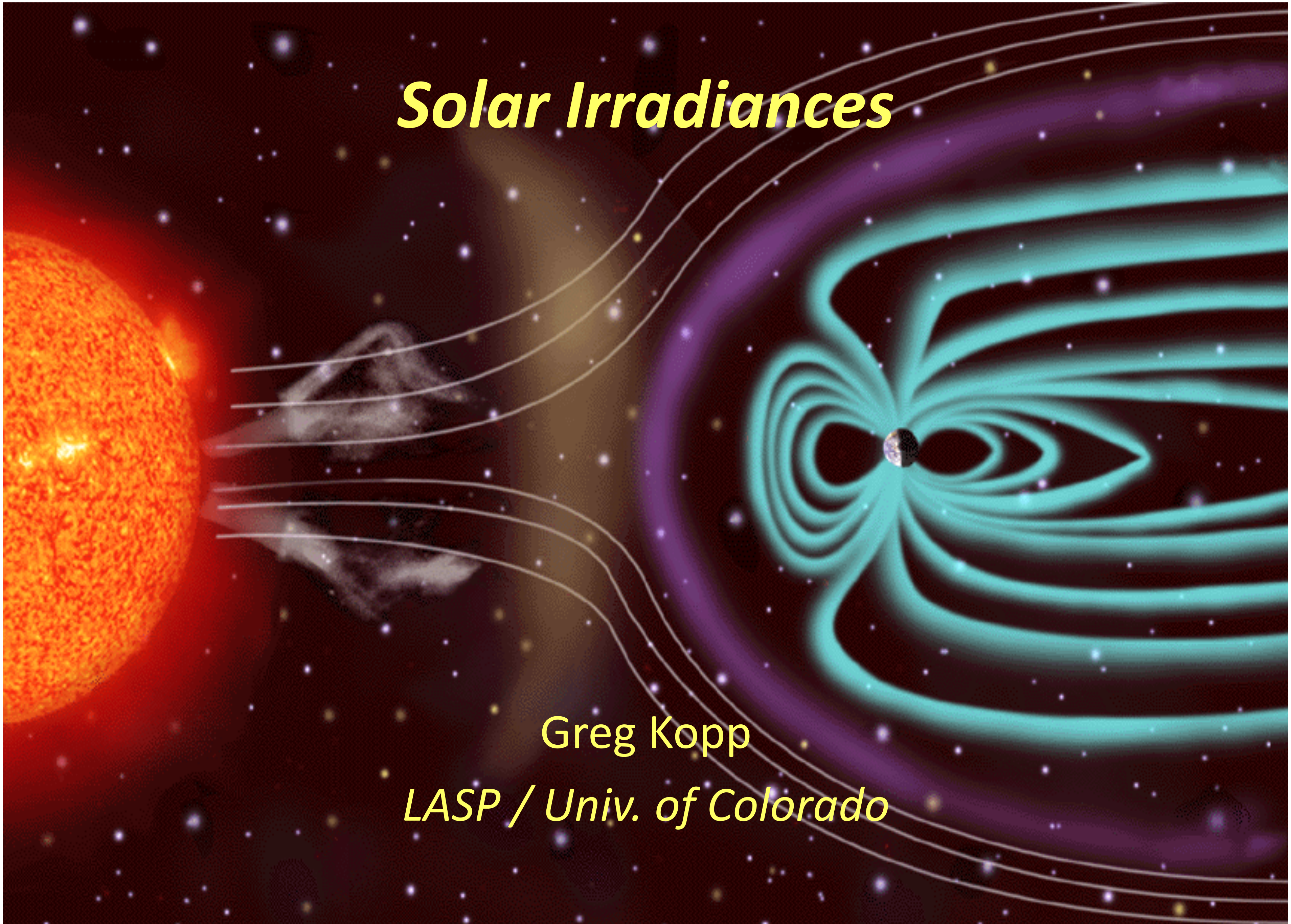
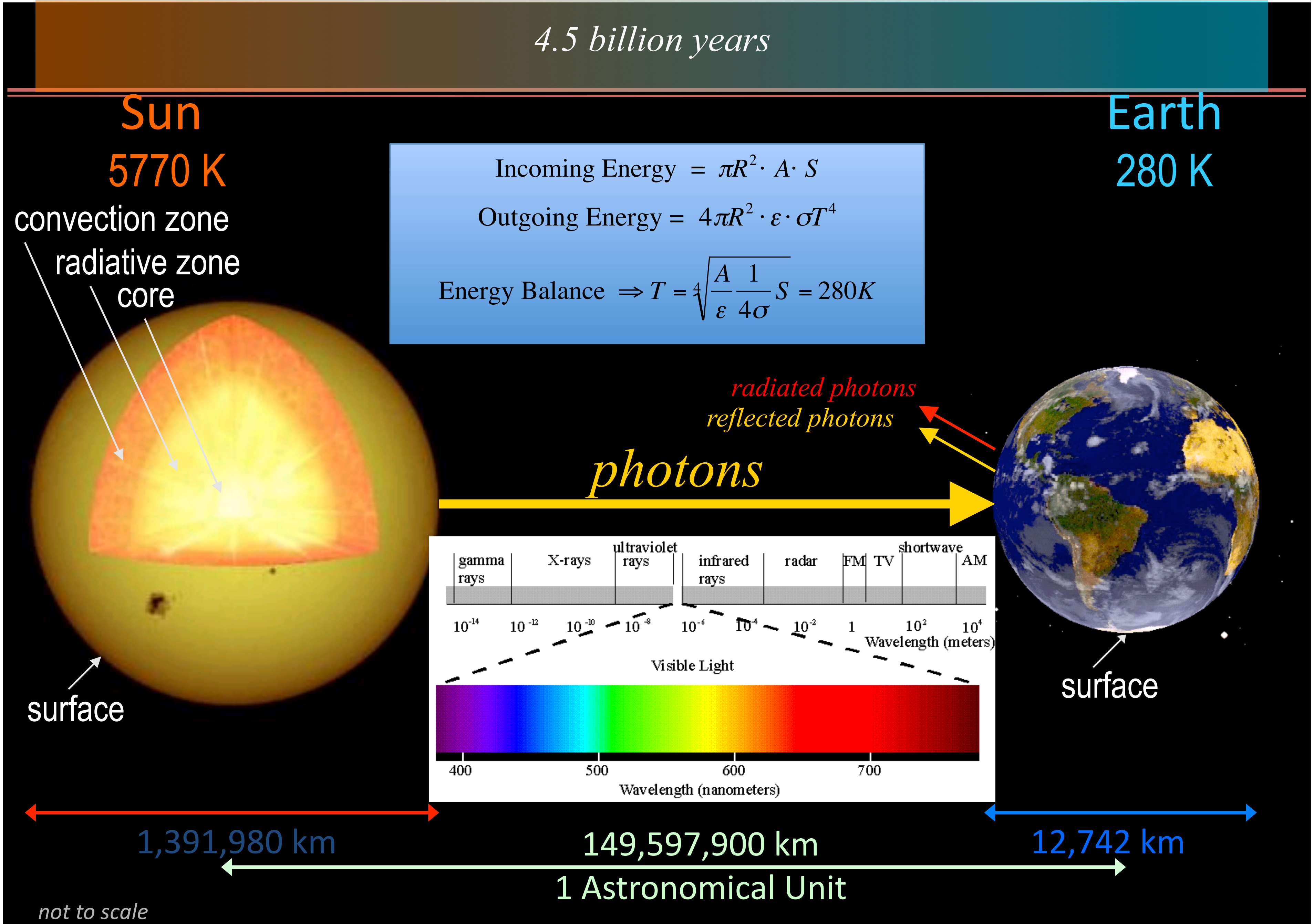
Solar Irradiances



Greg Kopp

LASP / Univ. of Colorado


4.5 billion years
Sun
5770 K
convection zone
radiative zone
core
surface
Earth
280 K
surface
Incoming Energy $= \pi R^2 \cdot A \cdot S$
Outgoing Energy $= 4\pi R^2 \cdot \varepsilon \cdot \sigma T^4$
Energy Balance $\Rightarrow T = \sqrt[4]{\frac{A}{\varepsilon}\frac{1}{4\sigma}S} = 280K$
radiated photons
reflected photons
photons
gamma rays
X-rays
ultraviolet rays
infrared rays
radar
FM
TV
shortwave
AM
10^{-14} 10^{-12} 10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 1 10^{2} 10^{4}
Wavelength (meters)
Visible Light
400 500 600 700
Wavelength (nanometers)
1,391,980 km
149,597,900 km
12,742 km
1 Astronomical Unit
not to scale
courtesy of Judith Lean, NRL

Where Does the Earth Get Its Energy?

Heat Source	Heat Flux* [W/m^2]	Relative Input
Solar Irradiance	340.25	1.000
Heat Flux from Earth's Interior	0.0870	2.6E-04
Radioactive Decay	0.0550	1.6E-04
Geothermal	0.0320	9.4E-05
Worldwide Combustion of Coal, Oil, and Gas	0.0279	8.2E-05
Infrared Radiation from the Full Moon	0.0102	3.0E-05
Sun's Radiation Reflected from Moon	0.0037	1.1E-05
Energy Generated by Solar Tidal Forces in the Atmosphere	0.0017	5.0E-06
Dissipation of Magnetic Storm Energy	8.2E-04	2.4E-06
Radiation from Bright Aurora	4.8E-05	1.4E-07
Energy Dissipated in Lightning Discharges	2.0E-05	5.9E-08
Dissipation of Mechanical Energy of Micrometeorites	2.0E-05	5.9E-08
Energy Generated by Lunar Tidal Forces in the Atmosphere	2.0E-05	5.9E-08
Total Radiation from Stars	1.4E-05	4.1E-08
Energy of Cosmic Radiation	1.3E-05	3.8E-08
Radiation from Zodiacal Light	3.4E-07	1.0E-09
Total of All Non-Solar Energy Sources	*0.1315*	*3.9E-04*

2500 x

* global average

*Greenhouse gases are not an energy **source**.*

based on Physical Climatology, W.D. Sellers, Univ. of Chicago Press, 1965
Table 2 on p. 12 is from unpublished notes from
H.H. Lettau, Dept. of Meteorology, Univ. of Wisconsin.

What Is Resulting Earth Temperature?

Heat Source	Heat Flux* [W/m^2]	Relative Input
Solar Irradiance	**340.25**	**1.000**
Heat Flux from Earth's Interior	0.0870	2.6E-04
Radioactive Decay	0.0550	1.6E-04
Geothermal	0.0320	9.4E-05
Worldwide Combustion of Coal, Oil, and Gas	0.0279	8.2E-05
Infrared Radiation from the Full Moon	0.0102	3.0E-05
Sun's Radiation Reflected from Moon	0.0037	1.1E-05
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Energy of Cosmic Radiation	1.3E-05	3.8E-08
Radiation from Zodiacal Light	3.4E-07	1.0E-09
Total of All Non-Solar Energy Sources	***0.1315***	***3.9E-04***
* global average		
	Total Input (relative)	1.00
	Temperature (K)	280
	Temperature (F)	45

What If We Didn't Have the Sun?

Heat Source	Heat Flux* [W/m^2]	Relative Input
Solar Irradiance	340.25	1.000
Heat Flux from Earth's Interior	0.0870	2.6E-04
Radioactive Decay	0.0550	1.6E-04
Geothermal	0.0320	9.4E-05
Worldwide Combustion of Coal, Oil, and Gas	0.0279	8.2E-05
Infrared Radiation from the Full Moon	0.0102	3.0E-05
Sun's Radiation Reflected from Moon	0.0037	1.1E-05
Energy Generated by Solar Tidal Forces in the Atmosphere	0.0017	5.0E-06
Dissipation of Magnetic Storm Energy	8.2E-04	2.4E-06
Radiation from Bright Aurora	4.8E-05	1.4E-07
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Dissipation of Mechanical Energy of Micrometeorites	2.0E-05	5.9E-08
Energy Generated by Lunar Tidal Forces in the Atmosphere	2.0E-05	5.9E-08
Total Radiation from Stars	1.4E-05	4.1E-08
Energy of Cosmic Radiation	1.3E-05	3.8E-08
Radiation from Zodiacal Light	3.4E-07	1.0E-09
Total of All Non-Solar Energy Sources	*0.1315*	*3.9E-04*
* global average		
	Total Input (relative)	3.4E-04
	Temperature (K)	38
	Temperature (F)	-391

What If We Didn't Have the Sun?

Heat Source	Heat Flux* [W/m^2]	Relative Input
Solar Irradiance	340.25	1.000
Heat Flux from Earth's Interior	0.0870	2.6E-04
Radioactive Decay	0.0550	1.6E-04
Geothermal	0.0320	9.4E-05
Worldwide Combustion of Coal, Oil, and Gas	0.0279	8.2E-05
Infrared Radiation from the Full Moon	0.0102	3.0E-05
Sun's Radiation Reflected from Moon	0.0037	1.1E-05
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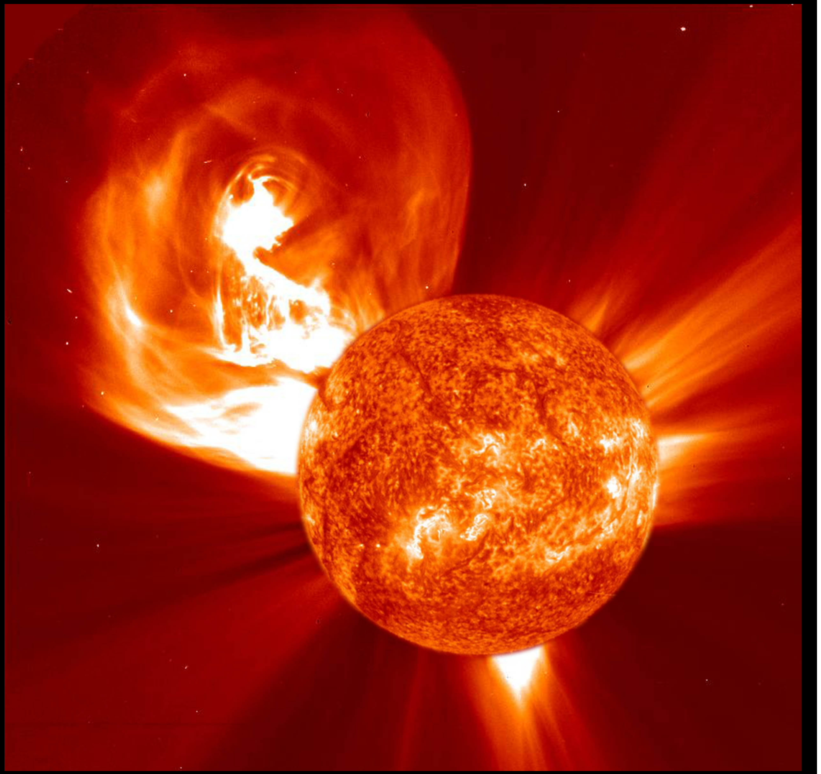
Energy of Cosmic Radiation	1.3E-05	3.8E-08
Radiation from Zodiacal Light	3.4E-07	1.0E-09
Total of All Non-Solar Energy Sources	*0.1315*	*3.9E-04*
* global average		
	Total Input (relative)	2.6E-04
	Temperature (K)	35
	Temperature (F)	-396

The Sun's Energy

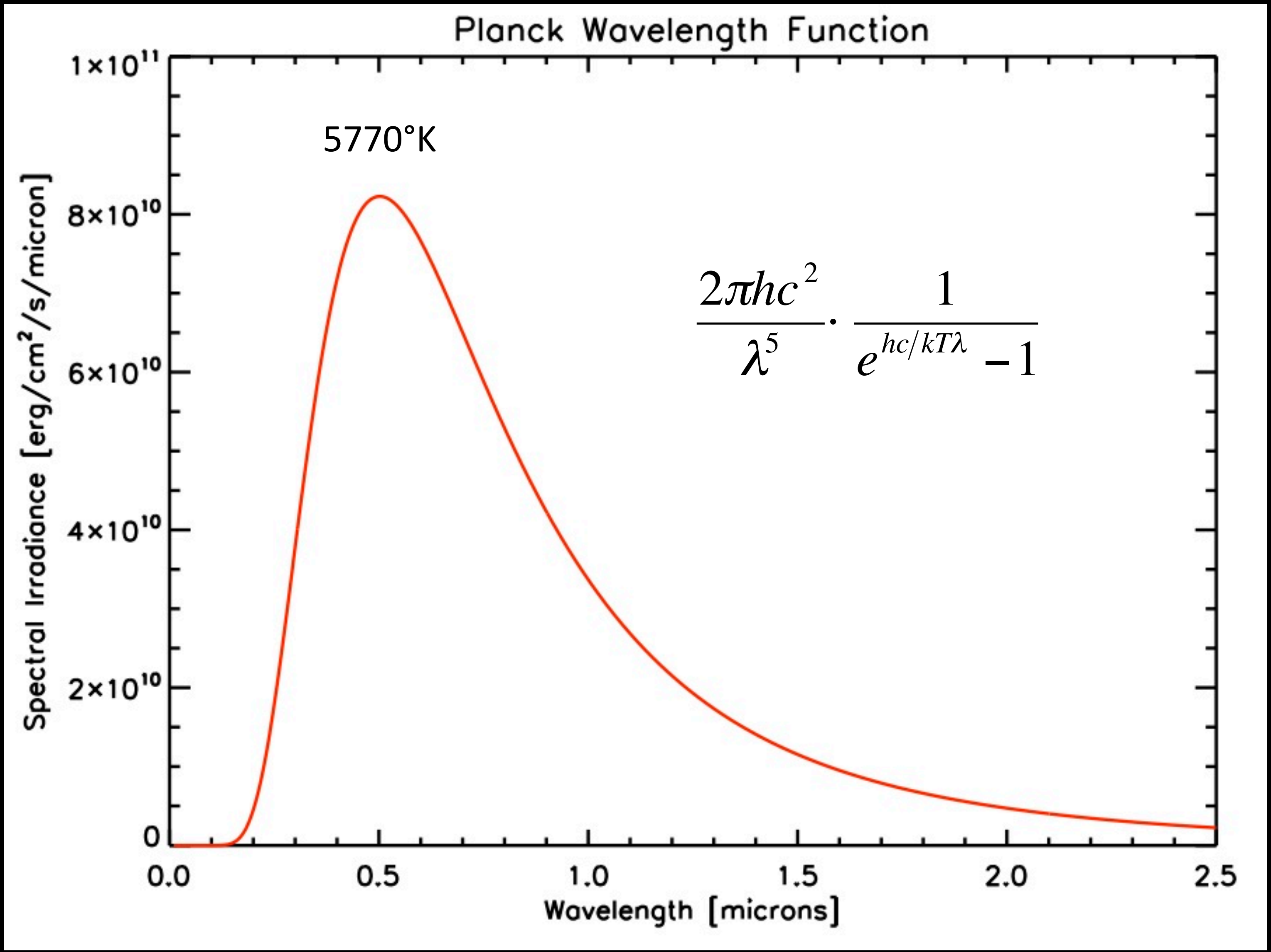
- Energy output
  - Sun's total output 3.8×10^{23} kW
  - Energy heating the Earth 1361 W/m^2
- Energy trivia
  - The total output of the Sun in one second would provide the U.S. with enough energy, at its current usage rate, for the next 9,000,000 years
- More fun (and unfathomable) trivia
  - The core is so dense (150 g/cm^3) and the size of the Sun so great (7×10^{10} cm radius) that energy released at the center takes about 100,000 years to make its way to the surface



Problems

- Determine the temperature of the Sun needed to produce 1361 W/m^2 irradiance at 1 AU
  - Need Sun's radius and distance of 1 AU
- Compute the resulting Earth temperature at 1 AU
  - Assume Earth is a grey-body with equal albedo and emissivity

