Mid-IR FORCAST/SOFIA Observations of M82

Thomas Nikola
Cornell University

Collaborators:
Cornell University: T.L. Herter, J.D. Adams, G.E. Gull, C.P. Henderson, J. Schoenwald, G. Stacey
USRA: W.D. Vacca, J.M. De Buizer
Ithaca College: L.D. Keller
UCLA: M.R. Morris
Leiden Observatory: A. Tielens

Nikola et al. 2012, ApJ, 749L, 19

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_{sun}/yr
  - most recent starburst: <=50 Myr (e.g. Foerster Schreiber et al. 2003, ApJ, 599, 193)
- Total Molecular Mass: ~1-2 x 10^9 M_{sun} (in disk: ~2 x 10^8 M_{sun}) (Walter et al. 2002, ApJ, 580, L21)
- Global Dust Mass: ~5 x 10^6 M_{sun} (Roussel et al. 2010, A&A, 518, L66)

Observation (1): FORCAST

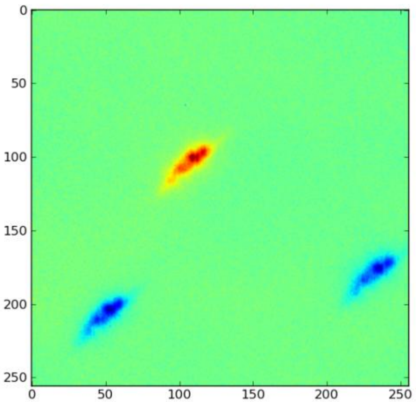
- Dual-channel mid-IR camera:
  - 5-25 micron
  - 25-40 micron
  - Simultaneous observation possible with dichroic
  - Various bandpass filters available at each channel
- Detectors: 256 x 256 pixels
- Field of view: 3.4’ x 3.2’
- Pixel size: 0.768”

Observation (2)

- Observations taken in two flights:
- 1st flight:
  - 31.5 micron, 37.1 micron
  - On-Chip Chop-nod observing mode (chop: 120”, nod: 90”)
- 2nd 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)

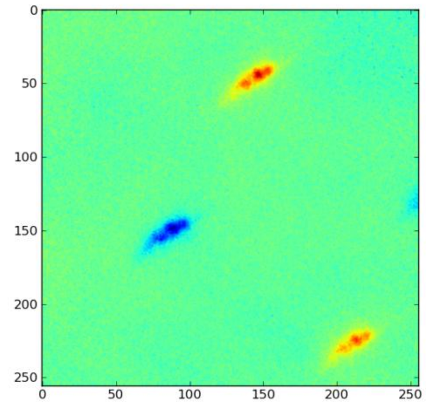
Observation (3)

