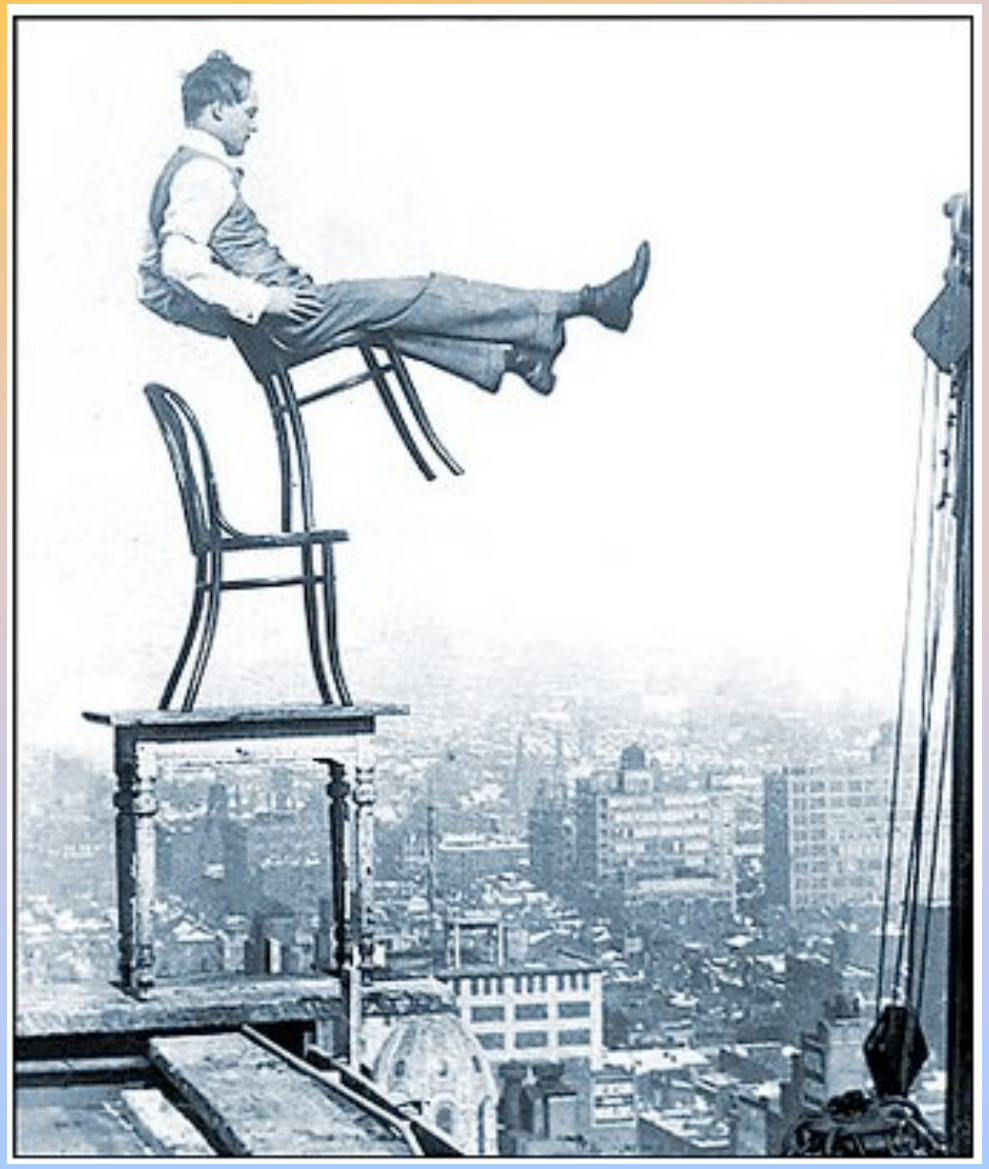
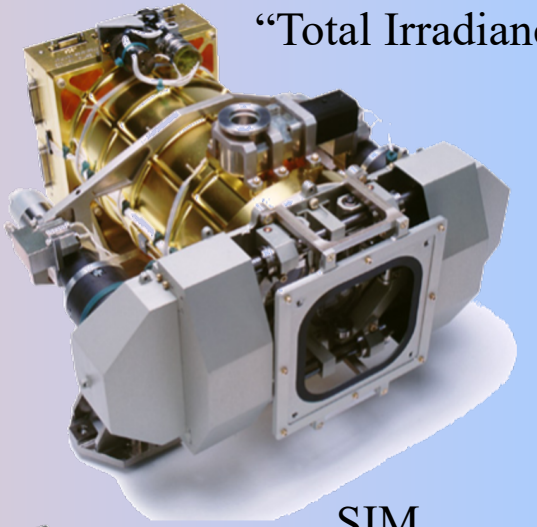
# *Celebrating* **SORCE**

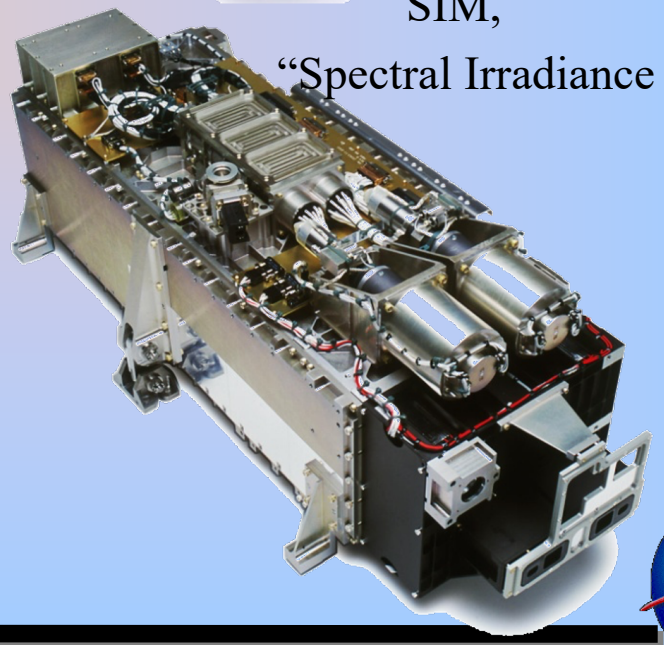
Robert Cahalan
NASA/Goddard, Emeritus



TIM,
"Total Irradiance Monitor"



SIM,
"Spectral Irradiance Monitor"

