Absolute Calibration for Infrared Photometry

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based on a paper about to be accepted by the Astronomical Journal
(meaning a very positive referee report has been received)

Infrared Calibration Goals

I will address 1 - 30μm range; extension to Herschel range should be straightforward and accurate

- **Absolute accuracy of 2% or better**
- **Confirmed by independent measurements**
- **Traced to well behaved stars that do not have individual spectral idiosyncracies**
  - **When you've seen one, you've seen 'em all!**
  - **No (or weak) molecular features**
  - **Can then apply easily without modeling individual stars**
- **Sun included in a systematic way**
- **Tied in with all-sky databases**
  - **Hipparcos**
  - **2MASS**
  - **Spitzer**
  - **HST/NICMOS**

Are we there yet?

the results [from MSX] are "in substantial disagreement with previous direct calibrations," - S. Price 2004, Space Science Reviews, 113, 409

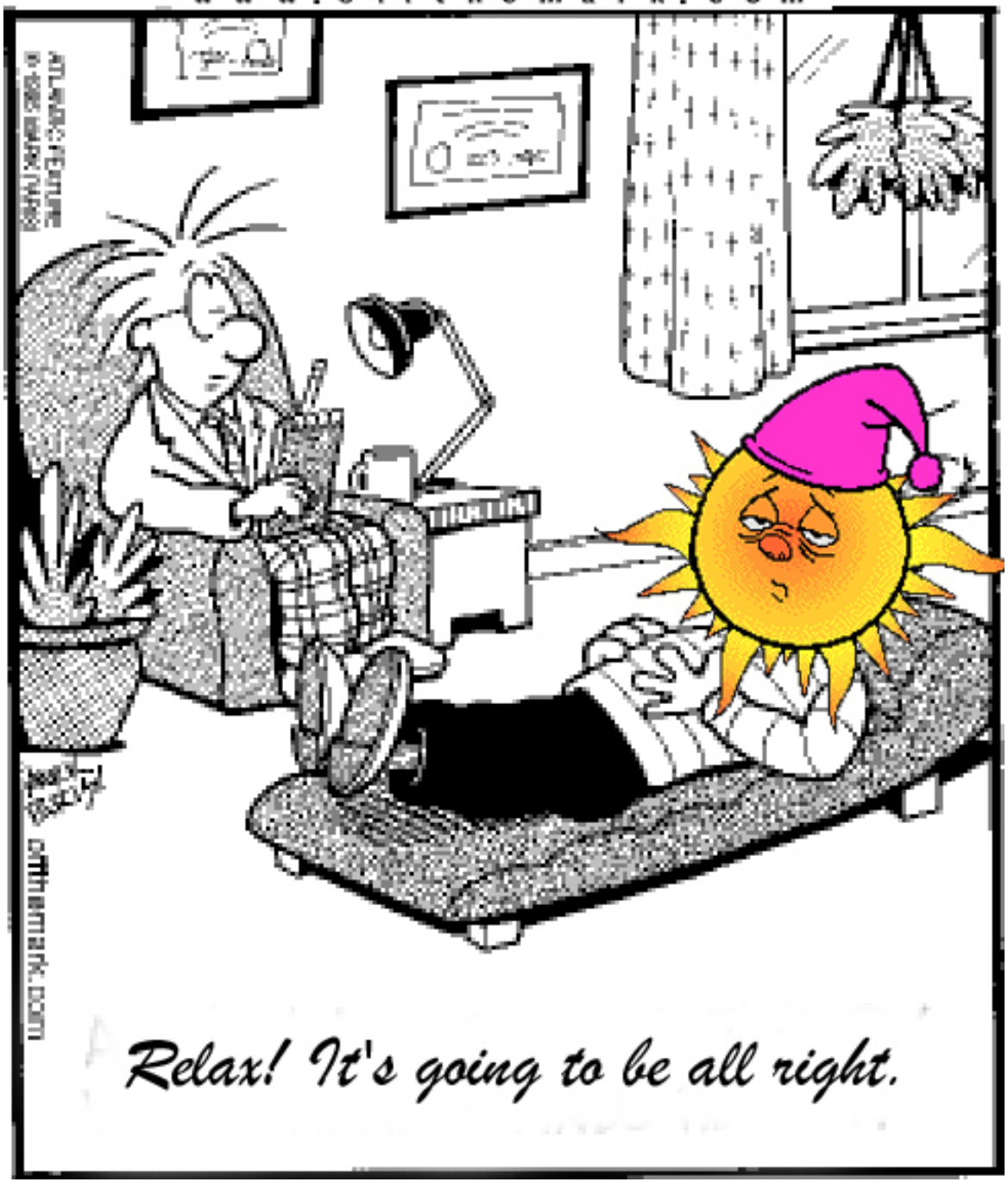
“Colina, Bohlin, and Castelli (1996) question the quality of the .. near-infrared solar spectrum, finding it too blue by 0.07 - 0.10 magnitudes…..Recent recalibrations of the absolute solar irradiance from satellite by Thuillier et al. (1998, 2003) exacerbate the discrepancy by increasing the absolute near infrared solar flux by several percent.” - S. Price 2004, Space Science Reviews, 113, 409

