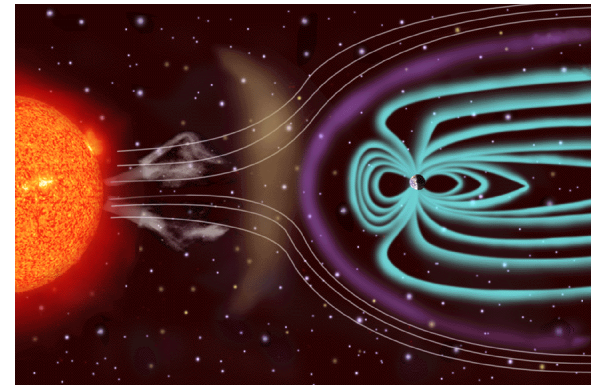
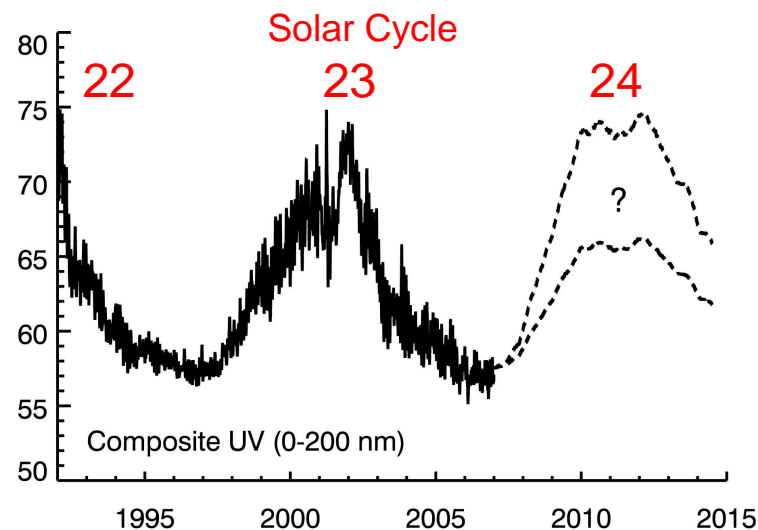


Solar Irradiance Variability Observed During Solar Cycle 23

- ❑ Introduction
- ❑ Solar Cycle Results for Climate Change
- ❑ Solar Cycle Results for Space Weather

Tom Woods

<tom.woods @ lasp.colorado.edu>
LASP / University of Colorado

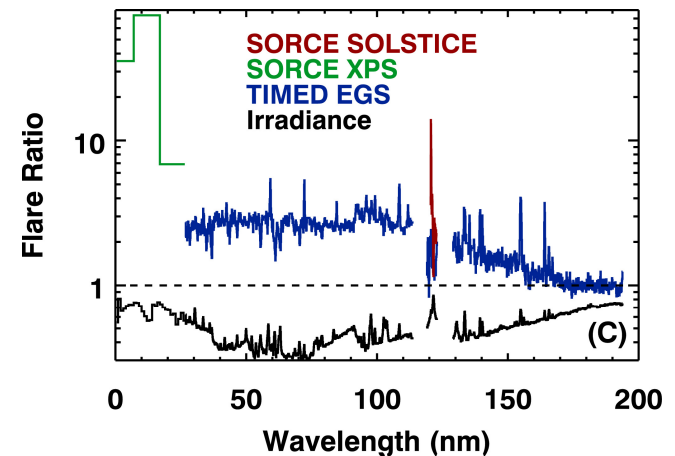
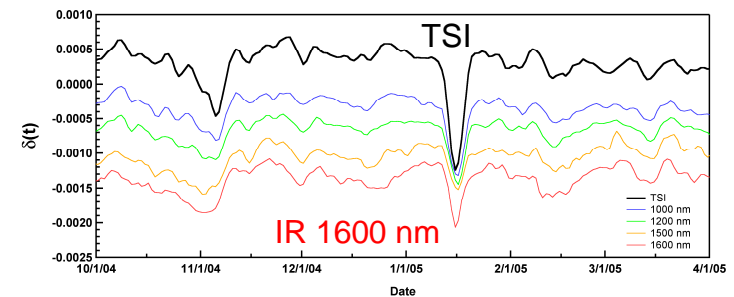
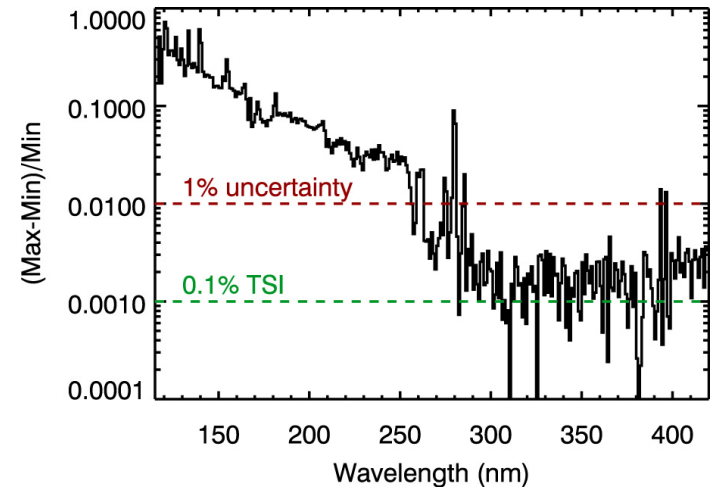


Summary of Solar Cycle (SC) 23 Results

- UARS & ATLAS observed UV irradiance during SC 22 and first half of SC 23
 - Best results for 115-260 nm
 - SC variability for $\lambda > 260$ nm is smaller than 1% uncertainty

- **SORCE confirms UARS-ATLAS results for $\lambda < 260$ nm and provides new results for TSI and for NUV, Visible, and IR (260 – 2400 nm)**
 - TIM TSI is lower value (1361 W/m²)
 - New IR observations by SIM indicate IR short-term variability is less than visible & TSI
 - **Preliminary** results indicate SC variability at some visible & IR wavelengths are out of phase with solar cycle trend

- **TIMED SEE provides new EUV observations**
 - Accuracy improved throughout the EUV
 - Flare variability is as large as SC variability



SORCE

Solar Variations Largely Driven by Magnetic Activity

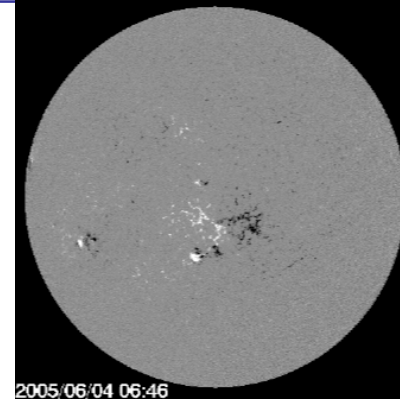
➤ What we know best:

- Day-to-day variations primarily from magnetic active regions

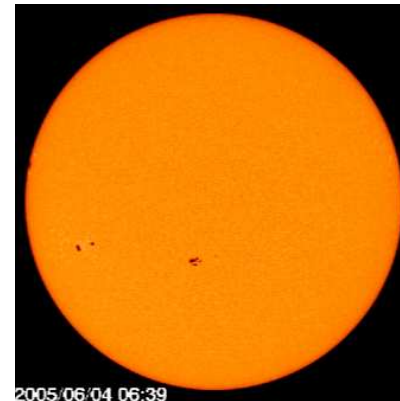
- Dark sunspots in visible
- Bright plage in UV

- Evolution of magnetic active regions drives solar cycle variations

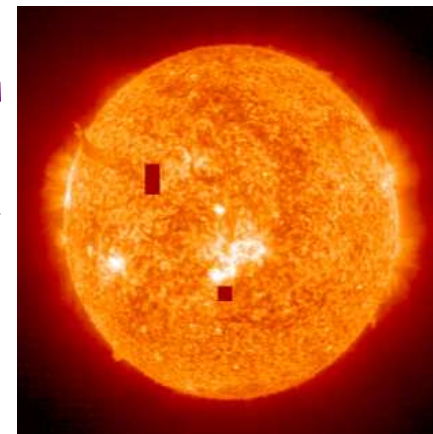
- Competing dark sunspots and bright faculae for TSI and visible radiation
- Active network contribution is most important for transition region emissions



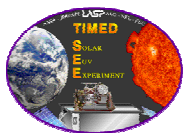
Magnetic Field



Visible (photosphere)

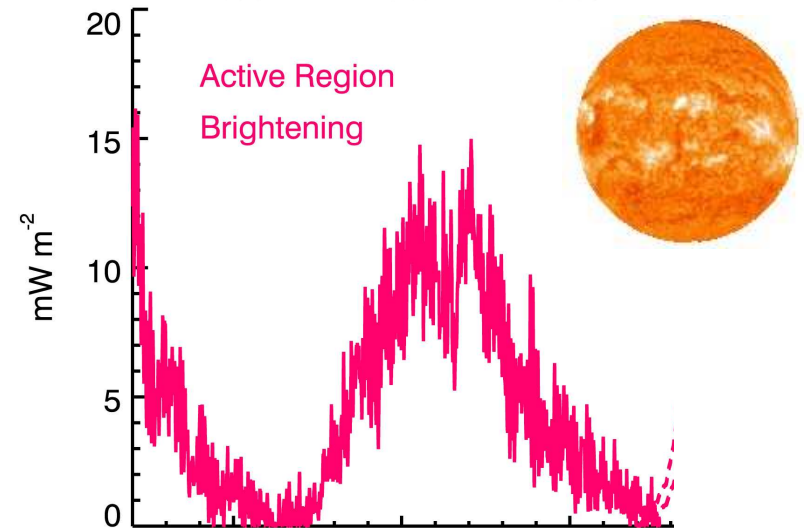
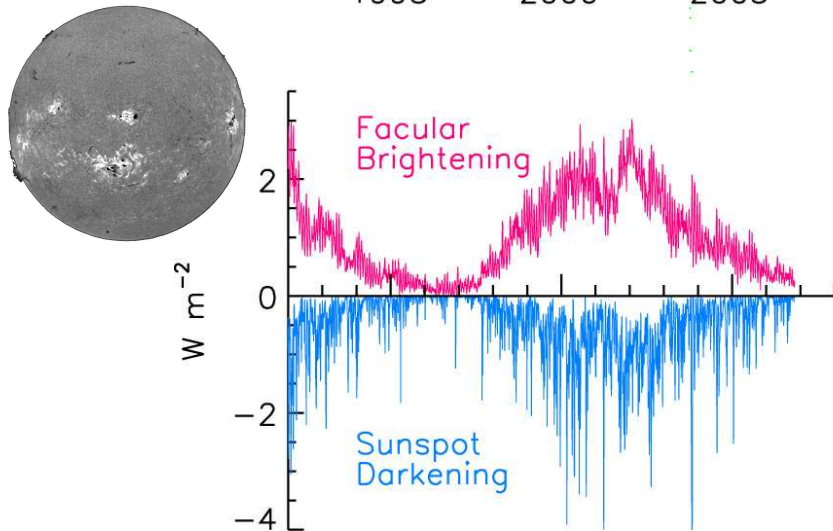
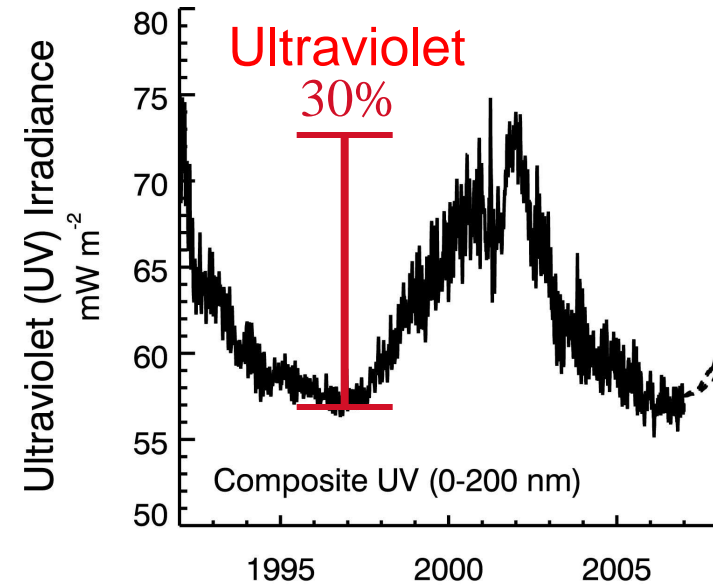
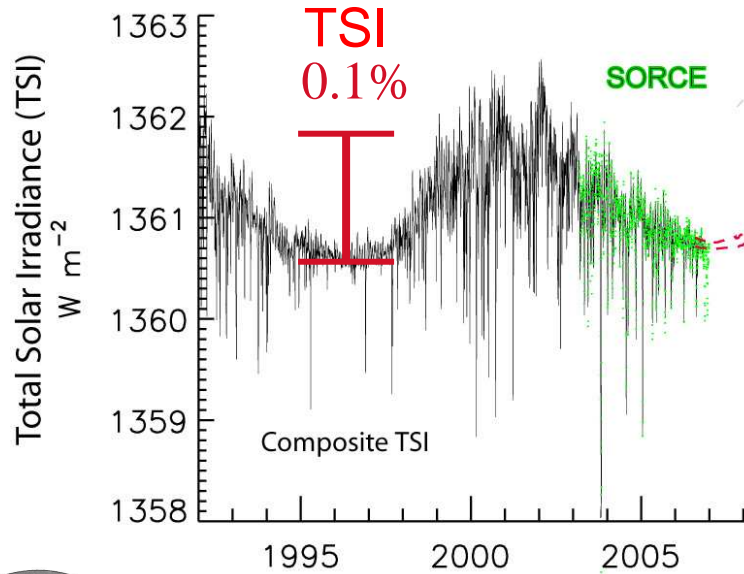


Ultraviolet (chromosphere, transition region)



