Mid-IR FORCAST/SOFIA Observations of M82

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M82: Overview

• Distance: 3.5 Mpc (1” = 17pc)
• Interaction with M81:
  – separation: ~38 kpc (projected) (e.g. Yun 1999, IAUS, 186, 81)
  – Last closest encounter: ~few 100 Myr
• SFR: ~10 M\text{sun}/yr
  – most recent starburst: <=50 Myr (e.g. Foerster Schreiber et al. 2003, ApJ, 599, 193)
• Global Dust Mass: ~5 x 10^6 M\text{sun} (Roussel et al. 2010, A&A, 518, L66)
Observation (1): FORCAST

• Dual-channel mid-IR camera:
  – 5-25 micron
  – 25-40 micron
  – Simultaneous observation possible with dichroic
  – Various bandpass filters available at each channel

• Detectors: 256 x 256 pixels
• Field of view: 3.4’ x 3.2’
• Pixel size: 0.768”
Observation (2)

• Observations taken in two flights:
  • 1\textsuperscript{st} flight:
    - 31.5 micron, 37.1 micron
    - On-Chip Chop-nod observing mode (chop: 120”, nod: 90”)
  • 2\textsuperscript{nd} flight:
    - 6.4, 6.6, and 7.7 together with 31.5 micron
    - On-Chip Chop-nod observing mode (chop & nod: 90”)
• 4 – 7 x 60 sec integrations
• Co-adding: 1) spatially registered each integration by fitting 2D Gaussian (ellipsoid), 2) then co-added integration
• Calibration: color-corrected, flat-fielded, standard stars: β Gem, βUMi, μUMa
• Due to pointing instabilities and drifts: beam size ~4” for all bands
• Positional calibration: IRAC 8 micron image
• Uncertainty: 20% (3 sigma)
Observation (3)

37 µm

31 µm

7.7 µm

6.6 µm

6.3 µm

Single Integration
Results (1): Maps

Maps of M82 in the FORCAST bands in units of Jy/pix at 31.5 micron, 37.1 micron. The color scale is linear and starts at the 3 sigma level of the statistical background noise (0.042 Jy at 31.5 micron, 0.051 Jy at 37.1 micron).

On next slide:
Maps of M82 in the FORCAST bands in units of Jy/pix at 6.4 micron, 6.6 micron, 7.7 micron. IRAC band 4 (8 micron) map (in MJy/sr) overplotted with FORCAST 7.7 micron contours. (3 sigma statistical noise limit: 0.009 Jy at 6.4 and 6.6 micron, 0.018 Jy at 7.7 micron). The dashed line in the 6.6 micron map indicates the position of the cut along the major axis (see next slides).
Results (2): Maps
# Results (3)