“To summarize, the solar analog method may suffice to form crude standards at the ~ 10% level; but G type stars with matching visible spectra can differ by a few percent.. In the IR, intrinsic differences in the magnetic regions apparently limit the accuracy of the technique to ~ 5%.” - R. Bohlin 2006, The Future of Photometric, Spectrophotometric, and Polarimetric Standardization, ed. C. Sterken, ASP

“The H and K_S bands[for the sun] show .. systematic differences of the order of 0.08 and 0.05 mag, respectively. Such large differences are not easily understood in terms of model failures.” – Casagrande et al. 2006, MNRAS, 373, 13

off the mark by Mark Parisi

www.offthemark.com



Actually, the agreement in calibrations at 10μm is excellent.

Reference	"Vega" Jy	error Jy
Rieke et al. (1985)	35.3	1.1
MSX weighted average	35.04	0.24
Weighted average	35.05	0.23
Hammersley et al. (1998)	35.2	--

Absolute measurements of Vega at 2μm also are in agreement.

There was a tendency to dis-believe these results because they conflicted with high quality visible measurements and theoretical spectral energy distributions

Reference	"Vega" Jy	error Jy
Walker et al. (1969)	638	64
Blackwell et al. (1983)	666	20
Selby et al. (1983)	623	25
Booth et al. (1989)	667	27
Weighted average	653	13
Corrected for disk emission	645	15
Extrapolated from 10.6μm	649	10

The 2μm and 10μm calibrations agree very well

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Comparing infrared and visible measurements, it is now clear that Vega is ~ 0.04 magnitudes red compared with typical A0V stars
This arises because Vega is a pole-on rapid rotator with a 1500K temperature differential between its poles and equator.

