides details of the primary beam model (see Fig. 4). * In 2010 the 1.5 GHz (20-cm) and 2.3 GHz (13-cm) bands were combined into one broad band covering the frequency range from 1.1 to 3.1 GHz (now referred to as the 16-cm band). Note that the 3- and 6-cm bands can be used simultaneously.

the ringing that was commonly seen with the original ATCA and other correlators while observing narrow spectral lines.

- Modes providing high velocity resolution (for spectral line studies), high time resolution (for the study of fast transients), or pulsar binning come as an addition to the basic wide-bandwidth modes.

- CABB also provides auto-correlation data.

These improvements have a major impact on the scientific ability of the ATCA (see examples in § 6), including the following:

- the much larger bandwidth reduces the time required to reach any particular continuum sensitivity, and the increased

<table>
<thead>
<tr>
<th>configuration</th>
<th>channel width</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>primary band</td>
</tr>
<tr>
<td>CFB 1M–0.5k</td>
<td>1.0 MHz</td>
</tr>
<tr>
<td>CFB 4M–2k</td>
<td>4.0 MHz</td>
</tr>
<tr>
<td>CFB 16M–8k</td>
<td>16.0 MHz</td>
</tr>
<tr>
<td>CFB 64M–32k</td>
<td>64.0 MHz</td>
</tr>
</tbody>
</table>

Table 2. Basic CABB configurations.

sampling depth allows for higher dynamic range and lower $T_{sys}$:

- narrow, independent channels allow for precise excision of narrowband interference;
The first 3mm CABB channel map. Observed on October 17-18, 2010 with ATCA
\[ L_{\text{CO}} = 3.25 \times 10^7 S_{\text{CO}} \Delta \nu \nu_{\text{obs}}^{-2} D_L^2 (1 + z)^{-3} \]

\[ L_{\text{CO}} \ [K \ km \ s^{-1} \ pc^2] \]

(Solomon & Vanden Bout 2005)

Fig. 4. Channel maps around the CO lines. The white circles indicate the positions of the Spitzer images A and B (G10). The central beam of each channel is noted in the upper left corners. The channel width is \( \sim 300 \ km \ s^{-1} \). The beam is shown in the bottom left corner and the color bar shows the range of surface brightnesses, in Jy beam\(^{-1}\). Top row: Channel maps at 3 mm, the band into which the CO(3–2) line is redshifted. Emission is clearly seen near image B (the western image) in the third panel. Faint emission near image A is seen in the third panel. Bottom row: Channel maps at 7 mm, the band into which the CO(1–0) line is redshifted. Emission is detected close to images A and B and is best seen in the third panel. The continuum source discussed in Sect. 3.2 lies outside the field displayed here.

Table 2. Integrated flux densities and upper limits on interesting molecular transitions in the ATCA bands.

<table>
<thead>
<tr>
<th>Line</th>
<th>( \nu_{\text{int}} ) [GHz]</th>
<th>( \chi [\text{Jy km s}^{-1}] )</th>
<th>( L_{\text{int}} (\mu_{\text{Jy}}/100)^{-1} ) [10(^7) K km s(^{-1}) pc(^2)]</th>
<th>Flux B/A</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{12}\text{CO}(1–0))</td>
<td>115.271</td>
<td>0.34 ± 0.07</td>
<td>0.29 ± 0.07</td>
<td>0.63 ± 0.10</td>
</tr>
<tr>
<td>(^{12}\text{CO}(3–2))</td>
<td>345.796</td>
<td>0.94 ± 0.03</td>
<td>1.25 ± 0.35</td>
<td>3.18 ± 0.30</td>
</tr>
<tr>
<td>HCN(4–3)</td>
<td>254.660</td>
<td>...</td>
<td>&lt; 0.7</td>
<td>94 ± 3.0</td>
</tr>
<tr>
<td>HCO(^{+})(4–3)</td>
<td>356.734</td>
<td>...</td>
<td>&lt; 0.7</td>
<td>94 ± 3.0</td>
</tr>
<tr>
<td>CS(7–6)</td>
<td>342.883</td>
<td>...</td>
<td>&lt; 0.5</td>
<td>94 ± 3.0</td>
</tr>
</tbody>
</table>

| Brightness temperature ratio (R\(_{\text{B}}\)) | 0.31±0.12 | 0.86±0.23 | 0.56±0.12 |