37 μm

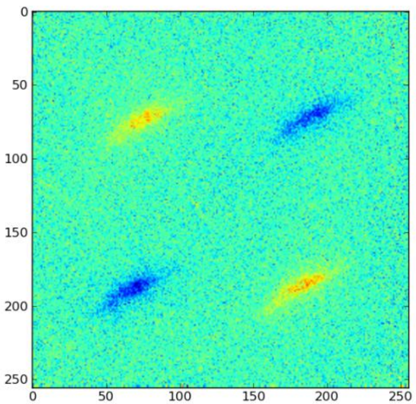


Single Integration

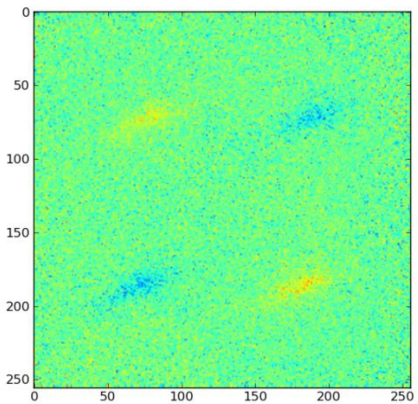
31 μm



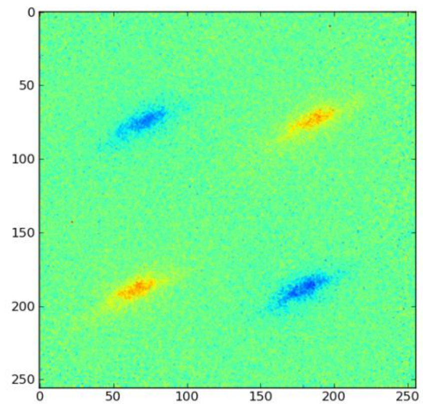
7.7 μm



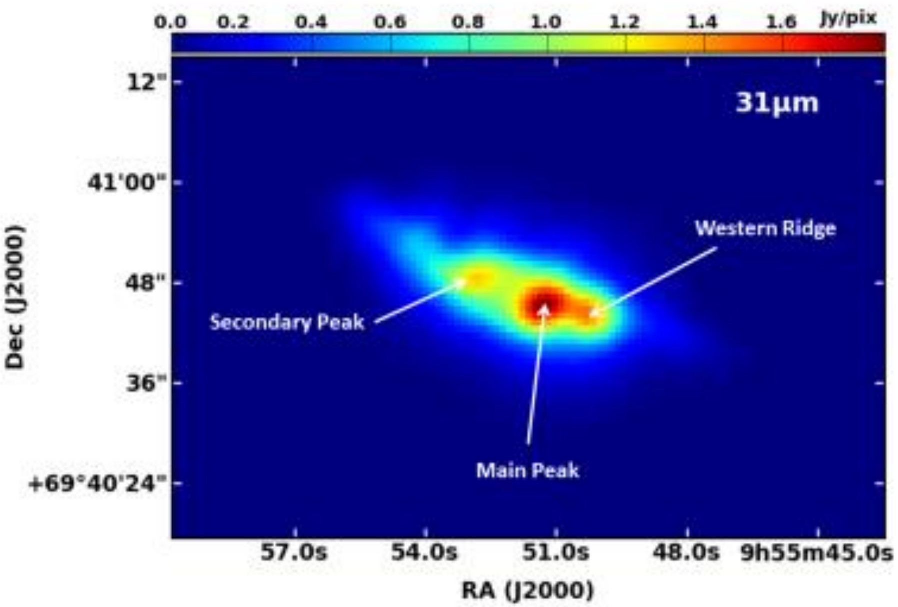
6.6 μm

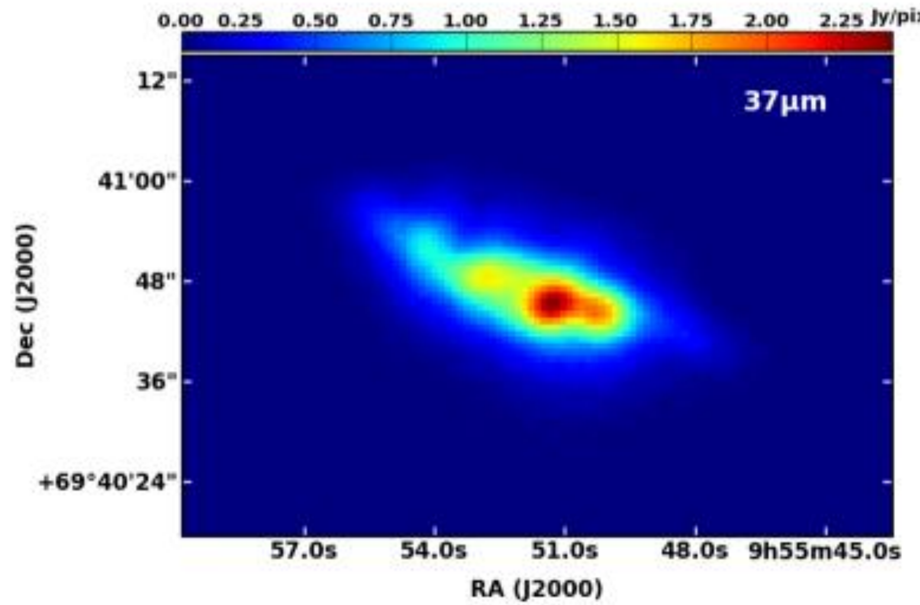


6.3 μm