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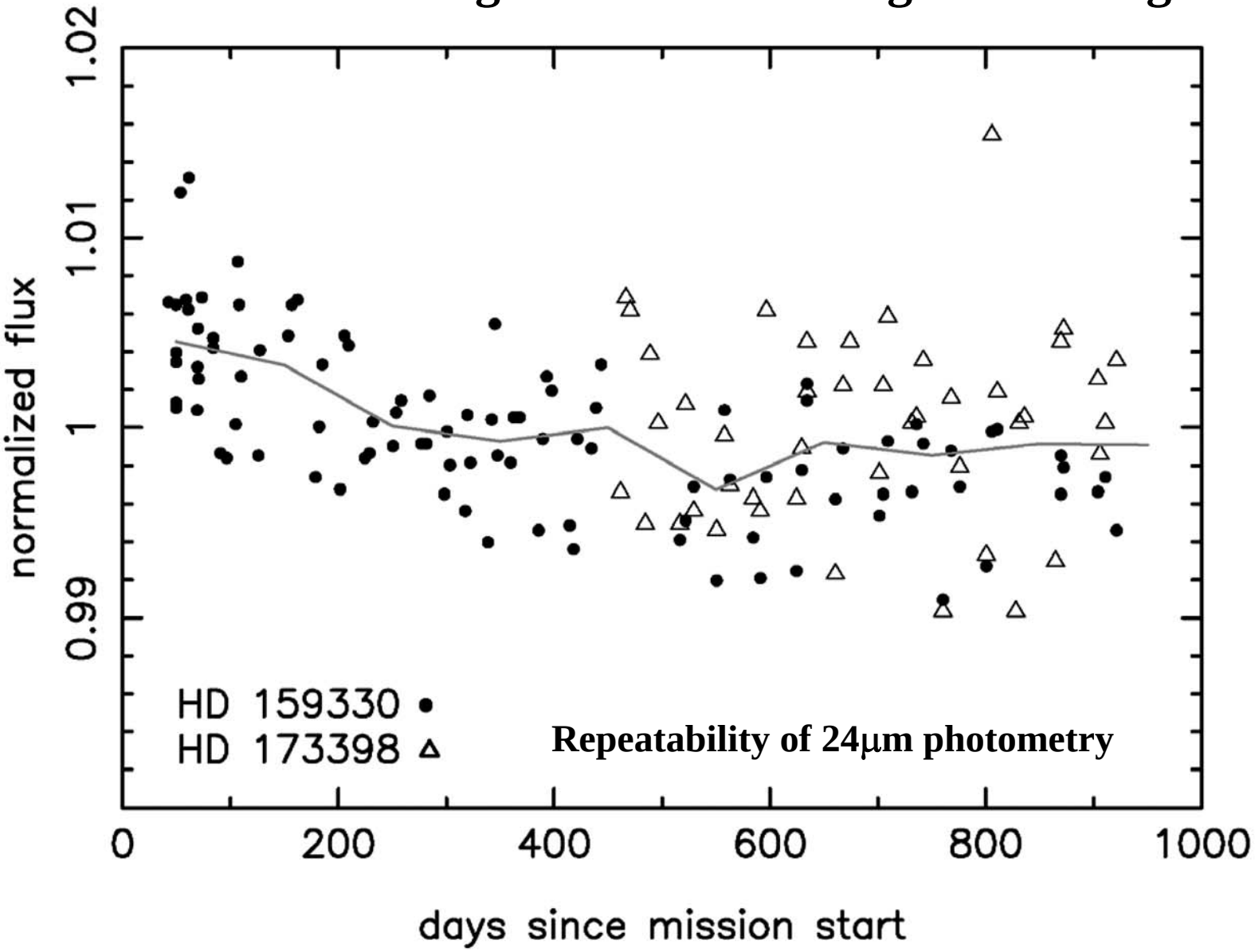
In the near infrared, solar colors (Thuillier) agree well with those of solar analog stars from 2MASS

This was not apparent previously because of
1.) small systematic offsets in 2MASS measurements (2% level)
2.) errors in stellar spectral types
3.) failure to take careful account of temperature differences

Band	Solar colors	Solar Analog colors	HM74 model	Fontenla et al. model
V_J	0.00	0.00		0.00
J	-1.158 ± 0.02	-1.158 ± 0.015		-1.20
H	-1.513 ± 0.02	-1.484 ± 0.020		-1.55
K_S	-1.568 ± 0.02	-1.545 ± 0.015	-1.550	-1.57
[8]	-1.596 ± 0.02	-1.591 ± 0.015	-1.596*	-1.615
[24]	-1.54 ± 0.05	-1.590 ± 0.020	-1.577	-1.564

Colors are averages for 30-50 solar type stars relative to 30-50 A stars

Spitzer provides very accurate photometry and allows extension of solar analog calibration to longer wavelengths.



Solar analog calibration in fine agreement at 10μm.

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Solar analog	34.53	1.1
All measurements, average	35.03	0.23
Average, Rieke, solar analog	34.92	0.8
Hammersley et al. (1998)	35.2	--

Independent calibrations agree to within 2% peak-to-peak!