Table 1. M82 FORCAST Flux Densities

<table>
<thead>
<tr>
<th>Band (μm)</th>
<th>$S_{\text{peak}}^a$ (Jy/pixel)</th>
<th>$S_{\text{mp}}^{b,c}$ (Jy)</th>
<th>$S_{\text{sp}}^{b,d}$ (Jy)</th>
<th>$S_{\text{wr}}^{b,e}$ (Jy)</th>
<th>$S_{\text{mp}}^{f,c}$ (Jy)</th>
<th>$S_{\text{sp}}^{f,d}$ (Jy)</th>
<th>$S(\text{Total Map})^g$ (Jy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.4</td>
<td>0.112 ± 0.007</td>
<td>3.42 ± 0.23</td>
<td>2.96 ± 0.20</td>
<td>2.75 ± 0.18</td>
<td>6.93 ± 0.46</td>
<td>6.02 ± 0.40</td>
<td>68 ± 5</td>
</tr>
<tr>
<td>6.6</td>
<td>0.047 ± 0.003</td>
<td>1.40 ± 0.09</td>
<td>1.21 ± 0.08</td>
<td>1.17 ± 0.08</td>
<td>2.90 ± 0.19</td>
<td>2.52 ± 0.17</td>
<td>32 ± 2</td>
</tr>
<tr>
<td>7.7</td>
<td>0.141 ± 0.009</td>
<td>4.12 ± 0.28</td>
<td>3.41 ± 0.23</td>
<td>3.20 ± 0.21</td>
<td>8.16 ± 0.54</td>
<td>6.94 ± 0.46</td>
<td>75 ± 5</td>
</tr>
<tr>
<td>31.5</td>
<td>1.86 ± 0.12</td>
<td>57.1 ± 3.8</td>
<td>40.6 ± 2.7</td>
<td>46.5 ± 3.1</td>
<td>110.0 ± 7.3</td>
<td>79.7 ± 5.3</td>
<td>676 ± 45</td>
</tr>
<tr>
<td>37.1</td>
<td>2.42 ± 0.16</td>
<td>74.5 ± 5.0</td>
<td>51.5 ± 3.4</td>
<td>61.4 ± 4.1</td>
<td>143.9 ± 9.6</td>
<td>102.2 ± 6.8</td>
<td>891 ± 59</td>
</tr>
</tbody>
</table>

$^a$Pixel size: 0.768″.

$^b$within 6 × 6 pixels, corresponding to a 4.6″ × 4.6″ region.

$^c$Main peak: 09$h$55$^m$51.28$^s$, +69°40′45.5″

$^d$Secondary peak: 09$h$55$^m$52.68$^s$, +69°40′48.5″

$^e$Western Ridge: 09$h$55$^m$50.47$^s$, +69°40′43.9″

$^f$within 9 × 9 pixels, corresponding to a 6.8″ × 6.8″ region.

$^g$Within 50″ × 75″ (65 × 98 pixel) region around center of M82.
Results (4): Cut along major axis

Flux densities (left) and flux density ratios (right), normalized to the value at the main peak position, along the major axis of M82. The reference position is the main peak, distances are in arcsec, and positive distance is toward the northeast. Flux densities are summed over 1 x 5 pixels perpendicular to the major axis.

Color (RGB) R.Gendler

http://coolcosmos.ipac.caltech.edu/cosmic_classroom/multiwavelength_astronomy/multiwavelength_museum/gallery.html

Green Box:
60”x90” (~1 kpc x 1.5 kpc)

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FIG. 16.—Schematic representation of M82 viewed face-on. Structures are roughly to scale. Dust lanes are those proposed by Larkin et al. (1994). Between the ionized ring and the molecular region lies a region occupied by both ionized and molecular material.
Spectral Energy Distribution (SED) (1)

- SED templates from Siebenmorgen & Kruegel 2007 A&A 461, 445–453:
- Starburst SEDs
- Parameters:
  - Total luminosity: $10^{10} - 10^{14} L_{\text{sun}}$ (0.1 increments)
  - Size of nuclear starburst: 350 pc, 1 kpc, 3 kpc
  - Visual extinction: $A_V \sim 2.2, 4.5, 7, 9, 18, 35, 70, 120$ mag
  - Contribution from OB stars to total luminosity: 40%, 60%, 90%
  - Hydrogen density in “hot spots”: $10^2, 10^3, 10^4$ cm$^{-3}$
- >7000 templates
SED (2): M82 SED from “central” region

- From Siebenmorgen & Kruegel 2007 A&A 461, 445–453
Mid-IR SED of the main peak (left) and secondary peak (right). The solid (black) line is the low-resolution Spitzer/IRS spectrum (Beirao et al. 2008), filled triangles (red) are the FORCAST observations, filled diamond (blue) is the Herschel/PACS 70 micron observation, filled squares (green) are IRTF observations (Telesco et al. 1991), multiplied by a factor of two (see text), dashed line (blue) is the Siebenmorgen & Kruegel SED model Siebenmorgen & Kruegel (2007). The error bars are smaller than the symbols.
SED (4): Results

