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} \cdot \frac{1}{4\sigma} \cdot S} = 280K

not to scale
### Where Does the Earth Get Its Energy?

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*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Table 2 on p. 12 is from unpublished notes from H.H. Lettau, Dept.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?

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* global average

| Total Input (relative)                                             | 2.6E-04           |
| Temperature (K)                                                    | 35                |
| Temperature (°F)                                                   | -396              |
The Sun’s Energy

• Energy output
  – Sun’s total output $3.8 \times 10^{23}$ 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 ($7 \times 10^{10}$ 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/m² 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

\[ \frac{2\pihc^2}{\lambda^5} \cdot \frac{1}{e^{hc/kT\lambda} - 1} \]

Planck Wavelength Function

5770°K

Spectral irradiance [erg/cm²/s/micron]

Wavelength [microns]
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
    \[ E_\lambda = \frac{d^2\Phi}{dAd\lambda} \]
The Sun – Condensed to Total Irradiance

Images/plots courtesy of NSO, SOHO, SORCE

Solar Spectral Irradiance

1361 W/m²

Total Solar Irradiance (TSI)

Δ
**SOHO/MDI Images and SORCE/TIM TSI**

MDI Intensitygram  

29-Oct-2003 00:00

SORCE/TIM Irradiance

Minimum at 29-Oct-2003

0.34% decrease

Sunspots and Faculae

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

Heliophysics Summer School
NCAR, 1 Aug. 2011
Solar Irradiances
Greg Kopp - p. 17
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

Group Sunspot Number


11-yr Average
Yearly Average
Monthly Average

Average Sunspot Number

Maunder Minimum

Year

1600 1700 1800 1900 2000
The Spaceborne Total Solar Irradiance Data Record

![Total Solar Irradiance Database](chart)

- ERB
- ACRIM I V1-8907
- SOVA2
- ERBS V-0508
- VIRGO V6-1102
- NOAA9
- NOAA10
- ACRIM II V3-0111
- TIM V11-1107
- ACRIM III V-1105

---

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Solar Irradiances

Greg Kopp - p. 20
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.
Spectral Irradiance Variations Across Spectrum

- Relative variability much greater at shorter wavelengths

1991

1995
Measured Spectral Irradiances

(a) 121 to 122 nm
- SME +1.60
- UARS SUSIM −0.85
- TIMED SEE −0.50
- NRLSSI

(b) 200 to 295 nm
- SME −0.30
- UARS SUSIM −0.03
- SORCE SOLSTICE +0.60
- NRLSSI

(c) 450 to 550 nm
- SORCE SIM −1.45
- NRLSSI

Solar 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 Irradiiances

Historical TSI Reconstructions

Cosmogenic Isotope Records


Total Solar Irradiance Composite

- Modern Sunspot Number
- Medieval Sunspot Number
- Maunder Minimum
- Sporer Minimum

11-yr Average
Yearly Average
Monthly Average

Group Sunspot Number


Total Solar Irradiance Database

Holocene Solar Activity Proxy

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Solar Irradiances

Greg Kopp - p. 26
Solar Irradiances

Galactic Cosmic Ray Flux at Earth
0.0000007 Wm^{-2}

Open flux modulates cosmogenic isotopes

Closed flux modulates irradiance

Sub-surface dynamo

Surface magnetic fields of opposite polarity

Transported by...
- Differential rotation,
- Meridional flow,
- Diffusion

0.05%

0.2%

NRL Flux Transport Model

Total Solar Irradiance

IPCC AR4

IPCC3

IPCC AR4

Solar Irradiances

Greg Kopp - p. 27

Estimating Long-Term Solar Variability
Maunder Minimum TSI Estimates

-ΔTSI for MM (W/m²)

<table>
<thead>
<tr>
<th>Year</th>
<th>Value</th>
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<td>1.2</td>
</tr>
<tr>
<td>1980</td>
<td>2.5</td>
</tr>
<tr>
<td>1990</td>
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<td>2010</td>
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Based on sun-like stars
Based on solar activity