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Solar colors from 0.55 through 24μm are in good agreement with solar analogs

Band	Solar colors	Solar Analog colors	HM74* model	Fontenla et al. model
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* From L. Decin

** Normalized color

Relatively low accuracy (note error)

And also in agreement with solar models

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*** From L. Decin**

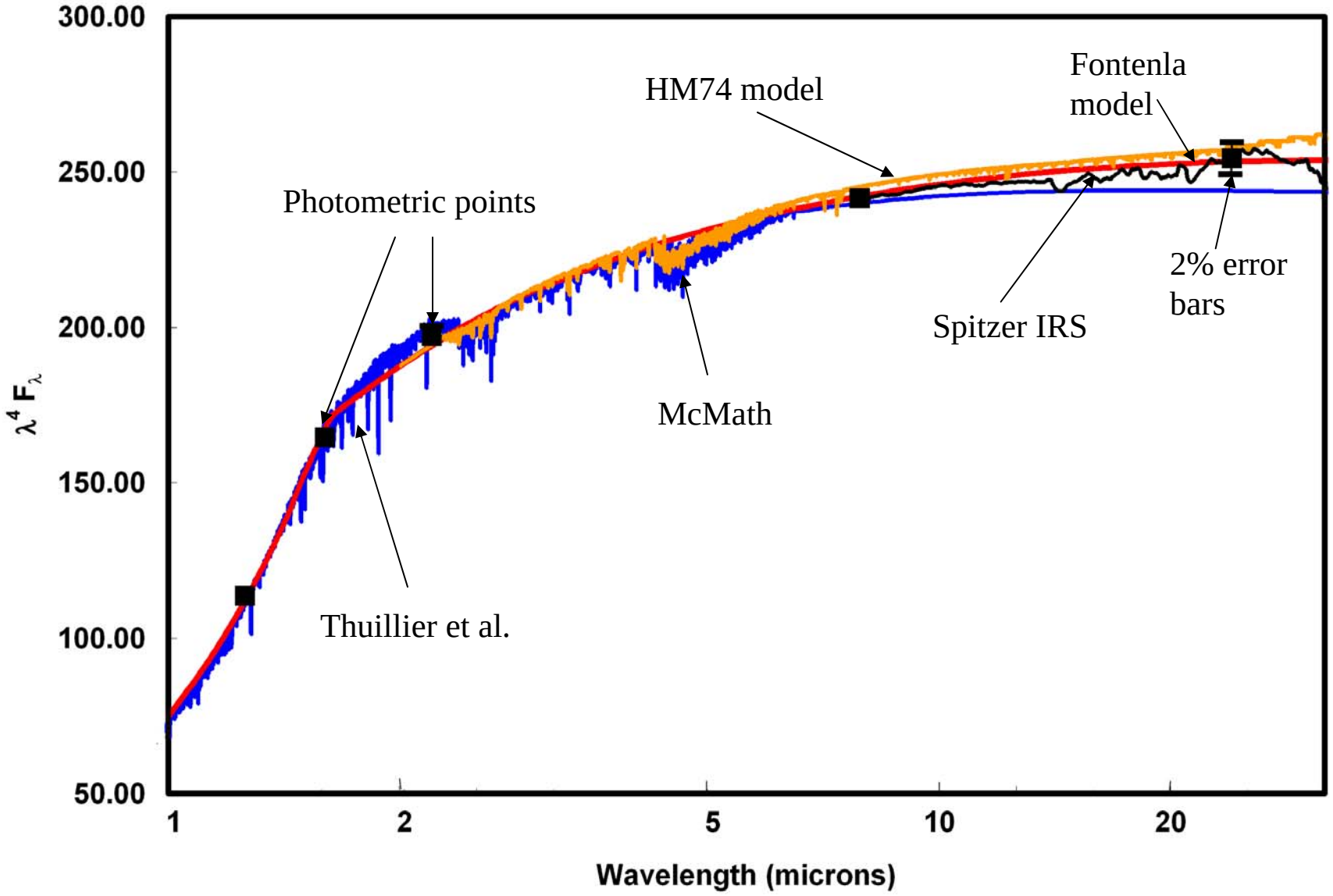
**** Normalized color**

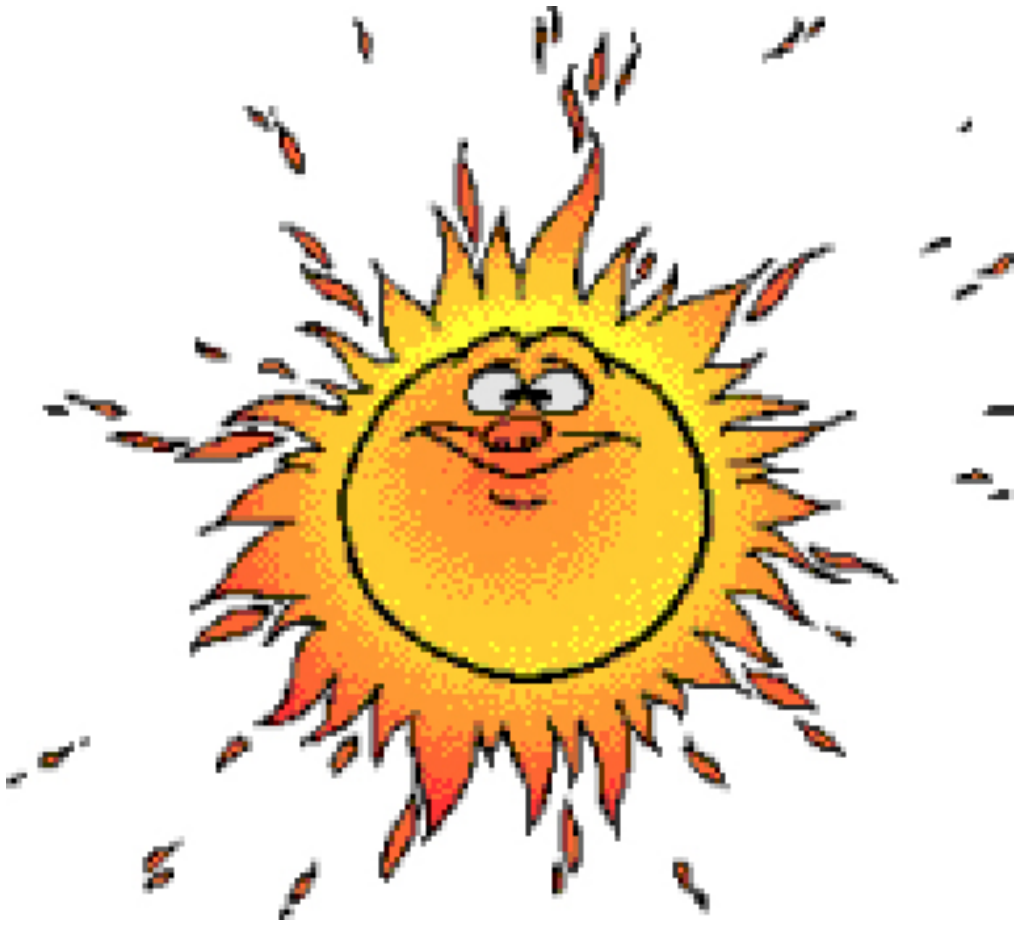
 # Relatively low accuracy (note error)

Similarity of Stellar Colors

- **Have learned to extrapolate photospheric SEDs to 24μm to within 2.5-3% rms**
- **Allows rejection of stars with excesses down to 6% level**
- **Error analysis then shows rms fluctuations in K - [8] and K - [24] colors are below detection level, i. e., within 1 - 2% rms.**
  - **Applies to both A and G stars**
- **At this level, near infrared data may be the limit**
  - **For example, there are 1 - 2% offsets in 2MASS between read 1 and read 2**
  - **Also ~ 2% residual colors for A0 stars in J-H and H-K**
- **Derived V - J,H,K of the sun deviate significantly from traditional values**
  - **Residual problems in the literature from red color of Vega**
  - **Offsets in 2MASS colors**
  - **Issues in correcting to the solar temperature (there is a persistent offset of 50K or more between the effective temperature of the sun and that of typical G2V stars)**

We can construct an accurate, absolutely calibrated solar spectrum





See, it was all fine in the end!