Planck Blackbody Spectrum



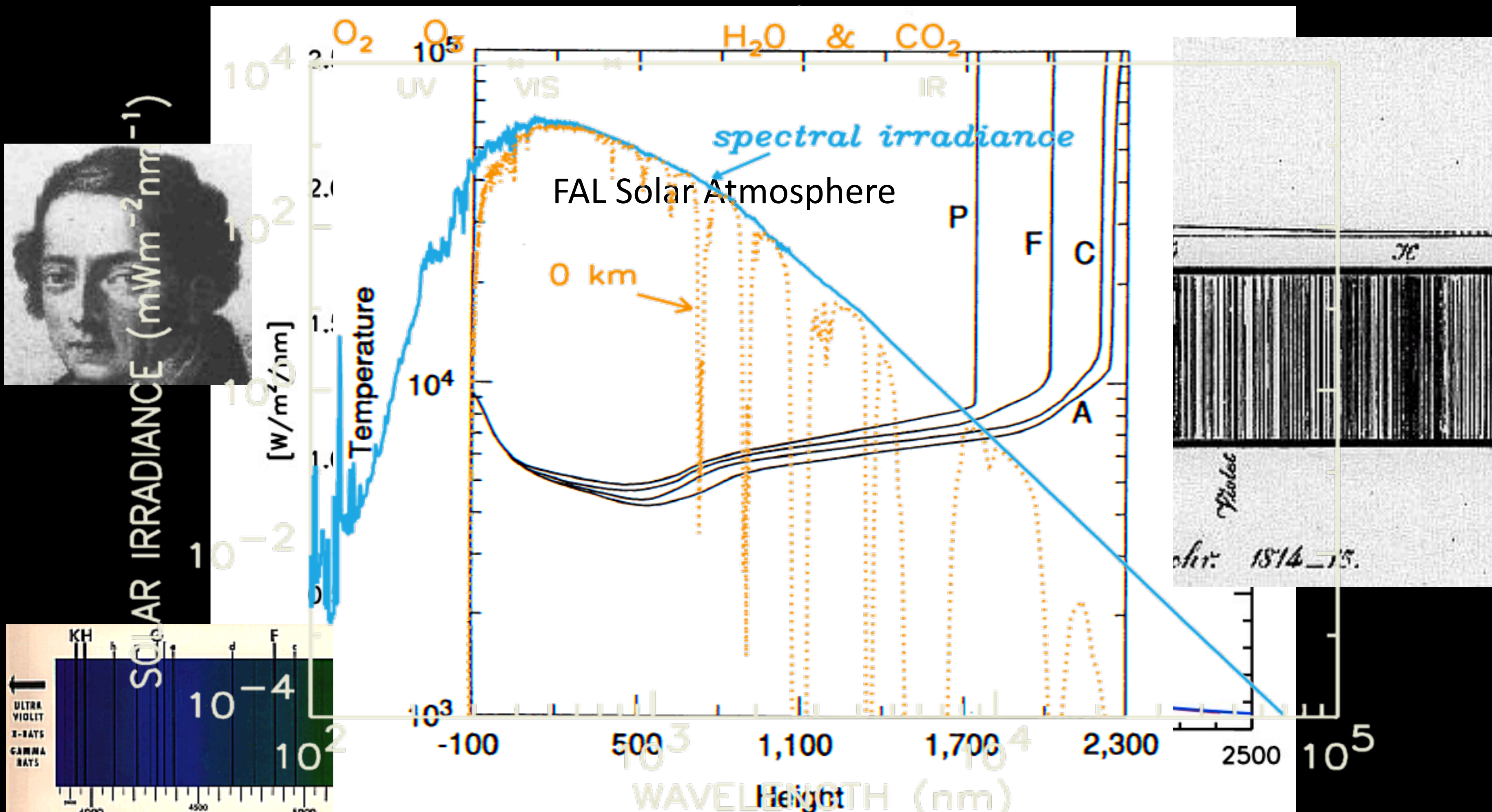
$$\frac{2\pi hc^2}{\lambda^5} \cdot \frac{1}{e^{hc/kT\lambda} - 1}$$

Problem

- Integrate the Planck blackbody for a 5770°K Sun to determine the fraction of total energy in:
  - the visible region from 400 to 700 nm; and
  - the NUV, visible, & NIR spectral region from 300 to 2500 nm

Solar Spectral Deviations from Planck Blackbody

- Fraunhofer (absorption) lines in visible and NIR
- EUV emission



Problem

- Determine the Fraunhofer line depth for a 500 nm (visible) absorption line with that of a line at 1.6 µm (NIR)
  - Assume the continuum is at photospheric temperatures (5770°K) and the absorption lines are formed in local thermodynamic equilibrium at temperature minimum values (~4500°K)
  - This shows one reason that the NIR is less sensitive to scattered light than the visible

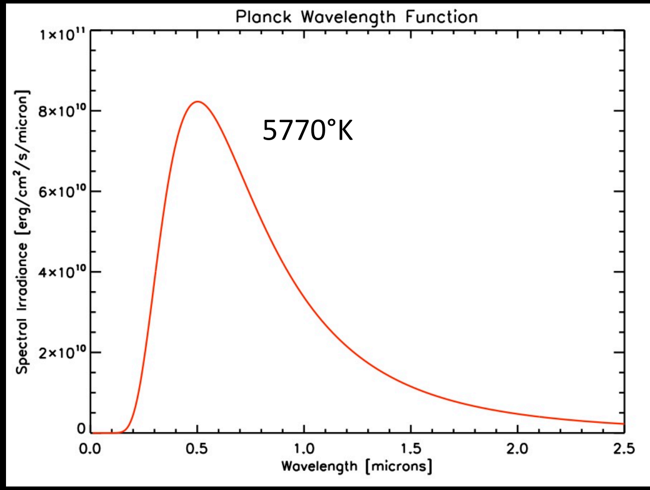
What Is "Irradiance"?

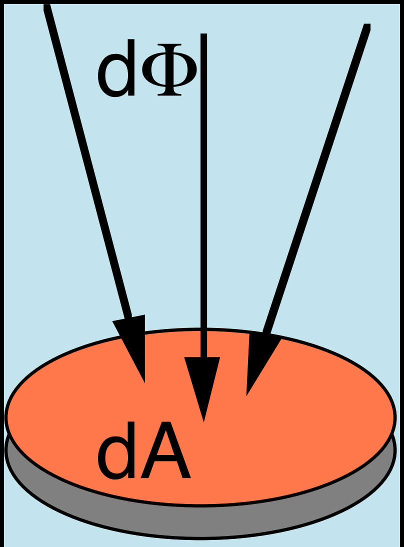
- Integrated radiant flux through an area
  - Total irradiance: spectrally integrated radiant flux through an area

$$E = \frac{d\Phi}{dA}$$

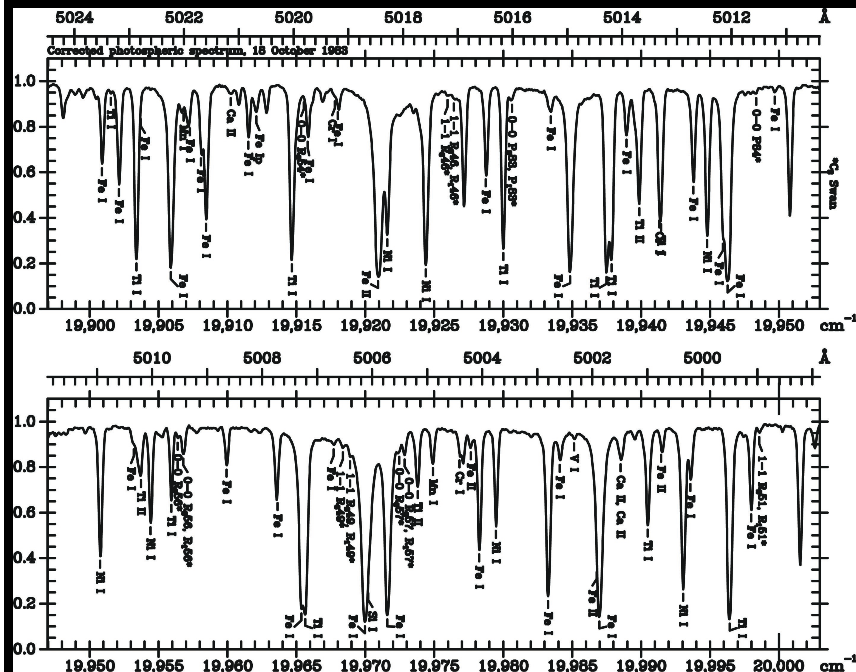
  - Spectral irradiance: radiant flux per wavelength unit through an area

$$E_\lambda = \frac{d^2\Phi}{dA\,d\lambda}$$

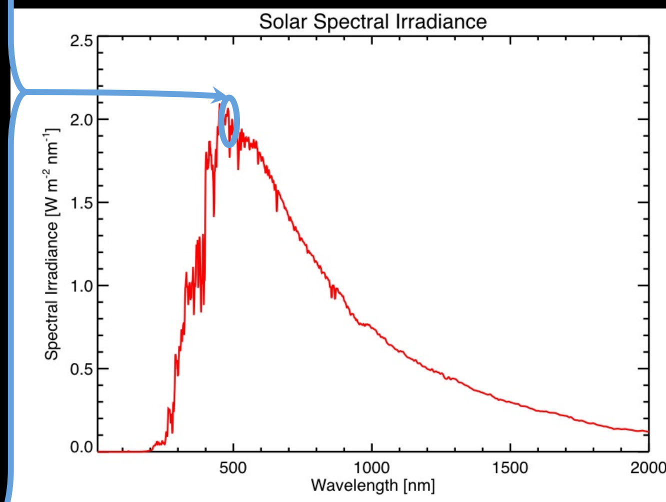




The Sun – Condensed to Total Irradiance



Images/plots courtesy of NSO, SOHO, SORCE

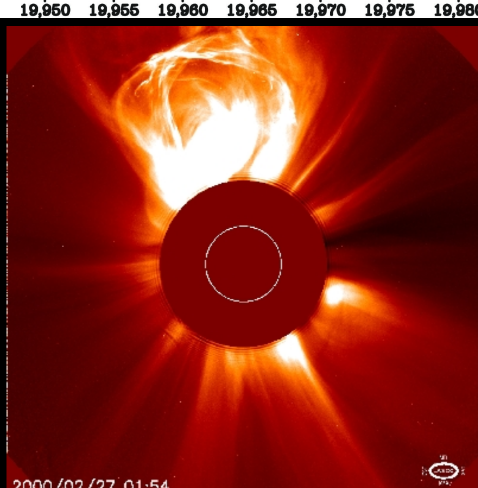


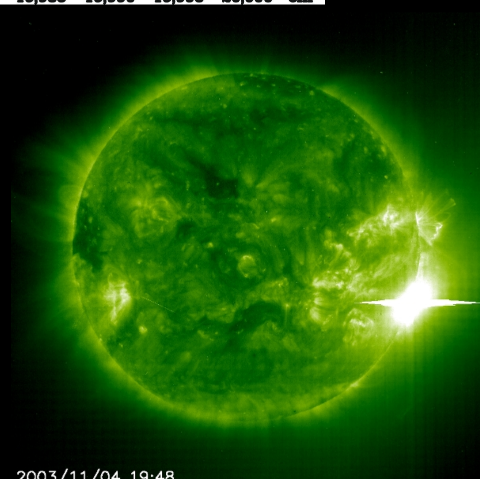
Spectral

Σ

1361 W/m^2

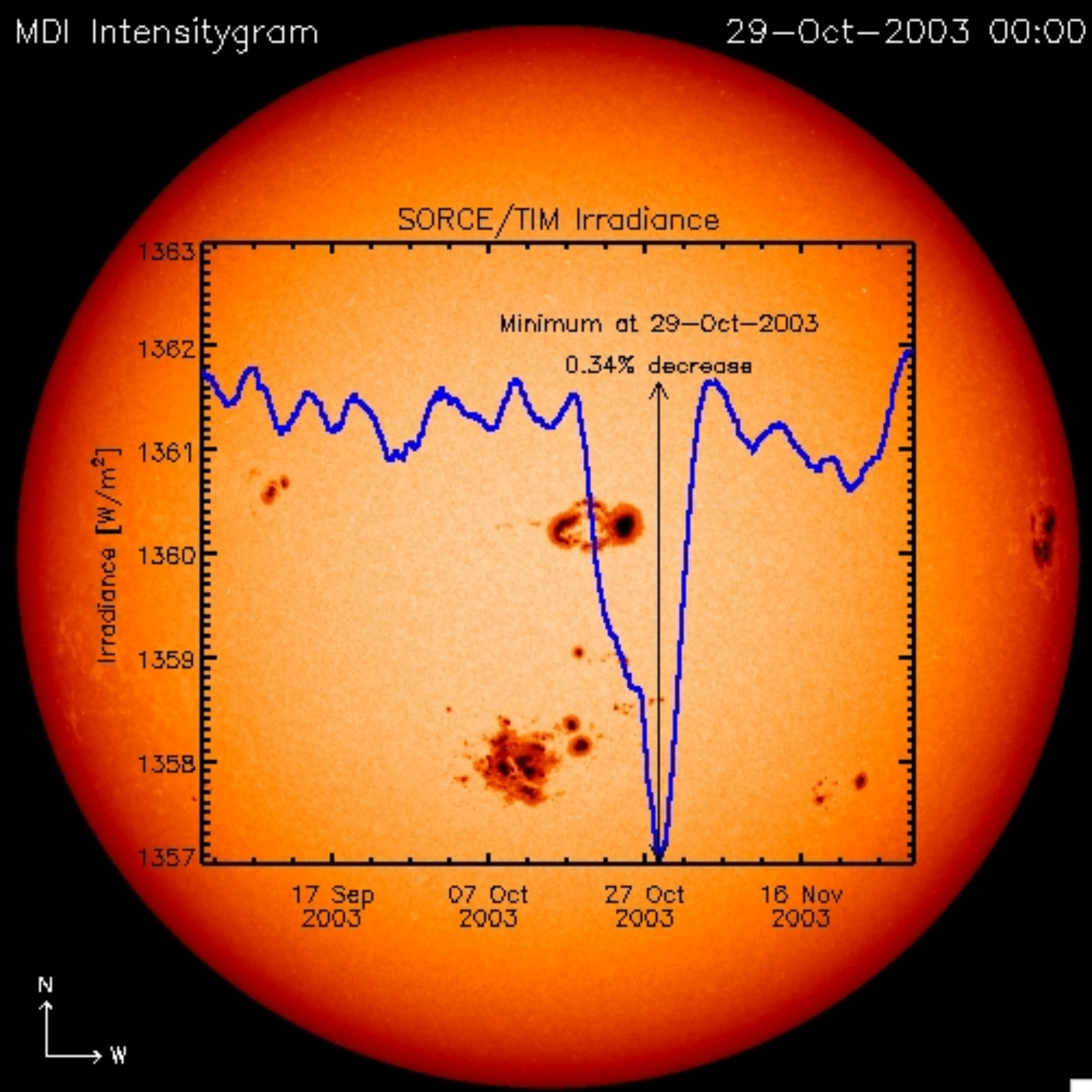
Total Solar Irradiance (TSI)

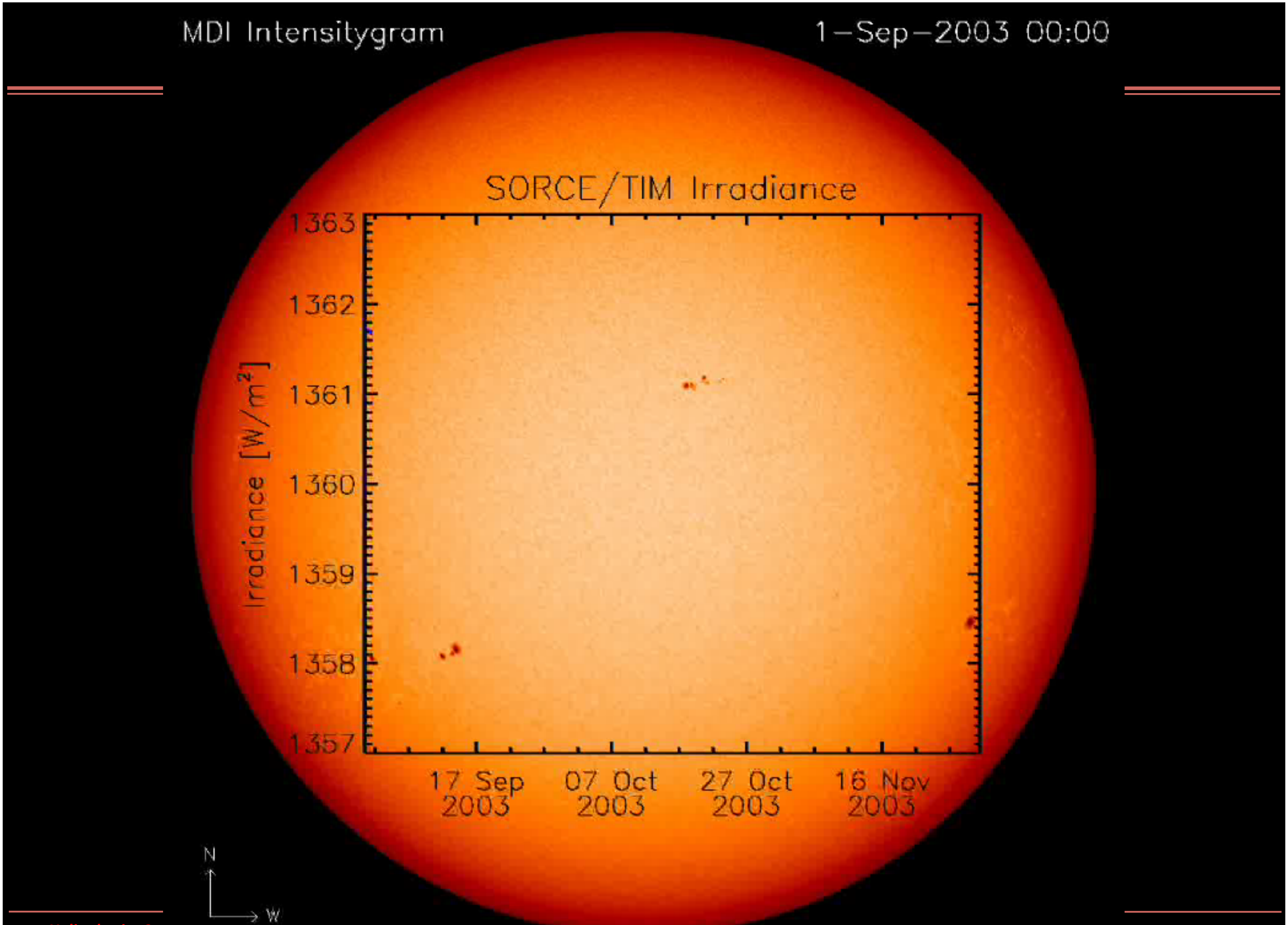




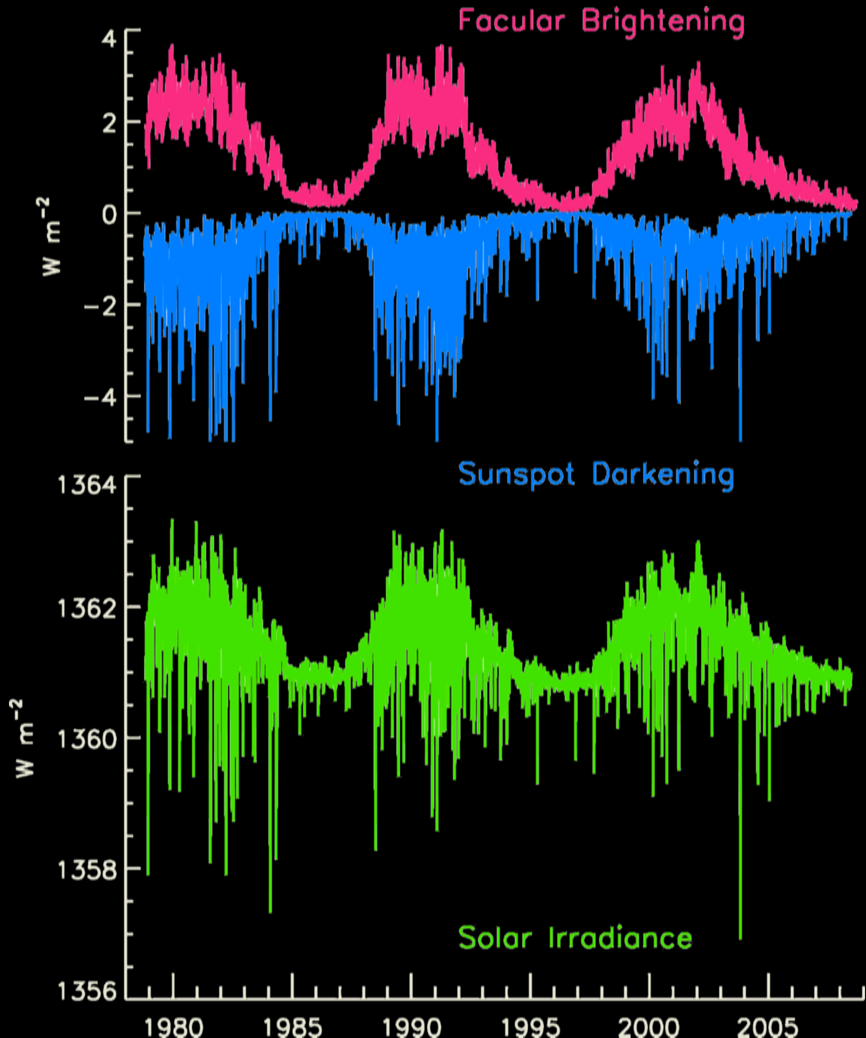
Spatial

SOHO/MDI Images and SORCE/TIM TSI

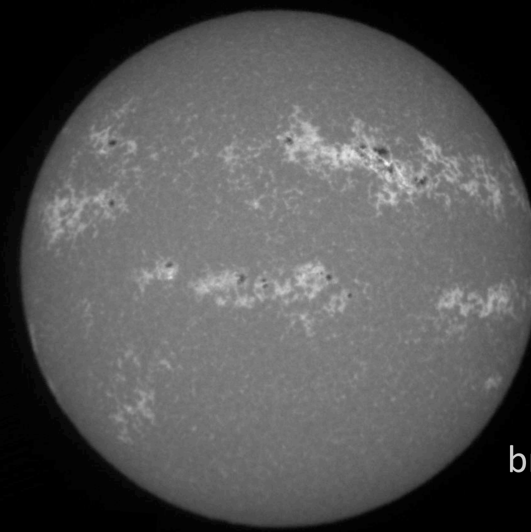



MDI Intensitygram
1-Sep-2003 00:00
SORCE/TIM Irradiance
Irradiance [W/m^2]
1363
1362
1361
1360
1359
1358
1357
17 Sep 2003
07 Oct 2003
27 Oct 2003
16 Nov 2003
N
W