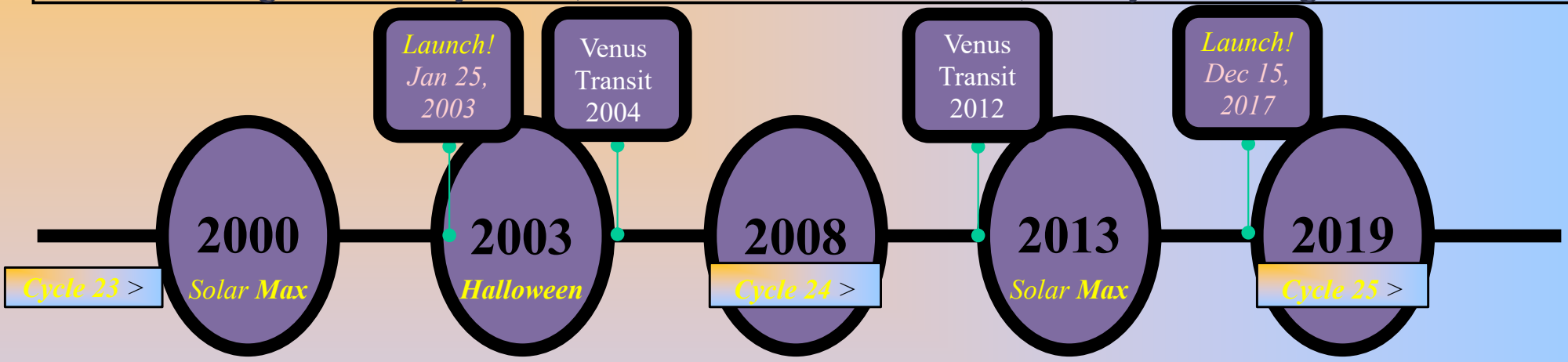


Jammie Reynolds, "The Human Fly,"on a DC furniture store, 1917

# SORCE *Timeline*

Recollections and …

… personal reflections as NASA SORCE Project Scientist, 1999 — 2015: the build, launch, Halloween X-rays, a "Great Minimum" during USA's "Great Recession," evolving from "Outlier" to "Gold Standard," dual Venus transits, our "Gap Year," dual Sol maxima, to a fitful winding down of cycle 24, as TSIS-1 takes the baton, and cycle 25 begins.




**Rattling Delta Wing**

Everyone is important!

**Launch Year**

Doug teaches Bob about Sol's seismology

"It's time we stop, hey, what's that sound Everybody look what's going down" (Buffalo Springfield)

**Grand Minimum**

Are successive solar min rising, falling, or equal?

**"Gap Year" -> July to Christmas 2013**

A chance to re-focus.

"Hybrid mode"

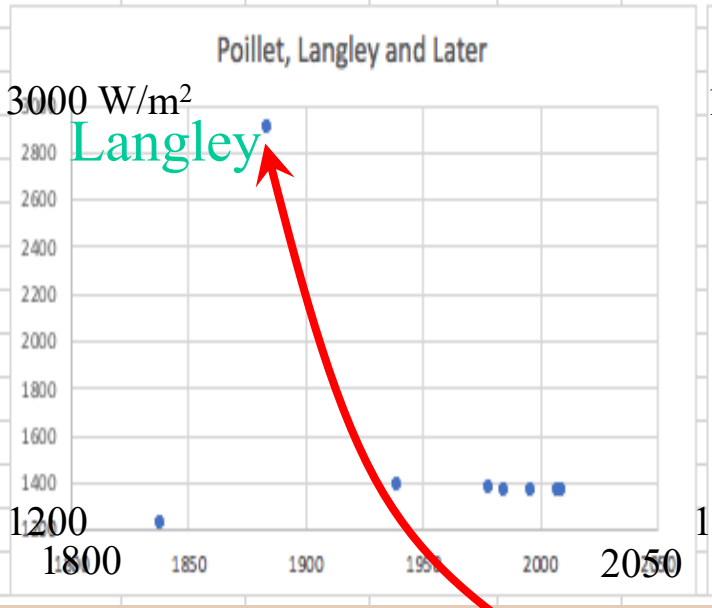
**Overlap!**

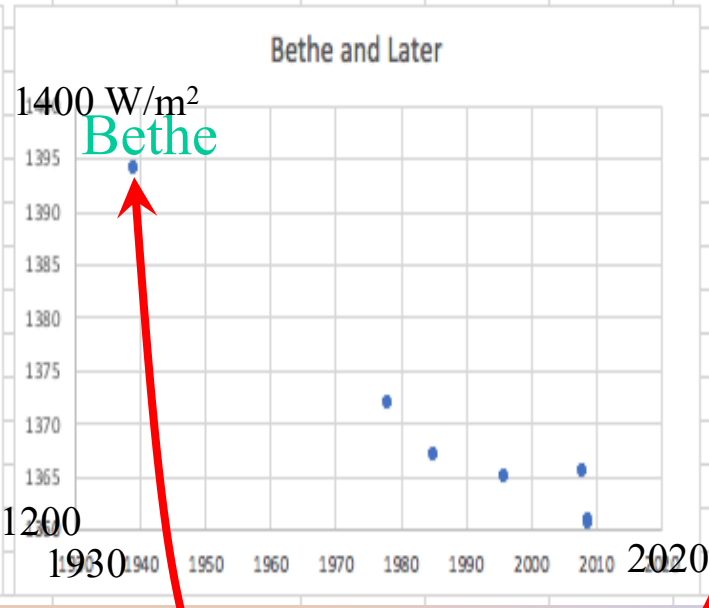
**TSIS-1 on ISS**

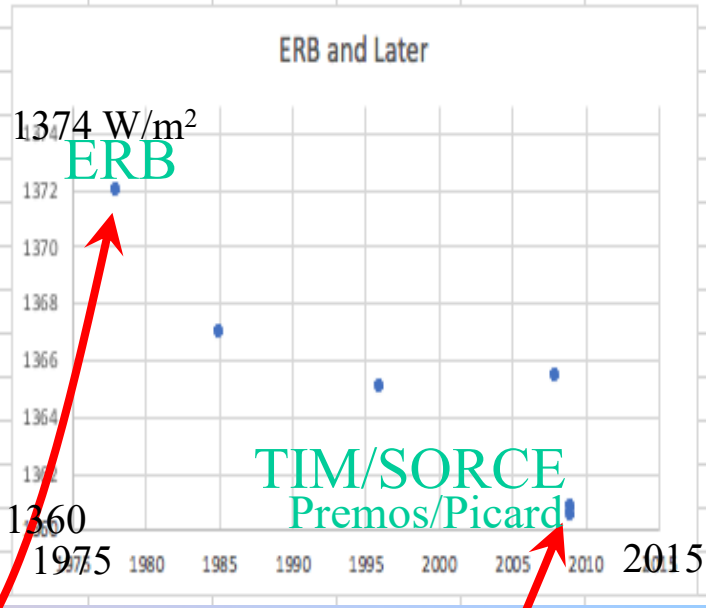
powered on Mar 2018, now extends SORCE TSI and SSI 17 yr record

*Robert F. Cahalan, NASA – Goddard*

# Historical Estimates of TSI (aka "solar constant")



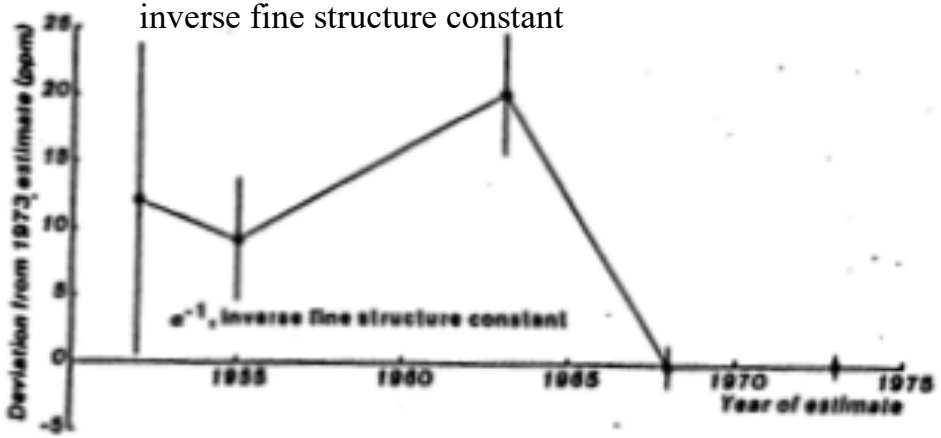




- 19th C → Wide variations : 10–113% > 1500 *W/m²*
- Narrowed after *Bethe's* 1939 paper* : ±5% ~ ± 70 *W/m²* → *+2.5%*
- *Further narrowed after satellites began → ± 1%*
- *Satellites showed TSI out-of-phase with sunspots*
- *Satellites gradually decreased & tightened estimates*
- *SORCE lower by* 4.5 *W/m² > 0.3%, an "outlier" !*
- *After 2005,* ***improved scattered light estimates*** *allowed acceptable agreement of independent measurements, making other measurements line up with SORCE*
- *SORCE became the new TSI "Gold Standard"*