Summary: Infrared Calibration

- **Absolute accuracy of 2% or better**
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- **Tied in with all-sky databases**
  - **– Hipparcos**
  - **– 2MASS**
  - **– Spitzer**
- **Remaining steps to tie in with NICMOS, prepare for JWST/NIRCam and MIRI**

Additional Calibration Measurements with Spitzer

- MIRI full-frame saturation limit is ~ 9th magnitude at 10 microns
- Imager calibration will need some boot strapping from internal MIRI measurements
- Accurate cross-calibration is the primary goal
- P330E (K = 11.42) is ideal for this goal (16 31 33.6 30 08 48)
  - G2V with behavior extremely similar to that of the sun
  - SED is therefore well determined using solar plus G stars
  - Primary NICMOS calibrator, implies extremely well measured in the near infrared (both ground and HST)
  - Measurements with IRAC will cross calibrate both NIRCam and MIRI with Spitzer and NICMOS
  - Measured to ~ 5% with MIPS (200 microJy)
- Need additional stars to cross calibrate with MIRI 5.6 to 24 micron
  - Using 1/4 array subarray readout can have 0.75 sec integration
  - Then need stars fainter than 8.3 (for MIRI saturation at 5.6 microns) and brighter than 9 (for MIPS sensitivity at 24 microns)

Additional Observations

- **Cross calibration at 24 microns is being achieved by observing brighter stars from Persson et al.'s list (1998, AJ, 116, 2475)**
  - **prime: cskd-18, J-K = 0.37, K=8.99 (12 31 59.2 - 63 41 42)**
  - **secondary: cskd-21, J-K = 0.73, K=9.65 (12 32 10.9 - 63 43 16)**
  - **for comparison, J-K for P330E is 0.39**
- **We are also observing some A stars (+ a few solar) from other array calibrator lists**
  - **UKIRT: Hawarden et al. 2001, MNRAS, 325, 563**
    - **FS 108, J-K = 0.34, K = 9.73 (1mJy at 24um)**
  - **Kidger & Martin-Luis 2003, AJ, 125, 3311**
    - **SAO 038705, F6V, K = 8.66 (2.4mJy at 24um)**
    - **HD 92764, A7V, K = 8.47 (2.9mJy)**
    - **HD 116405, A0V, K = 8.47 (2.9mJy)**
    - **HD 175617, G5, K = 8.41 (3.2mJy)**
  - **Hunt et al. 1998, AJ, 115, 2594**
    - **SAO 054271, K = 8.77, J-K = 0 (2.2mJy)**
    - **SAO 038218, K = 8.67, J-K=0.04 (2.4mJy)**
    - **SAO 058110, K = 9.18, J-K = 0.03 (1.5mJy)**
    - **SAO 013747, K = 8.59, J-K = 0.10 (2.6mJy)**
    - **SAO 062058, K = 9.03, J-K = 0.03 (1.8mJy)**
    - **SAO 119183, K = 8.83, J-K = 0.06 (2.2mJy)**
    - **SAO 015832, K = 9.34, J-K = 0.06 (1.4mJy)**

Conclusion

- **There is now a very accurate calibration from 1 to 30μm**
- **It is confirmed by multiple independent measurements**
- **It is also confirmed by comparing A-type and solar-type stars**

- **Steps are under way to link it firmly to**
  - **Spitzer**
  - **NICMOS**
  - **2MASS**
  - **Other NIR ground calibrator systems**
  - **It will be the foundation for NIRCam and MIRI on JWST**

- **We should be sure Herschel is on a consistent scale**
  - **Extrapolation to 70μm should have small errors**