Results (1): Maps



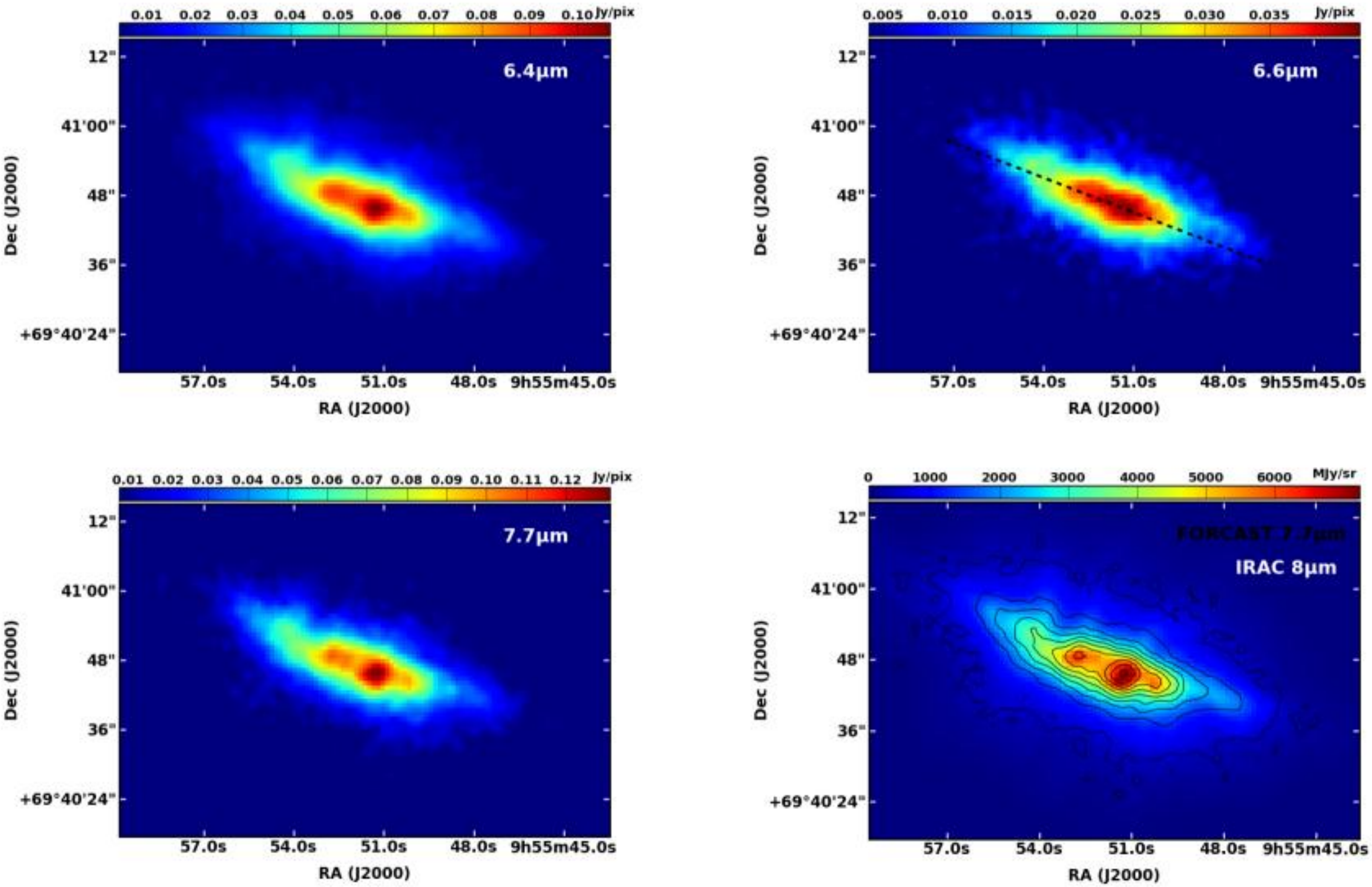


Maps of M82 in the FORCAST bands in units of Jy/pix at 31.5 micron, 37.1 micron. The color scale is linear and starts at the 3 sigma level of the statistical background noise (0.042 Jy at 31.5 micron, 0.051 Jy at 37.1 micron).