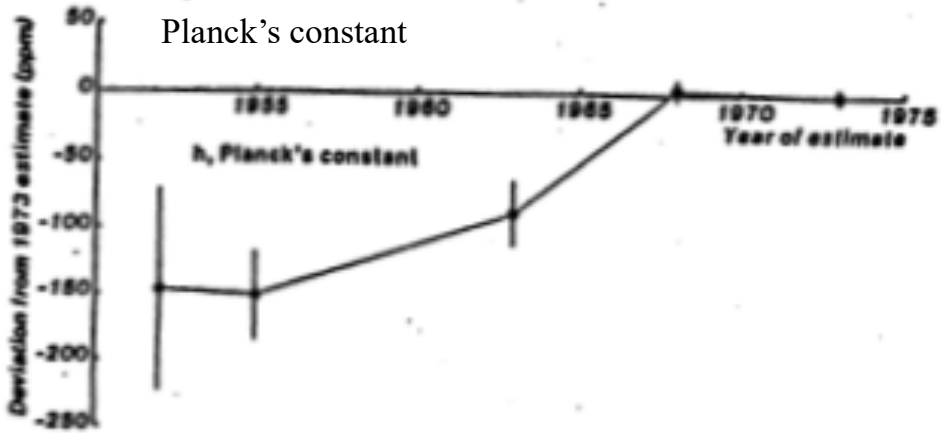
*H.A. Bethe, "Energy production in Stars," *Phys. Rev.* **55**, 436 (1939)

*Robert F. Cahalan, NASA – Goddard*

inverse fine structure constant




Planck's constant




electron charge

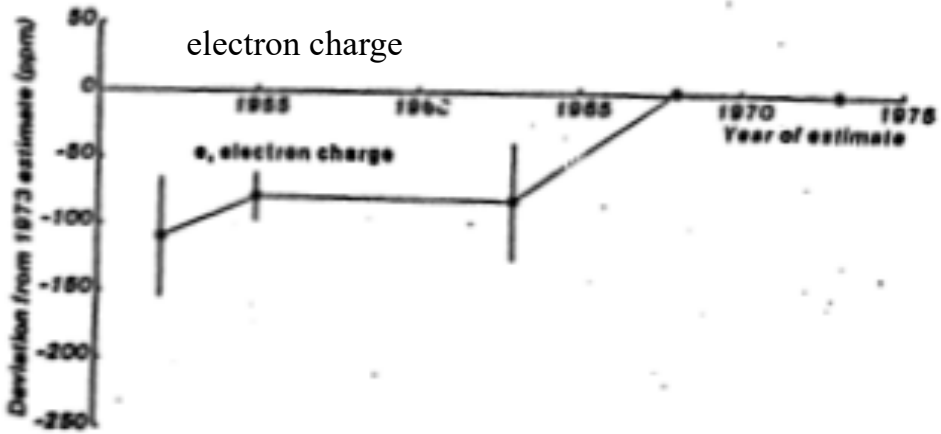
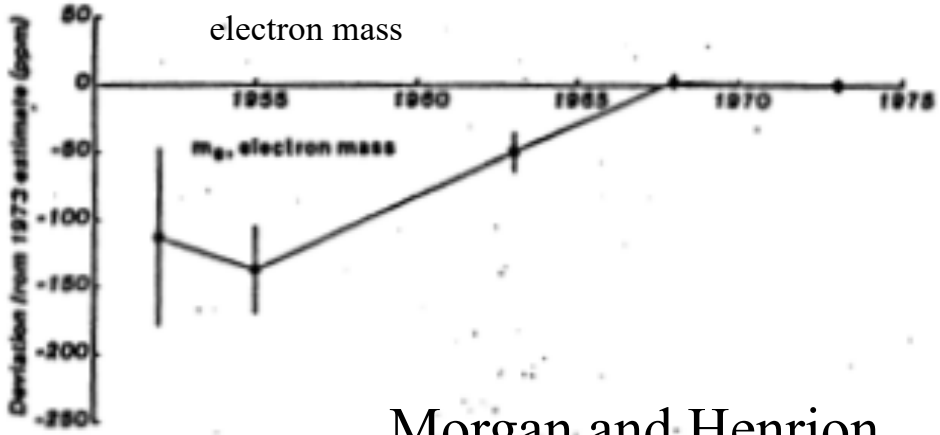



Figure 6.12. Recommended values for five standard physical constants, along with reported uncertainties for the period 1953–1973 (Henrion and Fischhoff, 1986).