Notes. Uncertainties correspond to the 1\,σ level while upper limits are < 3\,σ. Integrated flux values are derived from fitting point sources at the positions of images A and B in the CO(1–0) and CO(3–2) maps collapsed for velocities between −350 and +170 km s\(^{-1}\), as described in the text. This velocity range was determined from the spectral extent of the CO(3–2) spectrum.
Fig. 5. Hubble Space Telescope WFC3 1.6 \textmu m image of the region around SMM J0658. The blue contours show the CO(1–0) integrated intensity of both images of SMM J0658 and, red contours show the CO(3–2) integrated intensity. The 7 mm continuum emission from the $z = 0.35$ galaxy to the south is indicated by yellow contours. The two black squares indicate the locations of the two infrared Spitzer images, A to the east and B to the west (Gonzalez et al. 2009). The gray line between images A and B is the critical line, derived from the lensing model for a source redshift of $z = 2.7$ (Gonzalez et al. 2009), very similar to the redshift derived from the CO observations. The white circle shows the extent of the ATCA FWHM primary beam for the CO(3–2) observations; the primary beam at 7 mm is larger than the field displayed here. The offsets seen between the various components are discussed in Sect. 5.1.
Fig. 2. — Three-color image of 30 Dor: MIPS 24μm (red), Hα (green), and 0.5-8 keV X-rays (blue). White contours show the 12CO(1-0) emission (Johansson et al. 1998) in the region. Both large- and small-scale structures are evident. North is up, East is left.

Fig. 8. HST image (G10) of SMM J0658 overlaid with the two Spitzer image positions A and B (white squares). The red and blue contours are the same as in Fig. 5, and show the CO(3-2) and CO(1-0) emission. We used GALFIT to subtract a model of the elliptical galaxy at (α2000, δ2000) = (06:58:37.44, −55:57:2.4) and masked the region of that galaxy, a nearby star and four other objects (gray disks). The faint arc between images A and B is visible, roughly orthogonal to the critical line shown in black (see Fig. 3 in G10 for a color image). The cross and box markers show the centroid of the LABOCA and SABOCA detections. The synthesized beams at 3 mm and 7 mm are shown in the lower left corner as red and blue ellipses.
$z_{\text{CO}} = 2.7795 \pm 0.0010$  \hspace{1cm} \text{CO}(3-2)/\text{CO}(1-0) = 0.56$

Components at the same $z$; hence, we are dealing with a single galaxy.
Gas Mass and Dynamical Mass

CO-H$_2$ conversion.

Taking $M(H_2) = \alpha L_{CO}$ with $\alpha = 0.8M_\odot(K\text{ km s}^{-1}\text{ pc}^2)^{-1}$

$$M_{gas} = (1.8 \pm 0.3) \times 10^9 M_\odot$$

$$M_{dyn} = 1.16 \times 10^9 \left( \frac{\Delta V_{FWHM}}{100 \text{ km s}^{-1}} \right)^2 \left( \frac{\phi}{\text{kpc}} \right) (\sin i)^{-2}$$

Formula by Papadopoulos et al. 2000; taking $<\sin i> = 0.5$; L = 2 kpc

$$M_{dyn} = (1.3 \pm 0.4) \times 10^{10} \left( \frac{L}{1 \text{ Kpc}} \right) M_\odot$$
Dust Temperature

\[ S_\nu = A \left( \frac{\nu}{\nu_0} \right)^\beta B_\nu(T_{\text{dust}}) \]

\[ M_{\text{dust}} = \frac{D_L^2 S_{\nu_{\text{obs}}}}{(1 - z)k_{\nu}(\nu_{\text{em}})} \left[ B(\nu_{\text{em}}, T_d) - B(\nu_{\text{em}}, T_{\text{cmb}}(z)) \right]^{-1} \]

\[ T = 32.7 \pm 5.0 \text{ K} \]

\[ M_{\text{dust}} = 1.7 \times 10^7 M_\odot \]
Comparison with other highly magnify galaxies

Table 4. Summary and comparison of physical properties of SMM J0658 and other highly magnified SMGs.