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

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

[a]Pixel size: $0.768''$.

[b]within 6×6 pixels, corresponding to a $4.6'' \times 4.6''$ region.

[c]Main peak: $09^h55^m51.28^s$, $+69°40'45.5''$

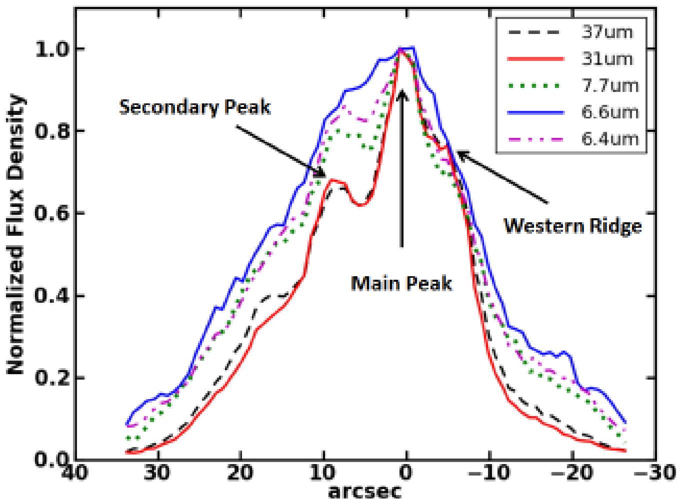
[d]Secondary peak: $09^h55^m52.68^s$, $+69°40'48.5''$

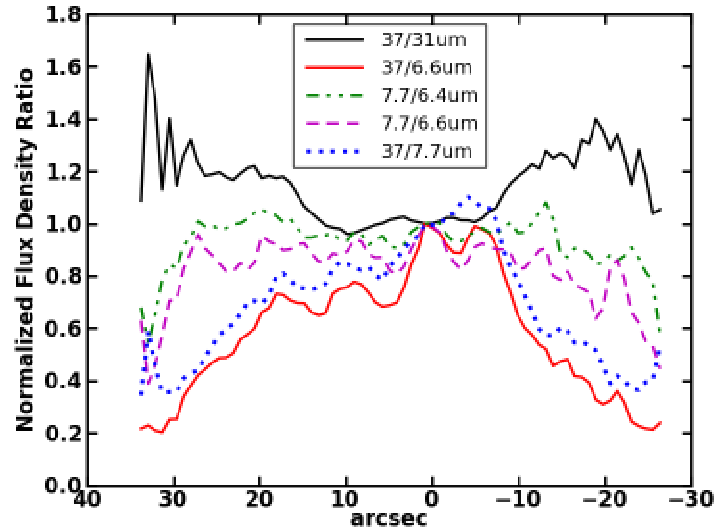
[e]Western Ridge: $09^h55^m50.47^s$, $+69°40'43.9''$

[f]within 9×9 pixels, corresponding to a $6.8'' \times 6.8''$ region.

[g]Within $50'' \times 75''$ (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.