• Main Peak:
  – \( L(\text{tot}) \sim 6.7 \times 10^9 \ L_{\odot} \)
  – \( A_V \sim 18 \ \text{mag} \)
  – \( n(\text{H}) \sim 5 \times 10^3 \ \text{cm}^{-3} \)

• Secondary Peak:
  – \( L(\text{tot}) \sim 5.7 \times 10^9 \ L_{\odot} \)
  – \( A_V \sim 9 \ \text{mag} \)
  – \( n(\text{H}) \sim 5 \times 10^3 \ \text{cm}^{-3} \)
Color Temperature & Mid-IR Extinction

- 3-10 micron extinction law similar in M82 and Galactic center \((R_V = A_V / E(B-V) = 5.5)\) (Foerster Schreiber et al. 2001, ApJ, 552, 544)

- Using extinction law model of Li & Draine (2001) and Weingartner & Draine (2001)

- Assuming emissivity index: \(\beta = 1.75\)

- \(\tau(31\text{micron}) \sim 0.1 – 0.2\)

- \(\tau(37\text{micron}) \sim 0.08 – 0.16\)

- \(T(\text{color}) \sim 68 \pm 10 \text{ K}\)
Dust Mass (1)

- \( M_g = \mu \times m_H \times N(H) \times \text{Area} \)
  - \( \mu = 1.4 \) : mean atomic mass
  - \( m_H \) : mass of atomic hydrogen
  - \( N(H) \) : total hydrogen column density
  - \( M_g/M_d = 105 \)

- \( M_g(\text{MP}) = 3.8 \times 10^6 \, M_{\text{sun}} \Rightarrow M_d(\text{MP}) = 3.6 \times 10^4 \, M_{\text{sun}} \)

- \( M_g(\text{SP}) = 1.9 \times 10^6 \, M_{\text{sun}} \Rightarrow M_d(\text{SP}) = 1.8 \times 10^4 \, M_{\text{sun}} \)
Dust Mass (2)

- $M_d = \frac{1}{\kappa_{abs}} \times F_{\nu}(\lambda) \times D^2 / B(\lambda, T)$
  - $\kappa_{abs}$: mass absorption coefficient
  - $F_{\nu}(\lambda)$: flux density
  - $D$: distance
  - $B(\lambda, T)$: Planck

- $M_d(MP) = 1.2 \times 10^4 \ M_{\text{sun}}$
- $M_d(SP) = 8 \times 10^3 \ M_{\text{sun}}$
Dust Mass (3)

\[ M_d = \left( \frac{L(FIR)}{10^8 L_{sun}} \right) \times \left( \frac{40K}{T_d} \right)^5 \times 10^4 M_{sun} \]

- (Sanders et al. 1991)
- FIR: 40 – 500 micron
- \( L_{SP}(FIR) = 2.5 \times 10^9 L_{sun} \) => \( M_d(SP) = 1.8 \times 10^4 M_{sun} \)
- \( L_{MP}(FIR) = 3.1 \times 10^9 L_{sun} \) => \( M_d(MP) = 2.2 \times 10^4 M_{sun} \)

- All three methods to calculate dust masses result in similar values
- Dust masses consistent with masses derived from CO measurements with 4.2” resolution at mid-IR peaks
Summary

• FORCAST observation of M82 at: 6.4, 6.6, 7.7, 31.5, & 37.1 micron
• Two strong peaks located 4.5” west-southwest and 4” east-northeast of nucleus
• Emission in 6.4, 6.6, & 7.7 micron bands is probably dominated by different dust component than emission at 31.5, & 37.1 micron bands.
• Luminosity in peaks: $L(\text{tot}) \sim 5.7 - 6.7 \times 10^9 \, L_{\odot}$
• Color temperature: $68 \pm 10 \, K$
• Dust masses in peaks: $10^4 \, M_{\odot}$