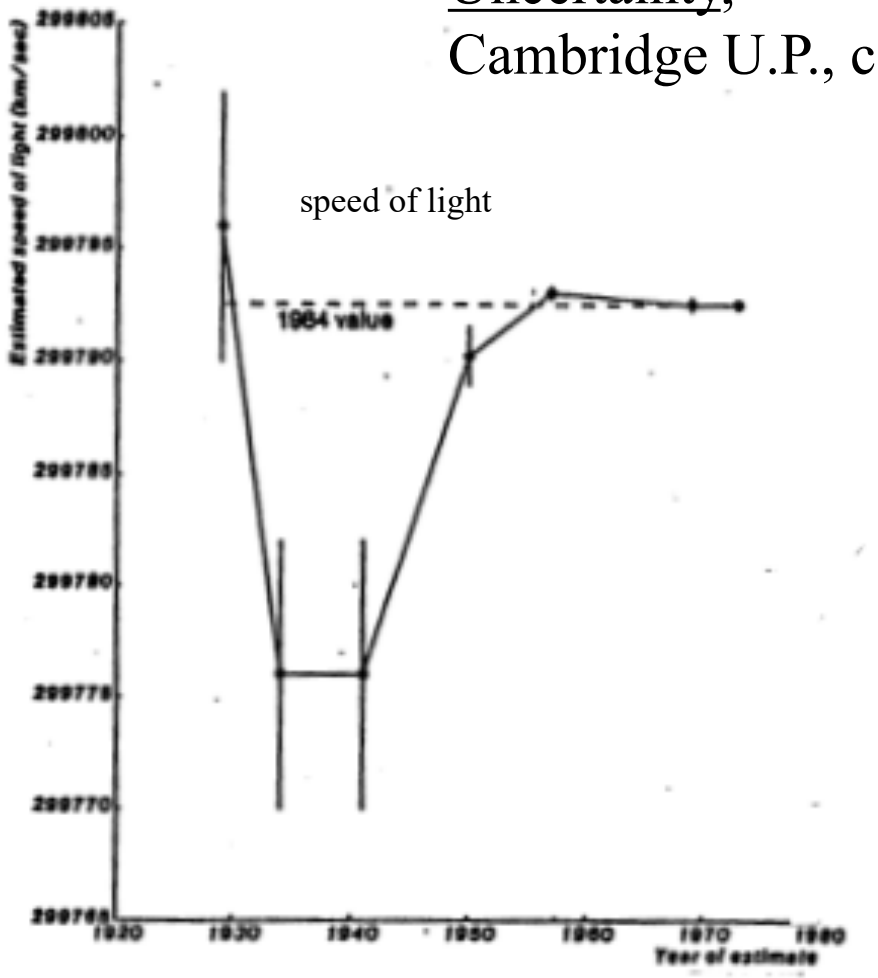


electron mass



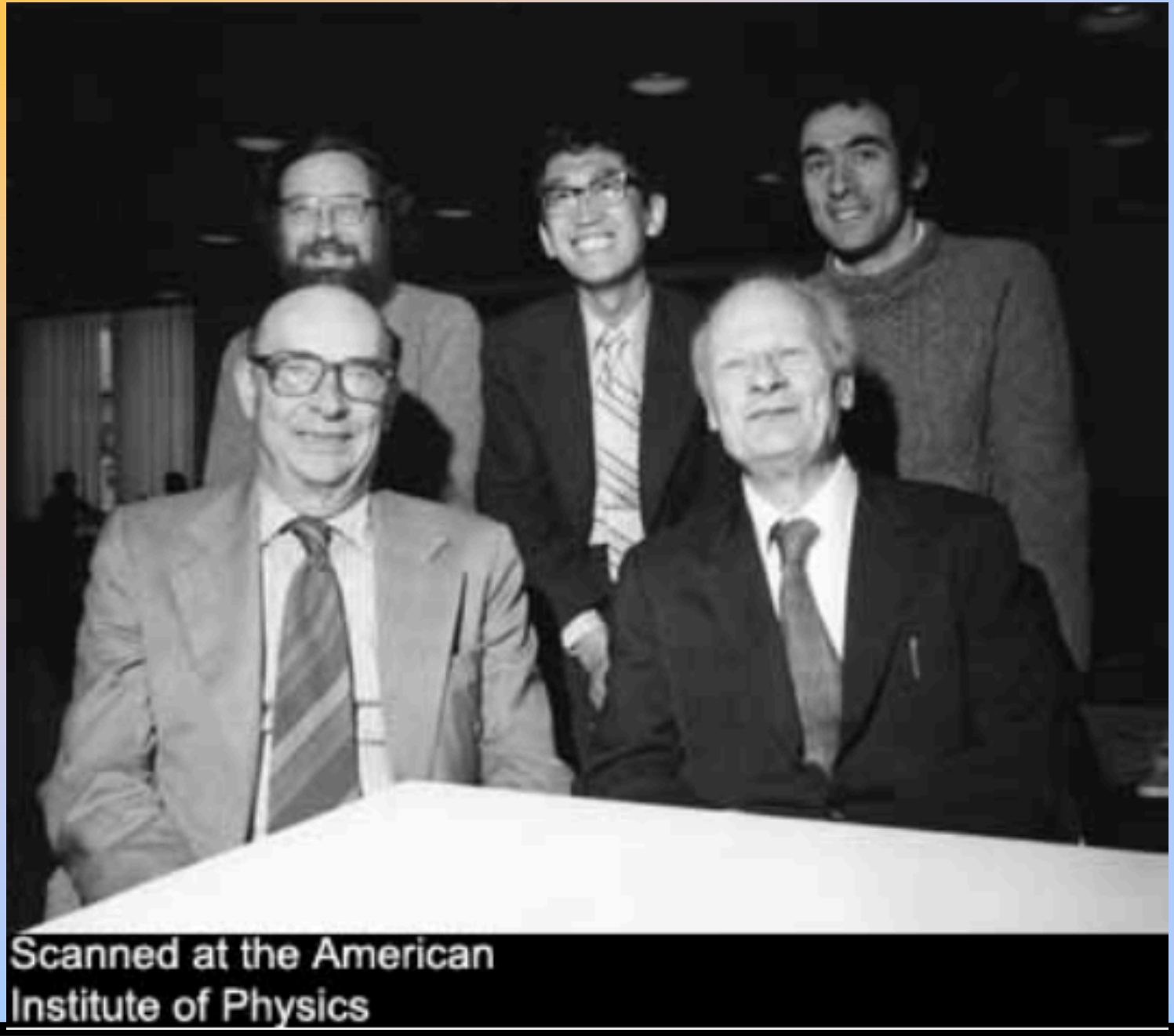

Morgan and Henrion,
Uncertainty,
Cambridge U.P., c1990.

speed of light



The expedition party that gathered in Rawlins, Wyoming Territory, to view the total solar eclipse of July 29, 1878, included (from far right) English astronomer Norman Lockyer, Thomas Edison, and Henry and Anna Draper. From "The Glass Universe," by Dava Sobel, Penguin Books, c2016.

# Bethe with Bardeen



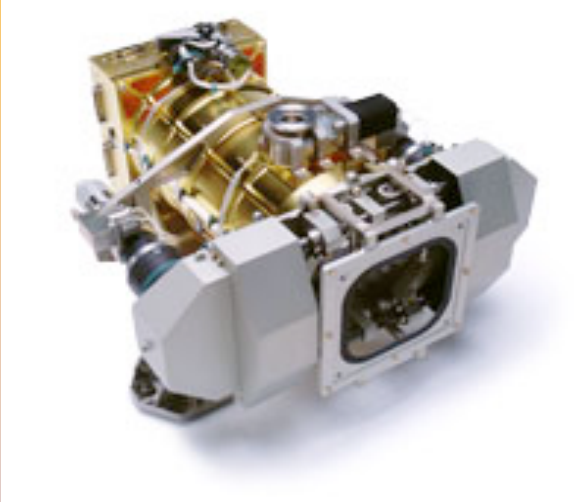

John Bardeen, Hans Bethe, Chris Pethick, Shau-jin Chang, Gordon Baym, U.Illinois 1977


Mike King, John Townsend, Ghassam Asrar, Mike Luther, Bob Cahalan, Gary Rottman, 2002.