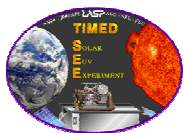
SORCE

Wavelength Dependent Contributions to Solar Variability



sources of TSI variations

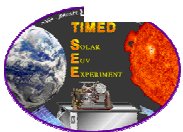
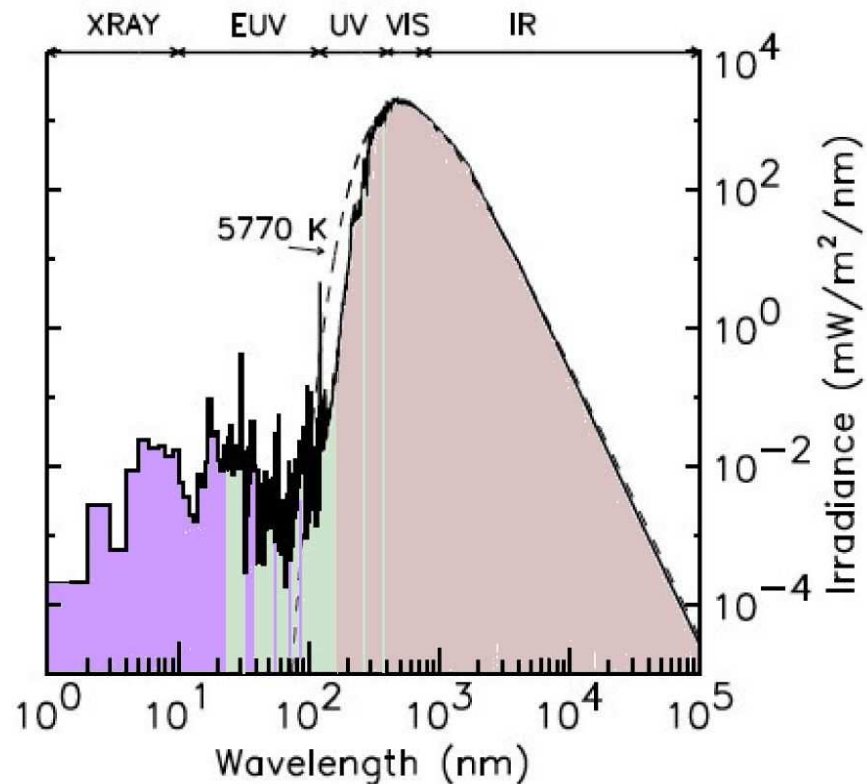
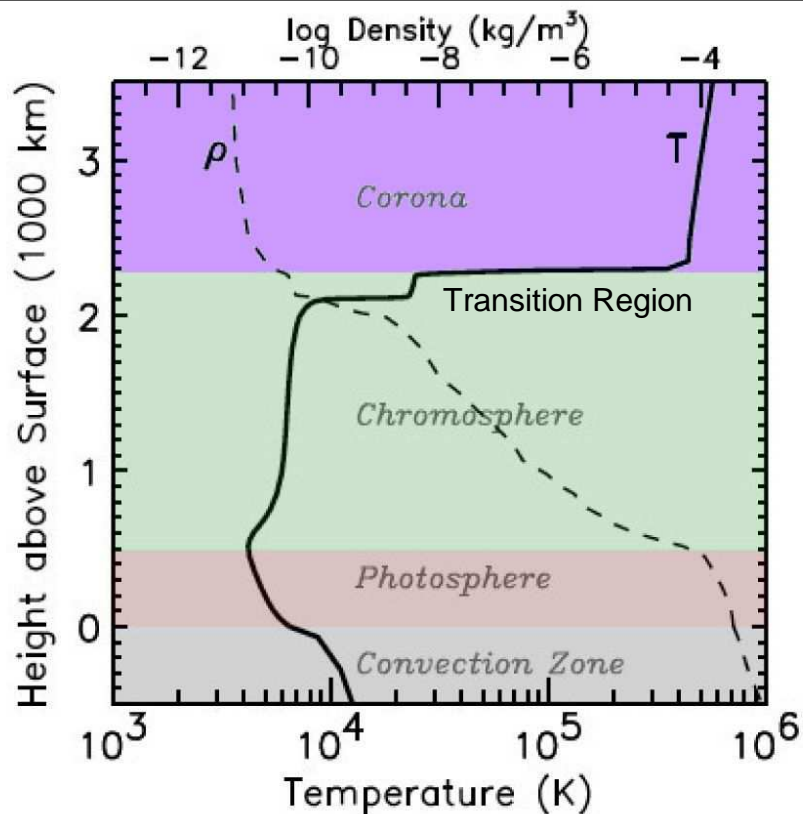
UV radiation has only bright contributions



SORCE

Layers of the Solar Atmosphere

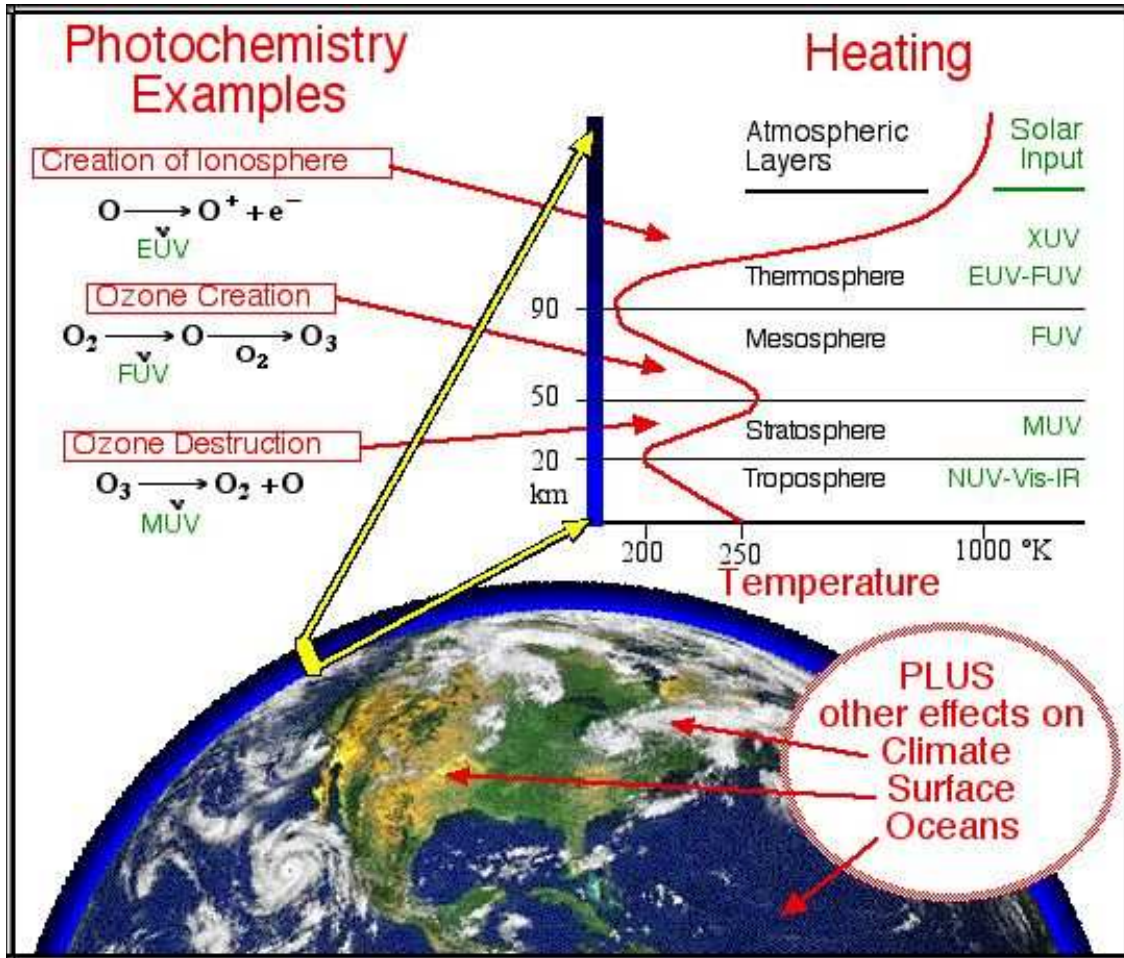
Layer	Spectral Features	Dominant Wavelengths	SC Variability
Photosphere	continuum, absorption lines	TSI, UV, Visible, IR	~ 0.1%
Chromosphere (& TR)	emission lines (e.g. H)	FUV, EUV	Factor 1.2 to 3
Corona	hot emission lines	X-ray, EUV	Factor 3 to 1000



SORCE

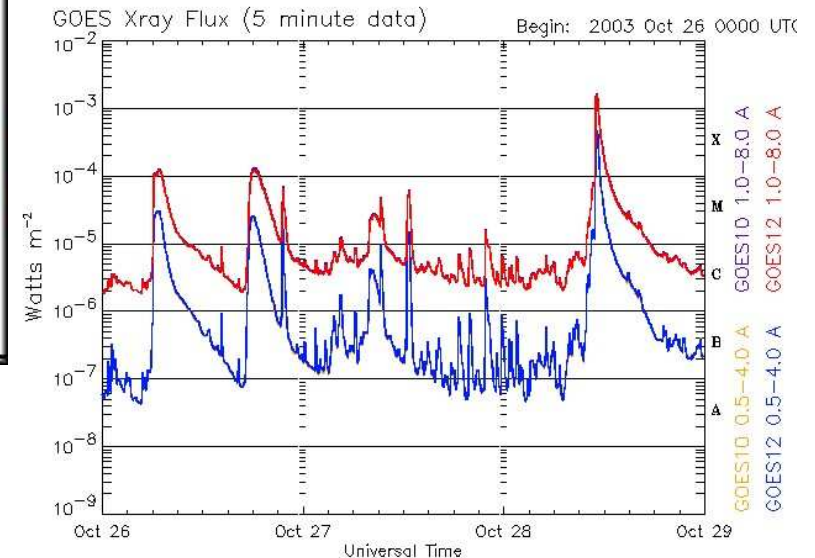
Figure adapted from Lean (ARAA, 1997)

Solar Influences on Earth



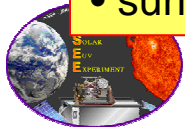
➤ Space Weather

- Short-term (flare) is focus
- Solar UV radiation absorbed in the thermosphere and ionosphere drive:
 - Atmospheric heating that affects density and thus satellite drag
 - Ionospheric density that can degrade or even disrupt comm. and navigation (GPS)



Solar Cycle effects include:

- thermospheric density changes by factor of 10
- thermospheric temperature changes by factor of 2
- surface temperature changes by 0.1 C

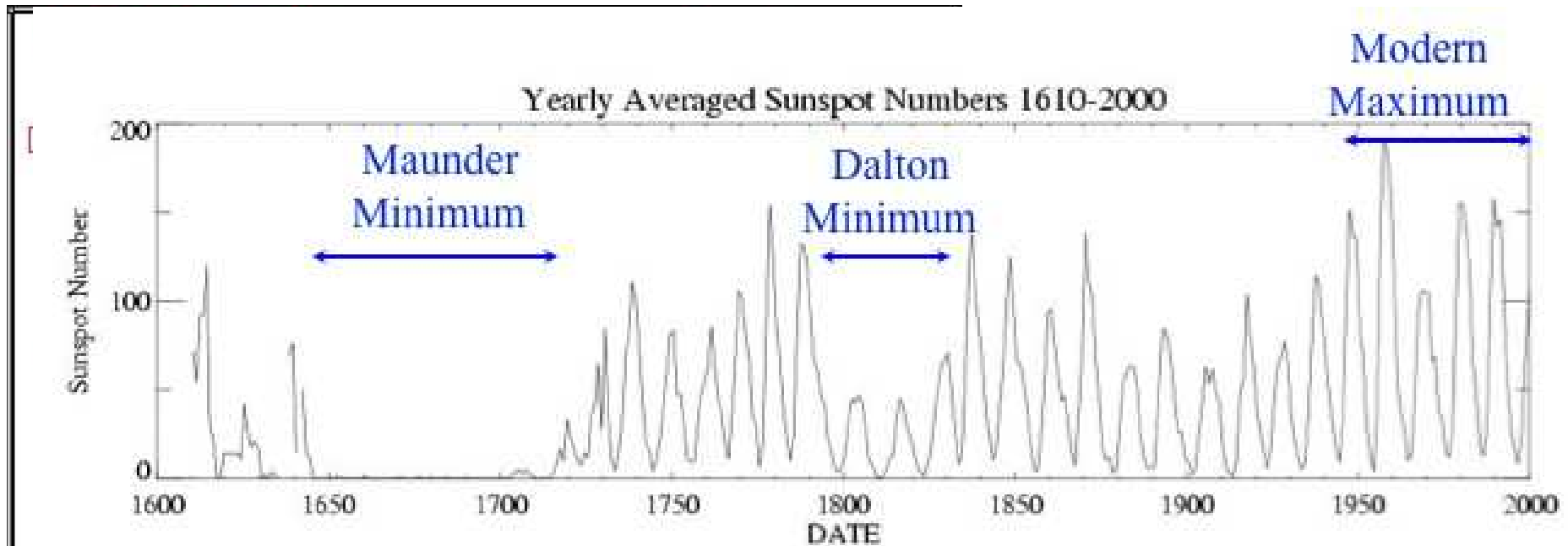


SORCE

Solar Cycle Variability Observations

See WG-II Talks about Space Weather on Thur. morning.