Sunspots and Faculae



Net effect of sunspot darkening and facular brightening - model developed from observations of total solar irradiance (*Lean et al. 2005*)



bright faculae

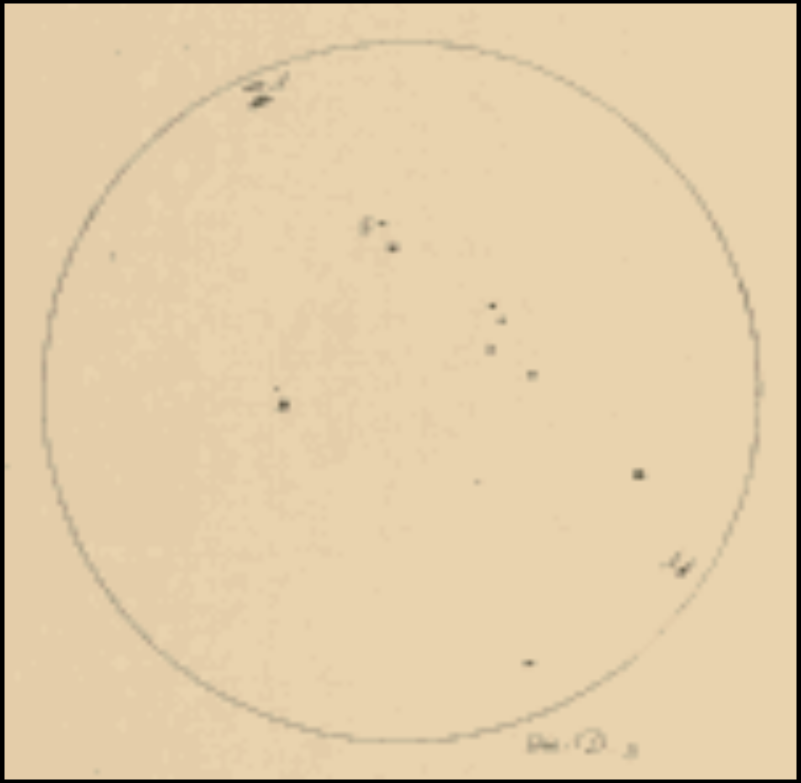
dark sunspots

courtesy of Judith Lean, NRL

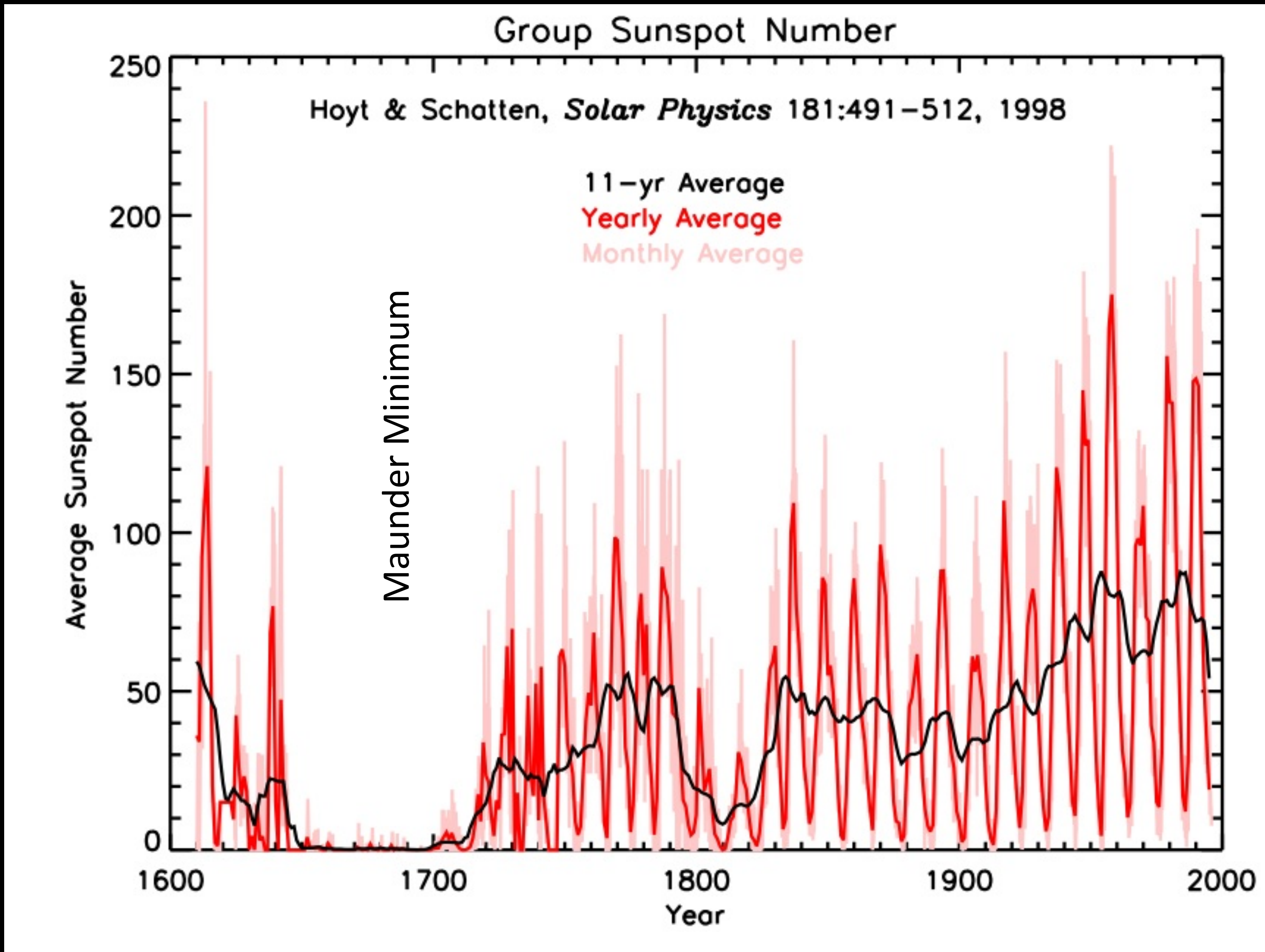
History - Use of Telescope

1610 - First telescopic observations of sunspots

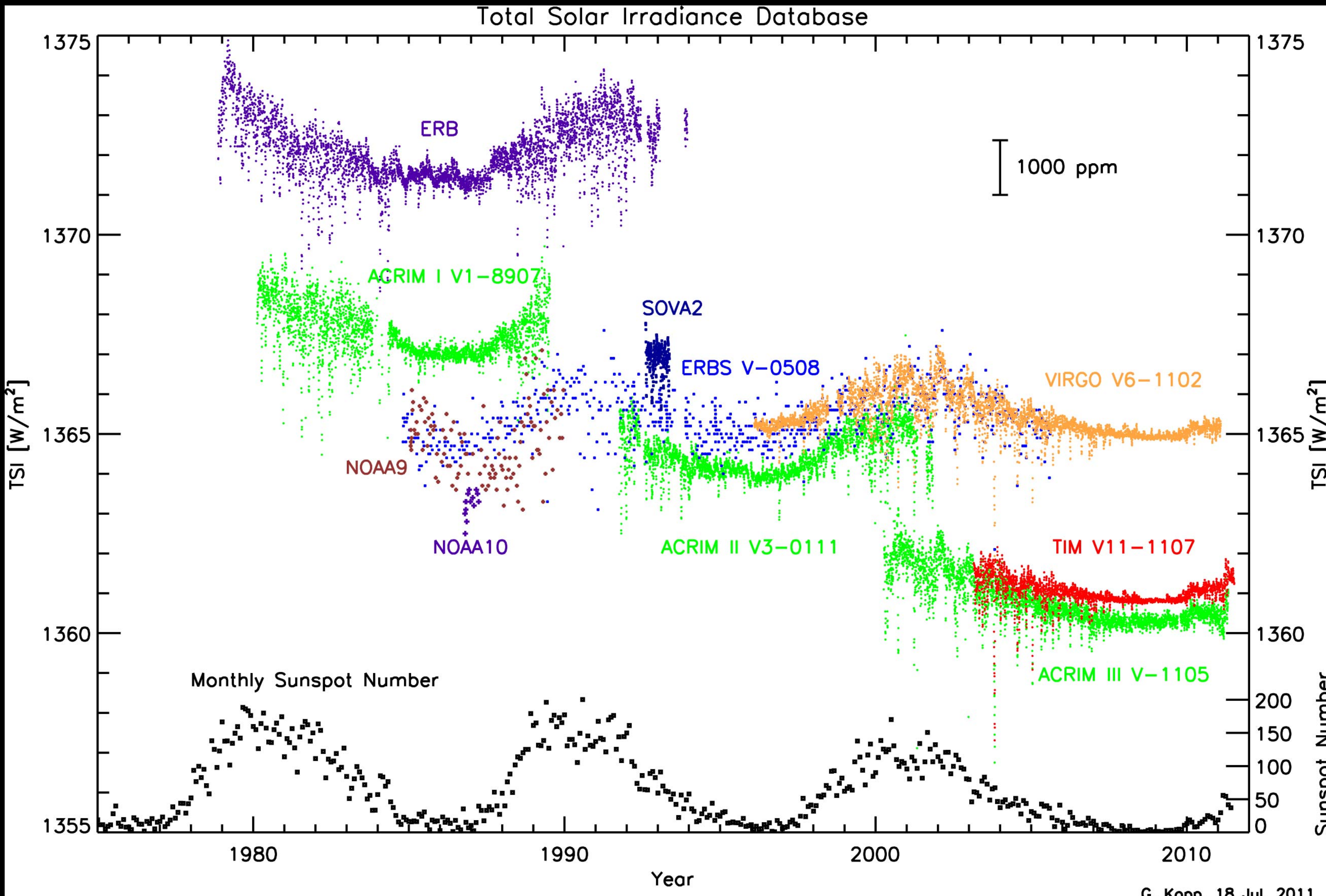
- Johann Goldsmid (1587-1616) in Holland
- Thomas Harriot (1560-1621) in England
- Galileo Galilei (1564-1642) in Italy
- Christoph Scheiner (1575-1650) in Germany



The 400-Year Sunspot Record

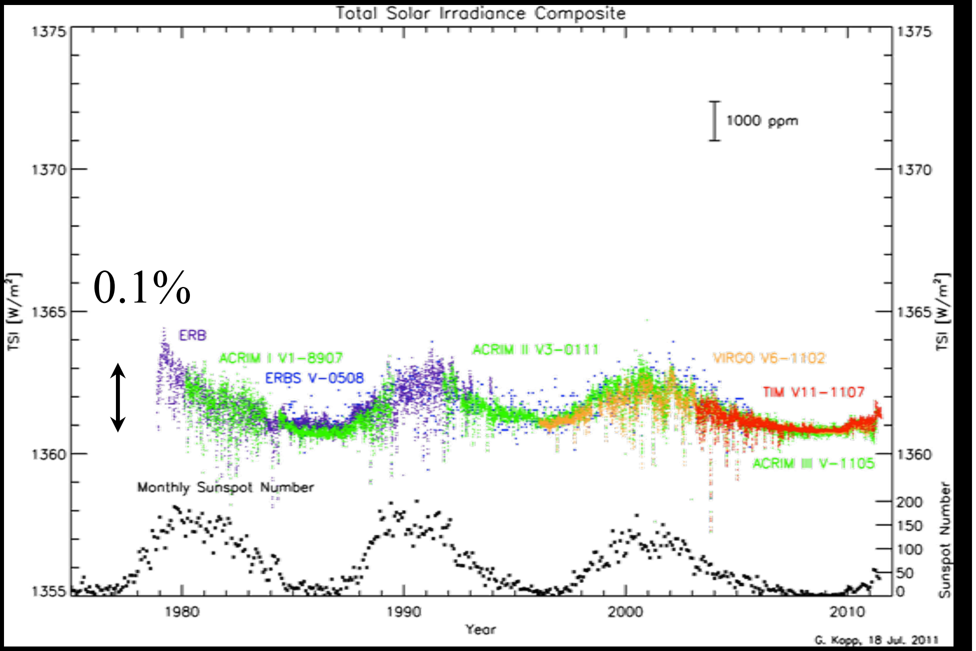


The *Spaceborne* Total Solar Irradiance Data Record



What Are the Time Scales of TSI Variability?

- 0.1-0.3% over a few days
  - Short duration causes negligible climate effect
- 0.1% over 11-year solar cycle
  - Small but detectable effect on climate
- 0.05-0.3% over centuries (unknown)
  - Direct effect on climate (Maunder Minimum and Europe's Little Ice Age)

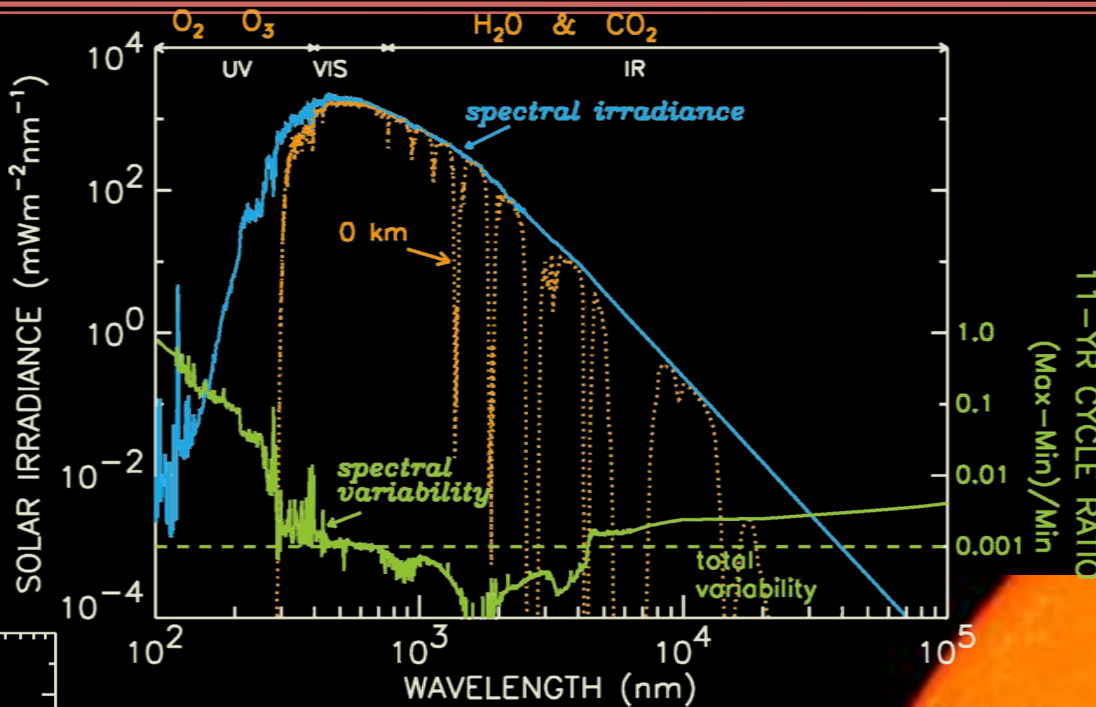


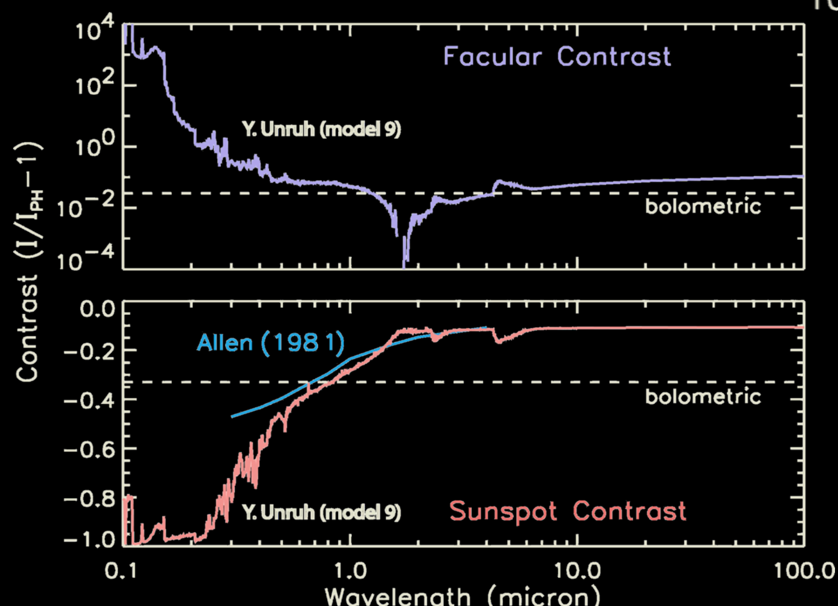
- An unequivocal link between climate change and TSI has been established over the past three decades.
  - Magnitude of natural climate forcing needs to be known for setting present and future climate policy regulating anthropogenic forcings.
  - Future long-term solar fluctuations, similar to historical variations, are not known from current measurements or TSI proxies.

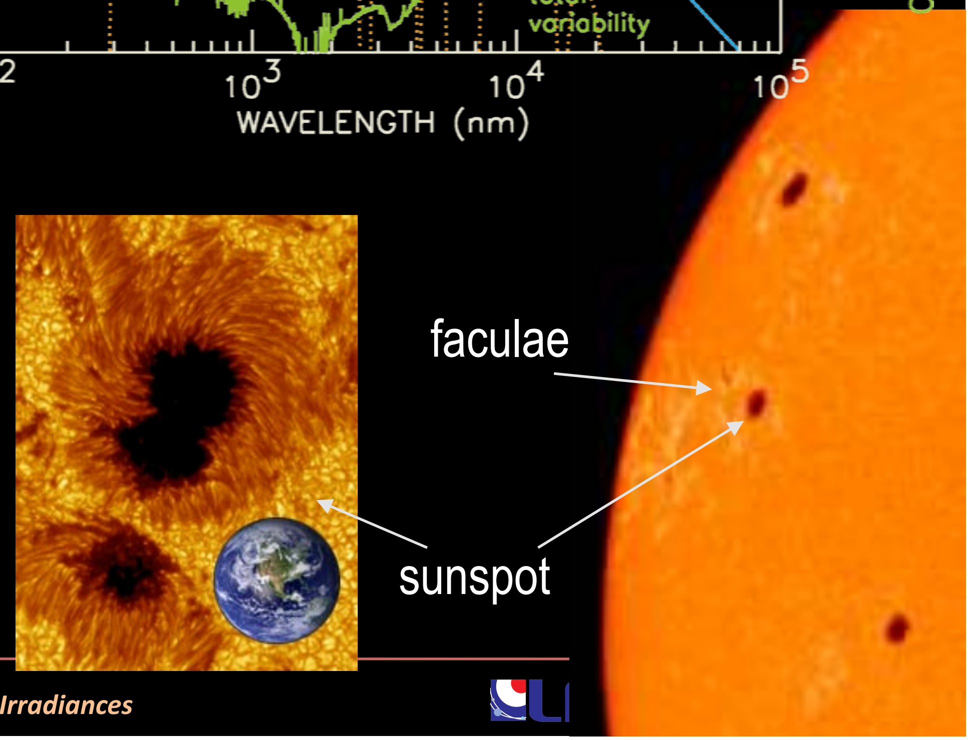
Solar Activity Causes Spectral Irradiance Variations