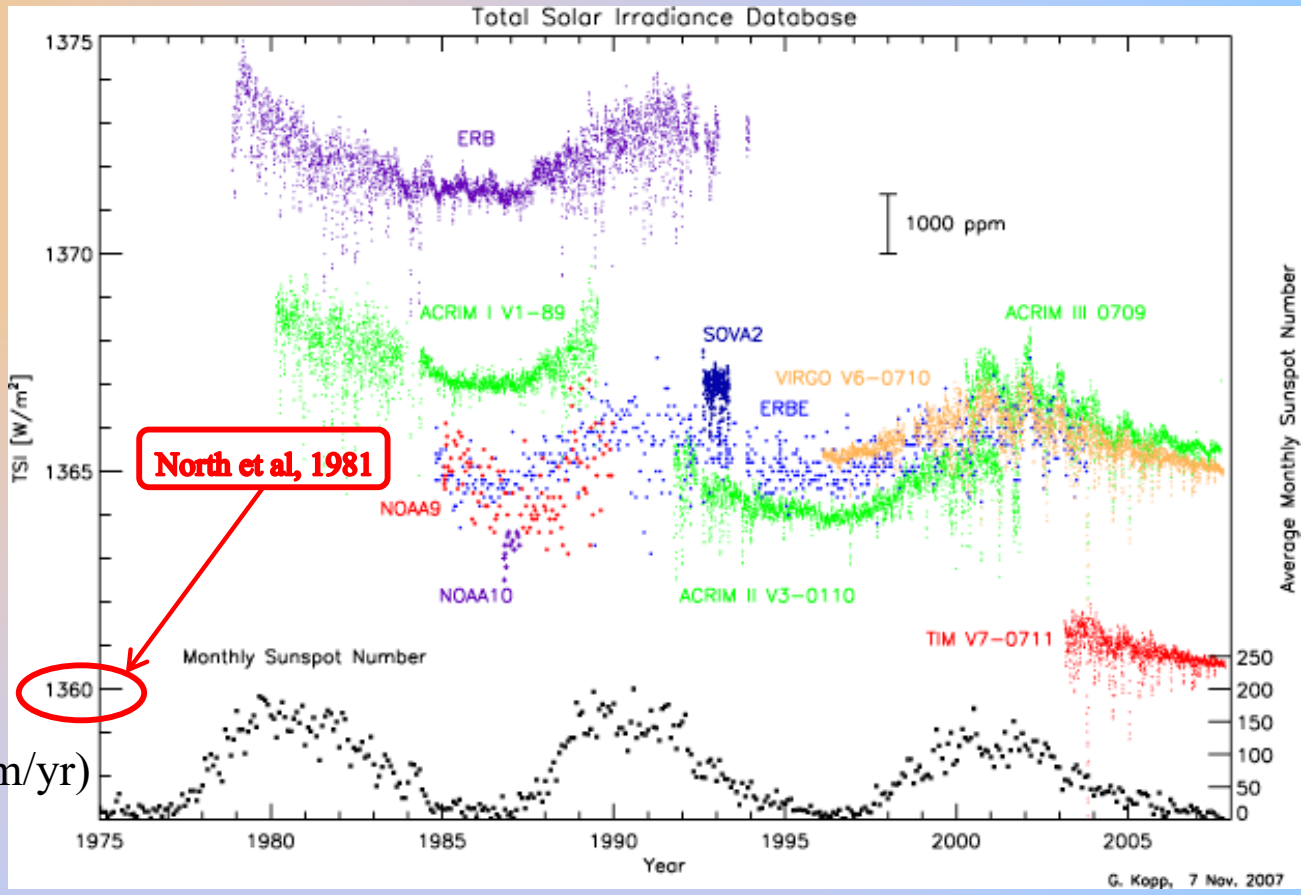
# Total Irradiance Monitor (TIM)

## TIM continues the 30-yr total solar irradiance (TSI) climate data record

***Kopp, G., et al., Solar Physics, 2005***



- Instrument Type: Cavity Bolometer
- Wavelength Range: All
- Absolute Accuracy: 0.035% (350 ppm)
- Long-term Stability: 0.001%/yr (10 ppm/yr)
- Mass: 10.7 kg
- Orbit Average Power: 12.4 W
- Orbit Average Data Rate: 1.0 kbits/s
- Redundancy: 4 ESRs (2 pairs)




**Key Technologies**

- NiP black cones
- In-phase analysis of ESRs at shutter frequency
- Precision aperture at front of instrument

Figure by Greg Kopp, UCO/LASP.

# TSI Record with SORCE TIM

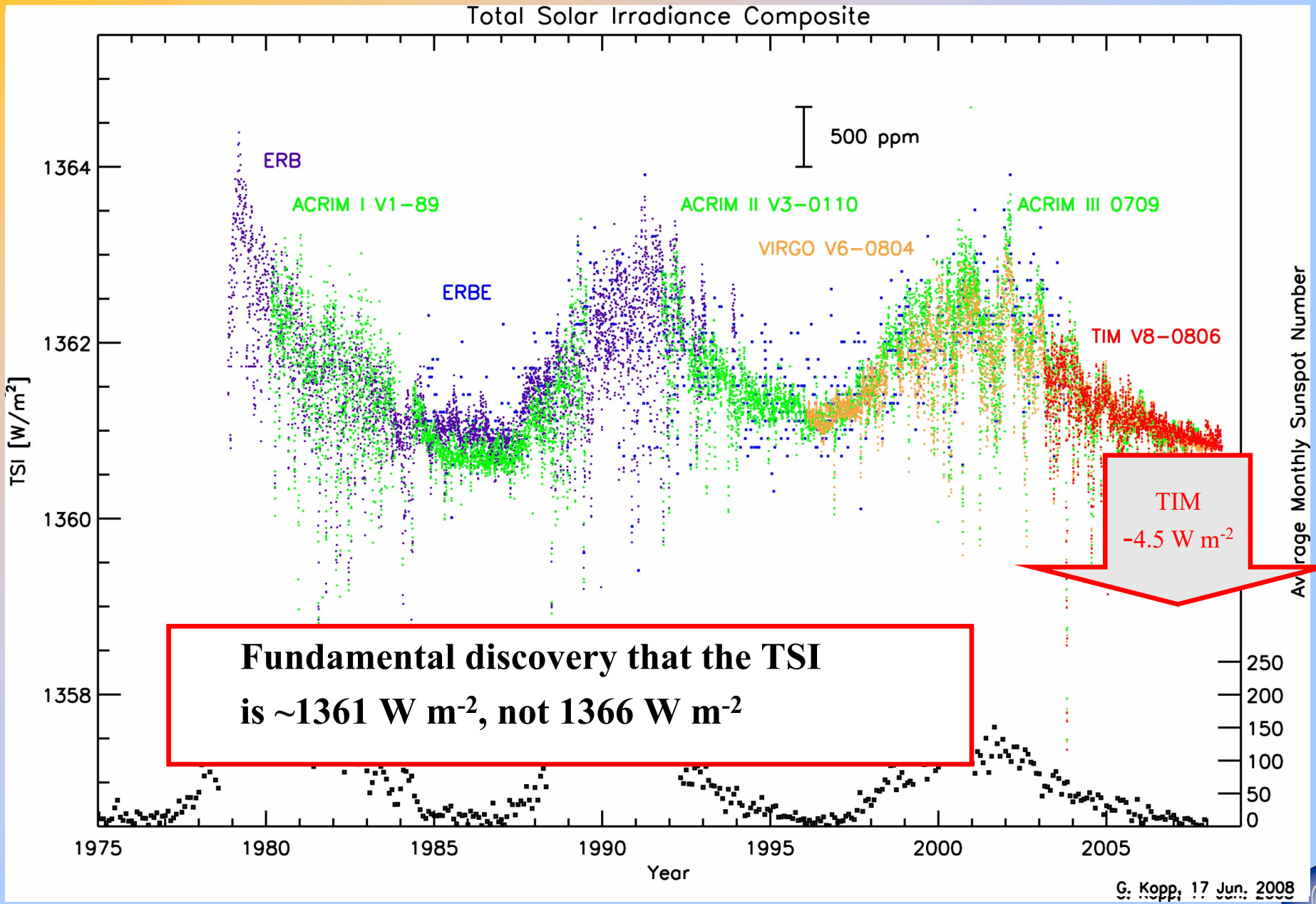



Figure by Greg Kopp, UCO/LASP, 2008.