Solar Influences on Earth

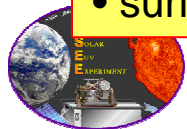


➤ Climate Change

- Long-term is focus
- Solar NUV-Vis-NIR radiation absorbed in the lower atmosphere and at the surface drive:
 - Temperature changes
 - Photochemistry (e.g. O₃)

Solar Cycle effects include:

- thermospheric density changes by factor of 10
- thermospheric temperature changes by factor of 2
- surface temperature changes by 0.1 C

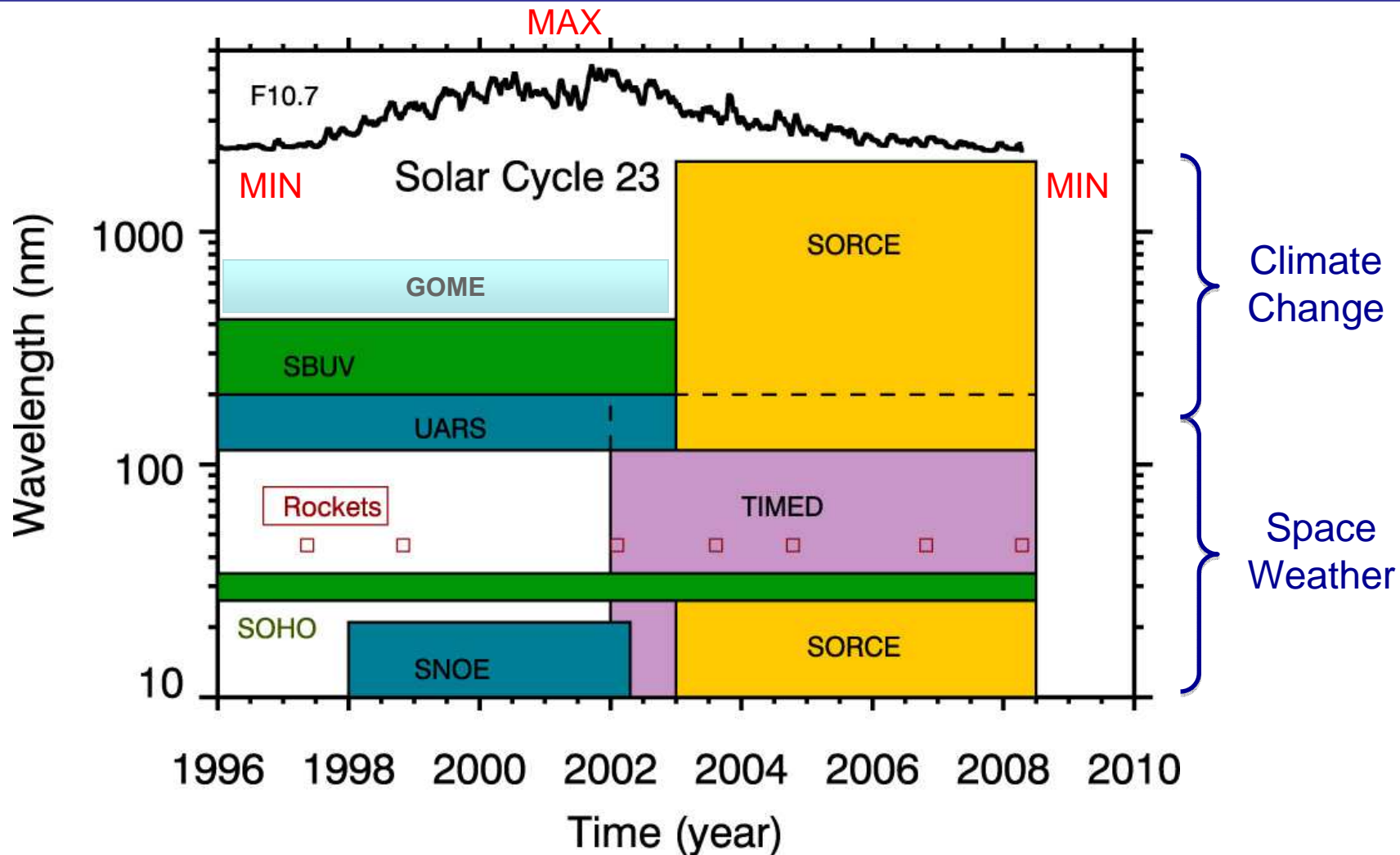


SORCE

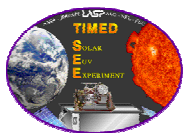
Solar Cycle Variability Observations

See Sun-Climate & WG-IV Talks on Wednesday.

Missions with Solar Irradiance Observations



First time to have **daily, full spectral coverage** from 0.1 nm to 2400 nm with the combination of SORCE and TIMED missions.

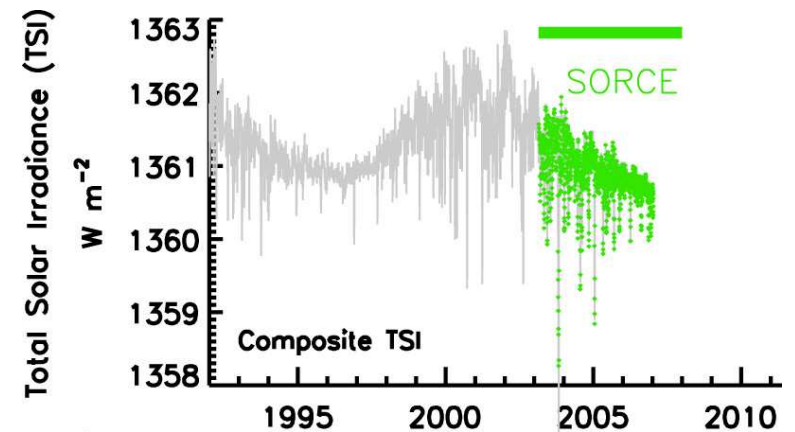


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SORCE: A Mission of Solar Irradiance for Climate Research

➤ SORCE Measurements

- Total Solar Irradiance (TSI)
 - Extend TSI record
 - Improve upon accuracy and stability
- Solar Spectral Irradiance (SSI)
 - 0.1-27 nm and 115-2400 nm
 - Continue UV record for $\lambda < 400$ nm
 - Start new NUV-Vis-NIR record
- Daily cadence for data products
 - March 2003 to present



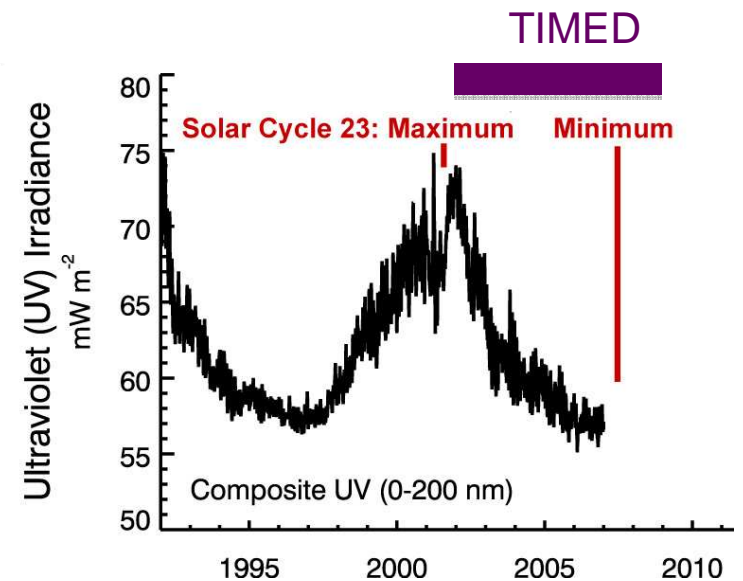
SORCE TSI and SSI Data Products
<http://lasp.colorado.edu/sorce/>

SORCE Book
Solar Physics
Vol. 230, 2005

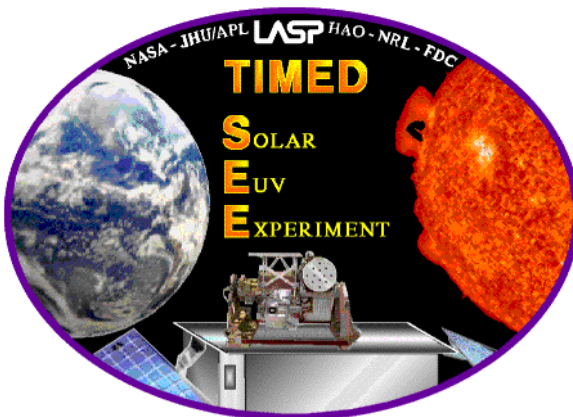
TIMED SEE: Solar Irradiance for Space Weather Research

➤ Solar EUV Experiment (SEE)

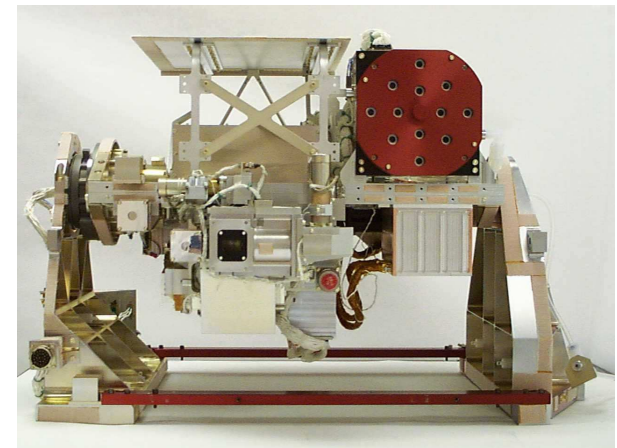
- Solar Spectral Irradiance (SSI)
 - 0.1-27 nm in broad bands
 - 27-194 nm at 0.4-nm resolution
- Daily cadence for data products
 - February 2002 to present
 - Also have flare observations



TIMED SEE Data Products
<http://lasp.colorado.edu/see/>



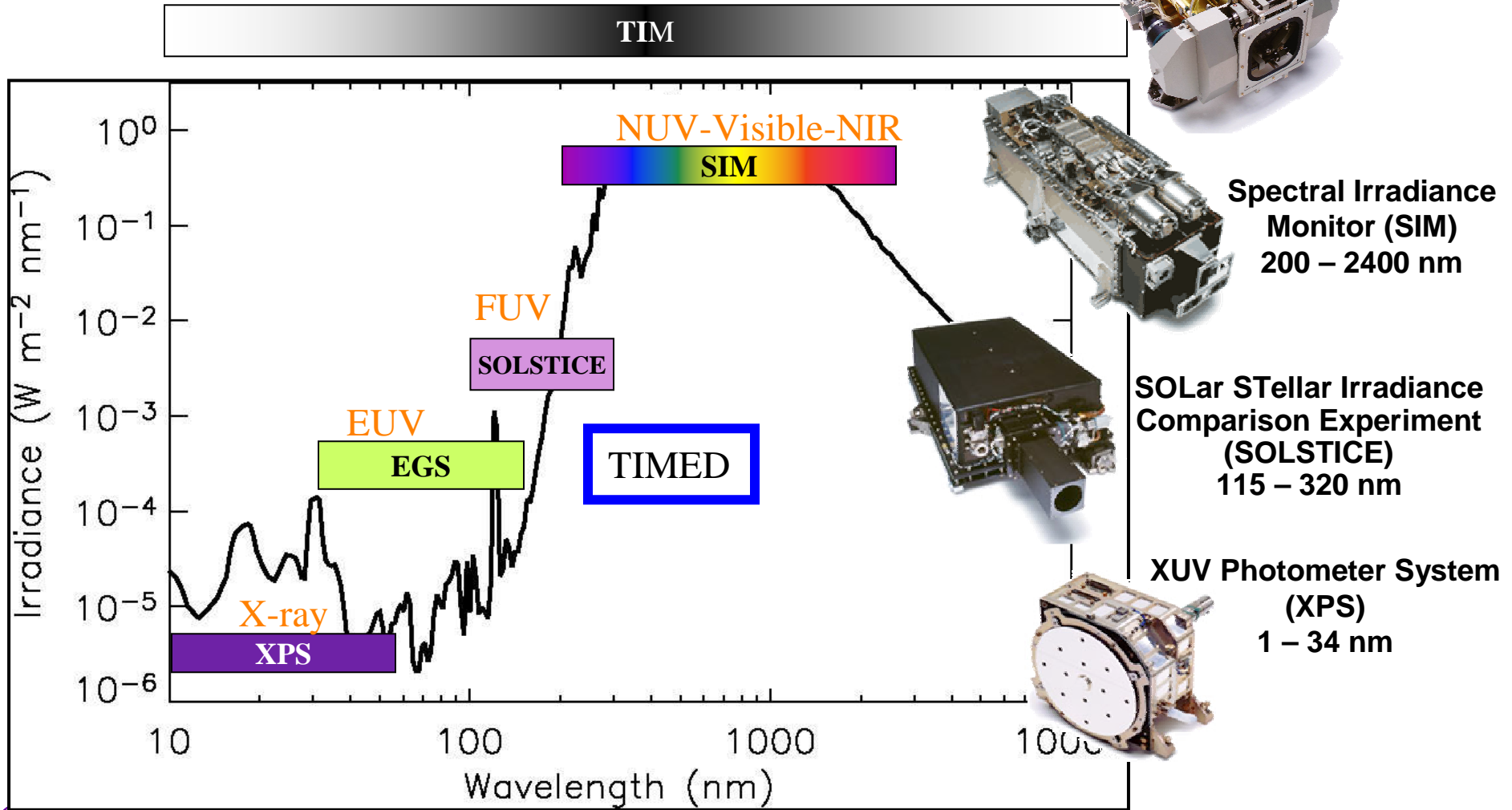
TIMED SEE Overview Paper
Woods *et al.*, *J. Geophys. Res.*
110, A01312, 2005



SORCE and TIMED Solar Irradiance Instruments

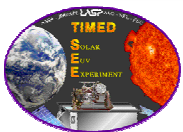
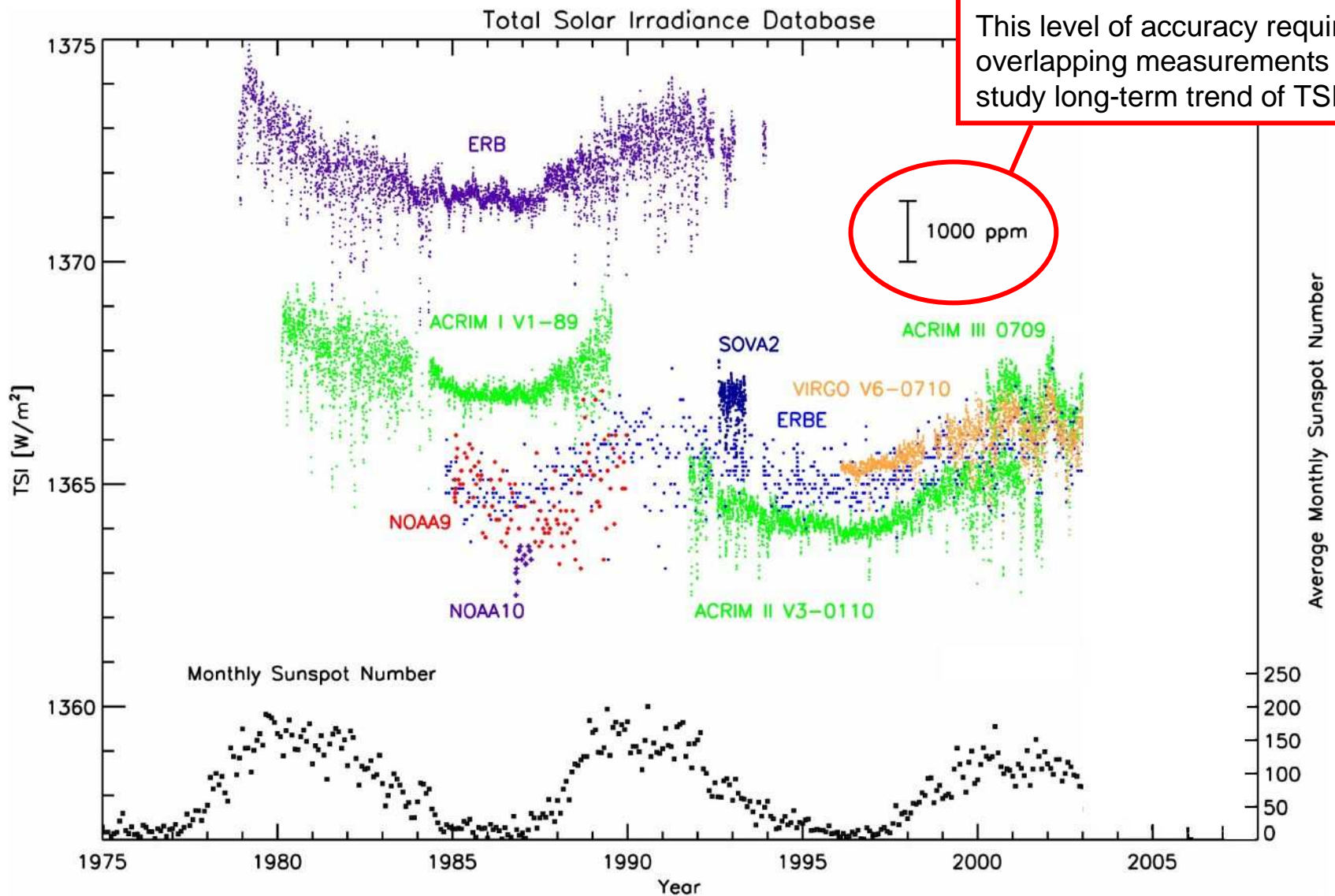
First time to simultaneously observe SSI from 0.1 nm to 2400 nm.