Solar variability sources are wavelength-dependent…

thus, irradiance variations depend on wavelength



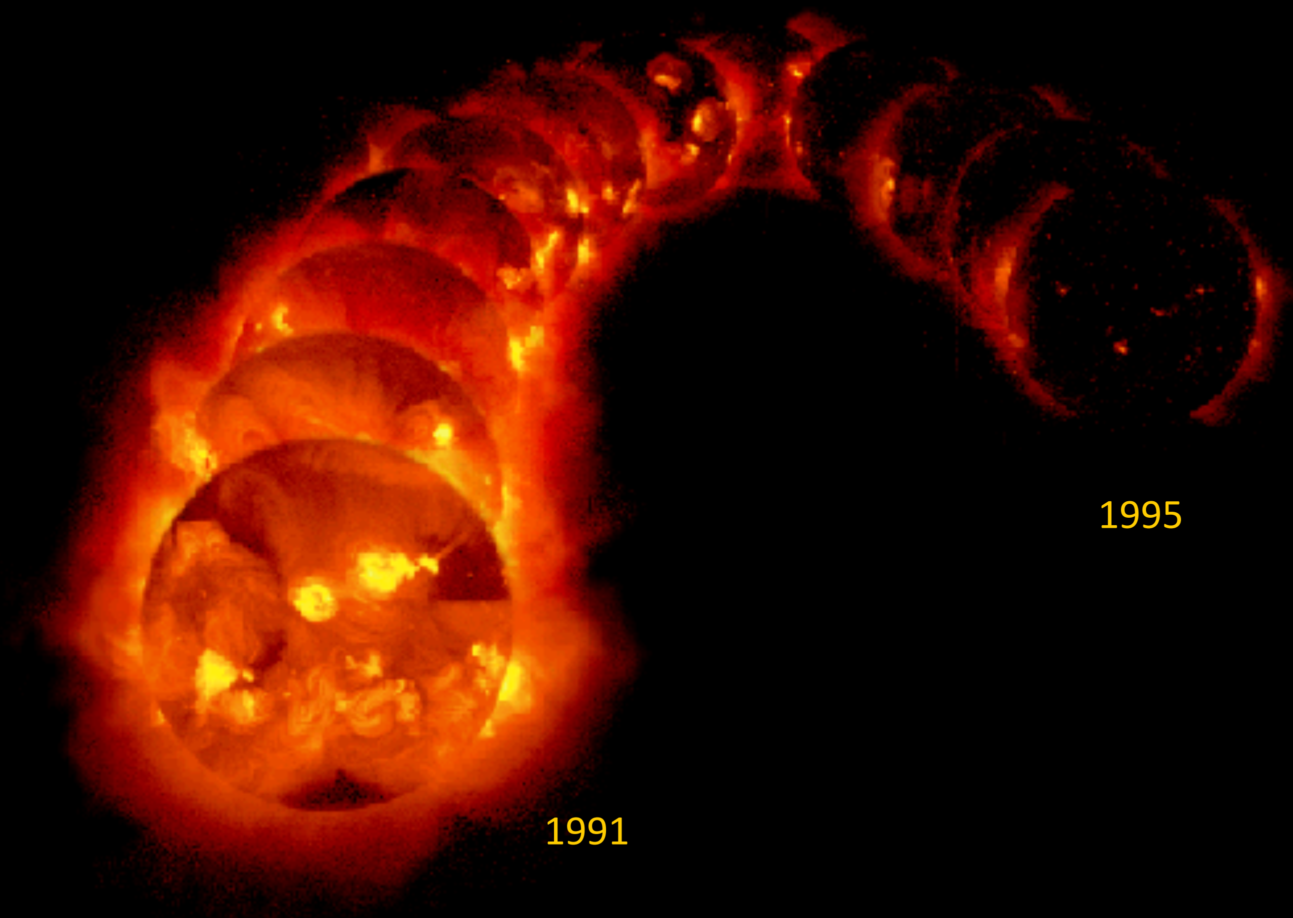




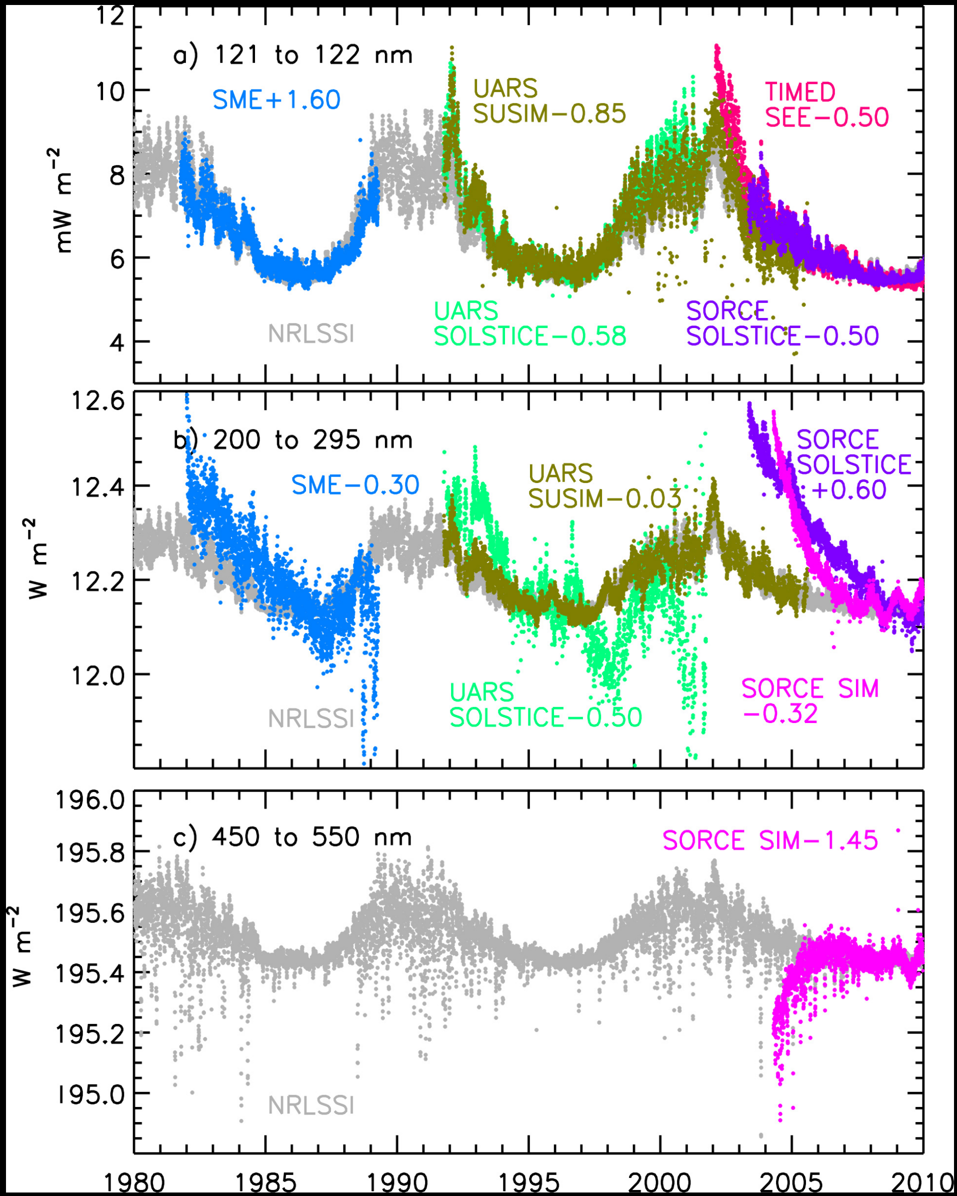
courtesy of Judith Lean, NRL

Spectral Irradiance Variations Across Spectrum

- Relative variability much greater at shorter wavelengths



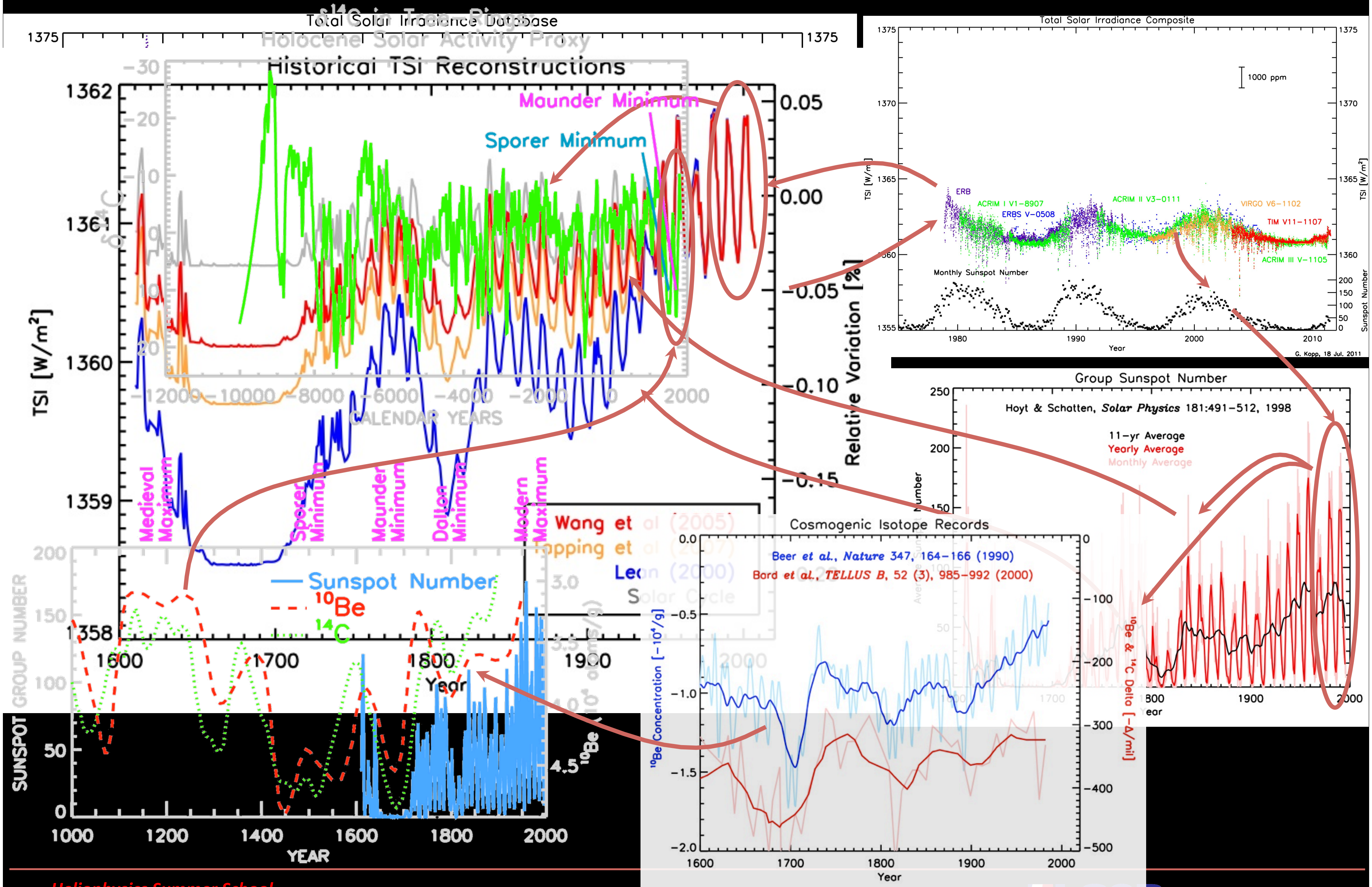
Measured Spectral Irradiances



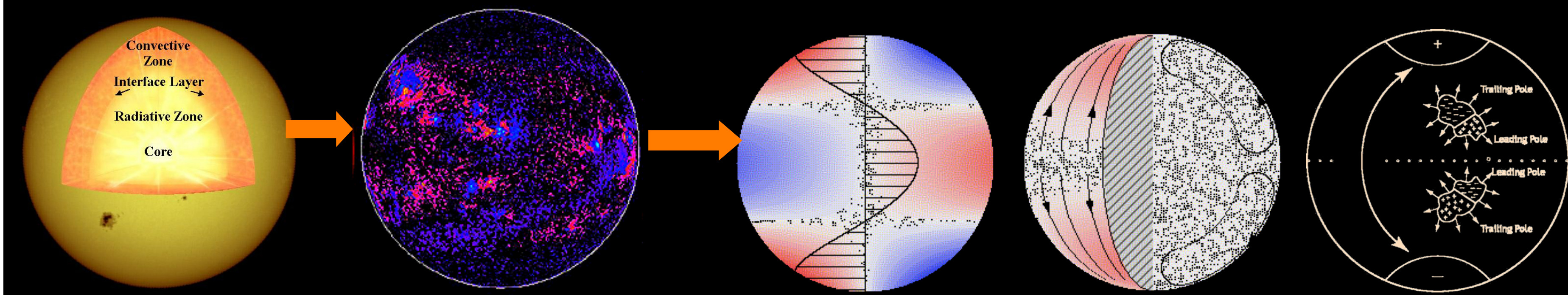
What Do You Need for a Climate Data Record?

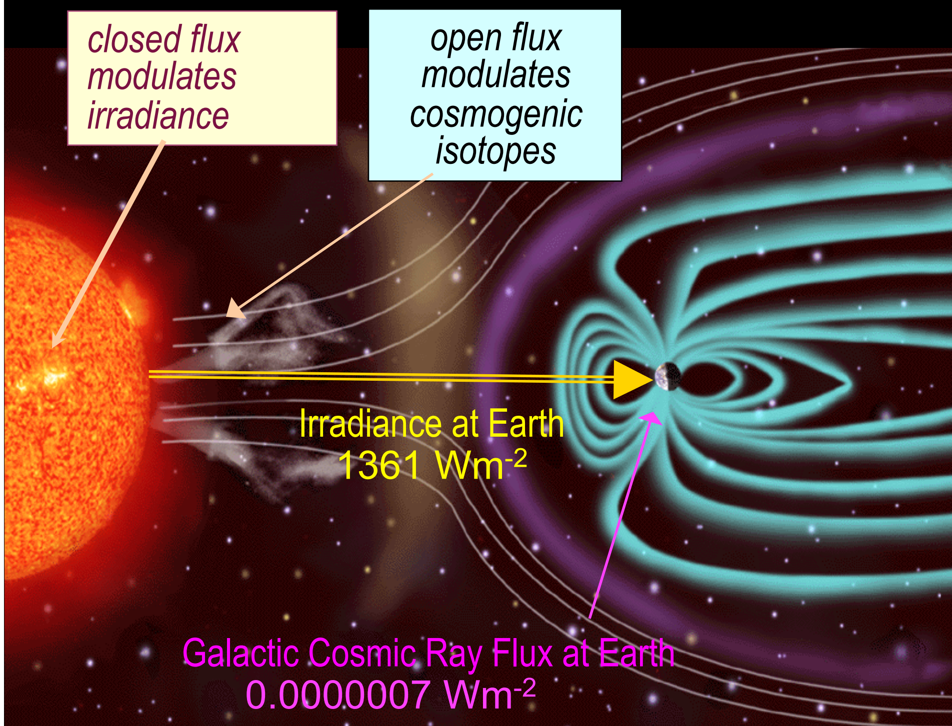
- Accurate measurements over long (climate scale) time periods
  - How accurate? How long?
    - Must detect small changes above natural fluctuations
    - Need estimates of expected variability
  - Drives modeling capability
  - Drives measurement stability and duration
- Patience...
  - ...Or a historical record...

