Stellar calibrators for HERSCHEL SPIRE & PACS

Herschel Calibration Workshop: Models and Observations of Astronomical Calibration Sources
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Outline

• Strategies for FIR calibration by stars
  – Building on the MSX absolute calibration
  – Extrapolating K0-M0III spectra to the FIR
  – Uncertainties of model atmospheric spectra
  – Closure of ISO FIR calibration: LWS/PHOT
  – Testing bright K-giants with LWS & BIMA
  – Mm observations of cool giants: a new view
  – PACS/SPIRE calibration stars: suggestions
  – “Real” stellar models? too soon, too simple
Absolute calibration by MSX

• Response of the 6 MSX MIR bands precisely (<0.5% rms) tied to Cohen-Walker-Witteborn (CWW) fluxes for α CMa

• Absolute MSX calibration by the emissive reference spheres averaged over 6 bands is within 1.1% of CWW 0-magnitude flux scale, well within the 1.5% assigned uncertainties

• The MSX calibration experiments thus confirm the scale of zero-magnitude fluxes proposed by Cohen et al. (1992a)

• MSX validates use of spectral templates based on composite spectra of the secondary standards for the energy distributions of fainter stars of the same spectral type

• The zero-magnitude absolute fluxes proposed by Cohen et al. are validated if the flux from Sirius is increased by 1%
## Ratio of MSX Measured to CWW Predicted Irradiances

<table>
<thead>
<tr>
<th>µm</th>
<th>8.28</th>
<th>4.29</th>
<th>4.35</th>
<th>12.13</th>
<th>14.65</th>
<th>21.34</th>
</tr>
</thead>
<tbody>
<tr>
<td>Star</td>
<td>A</td>
<td>B1</td>
<td>B2</td>
<td>C</td>
<td>D</td>
<td>E</td>
</tr>
<tr>
<td>α CMa</td>
<td>1 def.</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>α Boo</td>
<td>1.0015</td>
<td>1.0057</td>
<td>.9907</td>
<td>.9908</td>
<td>.9907</td>
<td>.9838</td>
</tr>
<tr>
<td>α Tau</td>
<td>.9795</td>
<td>1.0294</td>
<td>1.0060</td>
<td>.9903</td>
<td>.9942</td>
<td>.9962</td>
</tr>
<tr>
<td>α Lyr</td>
<td>.9893</td>
<td>1.0164</td>
<td>.9954</td>
<td>1.0479</td>
<td>1.0378</td>
<td>1.172</td>
</tr>
<tr>
<td>β Gem</td>
<td>.9800</td>
<td>.9786</td>
<td>.9487</td>
<td>.9907</td>
<td>.9909</td>
<td>1.088</td>
</tr>
<tr>
<td>γ Cru</td>
<td>.9449</td>
<td>.9812</td>
<td>.9654</td>
<td>.9989</td>
<td>.9975</td>
<td>1.005</td>
</tr>
<tr>
<td>γ Dra</td>
<td>.9738</td>
<td>1.012</td>
<td>1.001</td>
<td>.9987</td>
<td>.9976</td>
<td>1.005</td>
</tr>
<tr>
<td>Ave.</td>
<td>.986</td>
<td>1.014</td>
<td>.990</td>
<td>.991</td>
<td>.988</td>
<td>1.023</td>
</tr>
<tr>
<td>sN^{-0.5}</td>
<td>±0.004</td>
<td>±0.009</td>
<td>±0.010</td>
<td>±0.0005</td>
<td>±0.003</td>
<td>±0.020</td>
</tr>
</tbody>
</table>

Average MSX/CWW is 0.991 ⇒ brighten α CMa by 1%
## Emissive Reference Spheres

### CWW absolute flux biases in 4 MSX bands

<table>
<thead>
<tr>
<th>BAND</th>
<th>BIAS %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band A</td>
<td>0.4±0.7</td>
</tr>
<tr>
<td>Band C</td>
<td>−0.4±0.4</td>
</tr>
<tr>
<td>Band D</td>
<td>−1.9±0.4</td>
</tr>
<tr>
<td>Band E</td>
<td>−2.5±0.6</td>
</tr>
<tr>
<td>&lt;MIR&gt;</td>
<td>−1.1±0.7</td>
</tr>
</tbody>
</table>
MSX absolute validation of a Tau

\[ \lambda^4 F_\lambda (W \ cm^{-2} \ \mu m^3) \]

- MSX measured $\pm 1\sigma$
- CWW $\propto$ Tau
- CWW $\pm 1\sigma$
Advantages to Herschel of the common absolute scheme