Total Solar Irradiance (TSI)



SORCE

Total Solar Irradiance (TSI) - Before SORCE

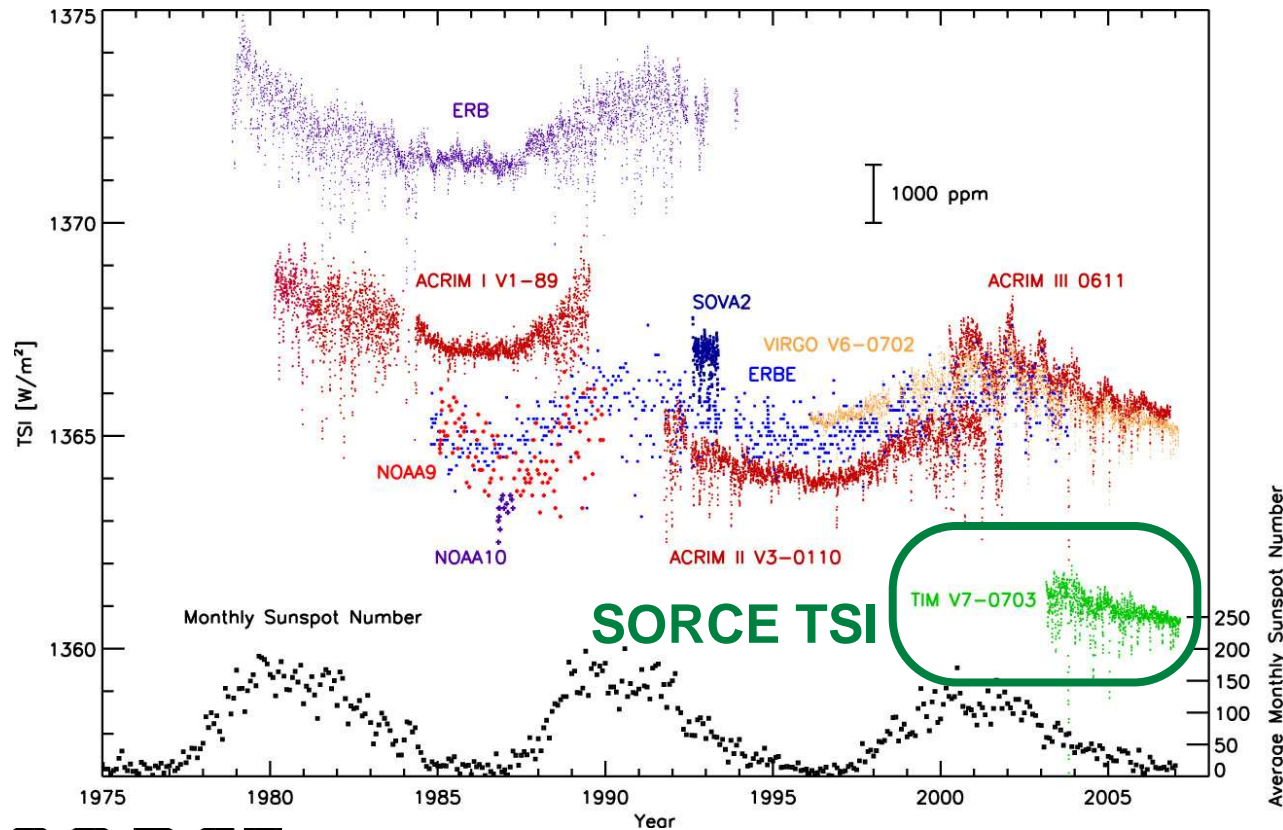


SORCE

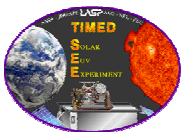
(figure from Greg Kopp)

SORCE TIM Extends the TSI - Establishes Lower Value

- Fundamental determination that the Total Solar Irradiance (TSI) is $\sim 1361 \text{ W/m}^2$, not 1366 W/m^2
 - SORCE TIM has most accurate measurement (350 ppm vs. 1000 ppm)
 - Validation effort with NIST is on-going; new TSI cal. facility at LASP
 - Impacts Earth's radiation energy budget (ES want lower value anyway)



TIM
-4.5 W/m²



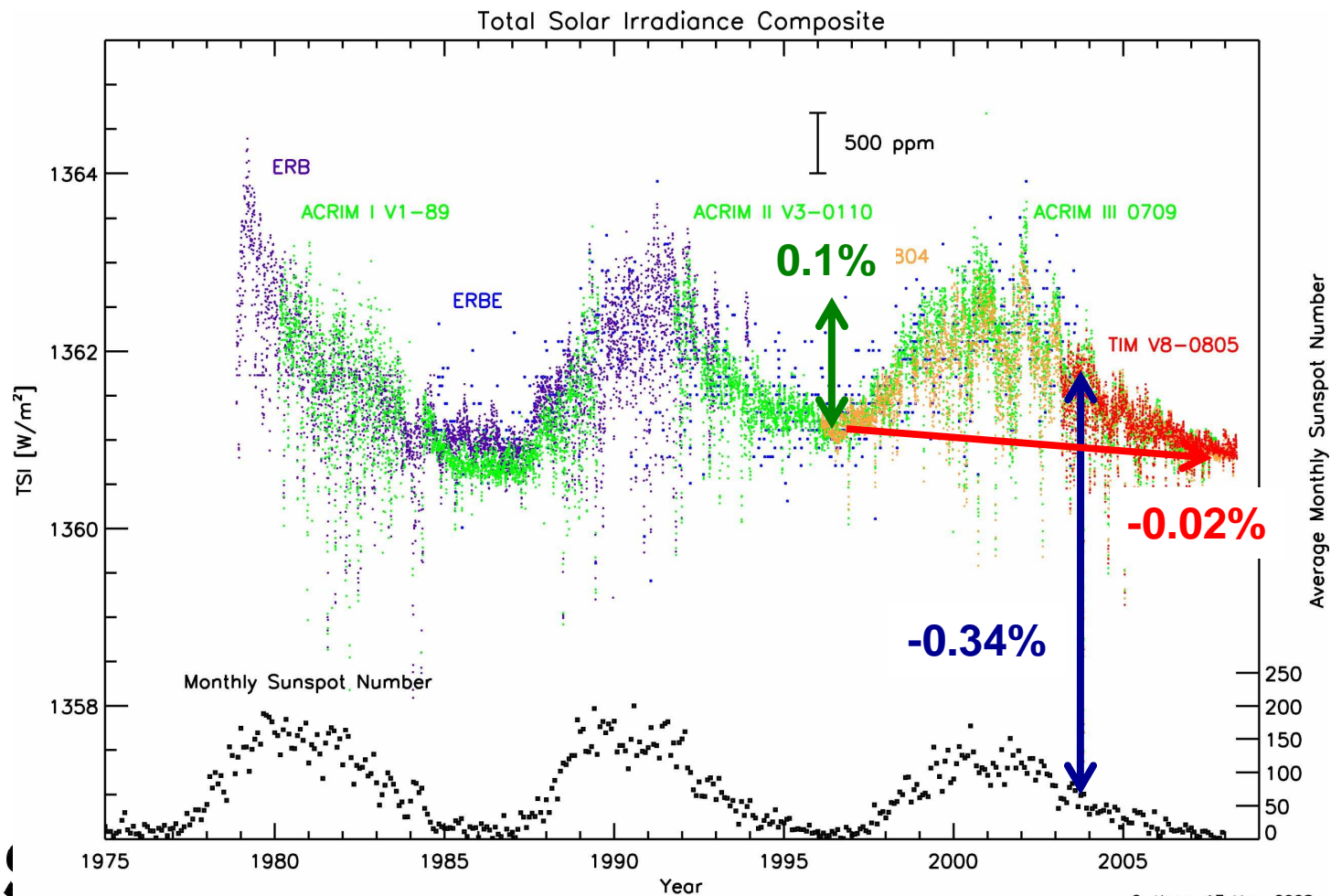
SORCE

(figure from Greg Kopp)

Composite TSI Time Series

➤ TSI variations for Solar Cycle 23:

- 0.1% for solar cycle 23
- -0.34% dip for Oct 2003 (large sunspots)
- **Preliminary**: TSI trend indicates -0.02% decrease from last minimum

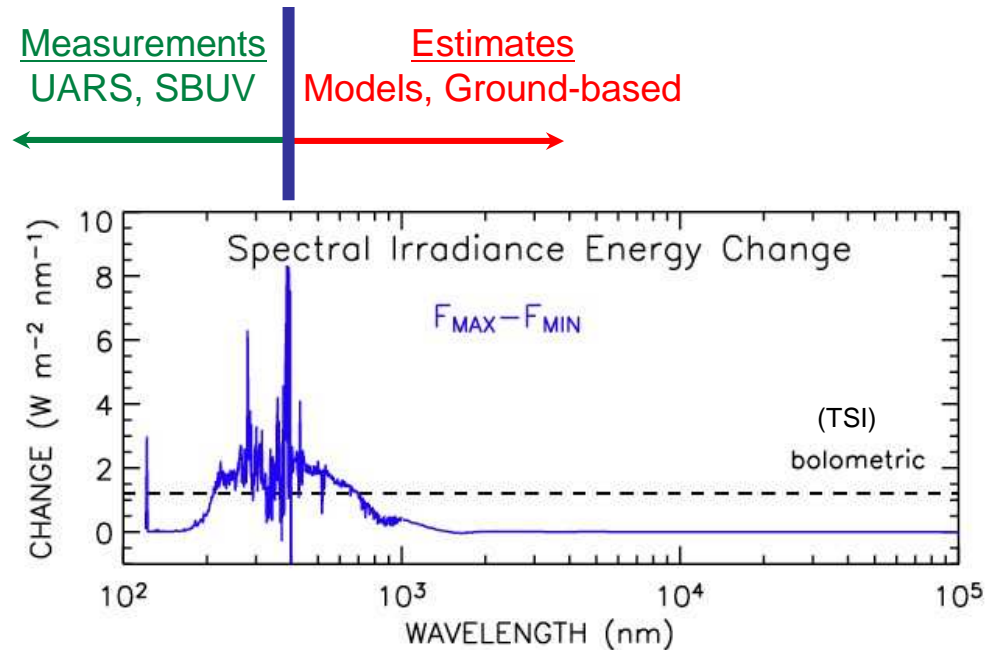


SSI Variability Before SORCE / TIMED

➤ SSI observations

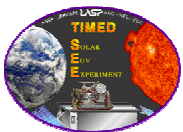
- UARS : 115-420 nm
 - SOLSTICE
 - SUSIM
- SBUV: 200-400 nm
- ATLAS: 115-1600 nm
 - SUSIM
 - SBUV
 - SOLSPEC

Reference Solar Spectra
Thuillier *et al.*, *Adv. Space Res.*,
34, 256, 2004



Solar Cycle (SC) variation estimate is from Fröhlich & Lean [AAR, 2004].

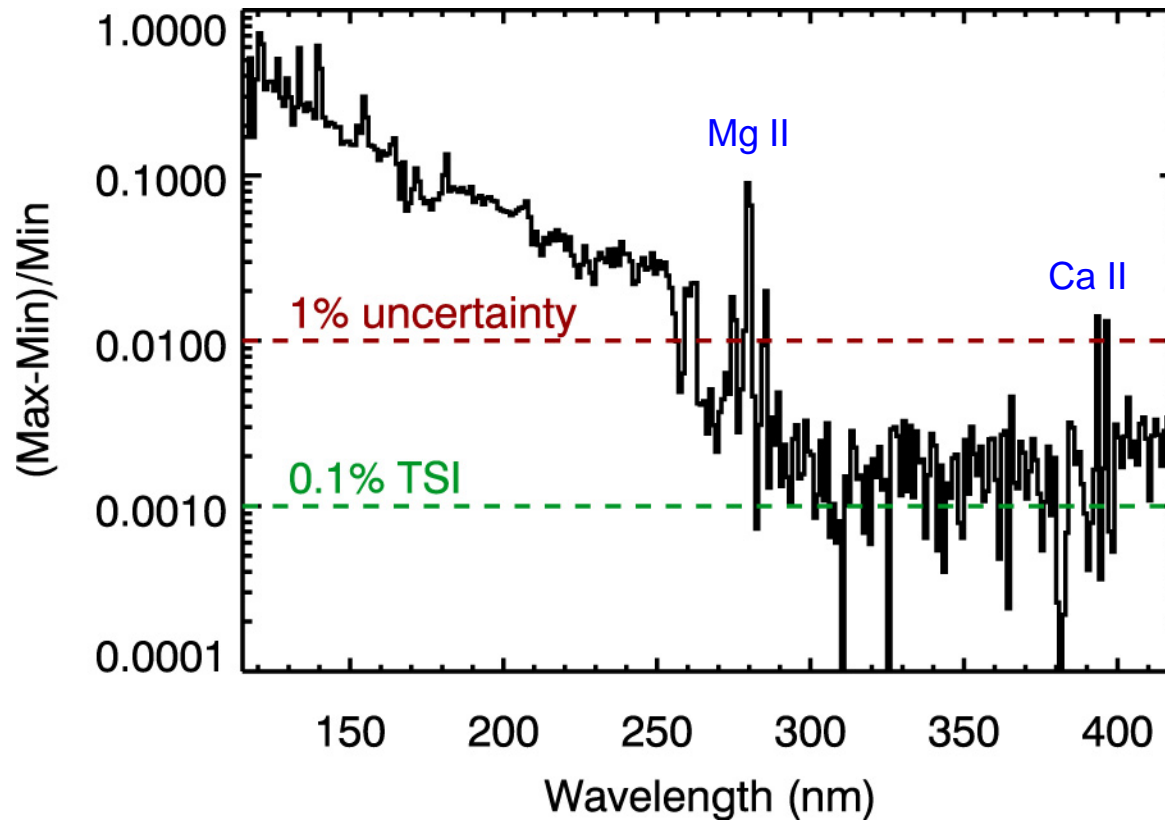
Note no variability assumed for $\lambda > 1600 \text{ nm}$



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Solar Cycle Results from UARS & ATLAS

- UARS & ATLAS observations in 1992-1996 period – last half of SC 22
 - Woods et al., *J. Geophys. Res.*, 1996.
 - Thuillier et al., *Adv. Space Res.*, 2004.
 - Woods & Rottman, in *Comparative Aeronomy in the Solar System*, 2002.