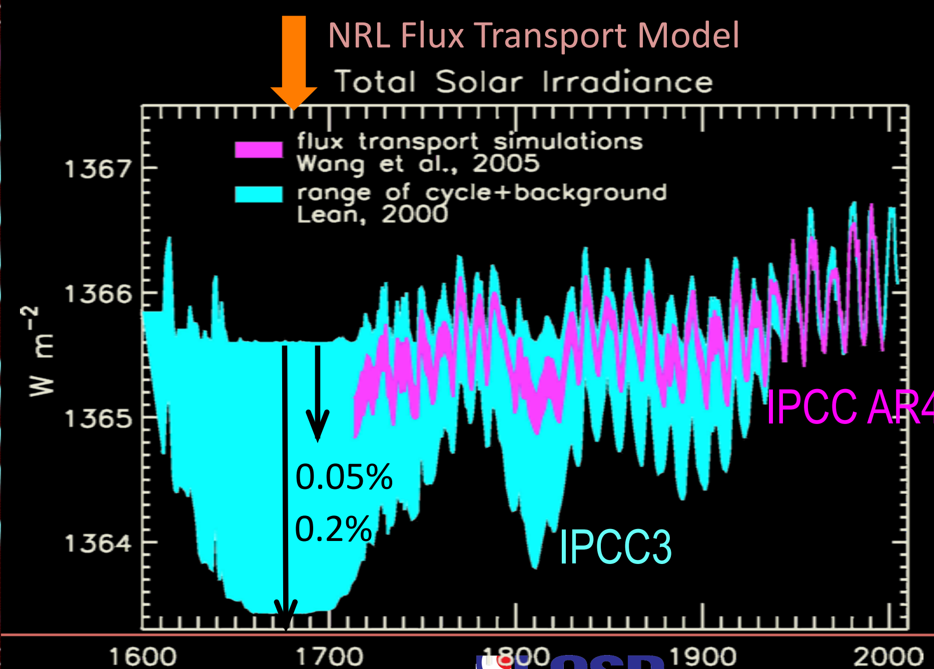
Constructing Historical Irradiances



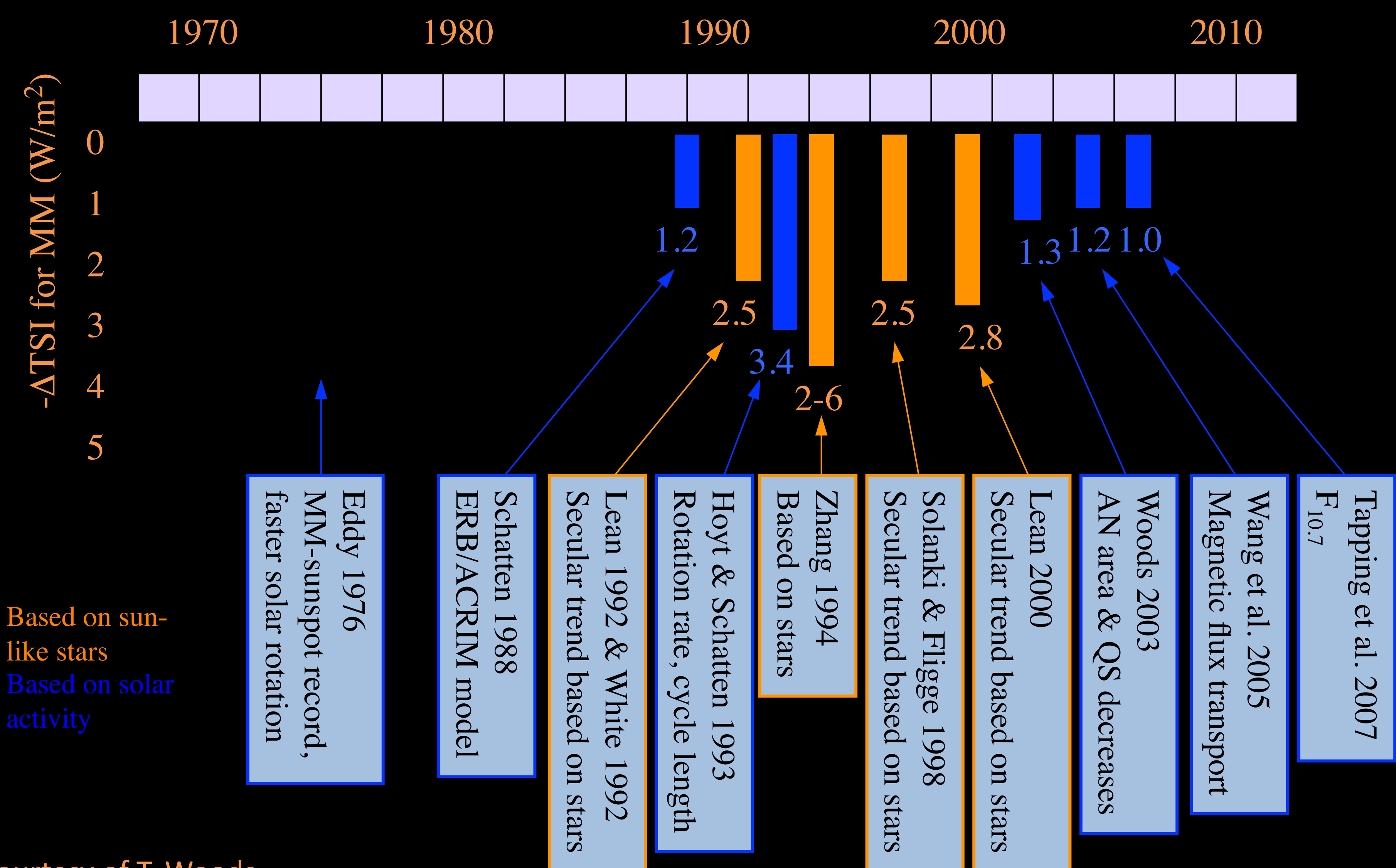
Estimating Long-Term Solar Variability







Maunder Minimum TSI Estimates

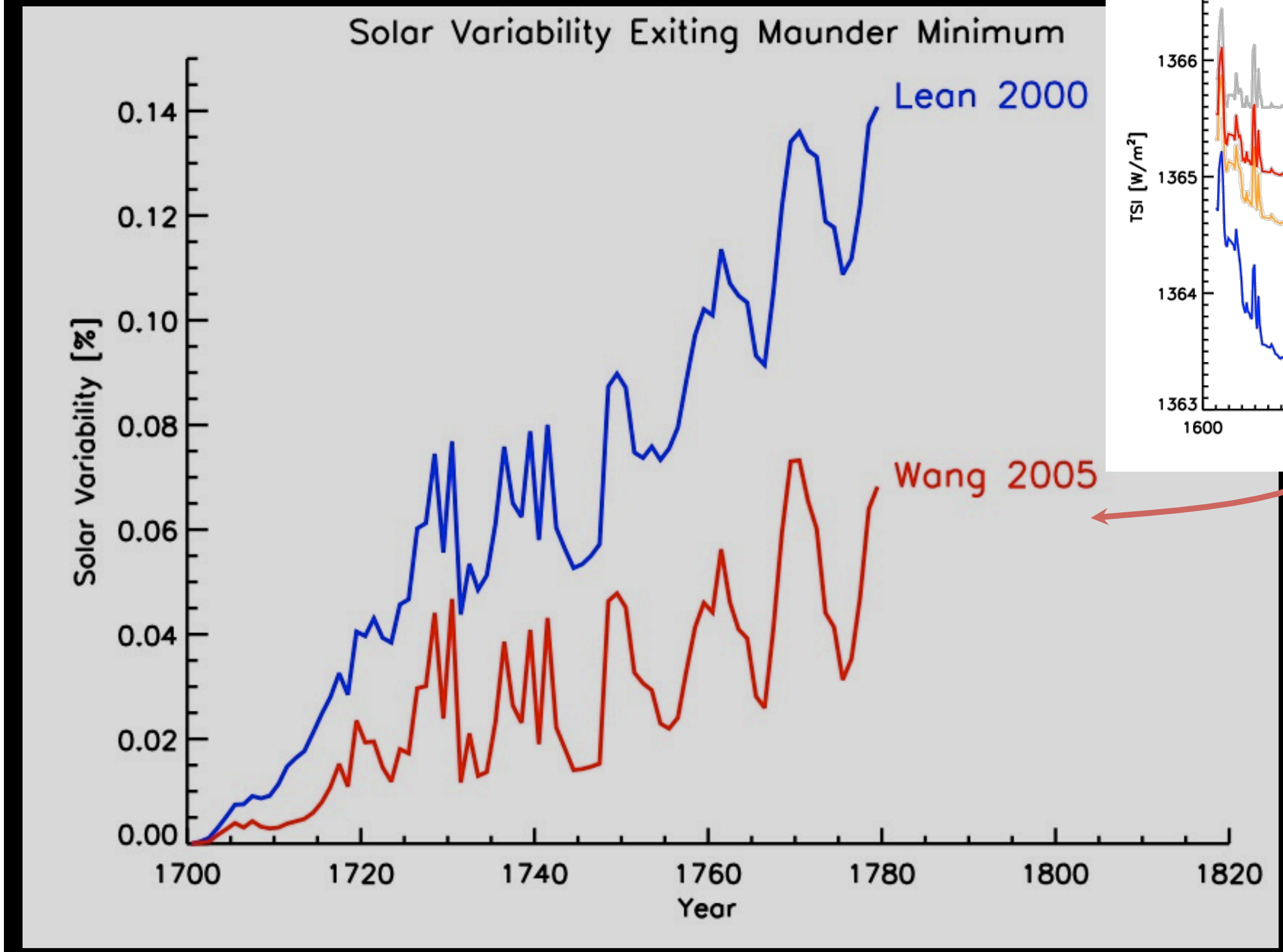


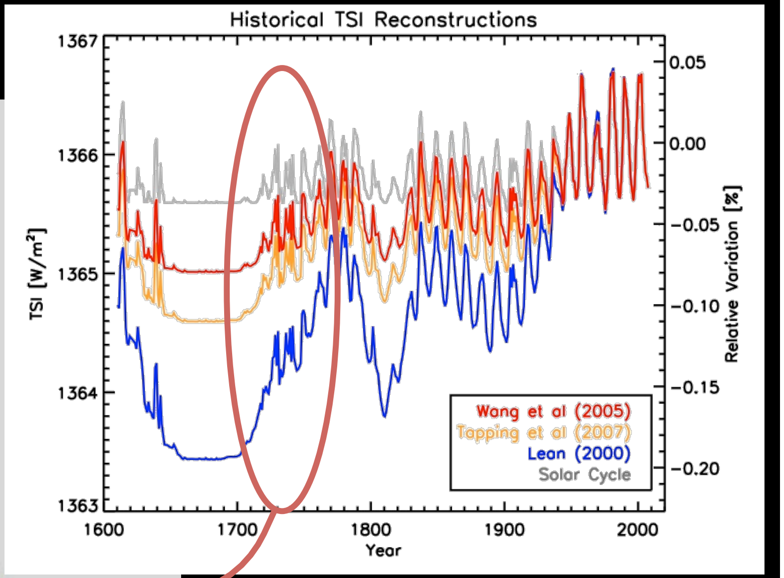
courtesy of T. Woods

Problems

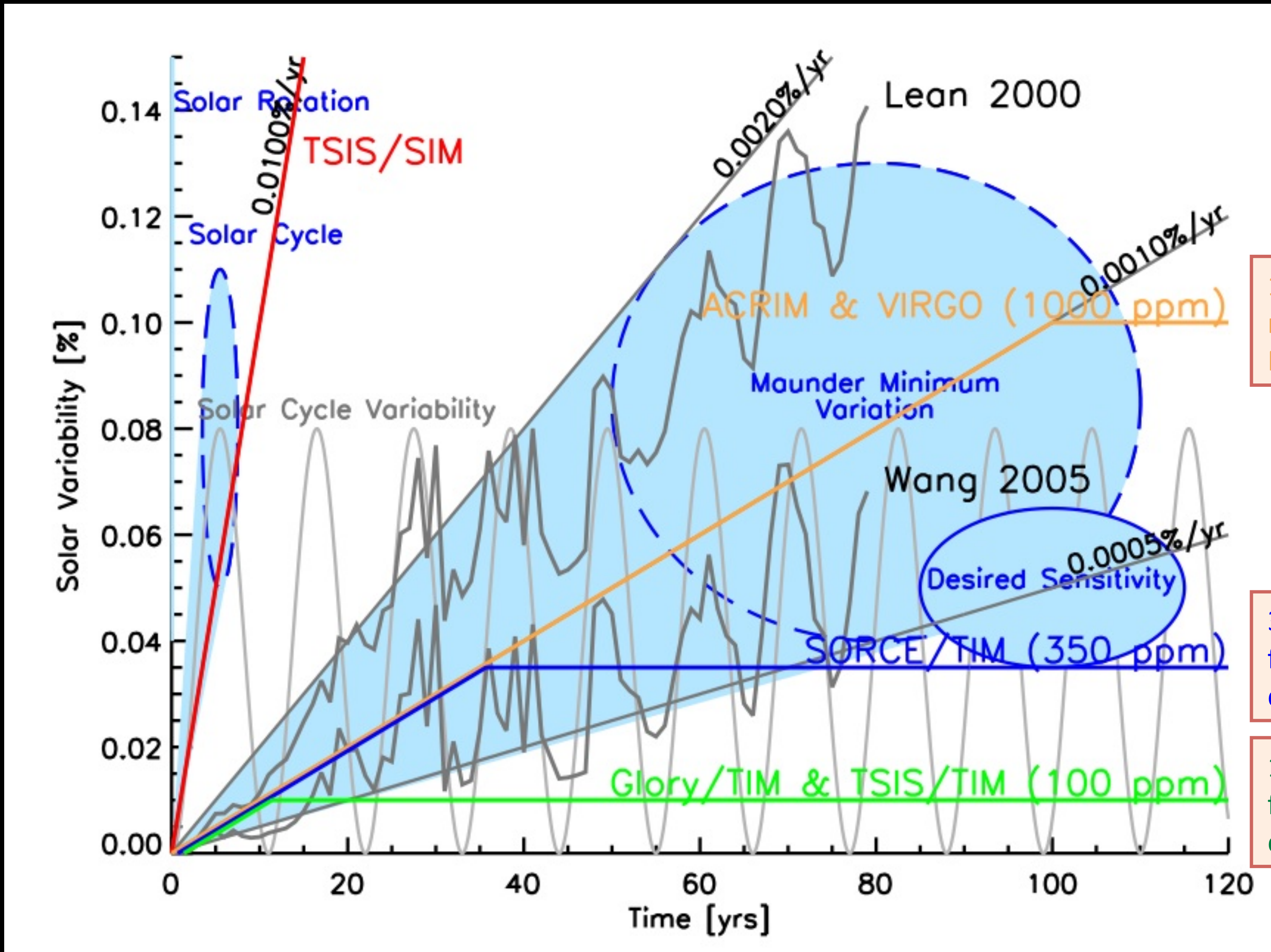
- Compute the sensitivity of Earth's temperature to TSI variations
  - Compute the expected temperature changes for a 0.04% lower Maunder Minimum TSI value
  - Compute the expected temperature changes for a 0.1% higher solar maximum TSI value (assuming the climate system has time to respond)

Climate-Quality Measurements Are Difficult





Solar Variability Drives Measurement Requirements



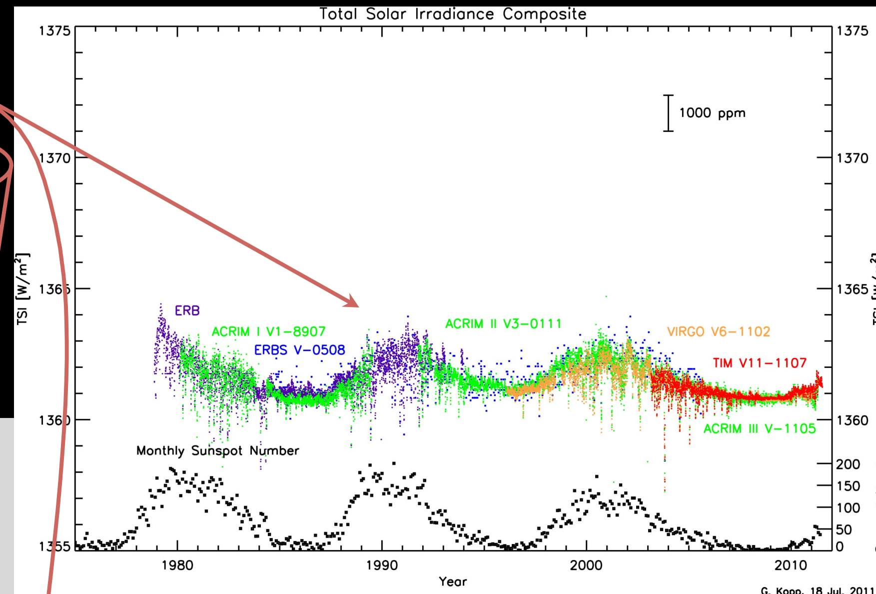
100-yrs needed for MM detection

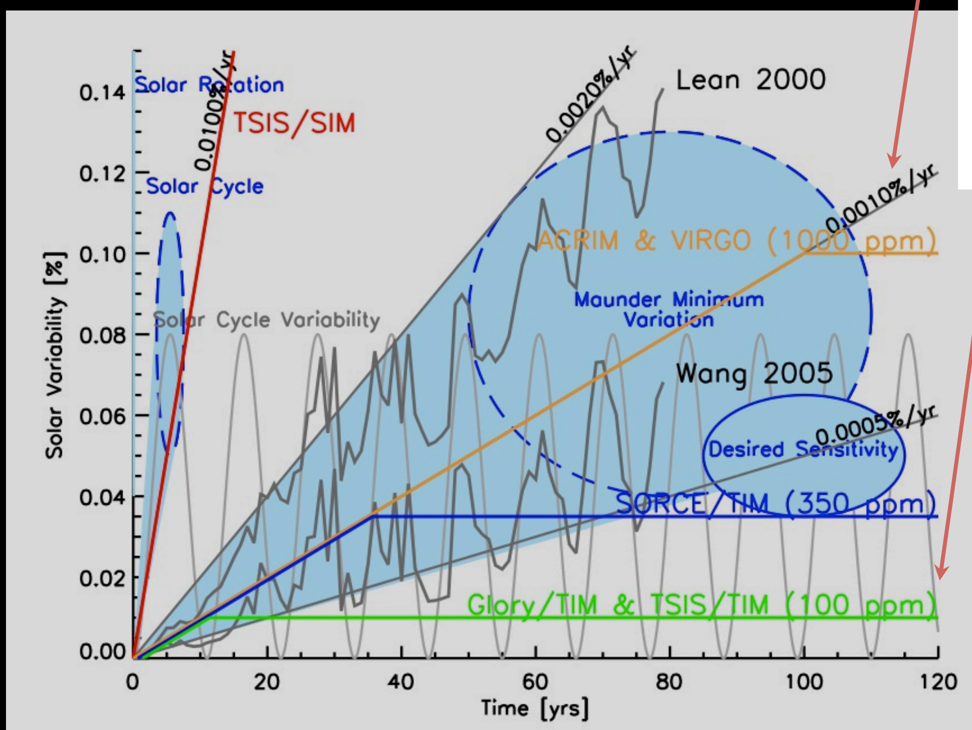
35-yrs needed for MM detection

10-yrs needed for MM detection

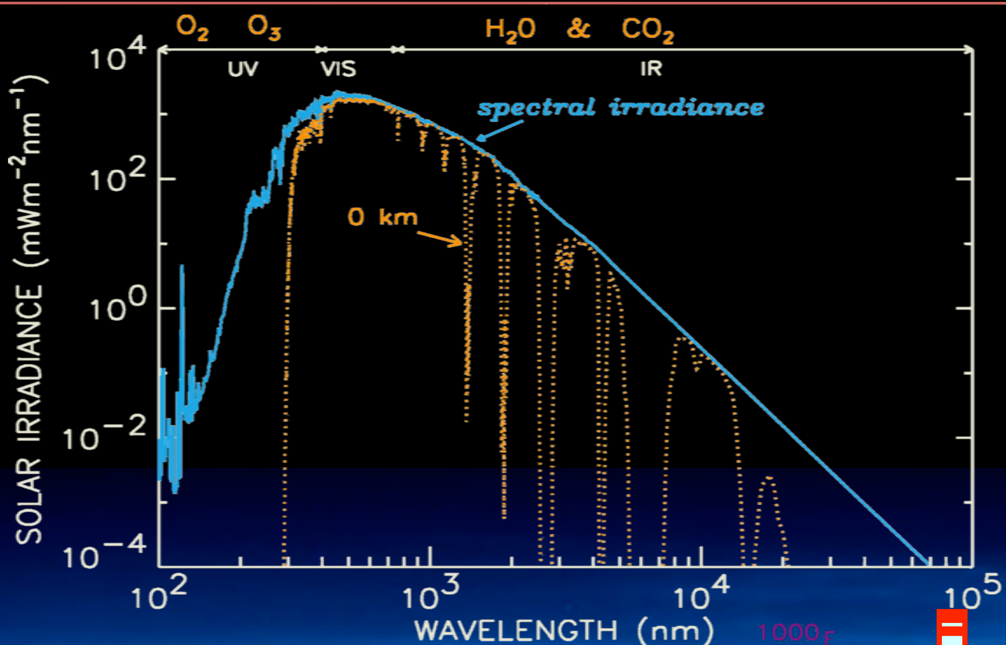
TSI Requirements To Address Climate Needs

- TIM Performance Requirements
  - Accuracy 0.01% (1 σ)
  - Stability 0.001%/yr (1 σ)
  - Noise 0.001% (1 σ)





Spectral Irradiances Needed for Atmospheric Studies

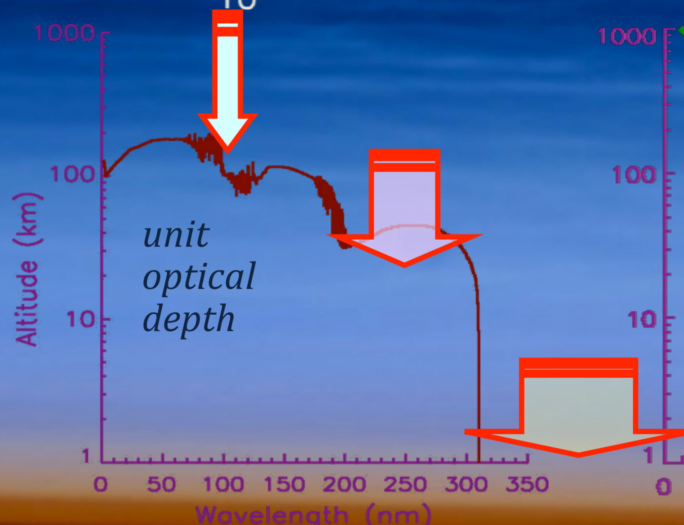


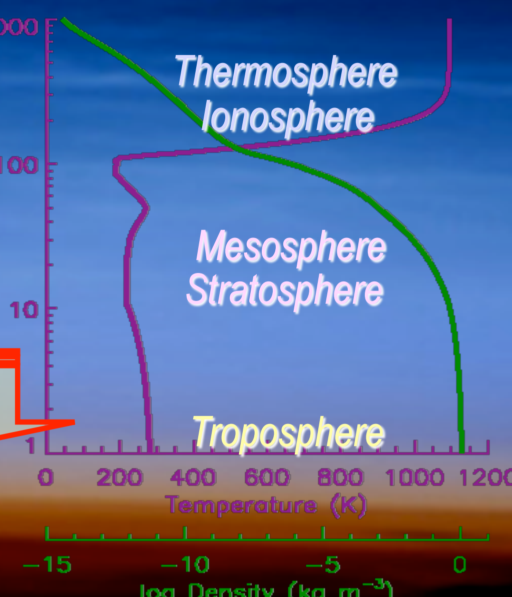
- MUV (200-300 nm) in stratosphere
- FUV (120-200 nm) and soft X-ray (1-10 nm) in upper stratosphere and lower thermosphere
- EUV (10-120 nm) in thermosphere

wavelengths < 120 nm
0.003±0.001 Wm^{-2}

wavelengths 120-300 nm
14.9±0.1 Wm^{-2}

wavelengths > 300 nm
1346 ± 0.5 Wm^{-2}

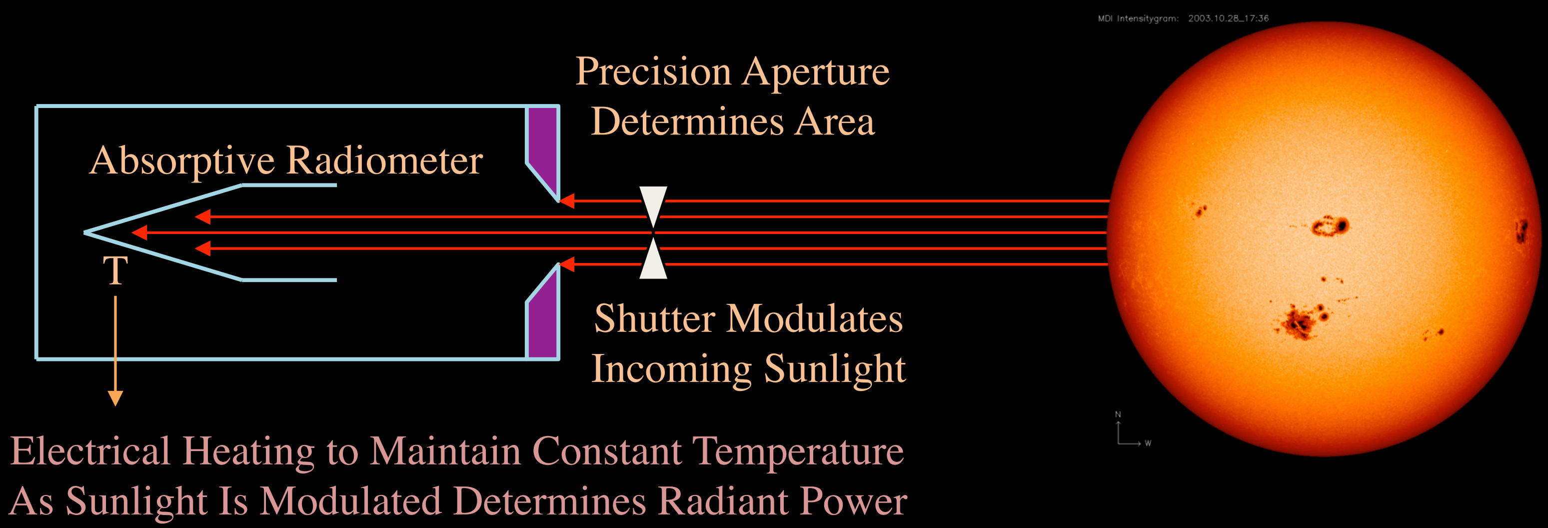




courtesy of Judith Lean, NRL

Irradiance Measurement Fundamentals

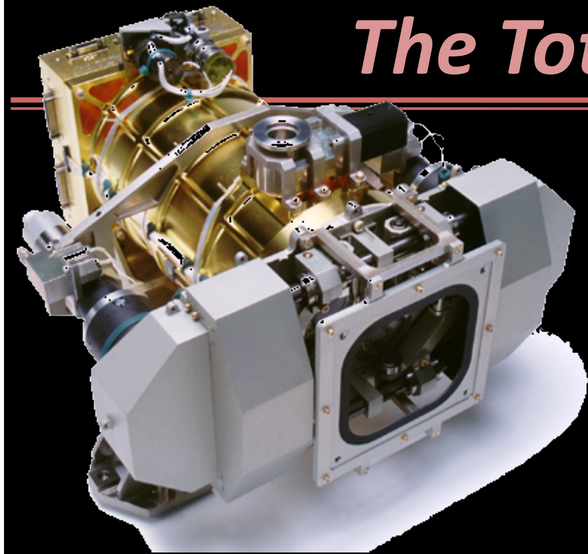
- Total irradiance (i.e. 1361 W/m^2) requires two measurements:
  - Power
  - Area



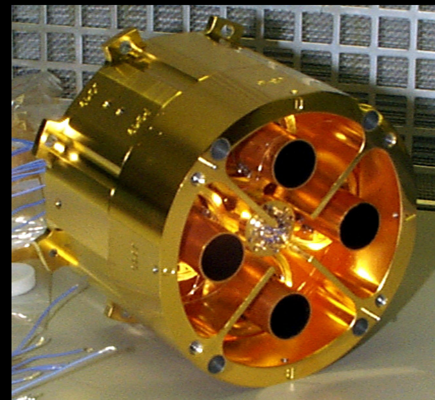
Methods of Spectral Selection

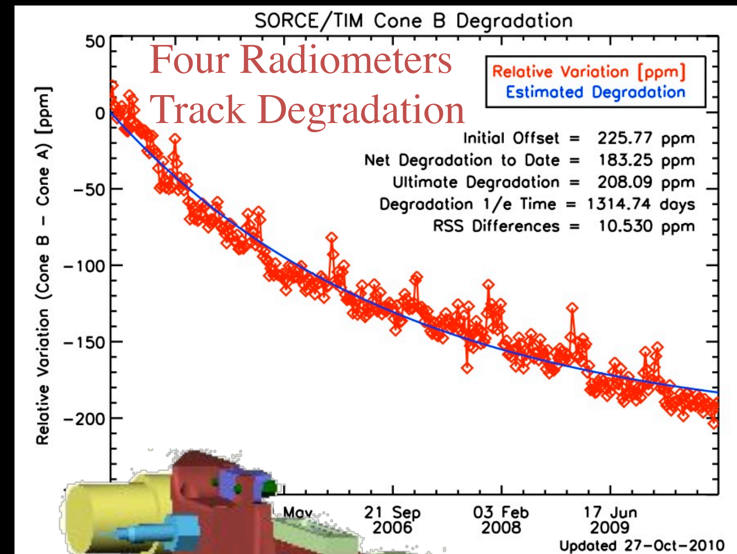
- Common methods
  - Prism
  - Grating
  - Filters
- Spectral solar irradiance signal levels are much lower
  - Limits accuracies
  - Requires sensitive detectors
- Units are power/area/wavelength unit
  - i.e. $W/m^2/nm$