M82: View

Achtermann & Lacy 1995, ApJ, 439, 136

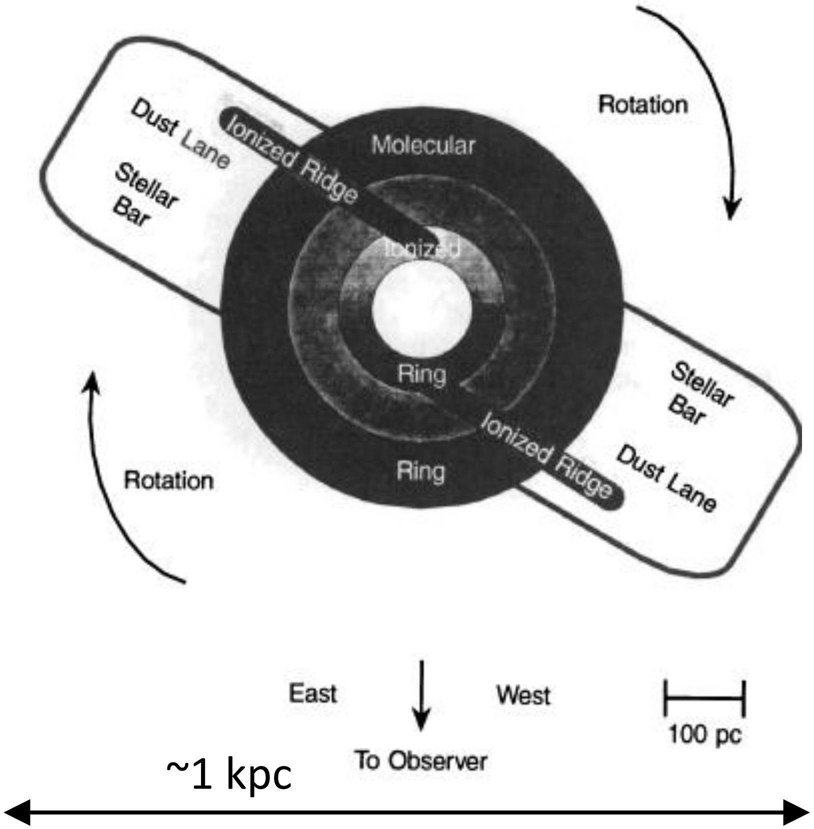


FIG. 16.—Schematic representation of M82 viewed face-on. Structures are roughly to scale. Dust lanes are those proposed by Larkin et al. (1994). Between the ionized ring and the molecular region lies a region occupied by both ionized and molecular material.

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)

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_{sun} (0.1 increments)
  - Size of nuclear starburst: 350 pc, 1 kpc, 3 kpc
  - Visual extinction: A_V ~ 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