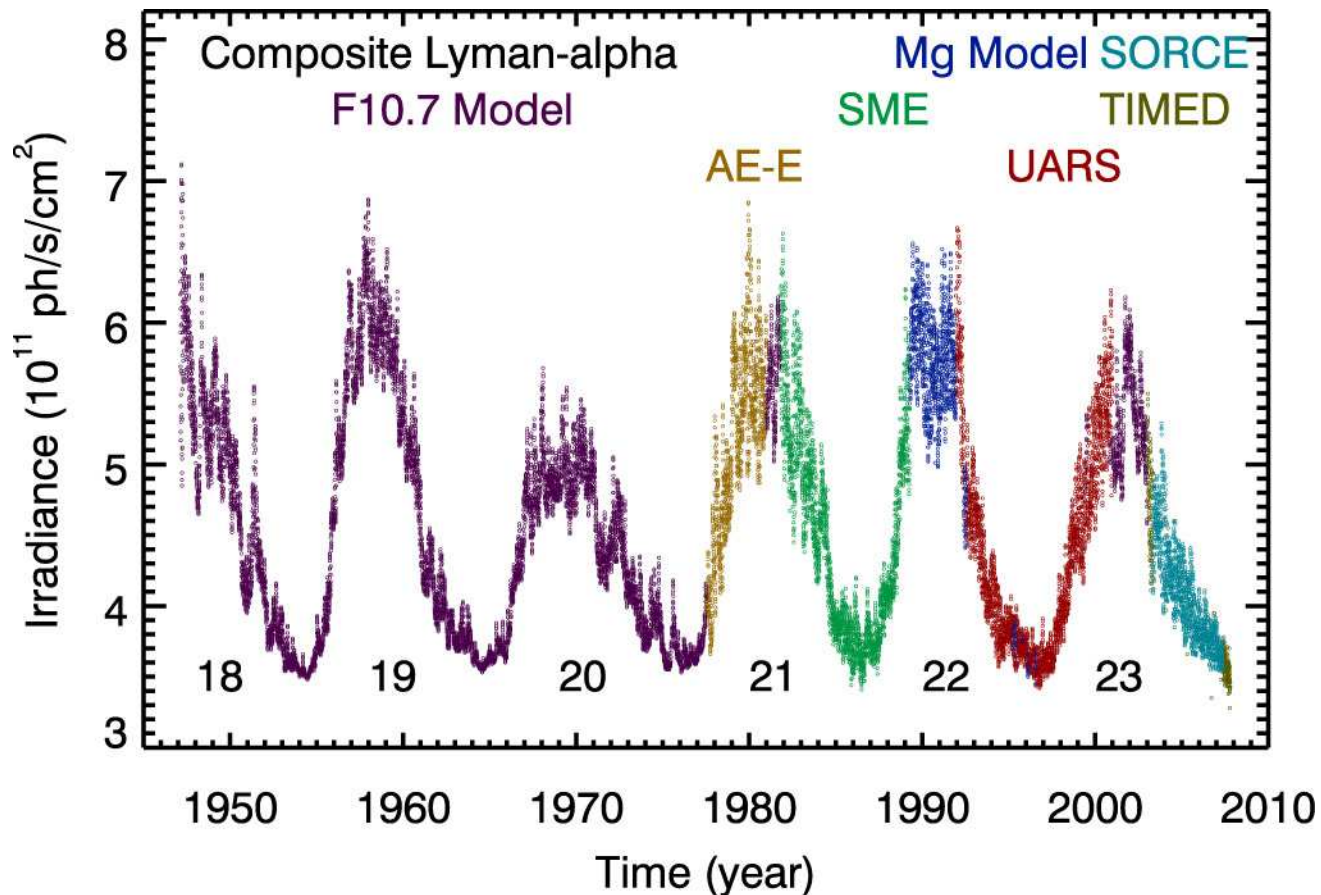
Results > 260 nm
are mostly below
uncertainty level



SORCE

Composite Solar Ultraviolet Time Series

- Lyman- α (121.6 nm) by Woods *et al.* (JGR, 2000)
- More complete UV range by DeLand *et al.*

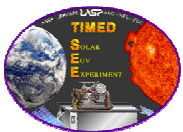
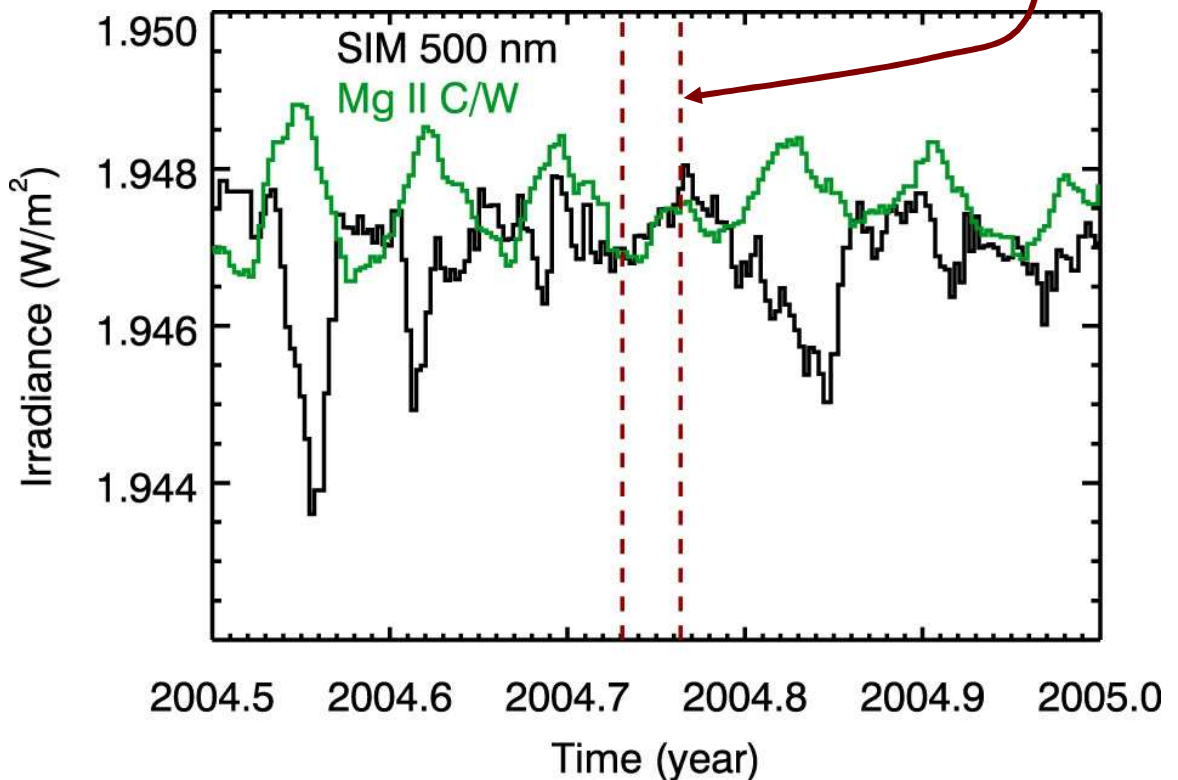


SORCE

Dark and Bright Contributions for $\lambda > 260$ nm

- Dark sunspots normally dominate photospheric emissions in the NUV-visible-NIR ranges
 - Bright plage above the sunspots dominate the chromospheric (ultraviolet) emissions such as the Mg II emission (anti-correlation with 500 nm)
- **Bright faculae (active network) sometimes dominates**
 - If so, then photospheric and chromospheric variations are in phase
 - This happens about once a year (during SOCR mission)

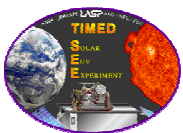
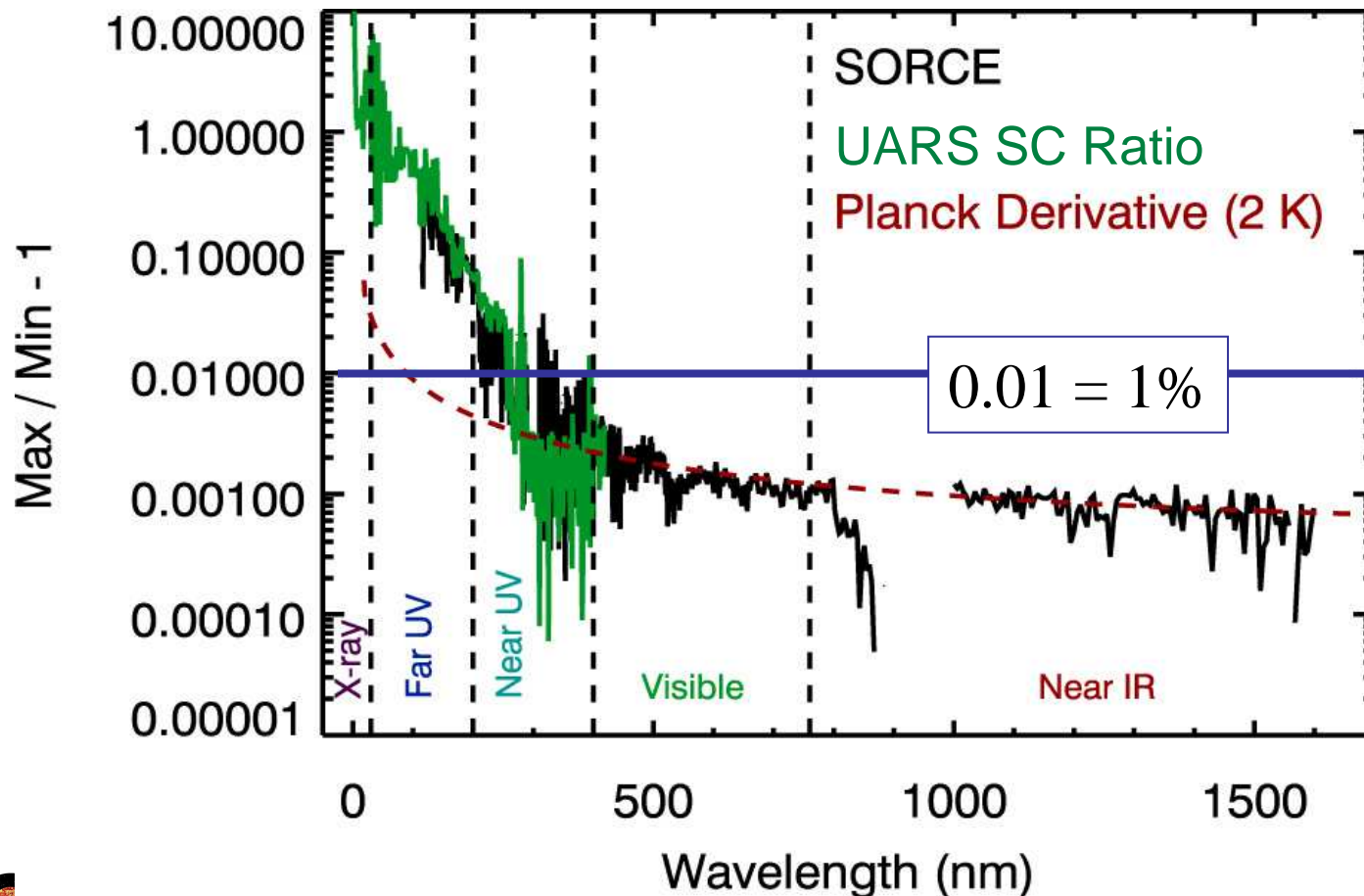
Need at least 3 parameters to model solar irradiance:
Active Region (sunspot, plage)
Active Network (faculae)
Quiet Sun (with LT trend)