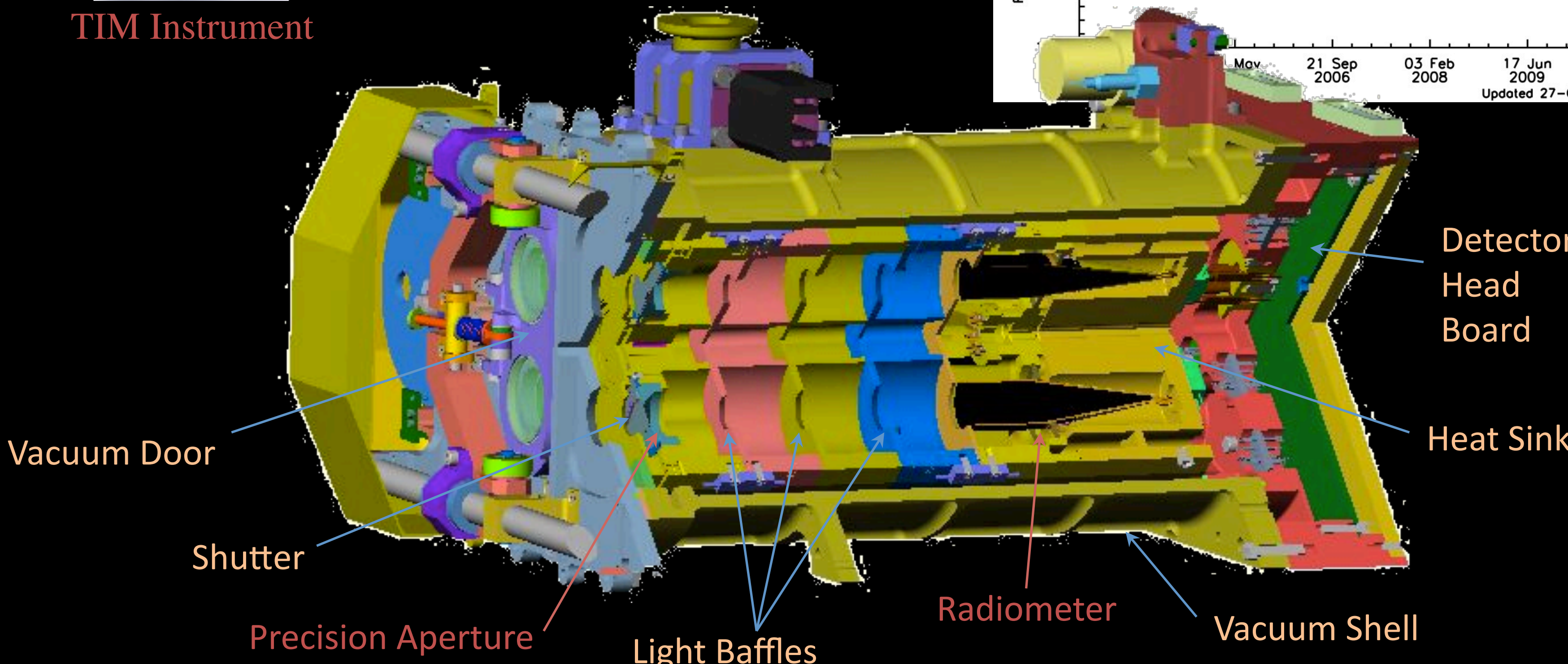
The Total Irradiance Monitor (TIM)



TIM Instrument







Problem

- Calculate the calibration accuracy needed of aperture area knowledge to achieve 0.01% accuracy
  - Assume a 1-cm diameter aperture

Accurate Radiometry Requires "Subtle" Corrections

- Aperture knowledge accuracy

$$\frac{\Delta A}{A} = \frac{2\pi r \cdot \Delta r}{\pi r^2} = 10^{-4} \ (100 \text{ ppm}) \ \Rightarrow \ \Delta r = 200 \text{ nm}$$

- Doppler correction due to S/C orbit velocity

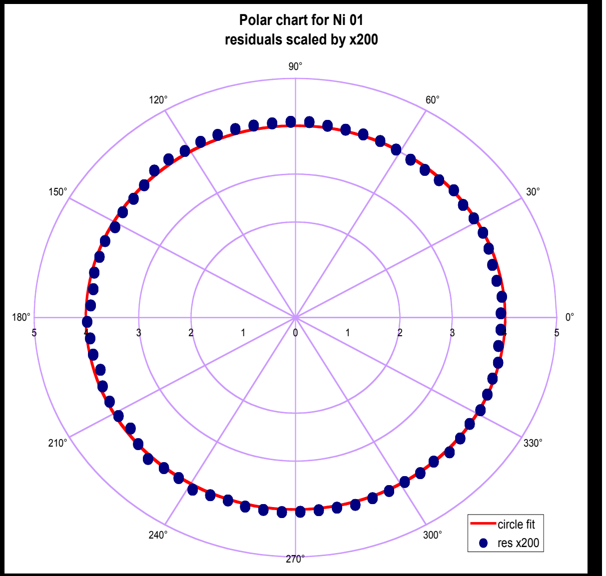
$$2\frac{v}{c} = 2 \cdot \frac{8\text{x}10^5 \text{ cm/s}}{3\text{x}10^{10} \text{ cm/s}} \approx 5\text{x}10^{-5} \ \Rightarrow \ \pm 50 \text{ ppm}$$

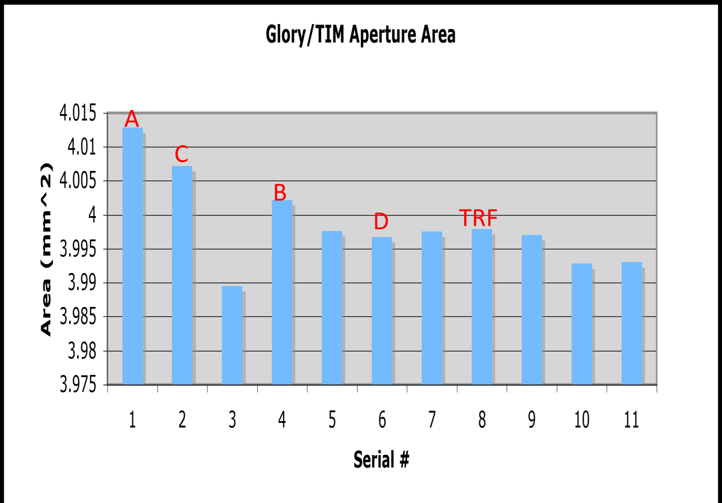
- Thermal (mid-IR) background

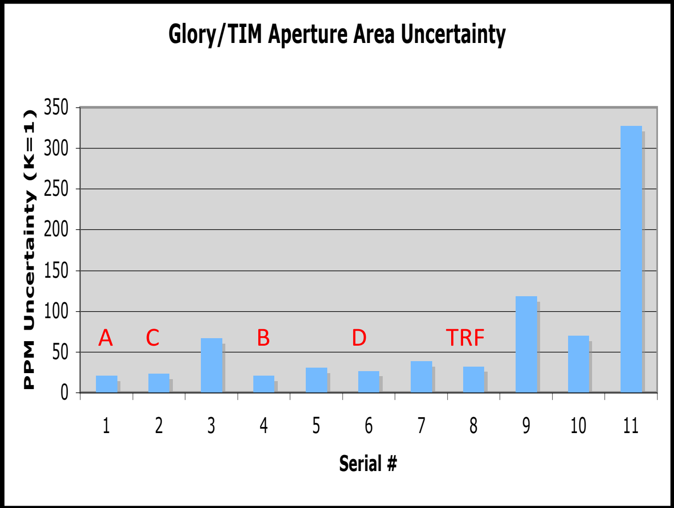
$$\sigma T^4 \cdot \text{Cone Entrance Area} = 8\text{x}10^5 \text{ ergs} \ \Rightarrow \ 1.2\text{x}10^6 \text{ ppm}$$

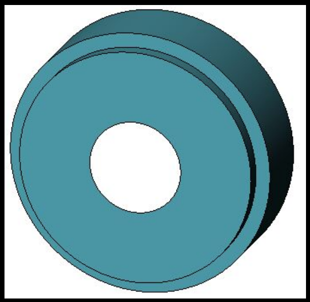
Apertures Calibrated by NIST to ~25 ppm

- Ni-coated Al apertures have sharp knife edges
- Area calibrated by NIST at the Optical Technology Division
  - Uncertainty ~25 ppm
- Coefficient of thermal expansion characterized
  - Uncertainty = 0.1 ppm/C
- Corrections for pressure applied



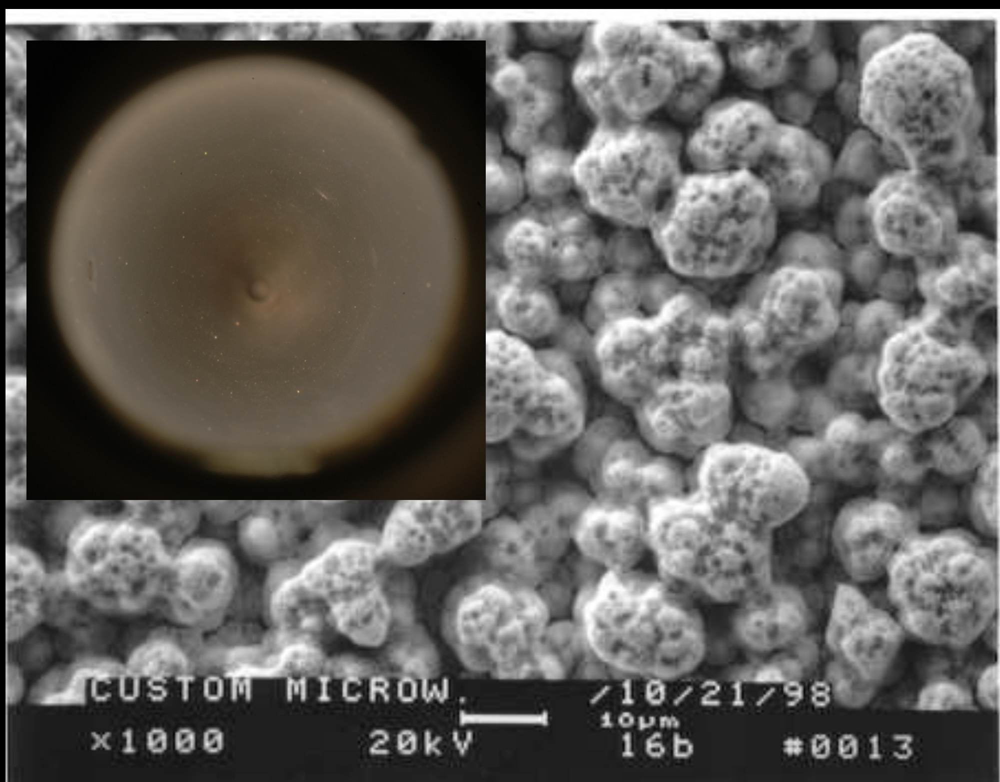






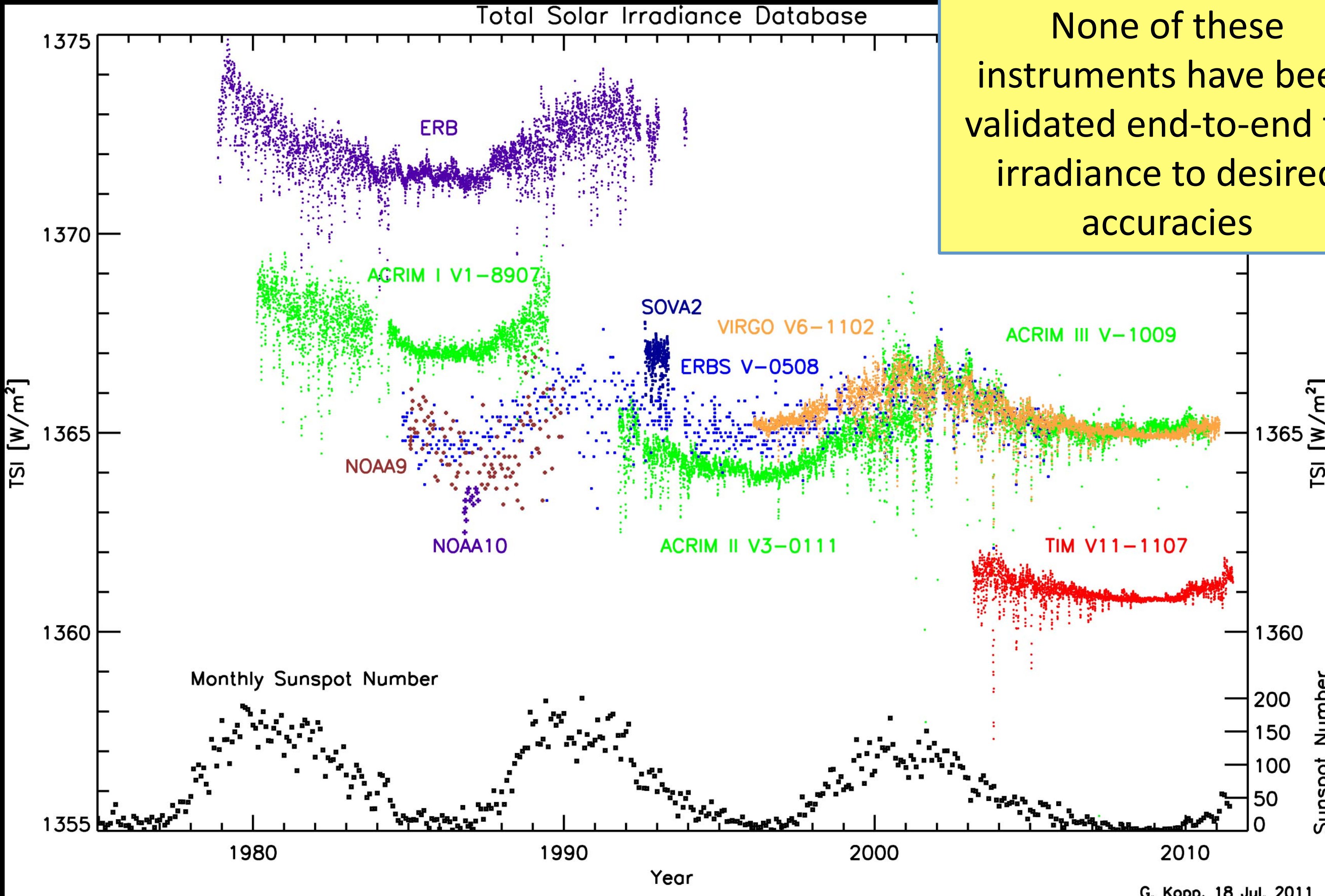
TIM Cavities Are Highly Absorptive

- Cone geometry – dominant losses are from first bounce
  - Cylindrical entrance reduces losses
  - 10° half-angle helps trap specular reflections
  - Measure ~150 ppm reflectance



- Absorptive surface – NiP Black
  - Stable
    - Radiation hard
    - UV insensitive
  - Thermally and electrically conductive

So What Causes the Instrument Offsets?



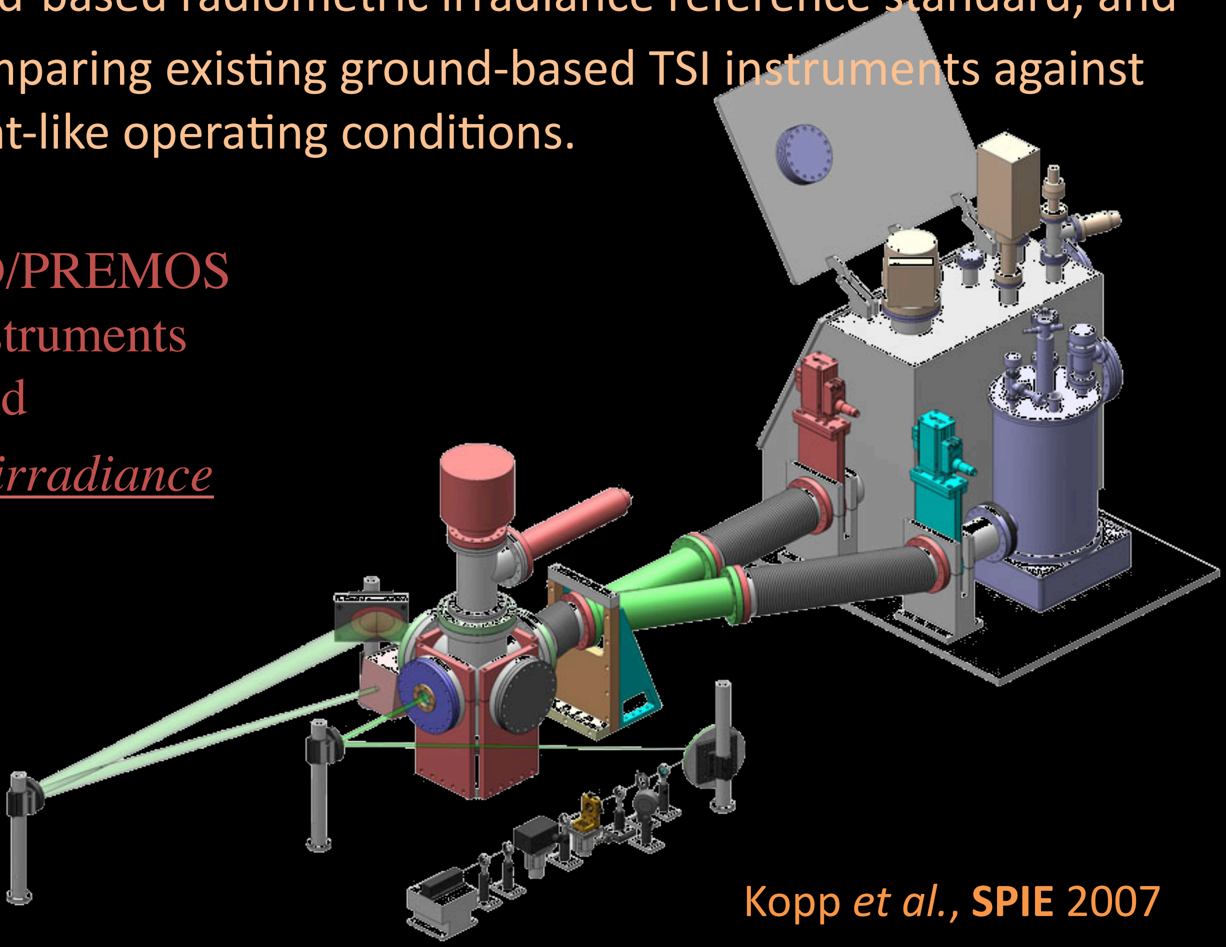
None of these instruments have been validated end-to-end for irradiance to desired accuracies

TSI Radiometer Facility (TRF) Measures Irradiance

The TRF

1. Improves the calibration accuracy of future TSI instruments,
2. Establishes a new ground-based radiometric irradiance reference standard, and
3. Provides a means of comparing existing ground-based TSI instruments against this standard under flight-like operating conditions.