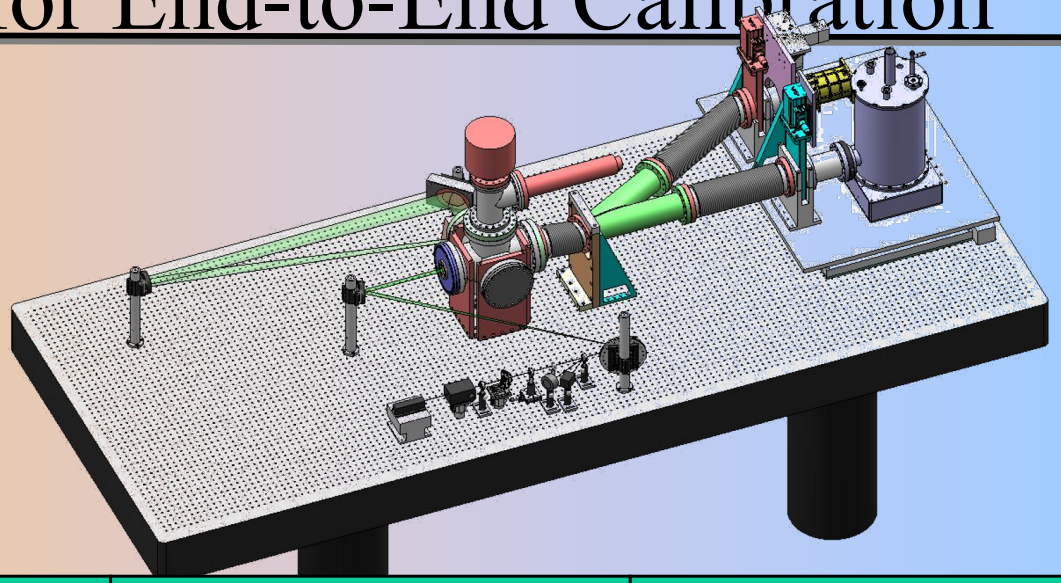
See Kopp and Lean, GRL, 2011, doi:10.1029/2010GL0457770

# New LASP Facility for End-to-End Calibration

- compare each TSI instrument against NIST-calibrated cryogenic radiometer in the TSI Radiometer Facility (TRF)

Glory TSI agrees to 200 ppm

PICARD PMO instrument at TRF late summer



| Facility | SI Reference | Operating Conditions | Comments |
|---|---|---|---|
| **Table Mountain** | none | •vacuum<br>•solar viewing<br>•window transmission<br>•circumsolar scatter | no link to SI and scatter effects limit usefulness of comparison |
| **World Radiation Reference (WRR)** | linked to NPL (with high uncertainties) | •solar viewing<br>•air operations<br>•circumsolar scatter | air operations and scatter limit absolute accuracy |
| **NRL Cryo Radiometer** | NIST calibrated cryo radiometer | •vacuum<br>•solar power level | not built |
| **TSI Radiometer Facility (TRF)** | NIST calibrated cryo radiometer | •vacuum<br>•solar power level | proven on Glory/TIM |

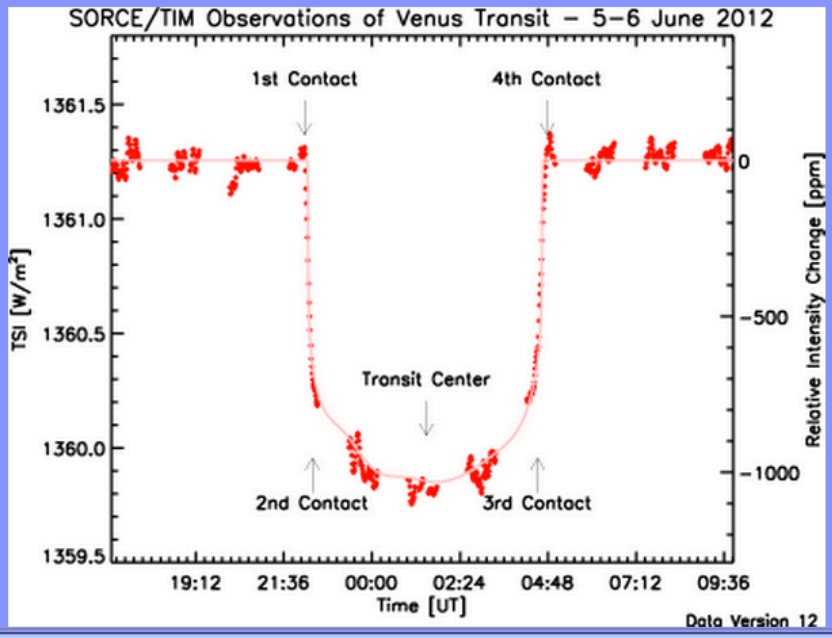
Figure by Greg Kopp, UCO/LASP.

# Venus transits: 2004 & 2012

**Planetary Transit Observations**

The TIM measured a decrease in the TSI (red dots) as Venus transited the Sun on both 5-6 June 2012 and 8 June 2004. In agreement with predictions (faint red curve) accounting for solar limb darkening and the SORCE position, the incident sunlight dropped approximately 0.1% during the transits, which is comparable to the effect of a medium sized sunspot. The gaps in the plotted data are from times when the SORCE spacecraft was in the Earth's shadow and could not view the Sun. Both 1st and 2nd Contacts, as Venus began its transit across the solar disk, were observed directly for both Venus transits. During the 2012 transit, egress (3rd and 4th Contacts) was also observed, although this occurred when the spacecraft was occulted by the Earth in 2004. The increases in brightness near ingress and egress during the transit are due to solar limb darkening, which makes the center of the solar disk brighter than the edges. The small fluctuations in brightness on short time scales are from normal solar convection and oscillations, and can be seen in the un-occulted times both before and after the transits.
Exo-solar planets are being discovered via transits in front of their stars using similar photometry techniques.
(Published in Kopp, G., Lawrence, G., and Rottman, G., The Total Irradiance Monitor (TIM): Science Results, *Solar Physics*, **230**, 1, Aug. 2005, pp. 129-140.)