SOHR

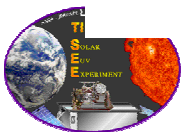
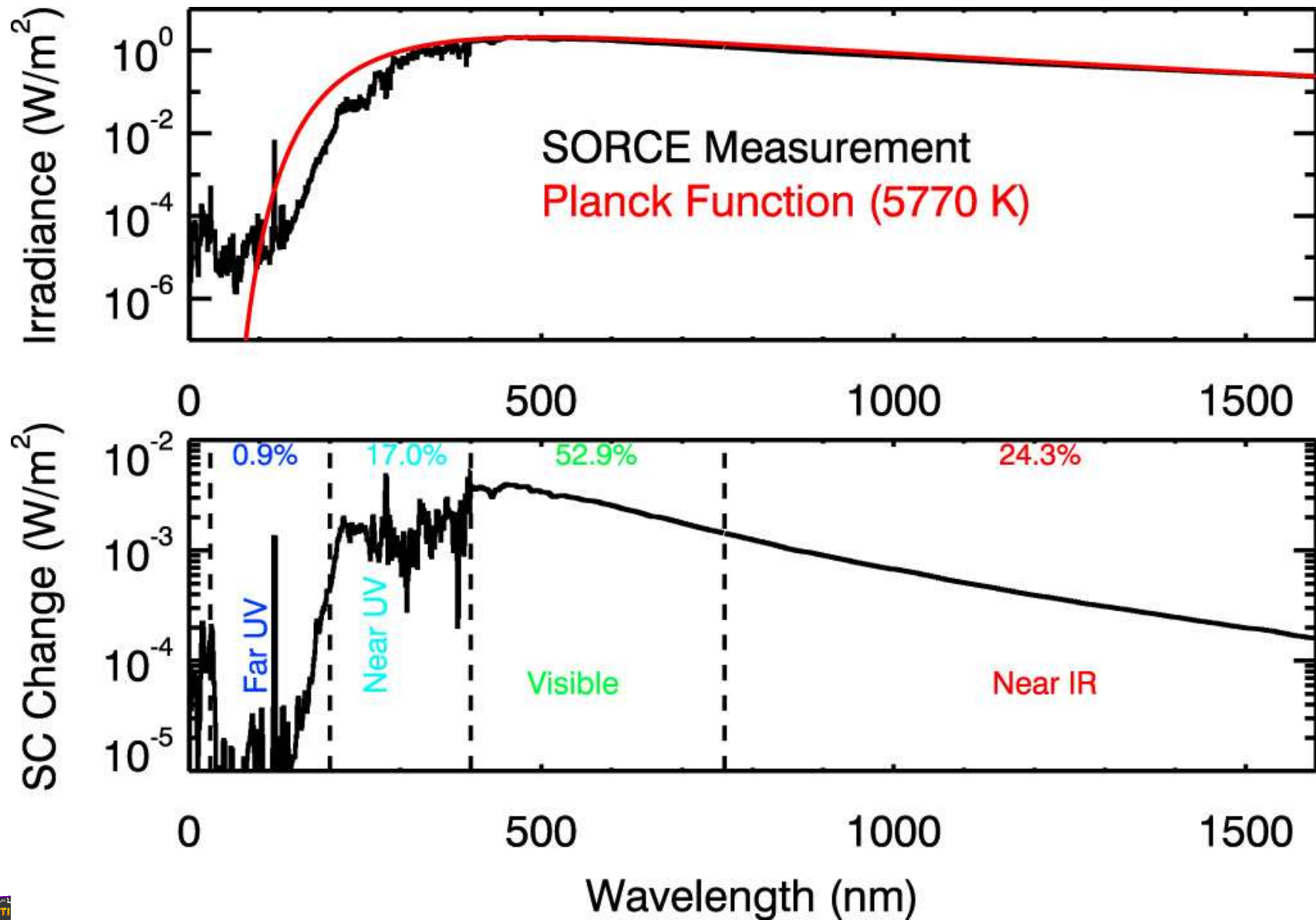
Early Estimate of 11-year Solar Cycle Variation

- In-phase variation in 2004 used as rough estimate of the 11-year solar cycle variation
 - assumes active network is primary cause of solar cycle variation
- Result suggests that the SC variation at $\lambda > 400$ nm could be described by 2 K change in photospheric temperature



SORCE

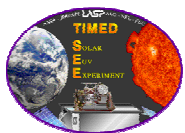
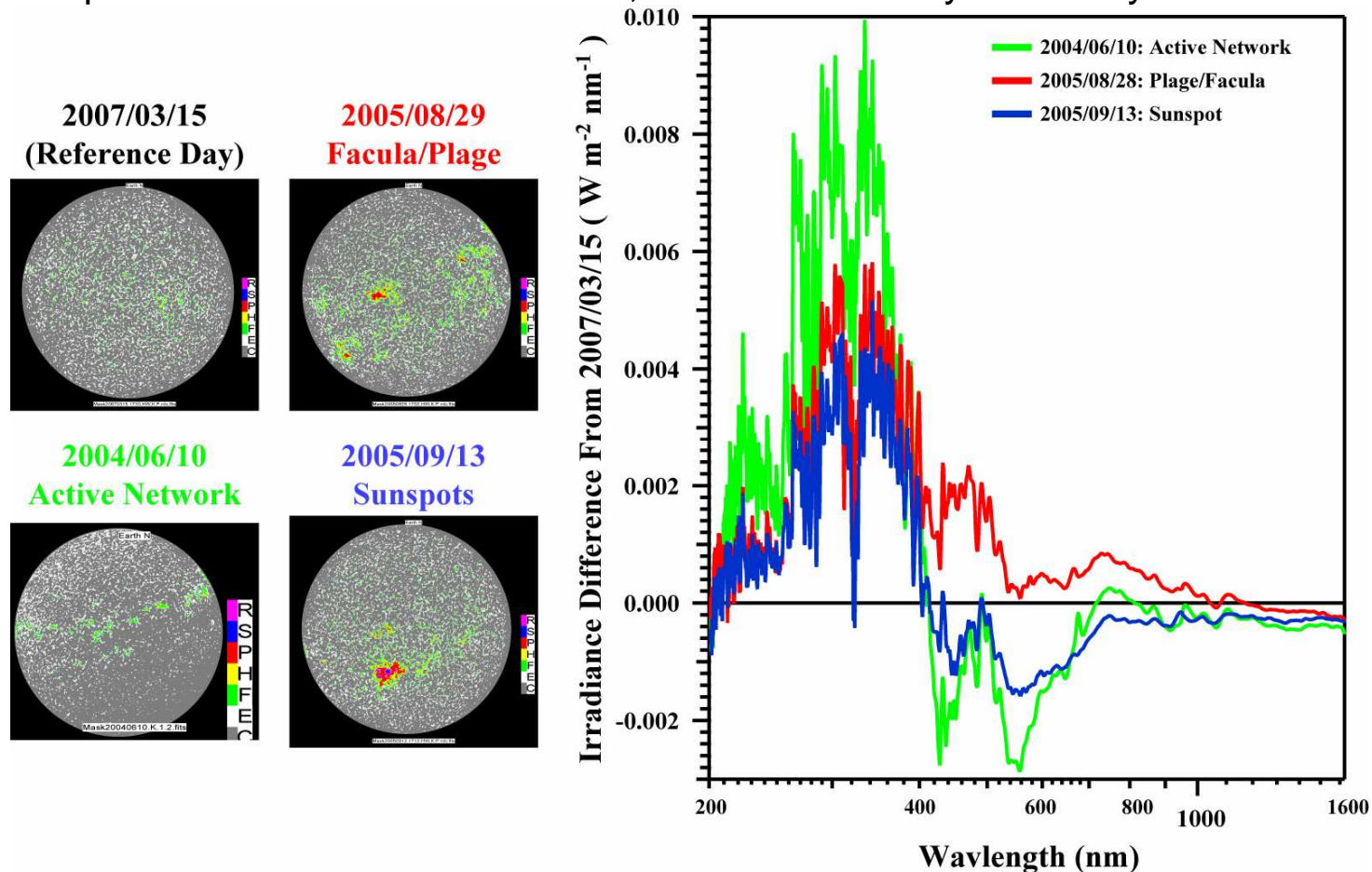
Estimated Solar Cycle Variability in Energy Units



SORCE

Additional Examples from SORCE SIM

- Although more active solar conditions in 2003, best SIM data are in 2004-2007
- Jerry Harder and Juan Fontenla examined solar images and selected several dates dominated by either sunspots, facula, or active network.
- Following example uses the **facula-reference example** (with 27-day averages)
 - Corresponds to $\langle F_{10.7} \rangle$ of 72 and 91, so ~12% of full cycle activity

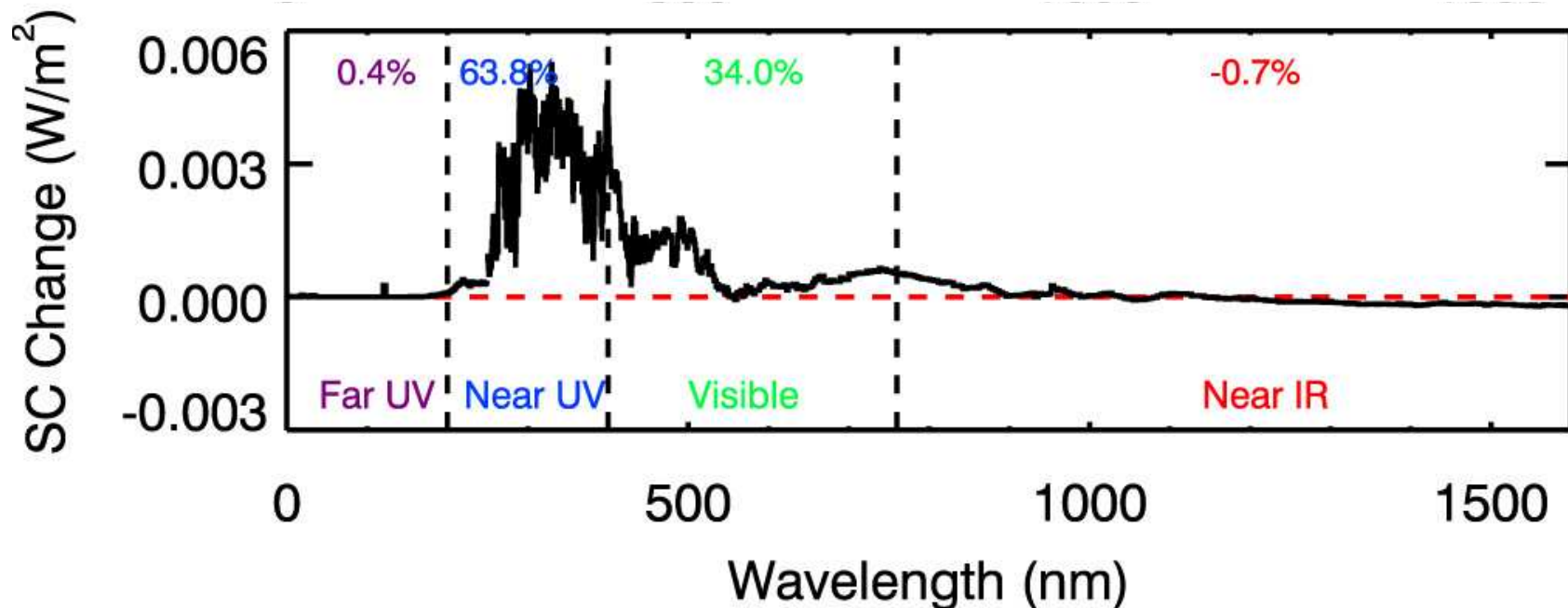


SORCE

(figure from Jerry Harder)

Spectral Contributions to TSI Variability are Different

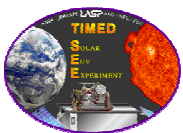
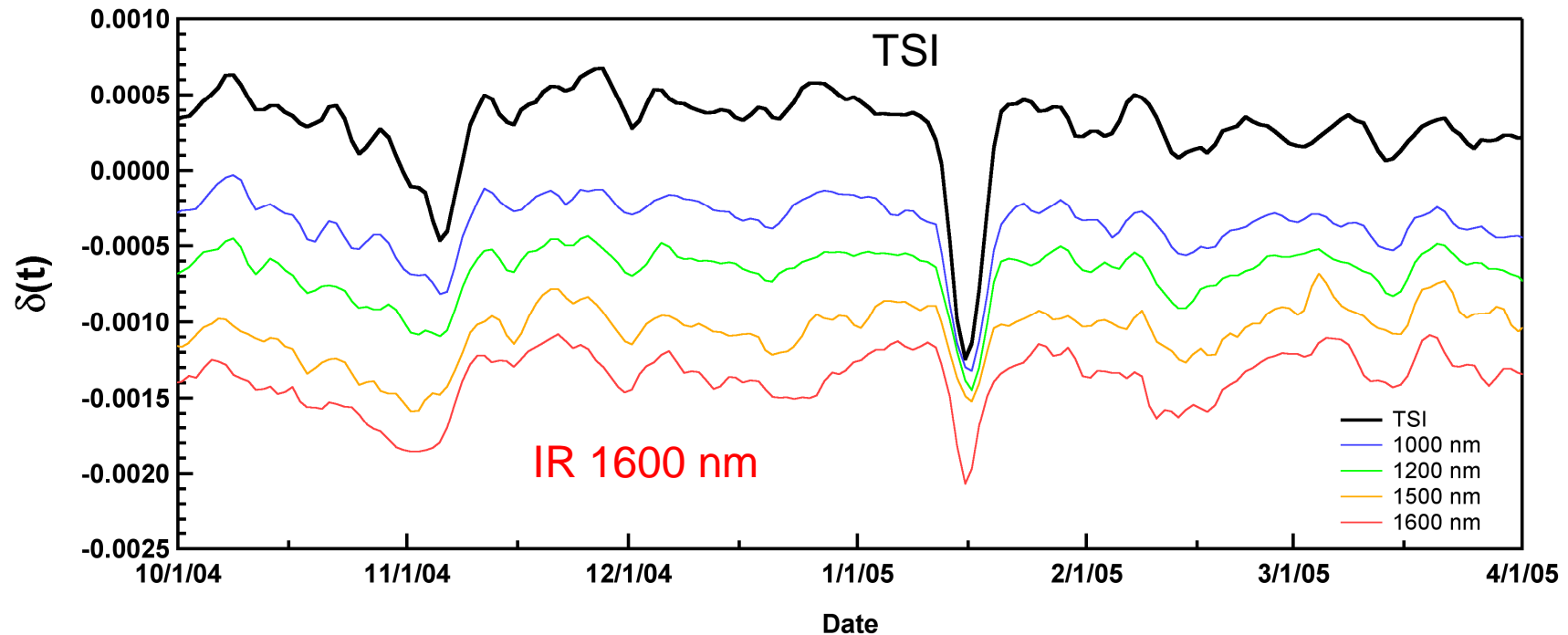
- The **facula** example has much more UV contribution to the TSI variation, less in visible, and much less in the IR
 - Some of the differences is due to solar variability from different time periods and some could be due to instrument degradation correction



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Infrared (IR) Variations are Less than Visible

- IR is in phase with the TSI for short-term variations (solar rotation)
 - Reduced variability in the IR relative to TSI variation
 - **Expected** result due to H⁻ opacity being low near 1600 nm