- Glory/TIM and PICARD/PREMOS are the first flight TSI instruments to be validated end-to-end
- First facility to measure *irradiance*
  - at solar power levels
  - in vacuum
  - at desired accuracies

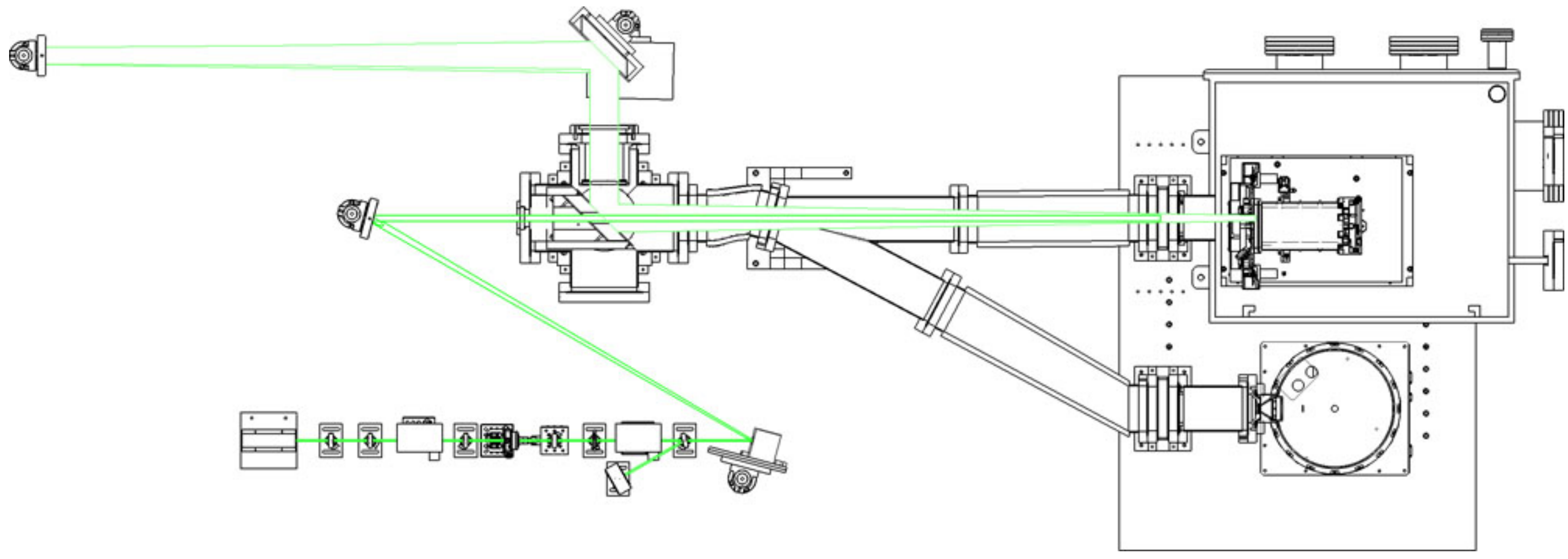


Kopp *et al.*, **SPIE** 2007

Common Vacuum Beam Path

- The facility is designed to allow a TSI instrument or the cryogenic radiometer to sample exactly the same beam
  - Beam is not displaced, instruments are placed at the same location in a stationary beam

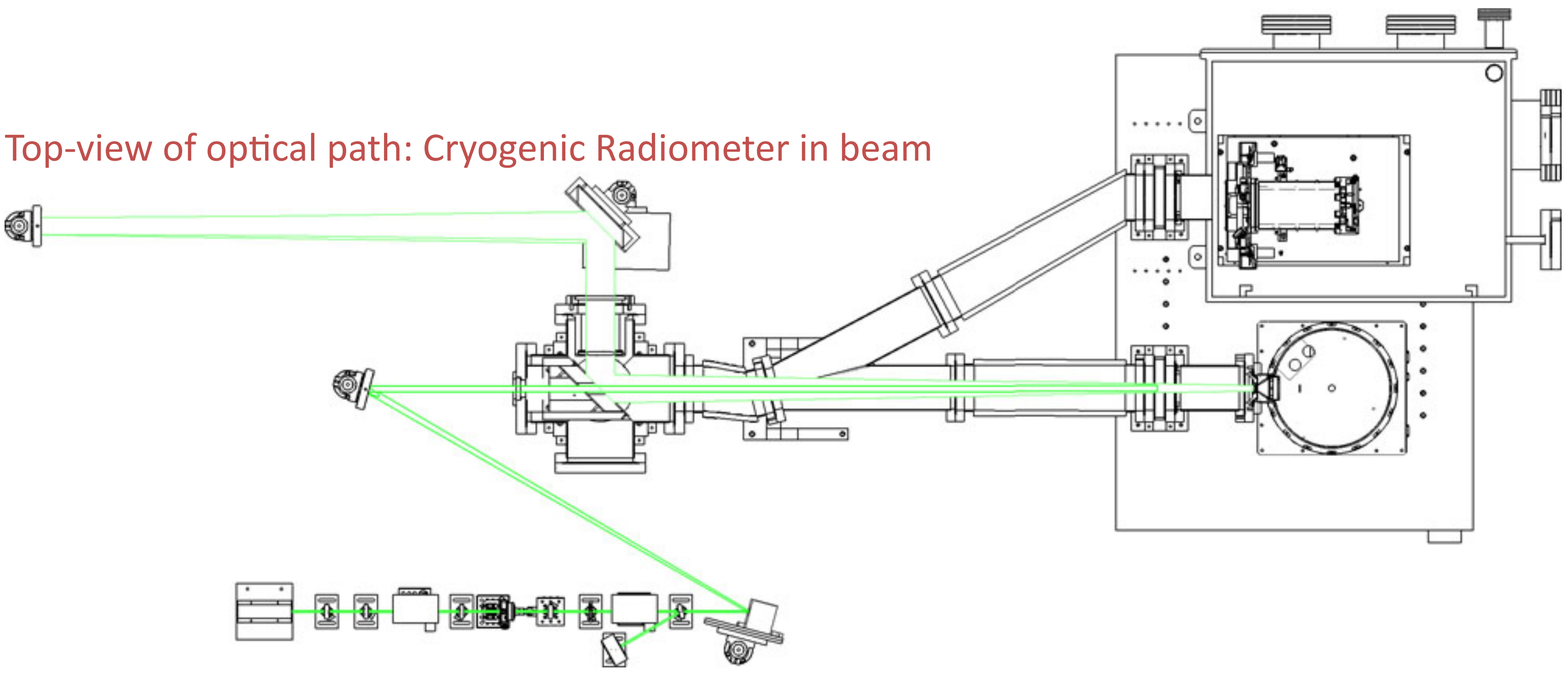
Top-view of optical path: TSI instrument in beam



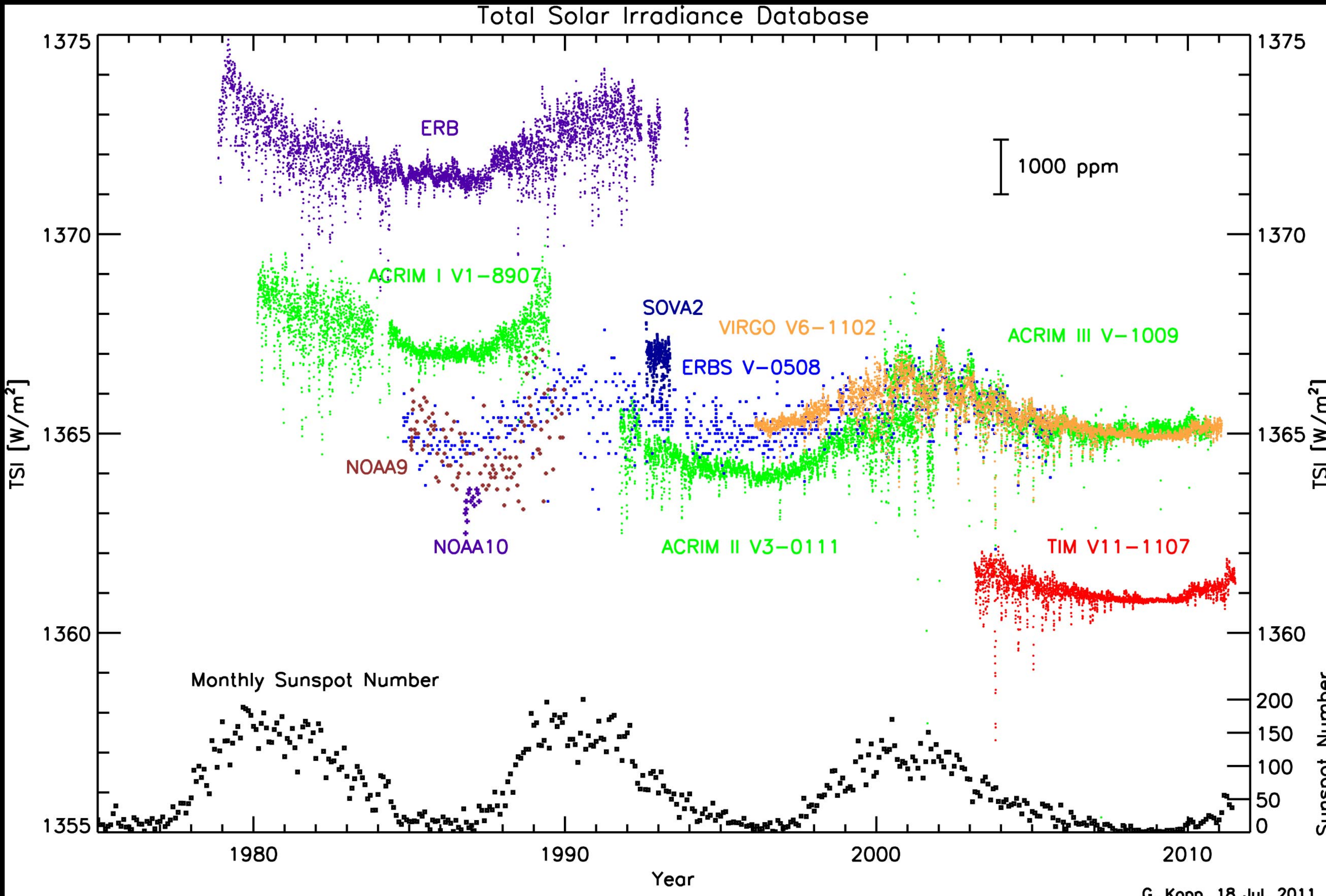
Common Vacuum Beam Path

- The facility is designed to allow a TSI instrument or the cryogenic radiometer to sample exactly the same beam
  - Beam is not displaced, instruments are placed at the same location in a stationary beam

Top-view of optical path: Cryogenic Radiometer in beam



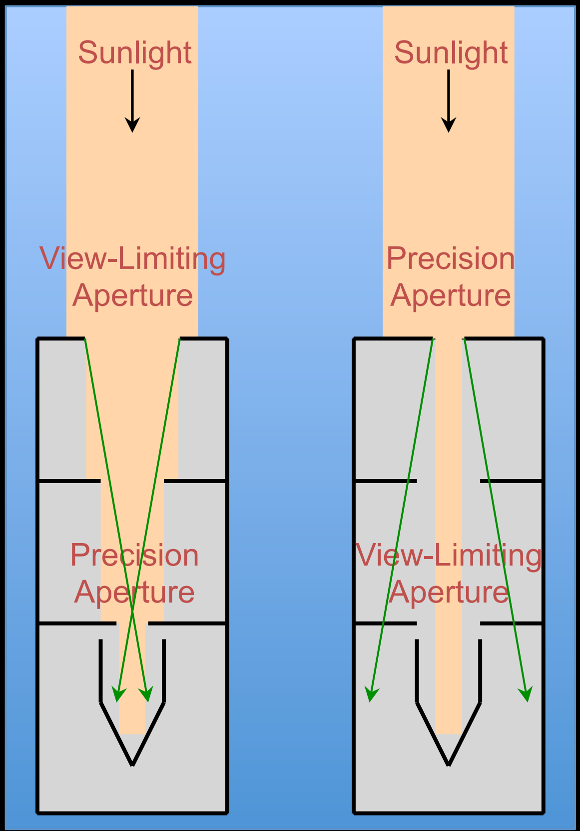
So What Causes the Instrument Offsets?



Diffraction & Scatter Erroneously Increase Signal

All instruments except the TIM put primary aperture close to the cavity

all other TSI instrument geometries



TIM geometry

NIST calculates this to be a 0.16% effect in the ACRIM instruments, and it is not corrected.

Failure to correct for light diffracted <u>into</u> cavity erroneously <u>increases</u> signal

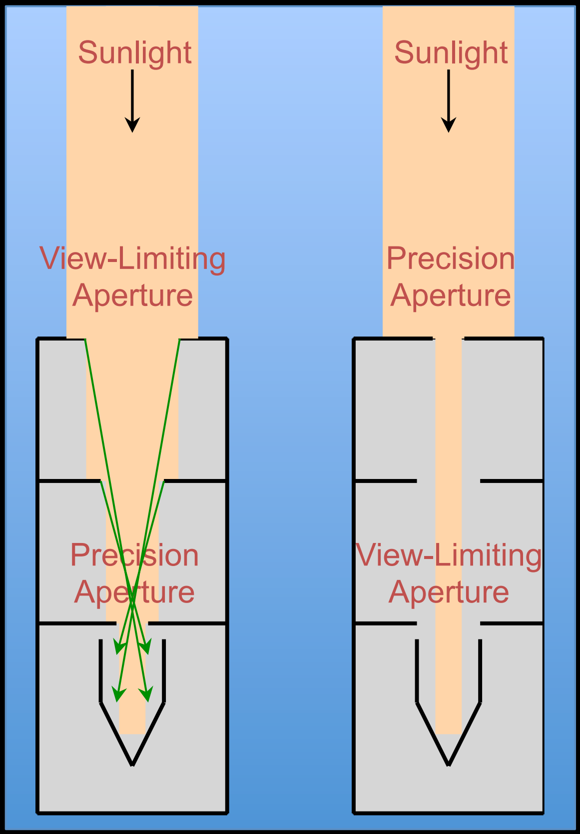
Failure to correct for light diffracted <u>out of</u> cavity erroneously <u>decreases</u> signal

Diffraction & Scatter Erroneously Increase Signal

All instruments except the TIM put primary aperture close to the cavity

Expanding TRF beam from filling precision aperture while underfilling view-limiting aperture to overfilling view-limiting aperture causes increase in signal due to scatter and diffraction from front and interior sections of instrument

all other TSI instrument geometries



TIM geometry

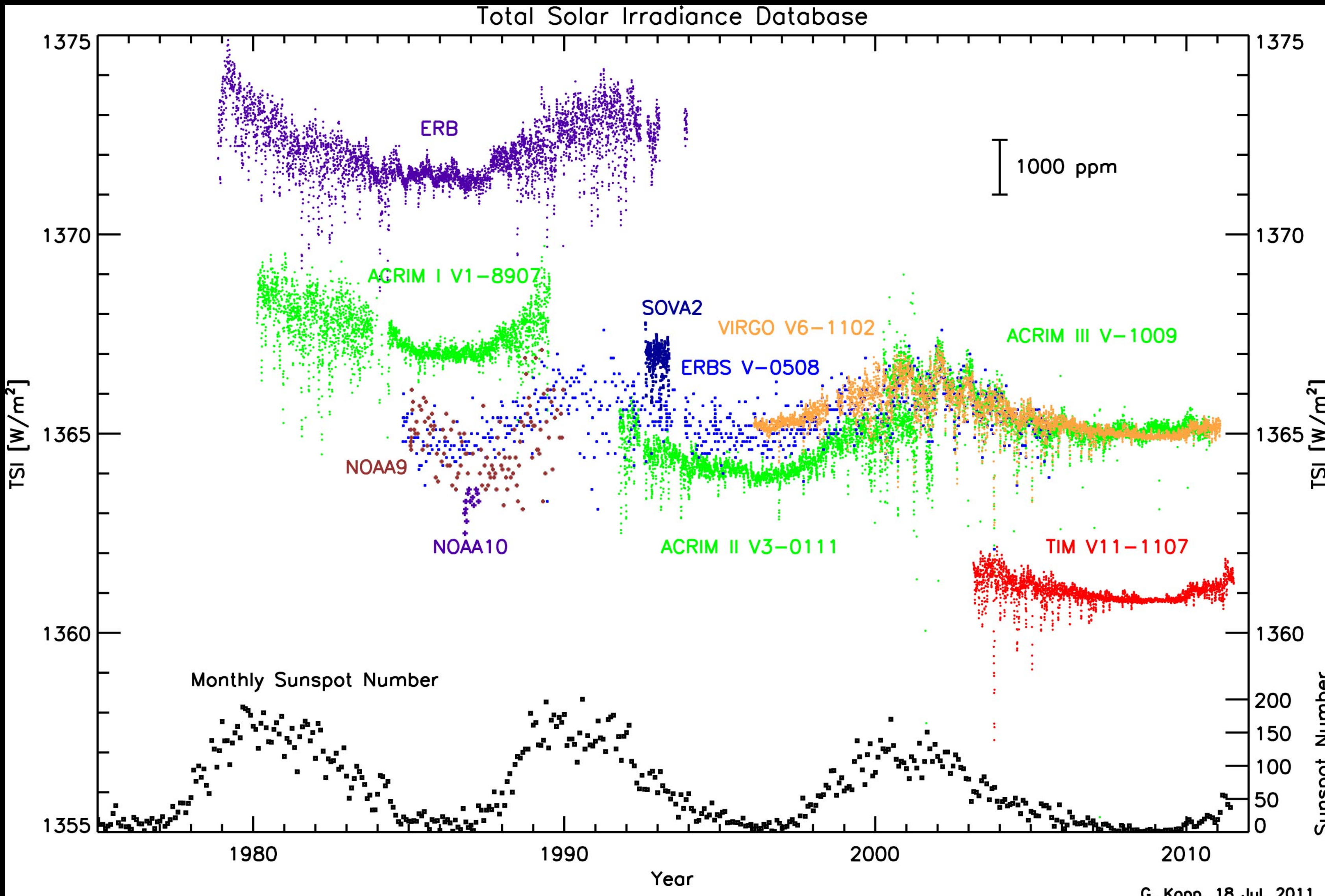
Additional light allowed into instrument can scatter into cavity

Majority of light is blocked before entering instrument

Measured increases due to uncorrected scatter/diffraction are surprisingly large

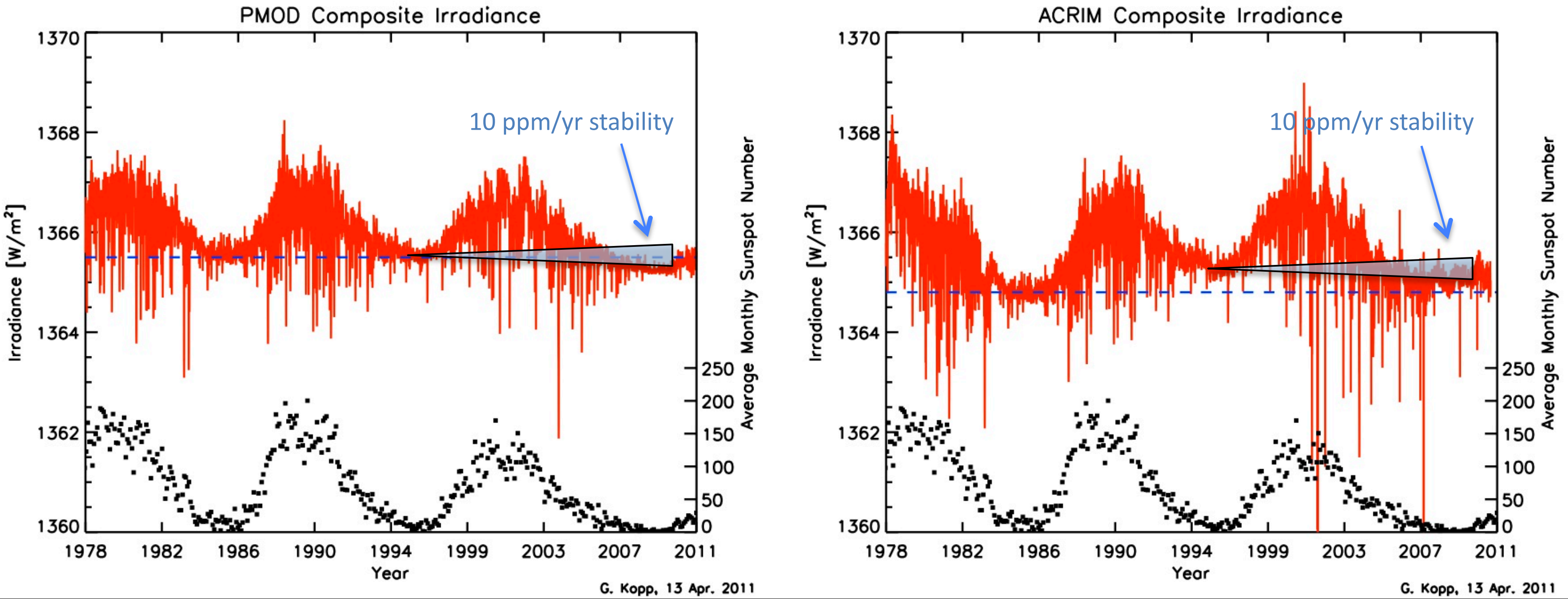
Instrument	Increase
PREMOS-1	0.10%
PREMOS-3	0.04%
VIRGO	0.15%
ACRIM-3	0.51%

TRF Corrections Now Applied by ACRIM Team



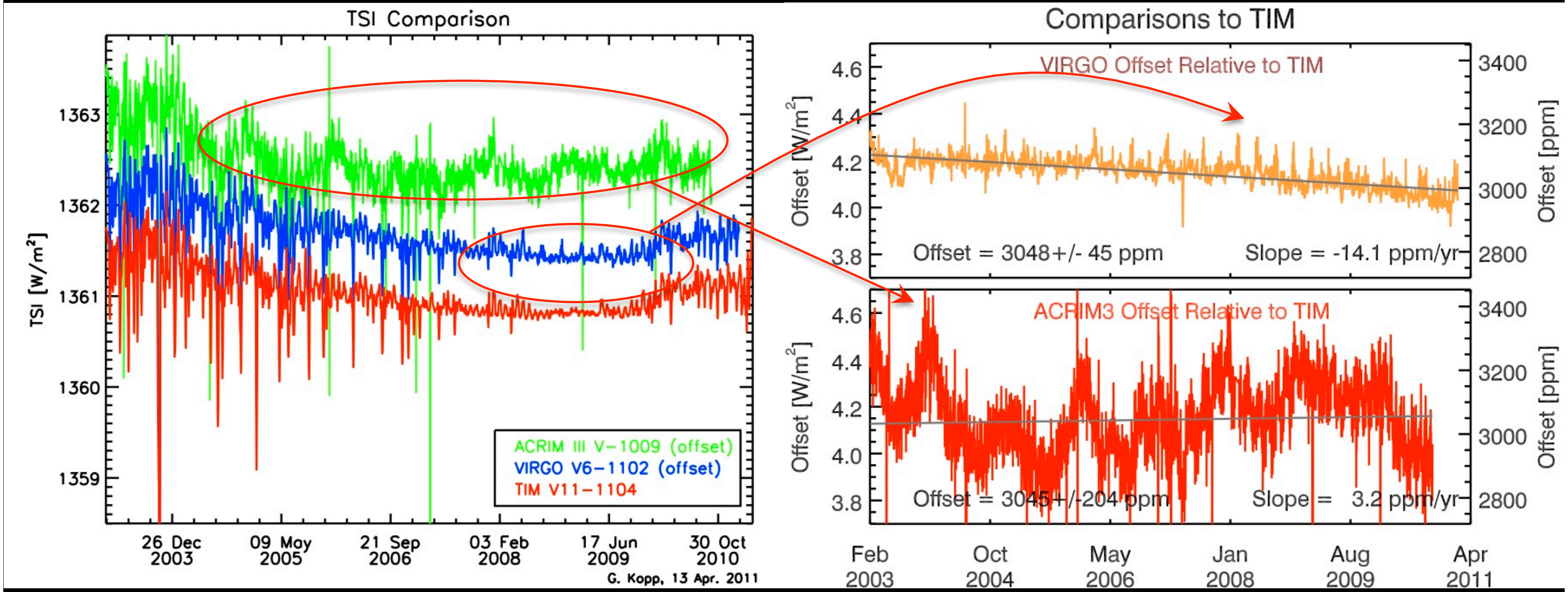
How Good Are Resulting Composites?