- Direct comparison with other missions: DIRBE, ISO, MSX, 2MASS, Spitzer, ASTRO-F, WISE
- 1.2–35µm absolute spectra of normal K0-M0IIIIs extrapolated to 300µm for ISOPHOT by NASA-Ames model SEDs (Duane Carbon), assuming all single-component atmospheres = pure photospheres
- Absolute accuracy of FIR stellar spectra made for ISOPHOT was estimated to be better than ±6%
- ISOPHOT products validated by Cray/Columbia stellar spectra; K/MIIIIs explored in 1-3 mm region
Criteria for Walker-Cohen Atlas

- All-sky, originally 1 source per 50 sq. degrees
- High quality IRAS F12 & F25, with F25>1 Jy
- Normal stars: F12/F25>=3.19; F25/F60>=4.28
- No variable, carbon, emission-line, nebulous, dusty stars, nor with IRAS VAR>90%
- Total flux of known sources within a 6´ radius contributes <5% to calibrator flux at 12/25 µm
- Limit cirrus contamination: CIRR3<6.3*F12
- Spectral types K0-M0III to minimize potential stellar variability in the MIR (92 DIRBE ‘BCC’ calibrators; have <2% ΔMIR with ΔV~1 mag)
Current bright calibrator network
(610 K0-M0IIIIs with 1.2–35μm absolute spectra)

Kurucz models
(a CMa)

Composites
bright giants
(a Tau)

Faint template
(HD) stars
Selection of FIR calibration stars

- Isolated predictable point sources, in clean sky
- Not extended objects (PNe, HII) due to spatio-spectral variations seen at Herschel resolution
- Bright enough for good SNR measurements
- Normal K/M-giants difficult to model but bright, well-observed & brightest are known not to vary in MIR > 2% from 1.2-25μm (DIRBE BCC): α Boo, α Cet, α Hya, α Tau, β And, β Peg, β UMi, γ Cru, γ Dra...
- Early-type stars problematic (O, B: winds; A: faint or debris disks; F, G: models + debris?)
- MIRAs: photospheric + dust modeling ⇒ spectral time variation very difficult to predict
- Well-characterized empirical spectra best
Testing model synthetic spectra of K/M giants in the FIR

Table 6. Ratios of IRAS flux densities synthesized by integration of the IRAS passbands over our observed composite spectra (12, 25 μm), extrapolated by model atmospheres (60, 100 μm), to those actually observed by IRAS.*

<table>
<thead>
<tr>
<th>IRAS data</th>
<th>12 μm</th>
<th>σ</th>
<th>25 μm</th>
<th>σ</th>
<th>60 μm</th>
<th>σ</th>
<th>100 μm</th>
<th>σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>FSS</td>
<td>0.961</td>
<td>0.012</td>
<td>0.946</td>
<td>0.013</td>
<td>0.997</td>
<td>0.015</td>
<td>1.038</td>
<td>0.040</td>
</tr>
<tr>
<td>PSC</td>
<td>0.961</td>
<td>0.010</td>
<td>0.943</td>
<td>0.010</td>
<td>0.985</td>
<td>0.029</td>
<td>1.015</td>
<td>0.026</td>
</tr>
</tbody>
</table>

Testing a Boo vs. ISOPHOT calibrators
K/MIII models: error sources >100\(\mu\)m


- Effective temperature: \(\pm 100\)K
- Gravity: \(\pm 0.5\) dex
- Metallicity: \(\pm 0.2\) dex
- Total from fundamental parameters: 4%
- Total from temperature structure: 1.5%
- H-minus opacity & CS dust: 2%
- RSS all these errors: 4.8%
- In 1996 we added 3% for errors of including the many molecules & their isotopes: total \(\pm 6\)%
Comparing model synthetic spectra

For Following Alpha Tau Models: RLK - , RLK High Si o, GBEN +, BJACS * , Solar ---

- Scaled solar model Solar
- Kurucz enhanced Si abundance RLK
- Kurucz normal III Si abundance RLK

Cool giant models based on scaling a solar model’s $T(\tau)$ by $T^*/T_{sun}$ (BJACS)

For Following RGB Models: 4500 - , 4000 +, 3500 o, 3000 *

Five different models for one star ($\alpha$ Tau) $\Rightarrow$ 4% spread in spectra at 200$\mu$m when normalized at 35$\mu$m

A single model grid for effective temperatures 3000 to 4500K $\Rightarrow$ only 2% spread in spectra at 200$\mu$m when normalized at 35$\mu$m
Cautions about stellar models (D. Carbon)