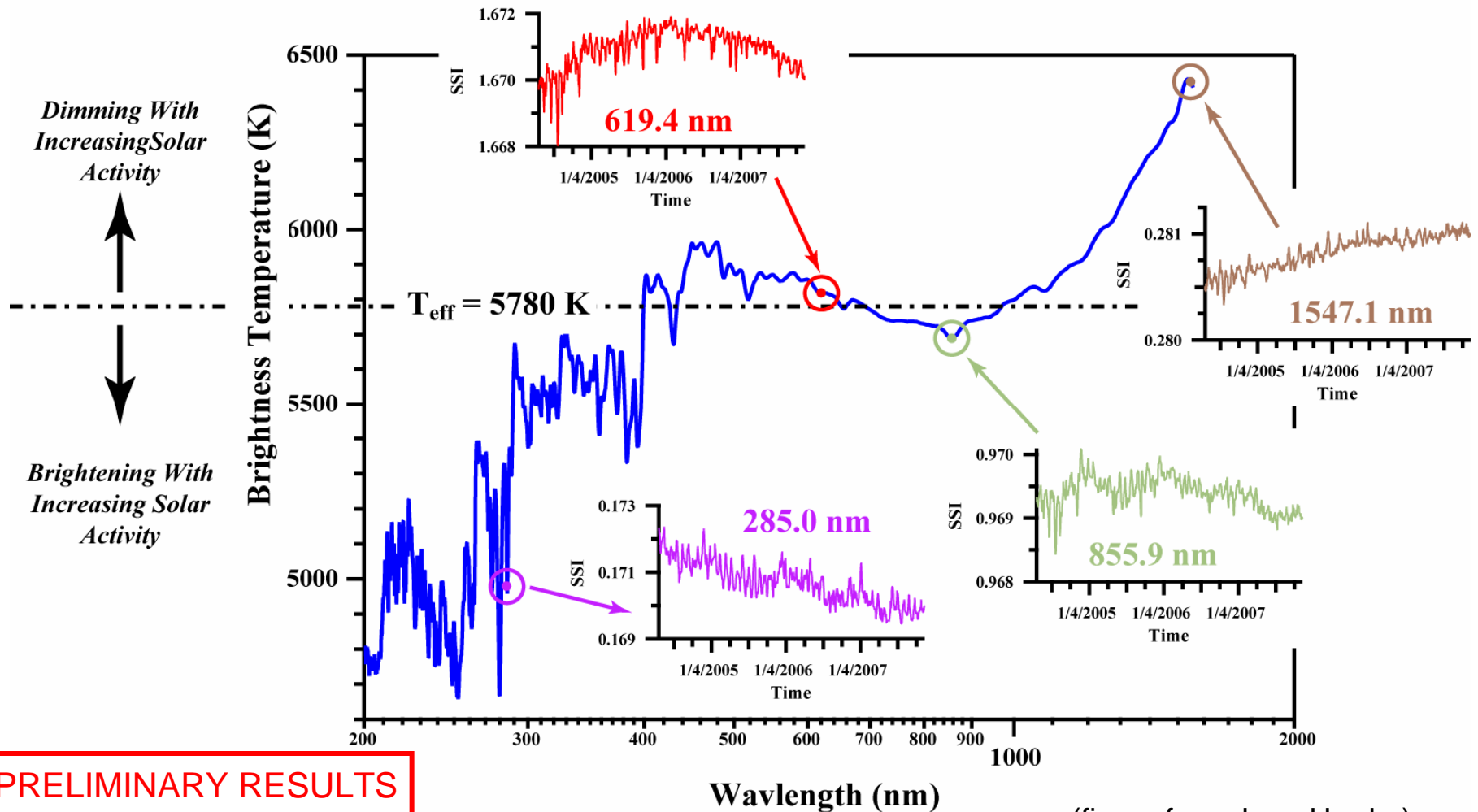


SORCE

(figure from Erik Richard)

Surprise for Infrared Solar Cycle Variations

- But IR irradiance is out of phase with solar cycle
 - UV decreases towards solar minimum, visible very similar to TSI
 - IR result is new, **unexpected** result from SORCE SIM

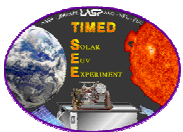
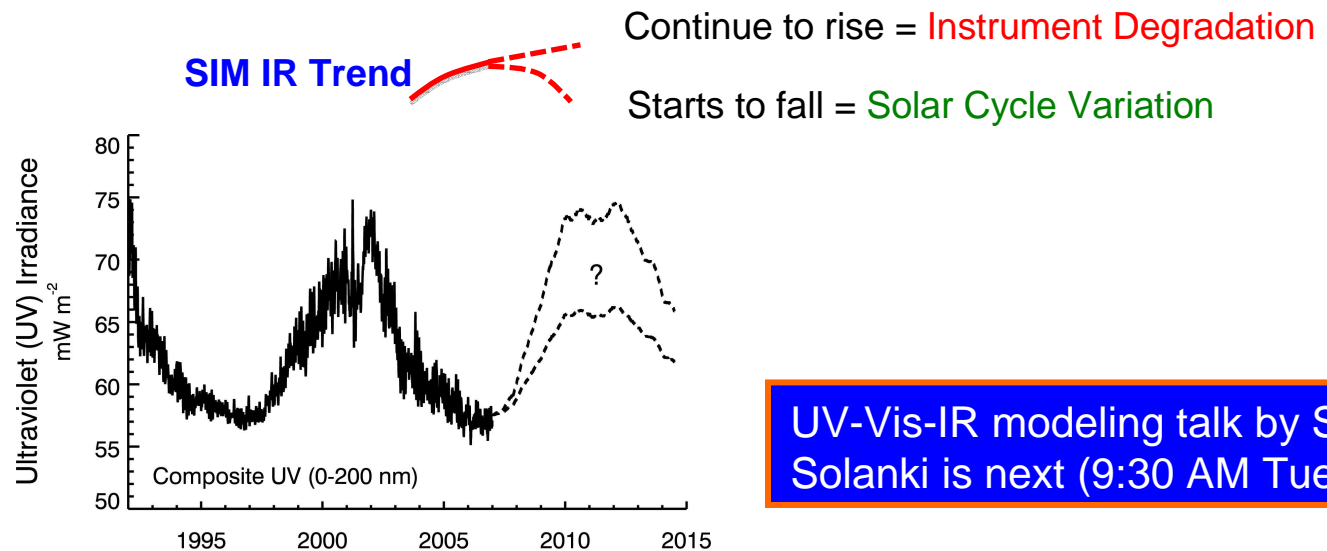


PRELIMINARY RESULTS
Validation is on-going

(figure from Jerry Harder)

What do these SIM observations tell us?

- SIM out-of-phase solar cycle results for 400-700 nm and 1000-2400 nm suggest out-of-phase temperature change in the lower photosphere.
 - Early result suggested 2 K cooler temperature for SC minimum
 - This result indicates temperature change is not uniform throughout the photosphere and even negative in deeper layers
- This is **preliminary** result...
 - Expect to know more as solar cycle leaves minimum
 - Trend should clarify differences between instrument degradation and solar cycle

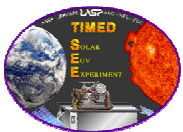
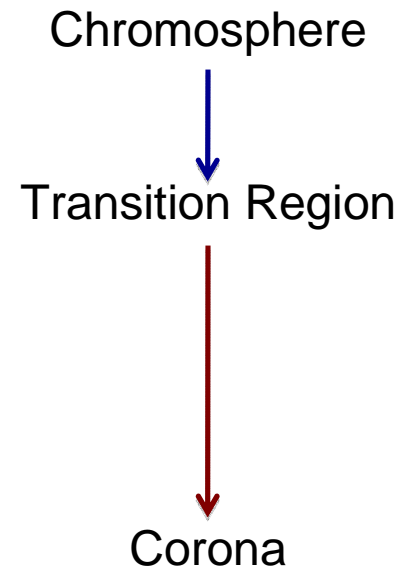
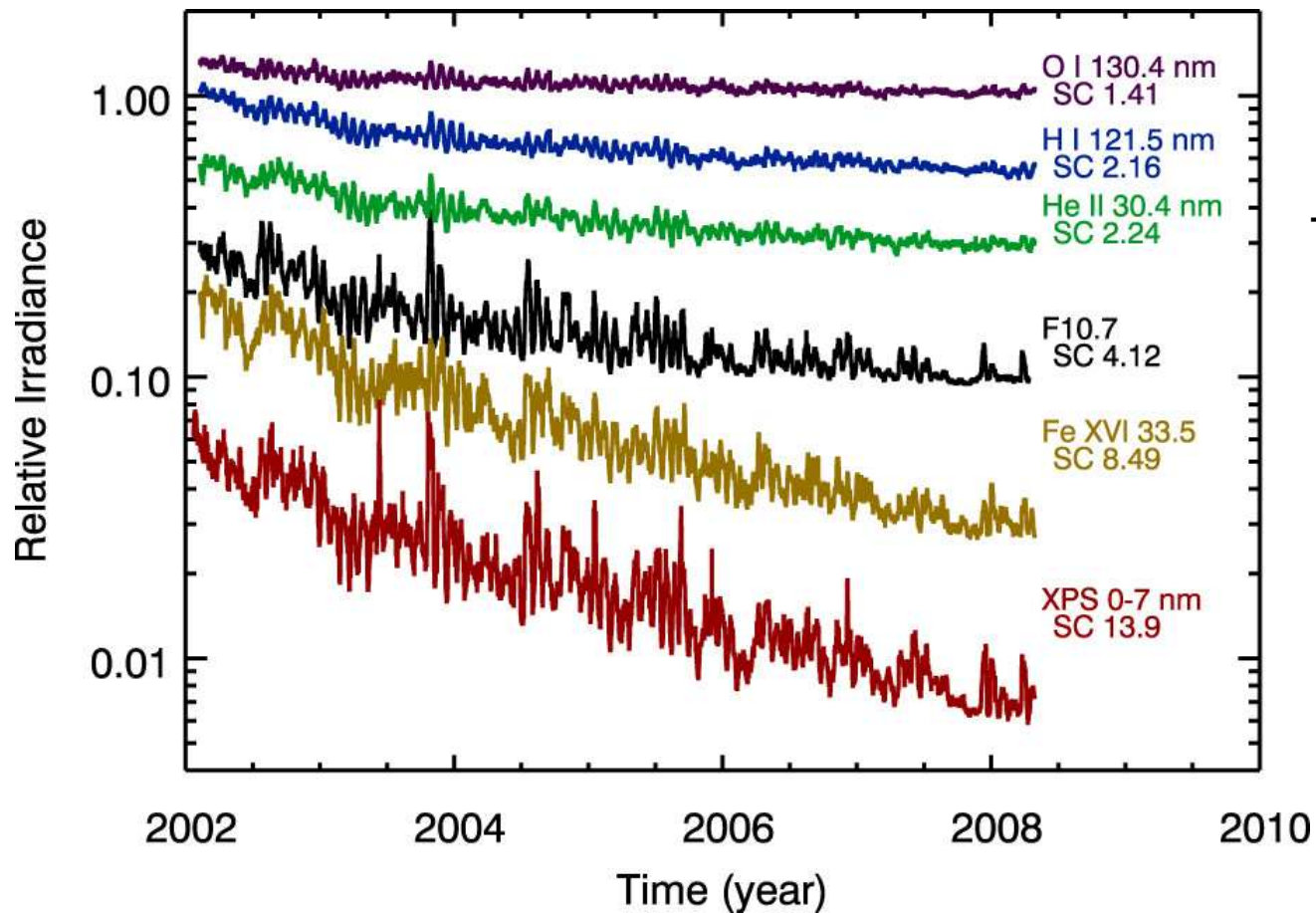


SORCE

UV-Vis-IR modeling talk by Sami Solanki is next (9:30 AM Tue).

Solar Irradiance for Space Weather

- X-rays, EUV, and FUV ranges are important for Space Weather studies
 - TIMED SEE providing full spectral coverage (0.1 – 194 nm)
 - Chromospheric emissions vary the least (factor 1.1 to 1.5)
 - Coronal emissions vary the most (factor 4 to 1000)

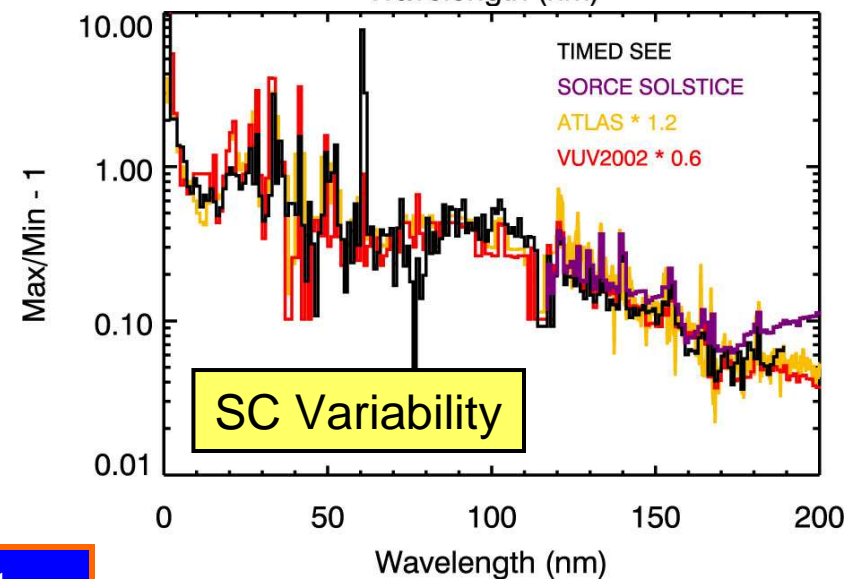
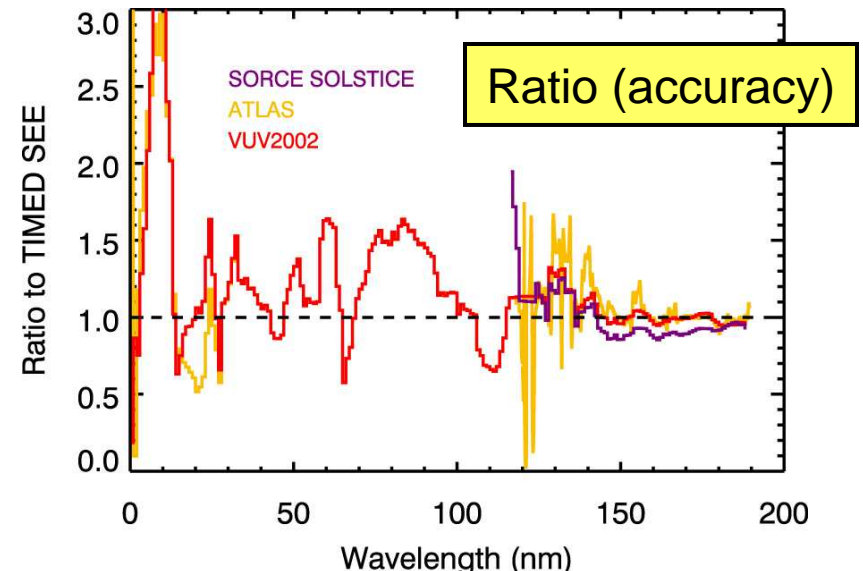


SORCE

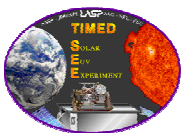
Solar Cycle Variability Observations – June 2008

EUV-FUV Variability Example for Solar Cycle 23

- 2007/316 for Low Activity and 2003/192 for High Activity
 - 27-day average used
 - $\langle F_{10.7} \rangle_{81}$ is 70.5 and 131.4
 - So ~40% of full cycle activity
- **SORCE SOLSTICE:**
 - FUV values and variability are consistent with UARS results (ATLAS and VUV2002)
- **TIMED SEE:**
 - SEE improves EUV accuracy
 - EUV variabilities are similar to AE-E (VUV2002)



See Linton Floyd talk about UV Variability at 10 AM (Tue).