- Trend detection between solar minima is currently marginal



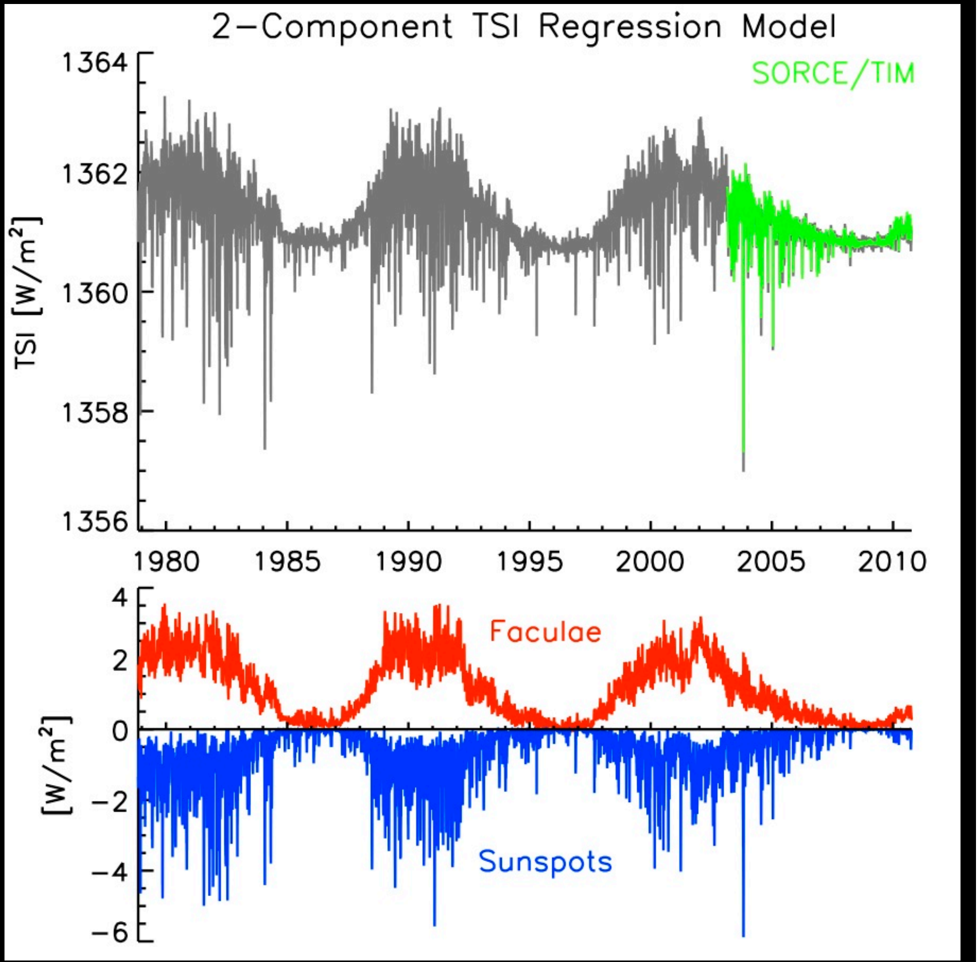
Need Stable Measurements

- There are significant differences between existing instruments

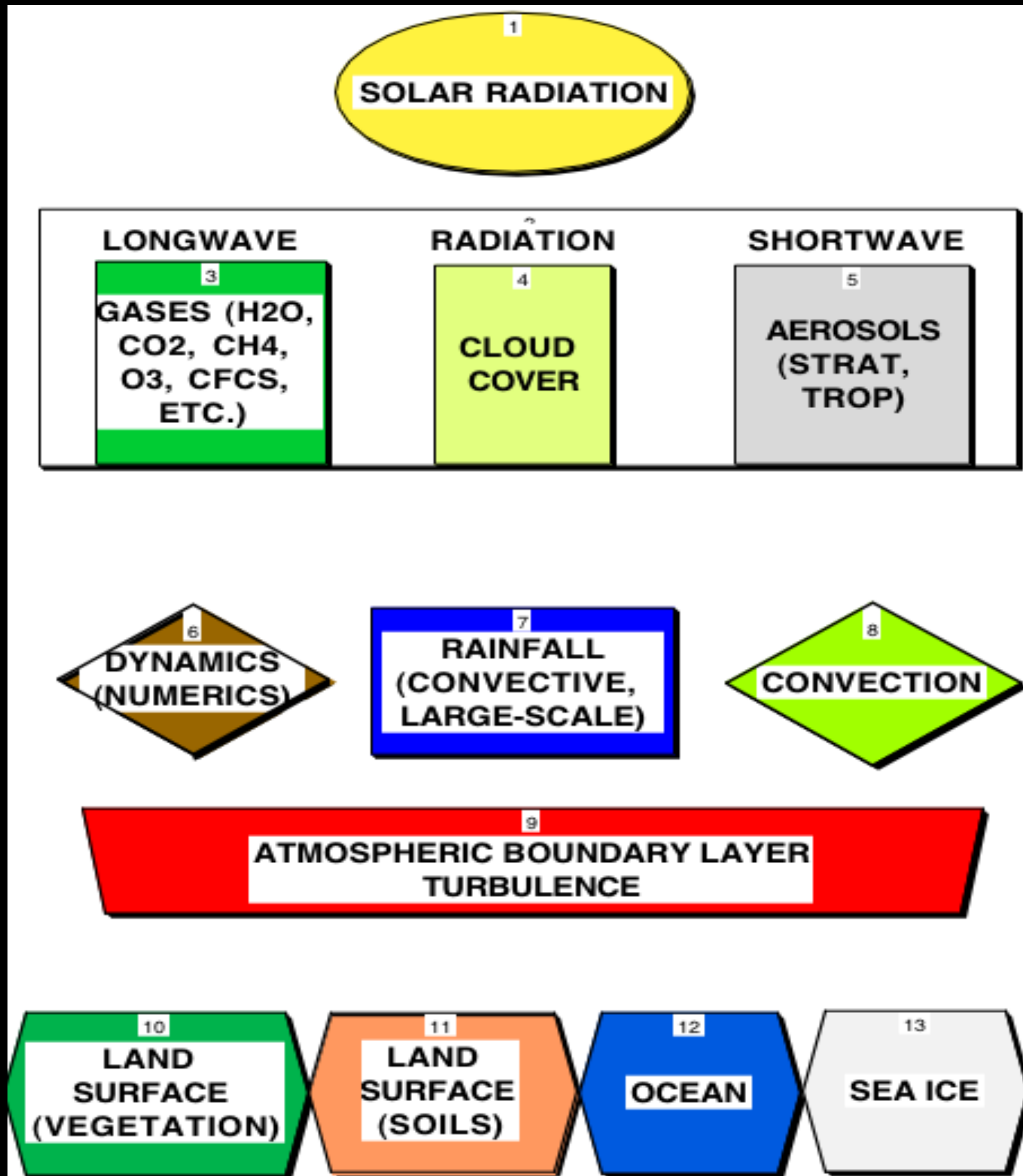


Models of Solar Irradiance Variations

- Empirical (regression)
  - TSI with sunspots and faculae (or other solar activity proxies)
  - SSI below 300 nm less sensitive to sunspot darkening
- Physical
  - Atomic processes and solar atmospheric models
- Summary of effectiveness
  - Good for short-term variations, poor for long-term (secular)



Climate Models Need Spectral Irradiance Inputs

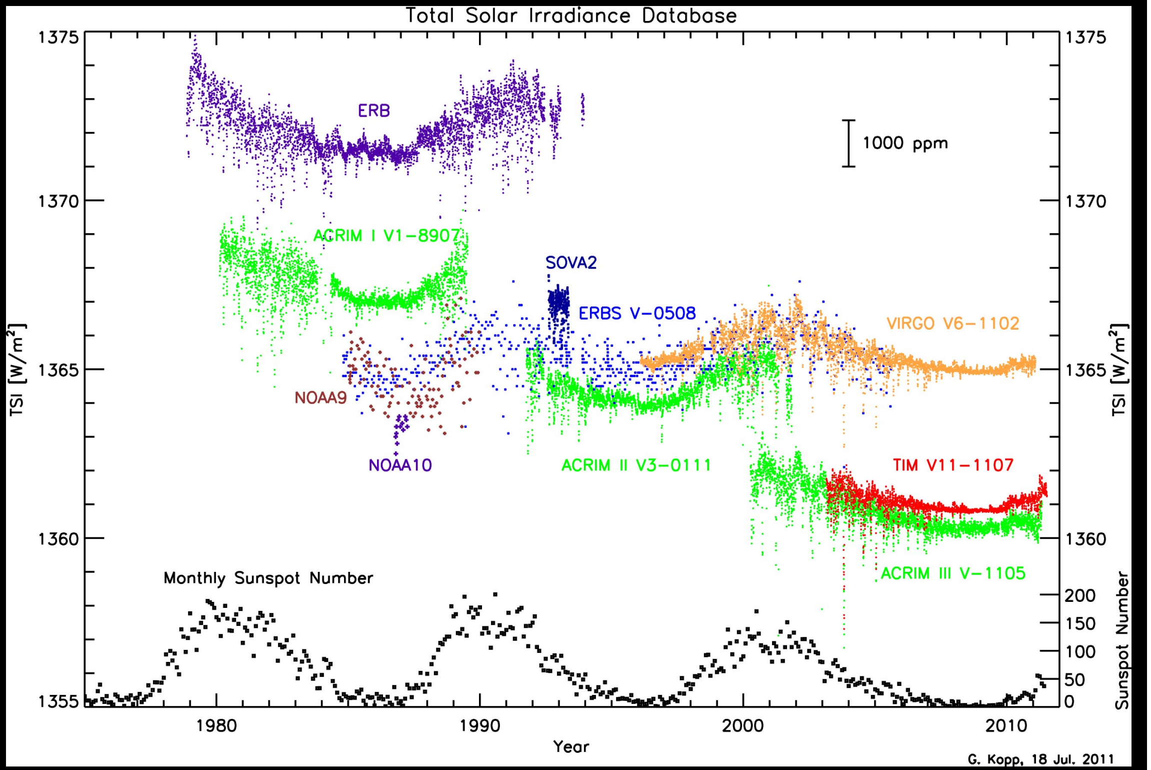


GISS GCM modules

courtesy of Judith Lean, NRL

Needed Solar Irradiance Absolute Accuracies

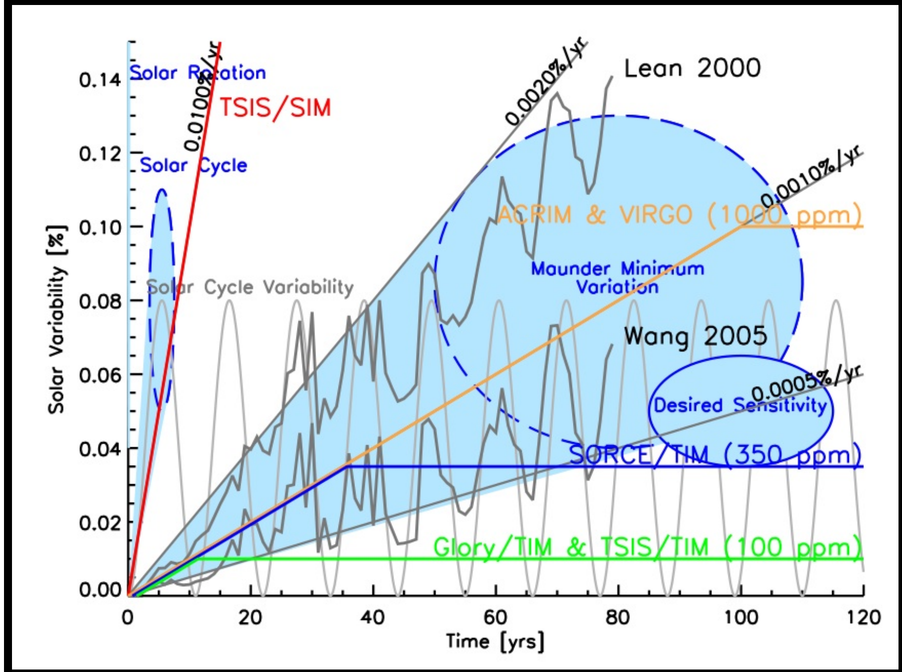
- Needs for improved TSI absolute accuracy
  1. Mitigate against potential future data gap, which would currently lose connectivity with existing 32-year data record
  2. Understand Earth's energy balance
- TRF helps achieve such accuracies
  1. Can validate future TSI instrument accuracies
  2. Can diagnose instrument differences to understand offsets
  3. Establish ground-based reference linking current and future instruments

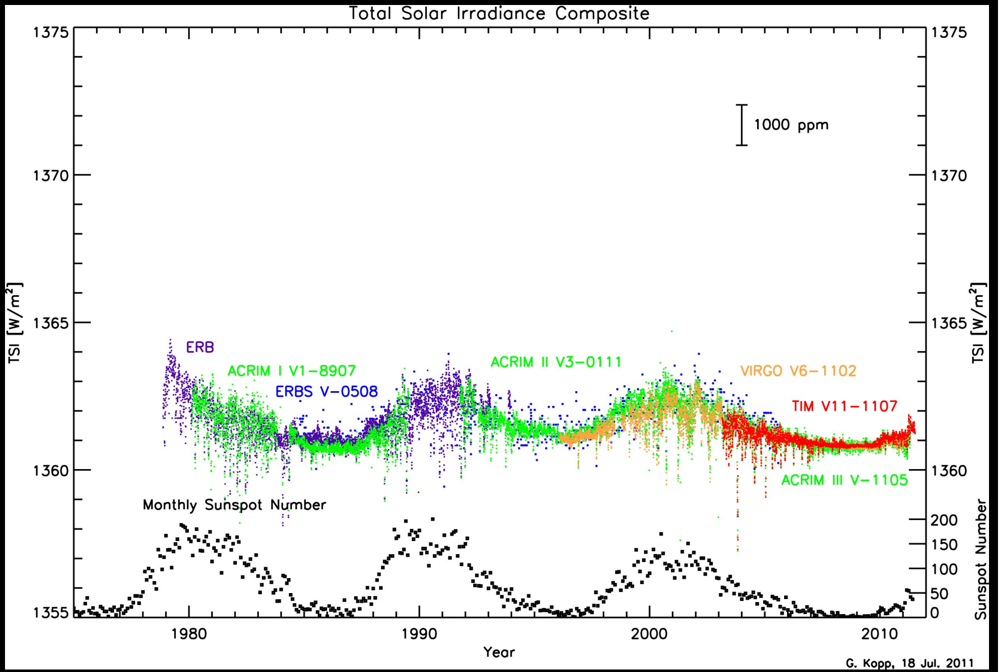


Value of TSI Measurements for Climate Science

TSI Measurements

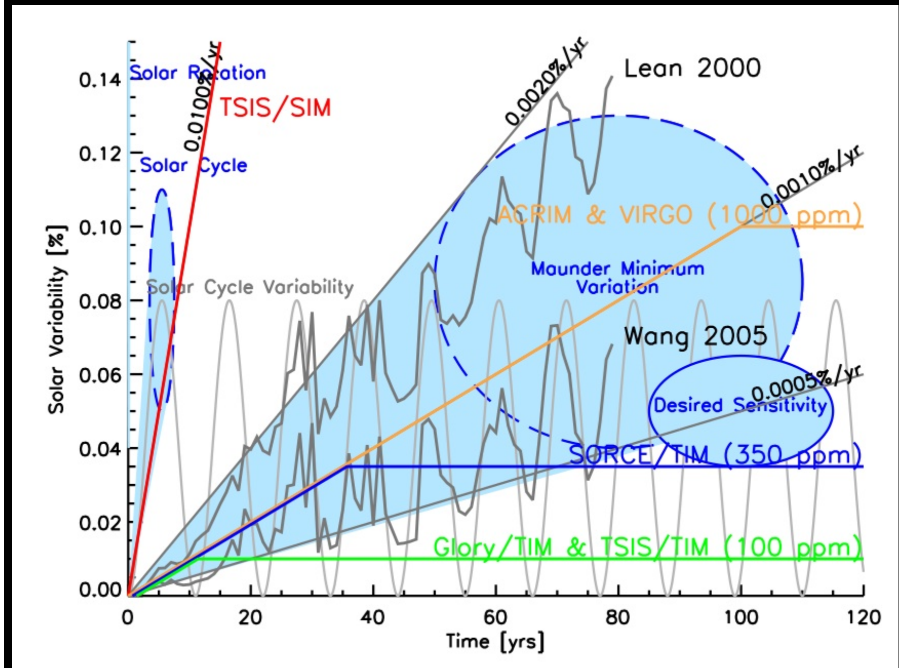
1. Are the most stable solar irradiance measurements
   – Achieve stabilities necessary to detect climate-relevant solar variability
2. Provide >30 year solar irradiance record of entire radiative input to Earth's climate system

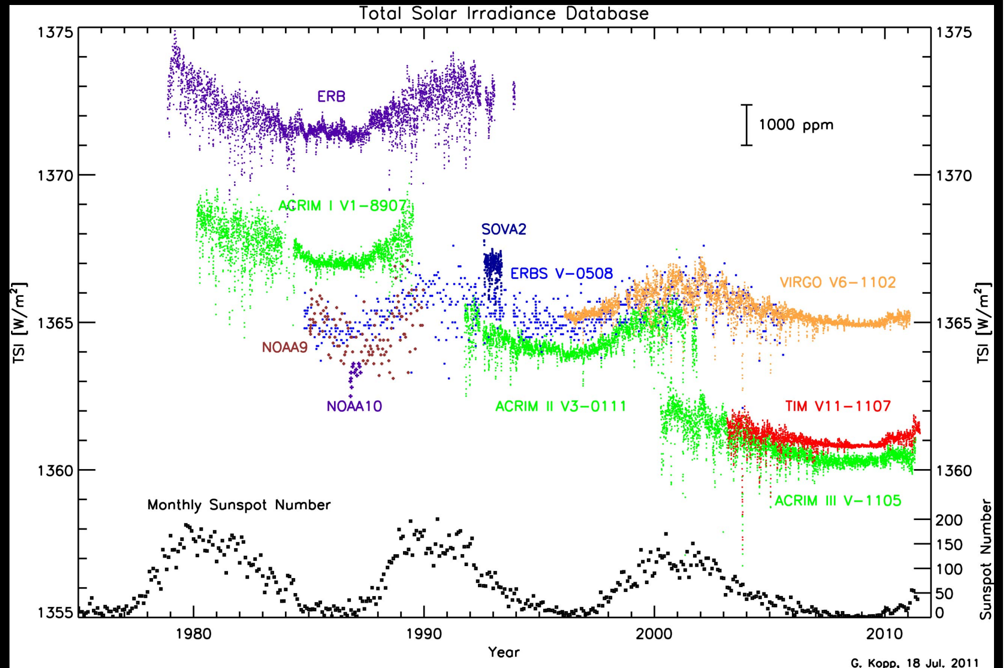




Requirements of Measurements for Climate Science

1. Improve absolute accuracy to 100 ppm. In the meanwhile,
2. Continue to rely on continuity and stabilities of <10 ppm/yr
3. Perform end-to-end ground irradiance validations against an SI-traceable reference (such as TRF)





Fundamental Solar Irradiance Science Questions

- What are secular (long-term) variations in solar irradiance?
- What solar activities cause variability at different wavelengths?
- What was the solar irradiance during the Maunder Minimum?
- How good are sunspot and isotope proxies of solar irradiances?
- How much solar variability is expected?
  - Based on observations of other stars?
  - Based on physical models?
- What is the Earth's climate sensitivity to solar variability?