**TIM Observations of 2012 Venus Transit**




**TIM Observations of 2004 Venus Transit**

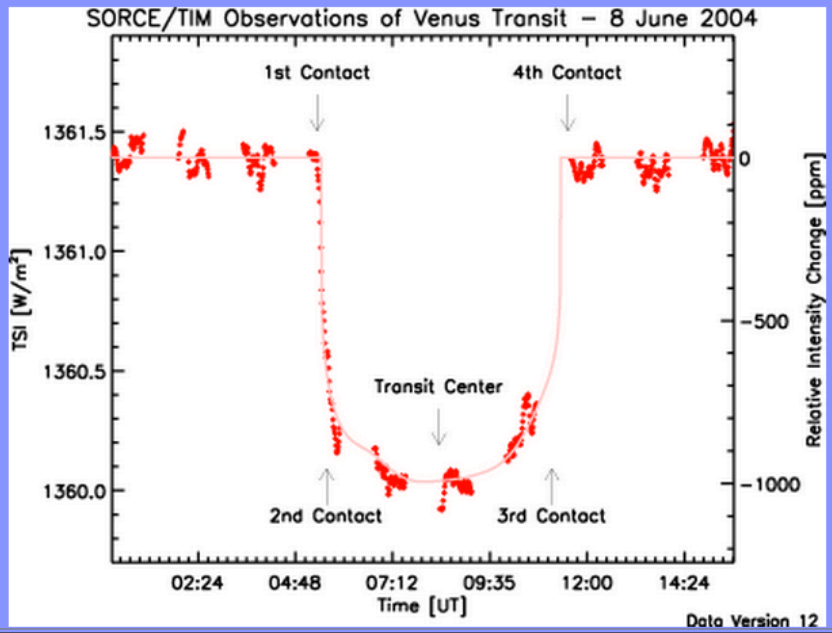
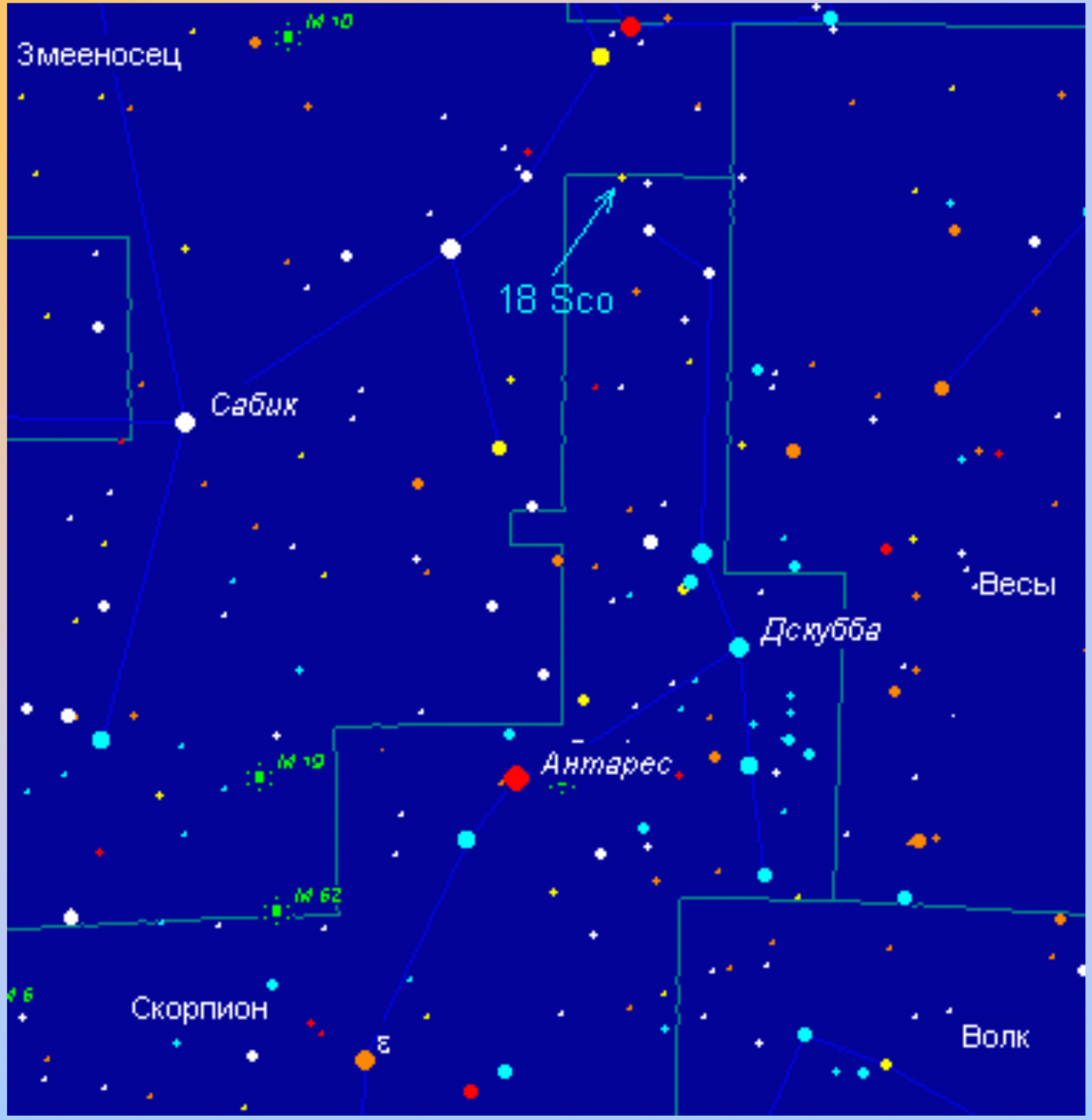



Figure by Greg Kopp, UCO/LASP.

# Sco 18 – Sol Twin ?

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# Diffraction and Scatter Corrections Affect TSI Results Differently

- All instruments except TIM put primary aperture close to the cavity
  - TIM processing makes corrections for diffraction and scattered light
  - VIRGO processing makes correction for diffraction but *not* for scattered light
  - ACRIM processing does **not** make either correction, and each would lower ACRIM values