- Just because models agree does not mean any are correct
- Issues of opacities used and the routines that implement them, numerical accuracy, and precision of calculations arise
- Disagreements between modelists arise due to different treatments of line lists, convection, and line blanketing
- If everybody was allowed to vary their parameters probably all models could be made to agree, but would not reflect EXACTLY the same calculations for the same star
- Which is correct? Probably no-one using an LTE, static model, with homogeneous layers is correct
- Computational facilities are finally available to do the problem roughly correctly; it will be some years before this approach is standard (NASA’s 10,240-processor Columbia, 20 SGI® Altix™ 3700 superclusters each of 512 Intel Itanium2s)
Bright K/MIIIls: physics & tests

- Wiedemann (1994): temperature bifurcation; material at common altitude has 2 temperatures: chromosphere & radiative equilibrium mediated by molecules (CO)
- Contributions from the two regions to overall stellar radiation varies greatly between stars of same type
- Bright IIIIs used as calibrators are the “quiet” stars: radiatively-cooled regions dominate surfaces so single component models valid (a Boo, a Hya, a Tau, ? Dra)
- Map a Tau & a Boo in 1-/3-mm continuum: sample temperature minimum; probe outer atmospheres
- Do these stars radiate as expected ⇒ stellar FIR calibration is viable, or have long-? chromospheres?
- Connect mm & FIR absolute flux calibrations
Using LWS on faint objects

- OLP10 used the “fixed dark currents” that are essentially measurements of dark backgrounds
- Dark current signals were constant through mission
- High cirrus: need an “off” spectrum to remove sky
- COBE-predicted sky flux in dark regions is large % of the LWS dark signal but is deemed undetected as no signal is seen over the signal from the blank
- Corrections for off-source emission in LWS are not appropriate for faint normal stars in low-cirrus sky * to subtract off-source sky ⇒ subtract dark twice!
- If measured sky backgrounds near the KIIIs at time observed < fixed darks then no “off” spectra needed
## Sky measured near α Tau & α Boo

<table>
<thead>
<tr>
<th>Star</th>
<th>ISOPHOT</th>
<th>LWS</th>
<th>Dark</th>
<th>Sky</th>
<th>Zodi</th>
</tr>
</thead>
<tbody>
<tr>
<td>α Tau</td>
<td>C1-60</td>
<td>SW2</td>
<td>4.2E-18</td>
<td>4.5E-19</td>
<td>3.8E-19</td>
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<tr>
<td>α Tau</td>
<td>C1-100</td>
<td>LW1</td>
<td>8.0E-19</td>
<td>1.3E-19</td>
<td>1.1E-19</td>
</tr>
<tr>
<td>α Tau</td>
<td>C2-160</td>
<td>LW4</td>
<td>9.1E-20</td>
<td>4.5E-20</td>
<td>5.9E-20</td>
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<tr>
<td>α Boo</td>
<td>C1-50</td>
<td>SW2</td>
<td>4.2E-18</td>
<td>2.0E-19</td>
<td>&gt;1.3E-19</td>
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<tr>
<td>α Boo</td>
<td>C1-90</td>
<td>SW5</td>
<td>3.2E-18</td>
<td>8.7E-20</td>
<td>---</td>
</tr>
<tr>
<td>α Boo</td>
<td>C1-105</td>
<td>LW1</td>
<td>8.0E-19</td>
<td>5.2E-20</td>
<td>2.4E-20</td>
</tr>
<tr>
<td>α Boo</td>
<td>C2-120</td>
<td>LW2</td>
<td>7.7E-21</td>
<td>3.2E-20</td>
<td>---</td>
</tr>
<tr>
<td>α Boo</td>
<td>C2-135</td>
<td>LW3</td>
<td>2.0E-20</td>
<td>1.7E-20</td>
<td>---</td>
</tr>
<tr>
<td>α Boo</td>
<td>C2-160</td>
<td>LW4</td>
<td>9.1E-20</td>
<td>1.5E-20</td>
<td>1.8E-20</td>
</tr>
<tr>
<td>α Boo</td>
<td>C2-200</td>
<td>LW5</td>
<td>4.4E-19</td>
<td>8.6E-21</td>
<td>---</td>
</tr>
</tbody>
</table>

BIMA mm-continuum imaging of stars

BIMA mm-continuum imaging of stars

IRAS
LWS
model
mm

IRAS
LWS
model
mm

Log $F_{\lambda}(W/cm^2 \mu m^{-1})$

Log $\lambda(\mu m)$

Log $F_{\lambda}(W/cm^2 \mu m^{-1})$

Log $\lambda(\mu m)$

Log $F_{\lambda}(W/cm^2 \mu m^{-1})$

Log $\lambda(\mu m)$

Log $F_{\lambda}(W/cm^2 \mu m^{-1})$

Log $\lambda(\mu m)$

Log $F_{\lambda}(W/cm^2 \mu m^{-1})$

Log $\lambda(\mu m)$

BIMA mm-continuum imaging of stars

a Tau radiates like a photosphere to 170 $\mu$m

a Boo: 3mm  a Boo: 1mm

a Tau: 3mm  a Tau: 1mm

a Tau: 3mm  a Tau: 1mm

a Tau: 3mm  a Tau: 1mm

a Tau: 3mm  a Tau: 1mm
LWS, 2004 model, 1996 PHOT delivery

MARCS/models/3920g1.50z0.00t2.0 structure by B. Plez. Synthetic spectrum: Cray/D. Carbon