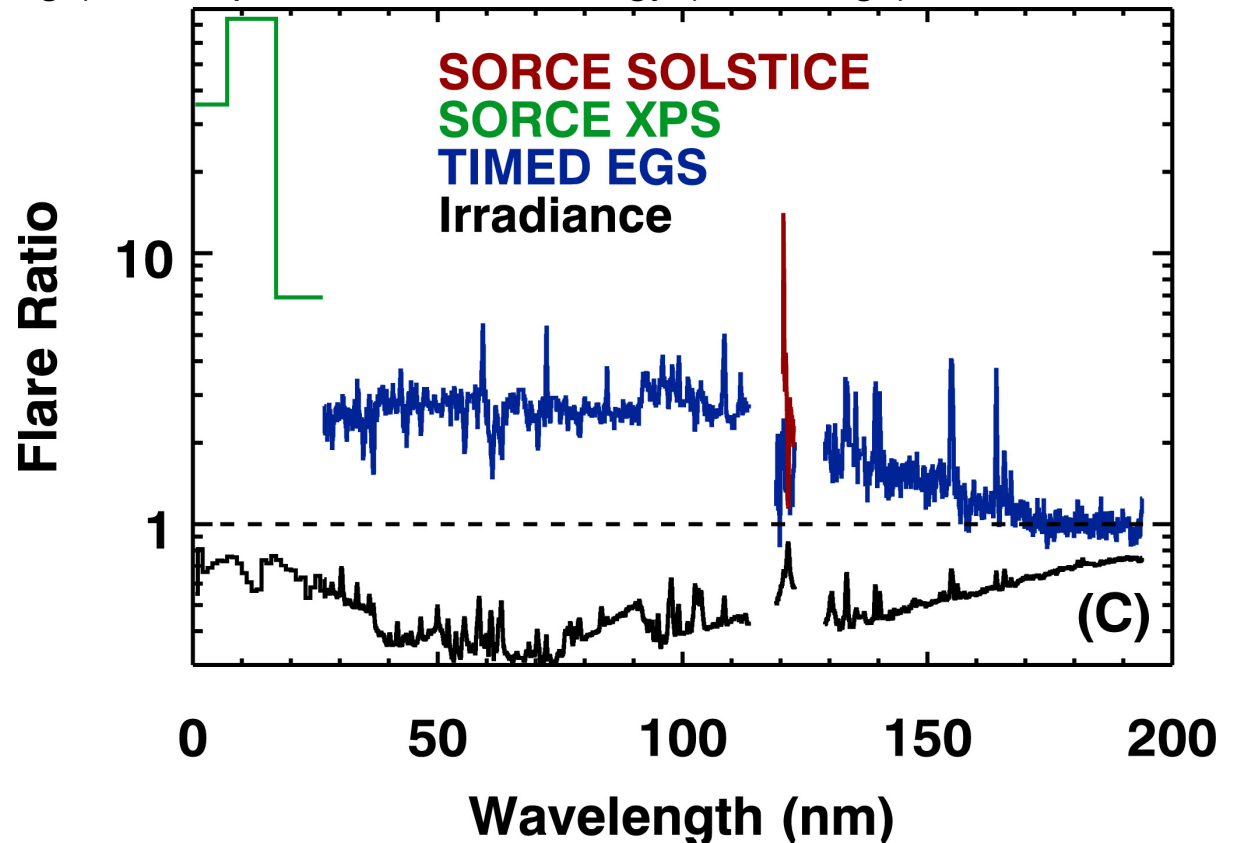
SORCE



New Flare Results from Irradiance Observations

- Flare variations can be larger than solar cycle variation
 - Largest flares during Oct-Nov 2003 [Woods et al., GRL, 2003]
- Total flare energy is about 10 times more than previous estimates
 - Prior estimates: total is 10-15 times the GOES X-ray energy (0.1-0.8 nm) [e.g., Hudson & Willson, 1983; Hudson, 1991]
 - TIM measurement: total is 150 times the GOES X-ray energy [Woods et al., JGR, 2006]
 - Flare energy ($2-6 \times 10^{32}$ ergs) is comparable to CME energy ($\sim 10^{32}$ ergs)

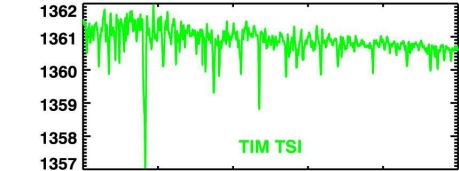
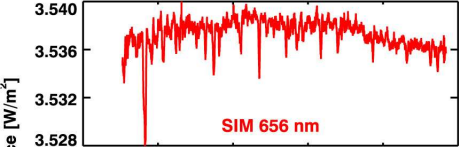
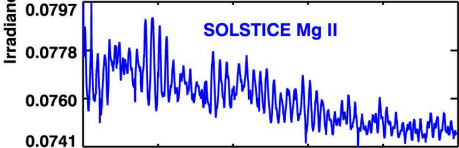
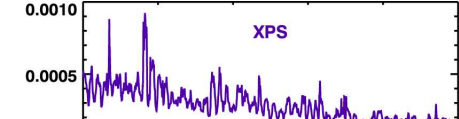
Flare Irradiance Spectral Model (FISM) developed with these new observations. See Phil Chamberlin talk



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Future Irradiance Observations for SC 24

- **ESA SOLAR installed on ISS in February 2008**
 - Includes TSI and SSI from 17 nm to 3000 nm
- **Glory TIM and PICARD will continue TSI but no SSI observations**
 - TSIS (TIM + SIM) re-selected to be on NPOESS, could launch 2013
- **SDO EVE and GOES XRS-EUVS will improve EUV with 100% duty cycle**
- **PROBA-2 LYRA will have high time cadence (2009 launch)**

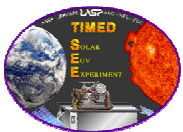
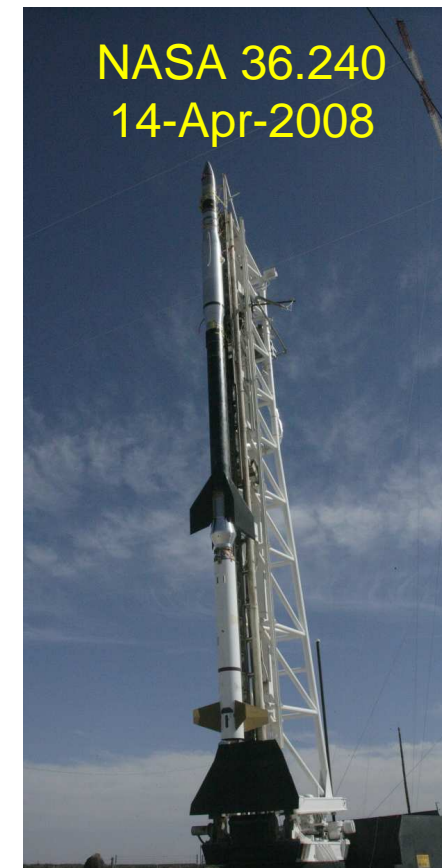
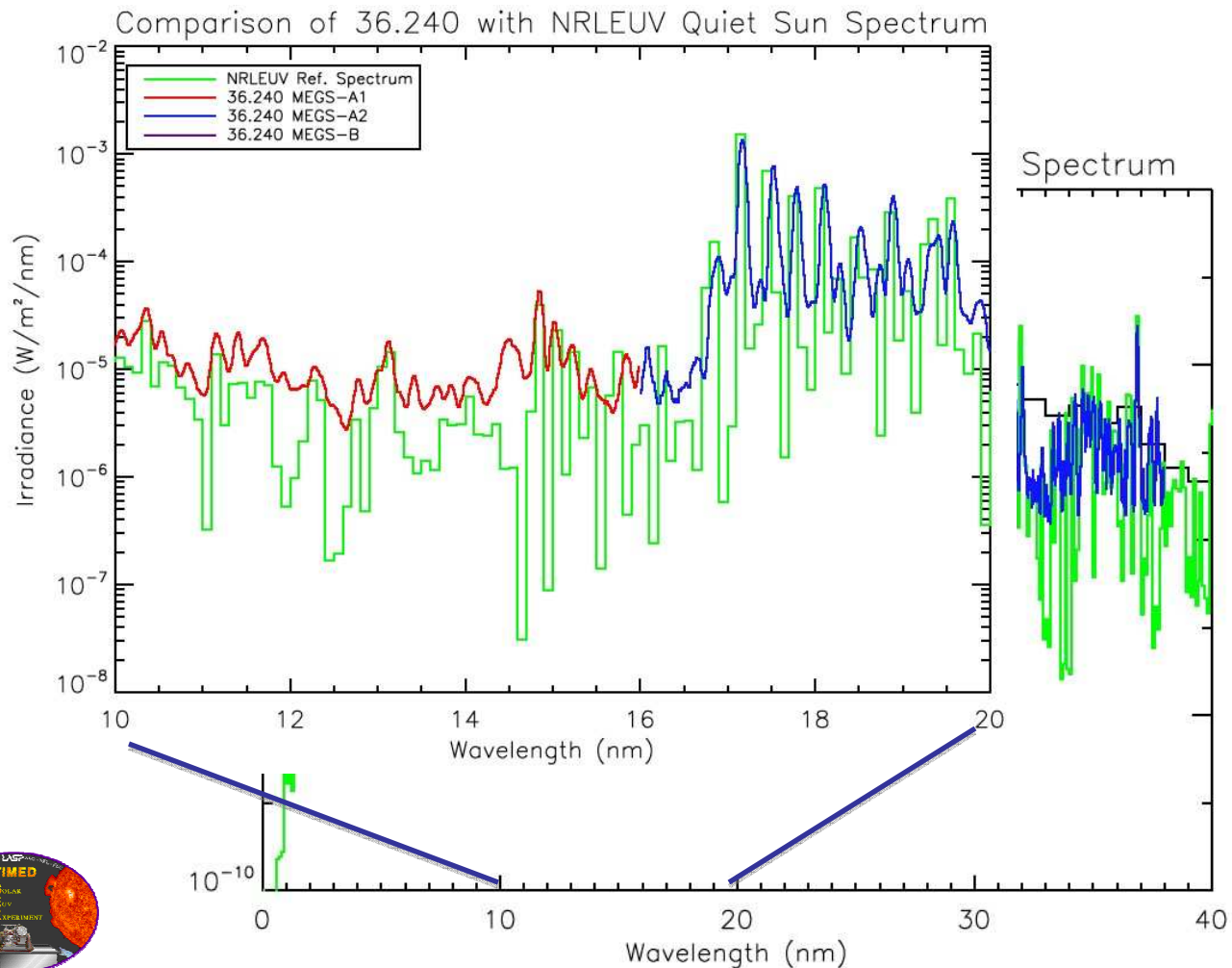
Wavelength Range	Previous & SC 23 Measurements	Current Measurements	Future SC 24 Measurements
TSI (all λ s)	ERBE, ACRIM, VIRGO, SORCE TIM, ESA SOLAR		Glory TIM (2009) PICARD (2009)
Visible-NIR (400-2400 nm)	SORCE SIM, ESA SOLAR (plus limited results from ESA SCIAMACHY & SOLSPEC)		NPOESS TSIS (2013)
FUV-MUV-NUV (120-400 nm)	SBUV, UARS, SORCE SOLSTICE, ESA SOLAR		NOAA SBUV (no FUV though)
EUV (0.1-120 nm)	GOES XRS, SOHO SEM, TIMED SEE, ESA SOLAR		SDO EVE (2009) GOES EXIS (2014)



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Example SDO EVE Solar EUV Spectrum

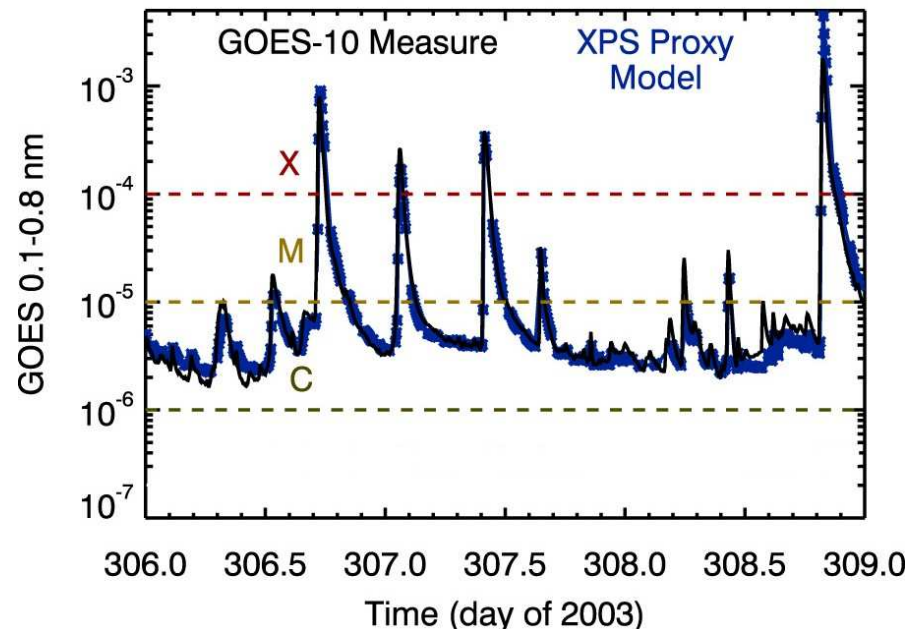
- Recent calibration rocket for TIMED SEE flew on April 14 and had on-board the prototype SDO EVE
 - EVE has 0.1 nm spectral resolution from 5 to 105 nm



Proxy Concept for GOES XRS

- GOES-10 X-Ray Sensor (XRS) is only one operational and its pointing platform could fail at any time
- NOAA may need realtime X-ray proxy soon (< 3 min latency). Some options include:
 - **SORCE XPS** – can use TDRSS for realtime data with 60% duty cycle
 - **SDO EVE** – launches into GEO (2009) and will have 100% duty cycle
 - **SOHO SEM** – its data latency is too slow
 - **TIMED SEE** – only has 3% duty cycle

Example X-ray Proxy
using SORCE XPS
0.1-7 nm channel



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