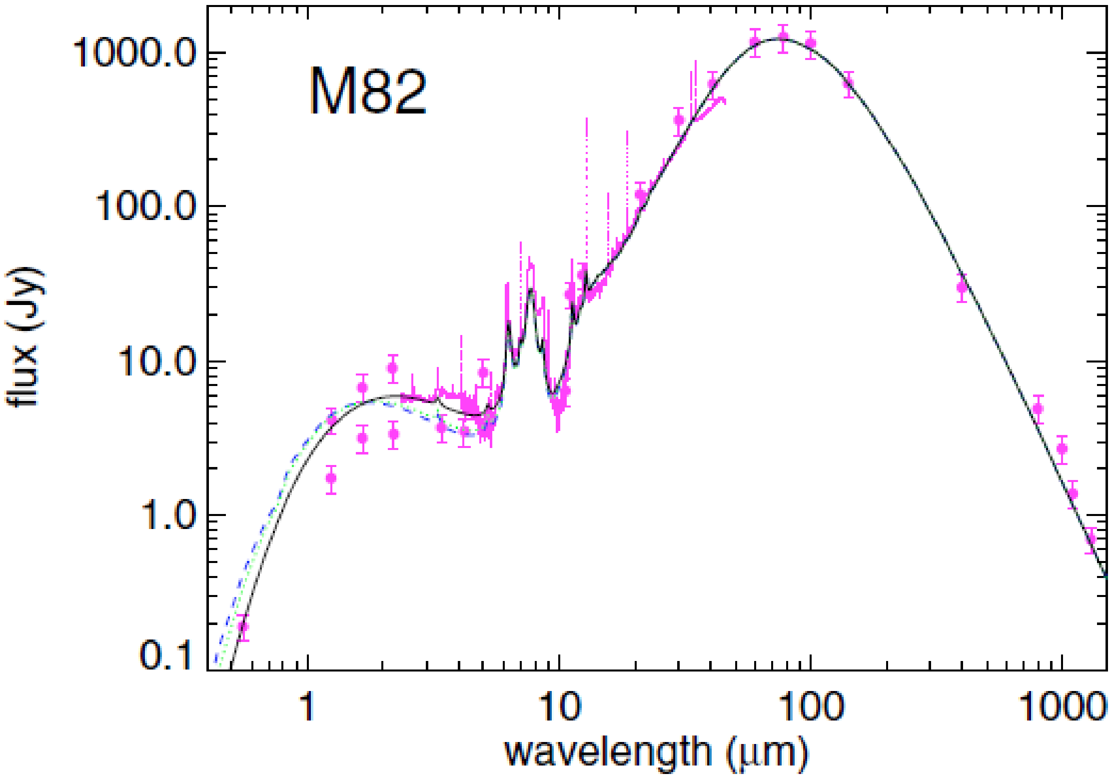
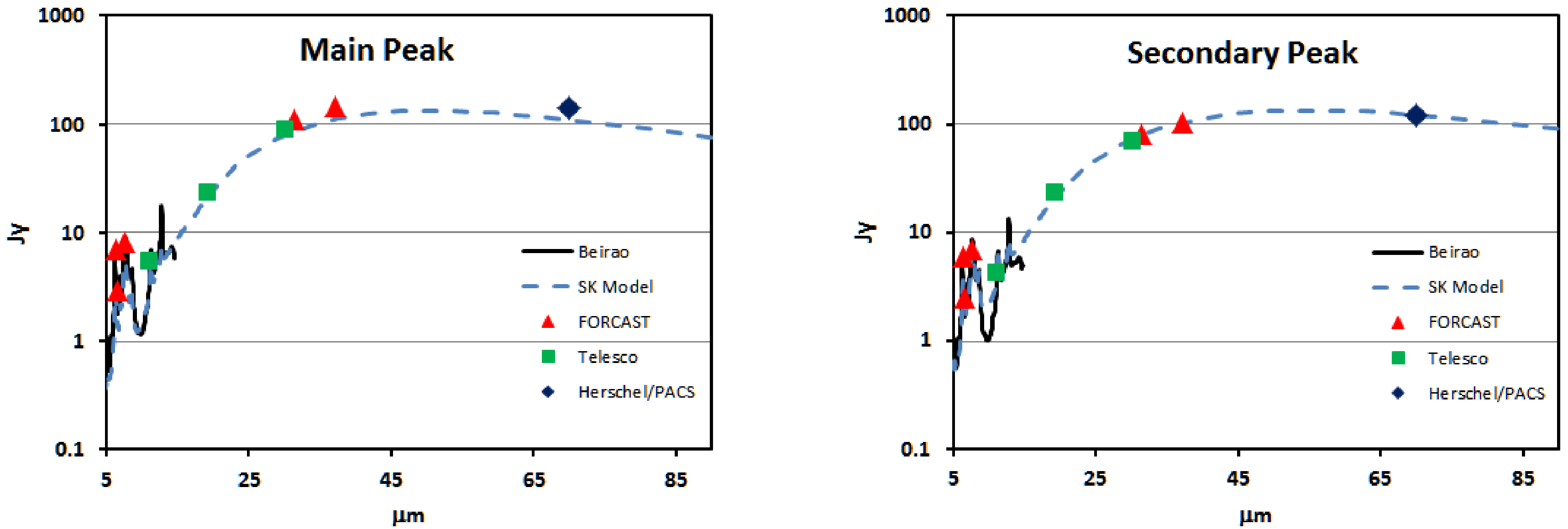


Fig. 2. SED of the central region of M 82, data points with 1σ error bar. Full line: library model with parameters in Table 1. To fit the data below 5 μm, we added to the SED library spectrum a blackbody, either unreddened (T = 2500 K, full line), or reddened (T = 8000 K, A_V = 4 mag, dashed, or T = 5000 K, A_V = 3 mag, dotted). *Top*: full wavelength range from 0.4 to 1500 μm, *bottom*: a zoom into the 12–34 μm region. Data references (1300 μm: Krügel et al. 1990; 1100 and 800 μm: Hughes et al. 1990; 400 μm: Jaffee et al. 1984; far IR: Telesco & Harper 1980; Rieke & Low 1972; Rieke et al. 1980; Telesco & Gezari 1992; IRAS; near infrared (NIR) photometry in 40″–100″ aperture: Kleinmann & Low 1970; Jarrett et al. 2003; Aaronson 1977; and Johnson 1966; between 2.3–40.4 μm ISOSWS spectrum: Sloan et al. 2003).