Binned detectors

H-band leaks

α Tau ±3σ
What NLTE chromospheres do: α Tau’s mm-flux densities (A.D. McMurry, Oslo)

Brightness temp. plot

Note excellent accord between the two different LTE radiative model calculations
BIMA mm-continuum imaging of stars

\[ \text{Log} \, F_{\lambda}(W \, \text{cm}^{-2} \, \mu\text{m}^{-1}) \]

\[ \text{Log} \, \lambda(\mu\text{m}) \]

\( \alpha \, \text{Boo} \) radiates like a photosphere to 125 \( \mu\text{m} \)
LWS, 2004 model, 1996 PHOT delivery

H-band leaks Binned detectors

Synthetic spectrum: Cray/D. Carbon

$\alpha$ Boo $\pm 2\sigma$
More BIMA mm-images obtained

- β Peg M2.5II-III at 1.4 & 2.7 mm
- β And M0III at 1.4 & 2.7 mm
- α Cet M1.5III at 2.7 mm
- γ Dra K5III at 2.7 mm
- α Hya K3II at 2.7 mm
- μ UMa M0III at 2.7 mm

Try to tie planets to stars: Mars, Venus, Jupiter, Uranus, Neptune, MWC349A
BIMA - SCUBA - CARMA - ALMA

• Sub-mm data are essential on potential calibrators!
• CARMA = 6x10m OVRO + 9x6m BIMA dishes
  5-6x more sensitive than BIMA at 3mm (>6 at 1mm)
• CARMA will enable many more normal K/MIIIIs to be observed at mm wavelengths
• Remove dependence on Mars, link planets to, & replace by, fiducial stars in mm region
• Upgrade heterogeneous calibrators in the sub-mm
• Lead the way for stellar calibration with ALMA
• Stars that fail as calibrators are “science”
• Jack Welch & Jim Gibson: new calibrations at 1cm & 3mm to ±1% ⇒ unified calibration 1µm-1cm
\( \tau_{1.2 \mu m} \) for \( \tau_\lambda = 1 \) in \( \alpha \) Tau: 1-1000\( \mu m \)

3D convection dominant

Predictions with LTE, static, homogeneous models best if line is formed at \( \tau < 1e^{-4}(1e^{-3}) \)

Temperature minimum 2700K

LTE static models are no use in here
Approximate flux densities for the 614 K/M-giant network, for PACS/SPIRE

- Start with Carbon SEDs to 300\(\mu\)m for ISOPHOT
- Extended all 1.2-35\(\mu\)m templates as composites
- These can support PACS broadbands (& spectra)
- Selected monochromatic \(F_\nu\) at 70, 110, 170\(\mu\)m
- Extended 300\(\mu\)m-3mm using new Carbon spectra (average of \(\alpha\) Tau and \(\alpha\) Boo models) as approx’n.
- These can support SPIRE broadband (& spectra)
- Selected monochromatic \(F_\nu\) at 250, 360, 520\(\mu\)m
- Must replace by integrals over broadband RSRs when the accurate complete RSRs are measured
Utility of 614 K/MIIIs for PACS, SPIRE

<table>
<thead>
<tr>
<th>BAND</th>
<th>Max.</th>
<th>Min.</th>
<th>Limit</th>
<th>No.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Jy</td>
<td>mJy</td>
<td>mJy</td>
<td></td>
</tr>
<tr>
<td>70 µm</td>
<td>19</td>
<td>4.2</td>
<td>100</td>
<td>585</td>
</tr>
<tr>
<td>110 µm</td>
<td>7.5</td>
<td>1.7</td>
<td>100</td>
<td>241</td>
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<tr>
<td>170 µm</td>
<td>3.1</td>
<td>0.7</td>
<td>100</td>
<td>114</td>
</tr>
<tr>
<td>250 µm</td>
<td>1.4</td>
<td>0.32</td>
<td>100</td>
<td>50</td>
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<td>360 µm</td>
<td>0.67</td>
<td>0.15</td>
<td>100</td>
<td>19</td>
</tr>
<tr>
<td>520 µm</td>
<td>0.31</td>
<td>0.07</td>
<td>100</td>
<td>5</td>
</tr>
</tbody>
</table>

Also 400 mostly faint Spitzer KIIIs & AVs