<table>
<thead>
<tr>
<th>Source</th>
<th>SMM J0658</th>
<th>SMM J16359+6612</th>
<th>SMM J2135–0102</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
</tr>
<tr>
<td>Redshift</td>
<td>2.7795</td>
<td>2.5174</td>
<td>2.3259</td>
</tr>
<tr>
<td>Magnification</td>
<td>100</td>
<td>45</td>
<td>32.5 ± 4.5</td>
</tr>
<tr>
<td>Submm flux density (mJy)</td>
<td>~0.5</td>
<td>~0.8</td>
<td>~3</td>
</tr>
<tr>
<td>L_{CO(1-0)} (10^8 K km s^{-1} pc^2)</td>
<td>22.6 ± 3.6</td>
<td>~</td>
<td>173 ± 9</td>
</tr>
<tr>
<td>L_{CO(3-2)} (10^8 K km s^{-1} pc^2)</td>
<td>12.7 ± 2.0</td>
<td>37 ± 2</td>
<td>117.6 ± 0.9</td>
</tr>
<tr>
<td>M(H_2) (10^6 M_\odot)</td>
<td>2.3</td>
<td>4.5 ± 1.0</td>
<td>14 ± 1</td>
</tr>
<tr>
<td>M_\text{dyn} (10^9 M_\odot)</td>
<td>24</td>
<td>~30</td>
<td>~53</td>
</tr>
<tr>
<td>L_{IR} (10^{12} L_\odot)</td>
<td>0.3</td>
<td>1.6 ± 0.4</td>
<td>2.3 ± 0.1</td>
</tr>
<tr>
<td>SFR (M_\odot yr^{-1})</td>
<td>100 – 150</td>
<td>~500</td>
<td>400 ± 20</td>
</tr>
<tr>
<td>SFE (L_{IR} M_\odot^{-1})</td>
<td>170</td>
<td>~320</td>
<td>165 ± 7</td>
</tr>
<tr>
<td>M_{dust} (10^6 M_\odot)</td>
<td>1.1</td>
<td>1.9 ± 0.3</td>
<td>~15</td>
</tr>
<tr>
<td>T_{dust} (K)</td>
<td>32.7 ± 5.0</td>
<td>51 ± 3</td>
<td>30; 57 ± 3</td>
</tr>
</tbody>
</table>

Notes. All values have been corrected for the individual gravitational magnification factors. \(^{(a)}\) Flux density measured at 850 \(\mu\)m while the other two flux densities were measured at 870 \(\mu\)m. For a submm spectral index of ~ 3 the flux difference between the two wavelengths is less than 3%. \(^{(b)}\) Star formation efficiency, defined as \(L_{IR}/M(H_2)\).

(1) This work.
(2) Kneib et al. (2004, 2005).
(3) Danielson et al. (2010).
Fig. 9. Far-infrared luminosity versus CO(1–0) luminosity for SMMJ0658, SMM J16359+6612 (Kneib et al. 2005) and SMM J2135–0102 (Danielson et al. 2010) (the three galaxies summarized in Table 4). Local luminous infrared galaxies (Yao et al. (2003), Solomon et al. (1997)) and high-redshift submm galaxies (Greve et al. 2005) are also shown. SMMJ0658 is the least FIR-luminous high-redshift galaxy.
SMG are usually ULIRGS

Michalowski et al. 2010
Figure 6.1: Median spectral energy distribution (SED) of SMGs (thick lines) and SEDs of individual SMGs (thin lines). Shaded areas enclose 90% of the SEDs. Top: all SEDs were divided by the corresponding 500 μm datapoint and scaled, so that the median SED has a flux of 5 mJy at the rest-frame 283 μm (observed 850 μm at z = 3). Bottom: SEDs were normalized to an infrared star formation rate of 100 M⊙ yr⁻¹.
Far-IR/submm template SEDs

Do these local templates adequately describe high-z galaxies?

$LTIR \uparrow \Rightarrow T_{dust} \downarrow \Rightarrow L_{FIR}/L_{MIR} \uparrow$

Rieke et al. (2009)

Chary & Elbaz (2001)
SMM J0658 SED

Published observation, modeled with GRASIL in progress
Conclusions

- Clusters of galaxies acting as natural telescopes allow us to study intrinsically faint SMG.
- We have detected CO for the first time using ATCA/CABBB. We have refined on the redshift on the brightest SMG behind the bullet cluster.
- The derived masses are consistent with galaxies smaller than the Milky Way. SMM J0658 is an starbursting young galaxy. It may be more representative of the overall population of galaxies at z ~3.
- Observations with ALMA will allow us to impose tighter constrains on the physical properties of this rather interesting low-mass galaxy.