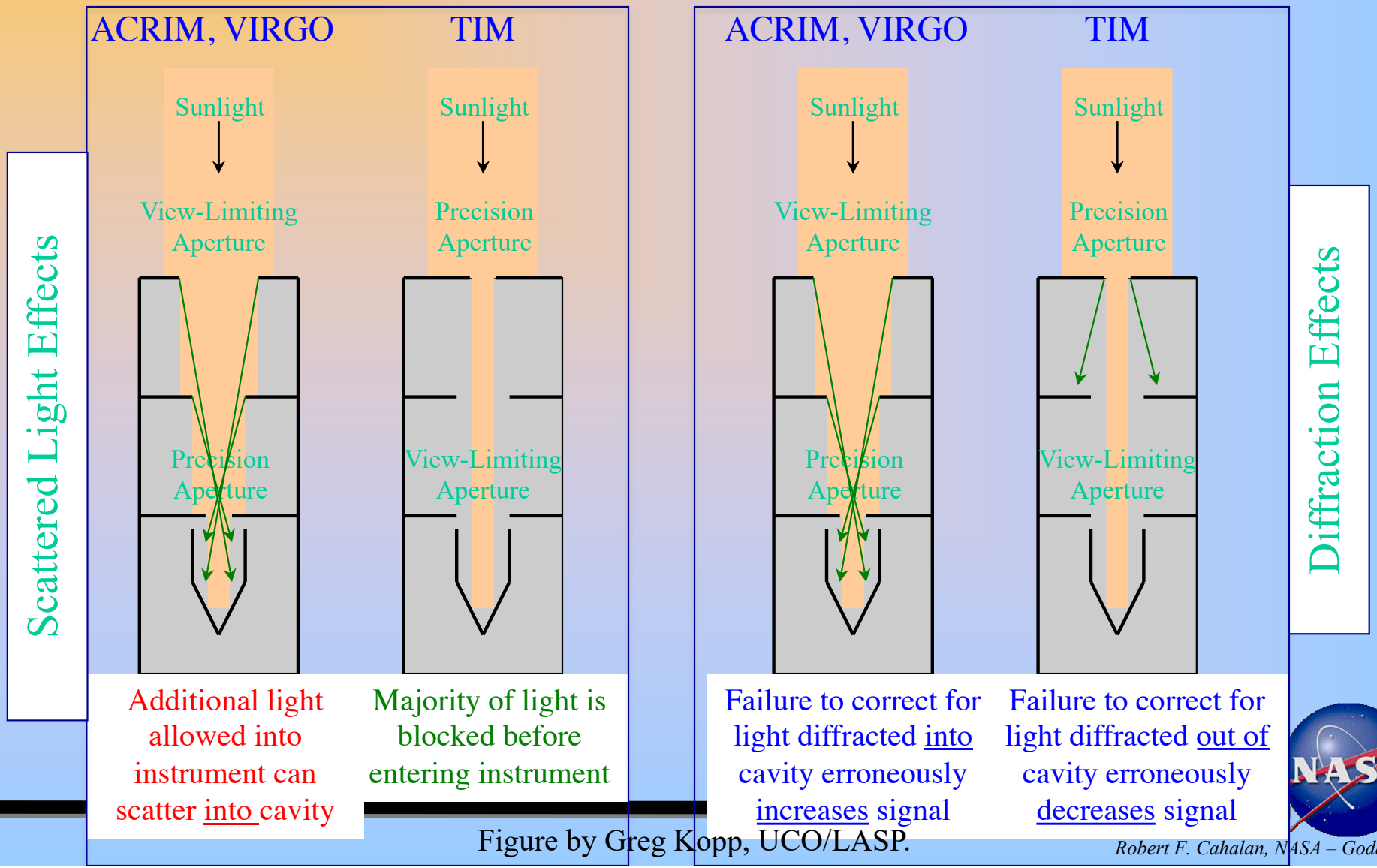


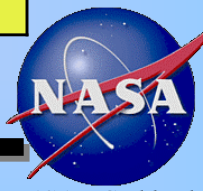

Figure by Greg Kopp, UCO/LASP.

# TIM Instrument Uncertainties

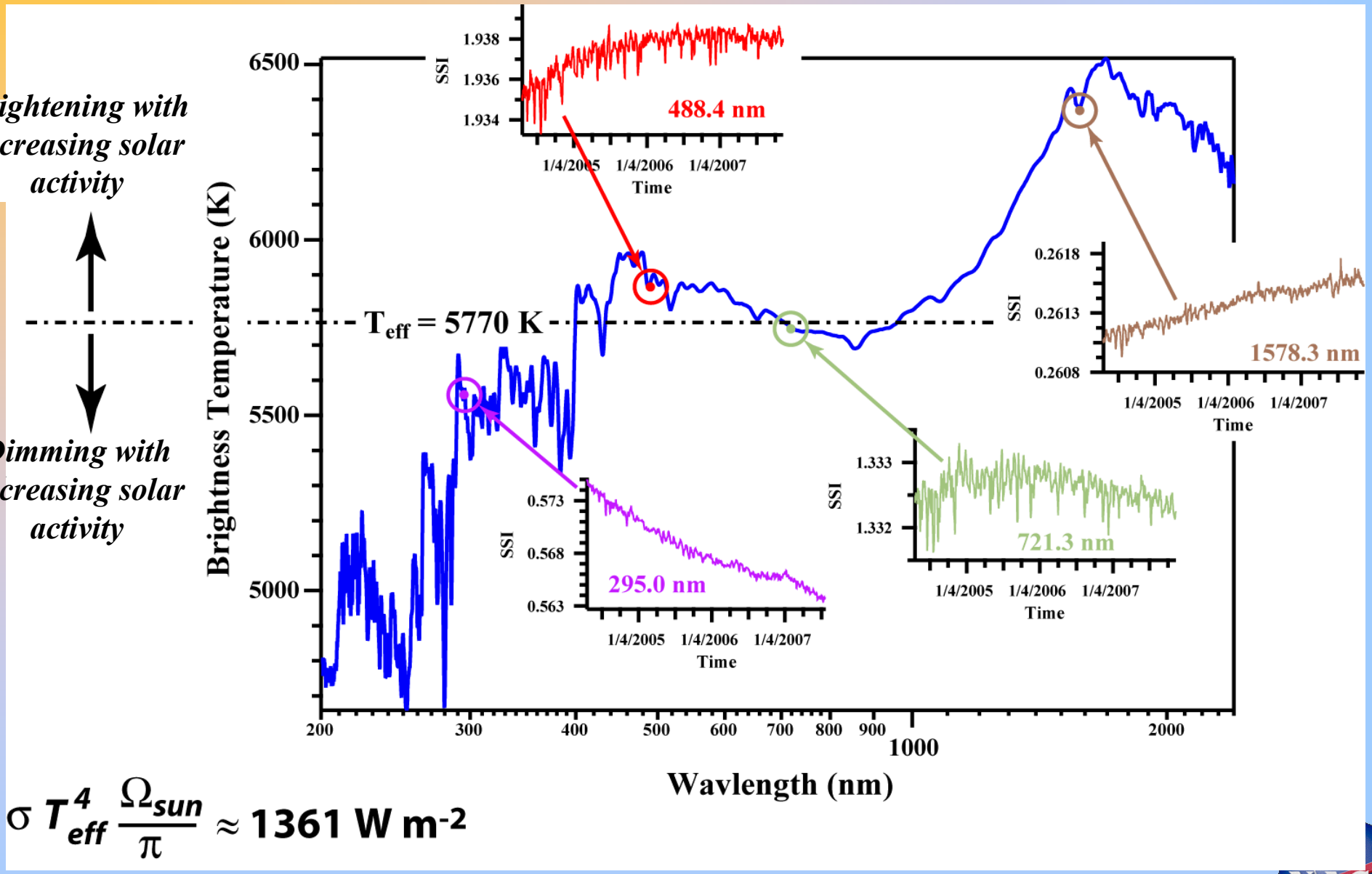
| Correction | Origin | Value [PPM] | 1σ [PPM] |
|---|---|---|---|
| Distance to Sun, Earth & S/C | Analysis | 33,537 | 0.1 |
| Doppler Velocity | Analysis | 57 | 0.7 |
| Shutter Waveform | Component | 100 | 1.0 |
| Aperture | Component | 1,000,000 | 28 |
| Diffraction | Component | 452 | 46 |
| Cone Reflectance | Component | 182 | 35 |
| Non-Equivalence, ZH/ZR-1 | Instrument | 782 | 43 |
| Servo Gain | Instrument | 2,115 | 0.0 |
| Standard Volt +DAC | Component | 1,000,000 | 15 |
| Pulse Width Linearity | Component | 800 | 3 |
| Standard Ohm + Leads | Component | 1,000,000 | 25 |
| Dark Signal | Instrument | 1,645 | 14 |
| Pointing | Analysis | 100 | 10 |
| Measurement Repeatability (Noise) | Instrument | - | 4 |
| Uncertainty due to Sampling | Analysis | - | 12 |
| Total RSS | | | 85.5 |

Table by George Lawrence, UCO/LASP.

See also 'TIM Calibration' by Karl Heuerman.



# A Contrast in Spectral Variability




$$\sigma T_{eff}^4 \frac{\Omega_{sun}}{\pi} \approx 1361 \text{ W m}^{-2}$$

Plot by Jerry Harder, UCO/LASP.

# To all who contributed, many thanks!

| **SORCE Top Ten Achievements** (*EOS*, **25**, Jan-Feb 2013) |
|---|
| 1. New TSI Level |
| 2. New SSI Record for 115-2400 nm range |
| 3. New SSI Reference Spectra |
| 4. Use of SORCE SSI & TSI in Climate Modeling |
| 5. Next-generation, highly-accurate Radiometers |
| 6. Extension of NOAA Mg II Solar Proxy |
| 7. Large Flare Measurements in SSI and TSI |
| 8. Advanced Models of the TSI and SSI |
| 9. Venus and Mercury Transit Observations |
| 10. Improved Calibrations for Stars and Lunar Reflectance |