Eddy 1976
Schatten 1988
Lean 1992 & White 1992
Hoyt & Schatten 1993
Zhang 1994
Solanki & Flige 1998
Lean 2000
Wang 2005
Woods 2003

Eddy 1976, MM-sunspot record, faster solar rotation
Schatten 1988, ERB/ACRIM model
Lean 1992 & White 1992, Secular trend based on stars
Hoyt & Schatten 1993, Rotation rate, cycle length
Zhang 1994, Based on stars
Solanki & Flige 1998, Secular trend based on stars
Lean 2000, Secular trend based on stars
Wang 2005, Magnetic flux transport
Woods 2003, AN area & QS decreases

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 Irradiances

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Greg Kopp - p. 30
Solar Variability Drives Measurement Requirements

Solar Rotation

TSIS/SIM

Lean 2000

ACRIM & VIRGO (1000 ppm)

Maunder Minimum Variation

Wang 2005

Desired Sensitivity

SORCE/TIM (350 ppm)

Glory/TIM & TSIS/TIM (100 ppm)

100-yr needed for MM detection

35-yr needed for MM detection

10-yr 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

**Spectral Irradiances**

- Wavelengths < 120 nm: $0.003 \pm 0.001 \text{ Wm}^{-2}$
- Wavelengths 120-300 nm: $14.9 \pm 0.1 \text{ Wm}^{-2}$
- Wavelengths > 300 nm: $1346 \pm 0.5 \text{ Wm}^{-2}$
Irradiance Measurement Fundamentals

• Total irradiance (i.e. 1361 W/m²) requires two measurements:
  – Power
  – Area

Electrical Heating to Maintain Constant Temperature
As Sunlight Is Modulated Determines Radiant Power

Shutter Modulates Incoming Sunlight

Precision Aperture Determines Area

Absorptive Radiometer

Total irradiance (i.e. 1361 W/m²) requires two measurements: Power and 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

Four Radiometers Track Degradation

- Radiometer
- Precision Aperture
- Light Baffles
- Vacuum Door
- Detector Head Board
- Vacuum Shell
- Heat Sink
- Shutter

Solar Irradiances

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

- Doppler correction due to S/C orbit velocity
  \[
  2 \frac{\nu}{c} = 2 \cdot \frac{8 \times 10^5 \text{ cm/s}}{3 \times 10^{10} \text{ cm/s}} \approx 5 \times 10^{-5} \implies \pm 50 \text{ ppm}
  \]

- Thermal (mid-IR) background
  \[
  \sigma T^4 \cdot \text{Cone Entrance Area} = 8 \times 10^5 \text{ ergs} \implies 1.2 \times 10^6 \text{ ppm}
  \]
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
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
So What Causes the Instrument Offsets?
Diffraction & Scatter Erroneously Increase Signal

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

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

Failure to correct for light diffracted into cavity erroneously increases signal
Failure to correct for light diffracted out of cavity erroneously decreases 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.

Measured increases due to uncorrected scatter/diffraction are surprisingly large.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>PREMOS-1</td>
<td>0.10%</td>
</tr>
<tr>
<td>PREMOS-3</td>
<td>0.04%</td>
</tr>
<tr>
<td>VIRGO</td>
<td>0.15%</td>
</tr>
<tr>
<td>ACRIM-3</td>
<td>0.51%</td>
</tr>
</tbody>
</table>

Additional light allowed into instrument can scatter into cavity.

Majority of light is blocked before entering instrument.
TRF Corrections Now Applied by ACRIM Team

Total Solar Irradiance Database

ERB
ACRIM I V1-8907
NOAA9
ACRIM II V3-0111
NOAA10
ACRIM III V-1009
SOVA2
ERBS V-0508
VIRGO V6-1102
TIM V11-1107

Monthly Sunspot Number

Year

1980 1990 2000 2010

Sunspot Number

0 50 100 150 200

TSI [W/m²]

1355 1360 1365 1370 1375

1000 ppm
How Good Are Resulting Composites?

- Trend detection between solar minima is currently marginal

10 ppm/yr stability
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

Solar Irradiances

Heliophysics Summer School
NCAR, 1 Aug. 2011

Greg Kopp - p. 52
**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?