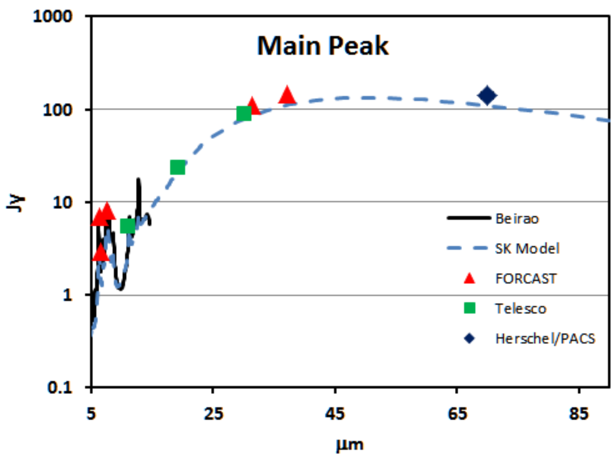
SED (3): At Main and Secondary Mid-IR Peak

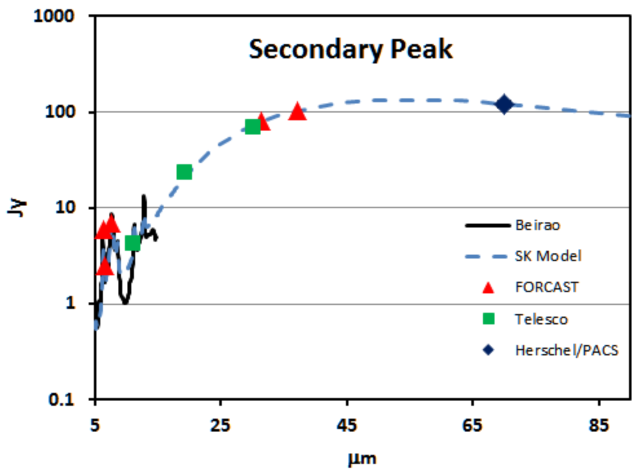


Mid-IR SED of the main peak (left) and secondary peak (right). The solid (black) line is the low-resolution Spitzer/IRS spectrum (Beirao et al. 2008), filled triangles (red) are the FORCAST observations, filled diamond (blue) is the Herschel/PACS 70 micron observation, filled squares (green) are IRTF 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(tot) ~ 6.7×10^9 L_{sun}
  - A_V ~ 18 mag
  - n(H) ~ 5×10^3 cm^{-3}
- Secondary Peak:
  - L(tot) ~ 5.7×10^9 L_{sun}
  - A_V ~ 9 mag
  - n(H) ~ 5×10^3 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: β=1.75
- τ(31micron) ~ 0.1 – 0.2
- τ(37micron) ~ 0.08 – 0.16
- T(color) ~ 68 ± 10 K

Dust Mass (1)

- $M_g = \mu \times m_H \times N(H) \times Area$
  - $\mu = 1.4$: mean atomic mass
  - m_H : mass of atomic hydrogen
  - $N(H)$: total hydrogen column density
  - $M_g/M_d = 105$
- $M_g(MP) = 3.8 \times 10^6\ M_{sun}$ => $M_d(MP) = 3.6 \times 10^4\ M_{sun}$
- $M_g(SP) = 1.9 \times 10^6\ M_{sun}$ => $M_d(SP) = 1.8 \times 10^4\ M_{sun}$

Dust Mass (2)

- $M_d = 1/\kappa_{abs} \times F_\nu(\lambda) \times D^2/B(\lambda,\mathrm{T})$
  - κ_{abs}: mass absorption coefficient
  - $F_\nu(\lambda)$: flux density
  - D: distance
  - $B(\lambda,\mathrm{T})$: Planck
- $M_d(MP) = 1.2 \times 10^4\ M_{sun}$
- $M_d(SP) = 8 \times 10^3\ M_{sun}$

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 x 10^9 L_{sun} => M_d(SP) = 1.8 x 10^4 M_{sun}
  - L_{MP}(FIR)= 3.1 x 10^9 L_{sun} => M_d(MP) = 2.2 x 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(tot) ~ 5.7 - 6.7 x 10^9 L_{sun}
- Color temperature: 68 ± 10 K
- Dust masses in peaks: 10^4 M_{sun}