Solar Irradiance Variability Observations during Solar Cycles 21 to 24

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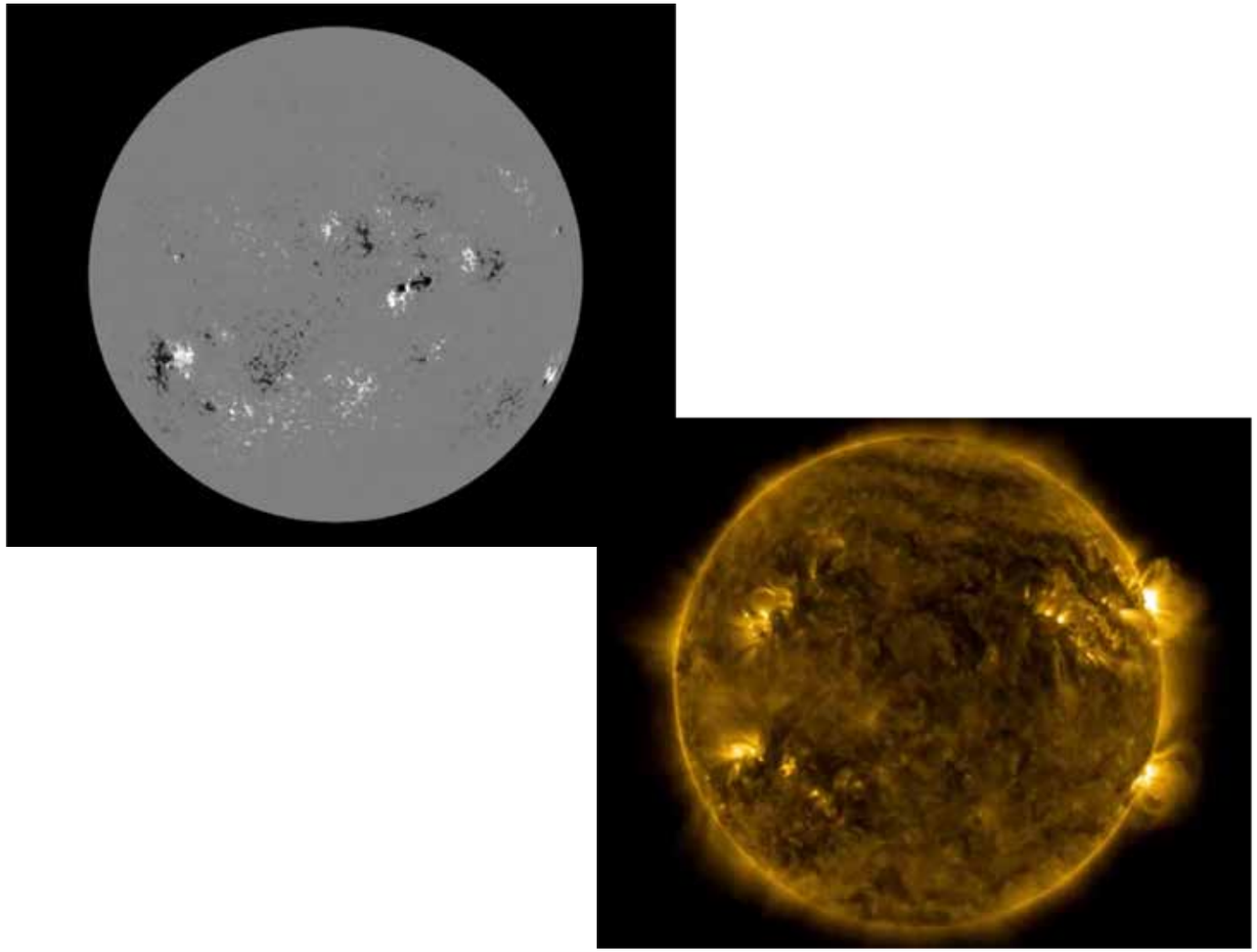
and Frank Eparvier, Greg Kopp, Erik Richard, Marty Snow

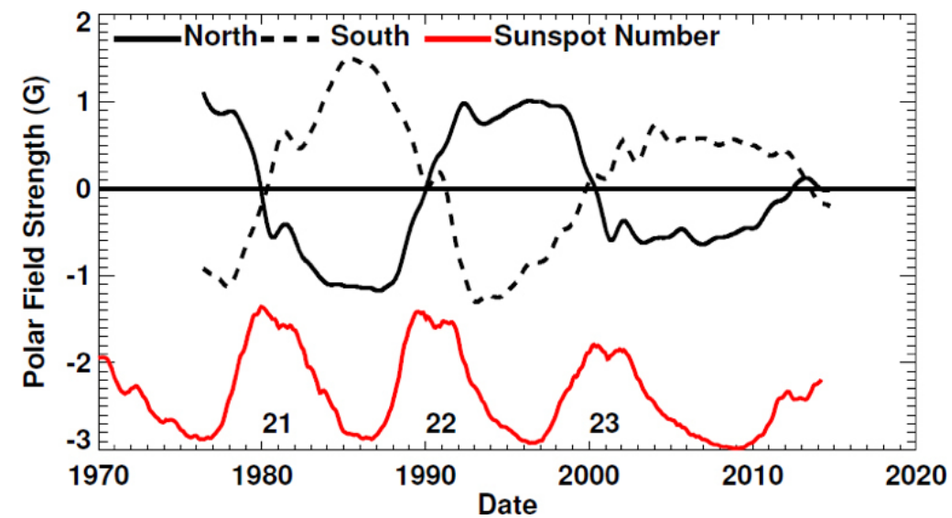
Evolving Magnetic Fields Drive Solar Activity

From NASA SDO HMI and AIA Images: 2010-2016



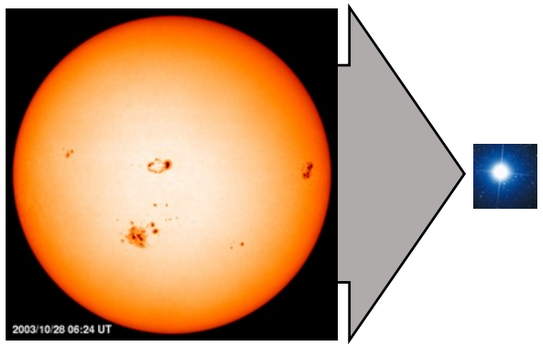
TALK OUTLINE

- What are the important solar climate records?
- Why are they important for space climate?
- How much does the Sun vary?
- What are the challenges in making these solar climate records?
- New technique to estimate degradation trends and then to make composite solar record.



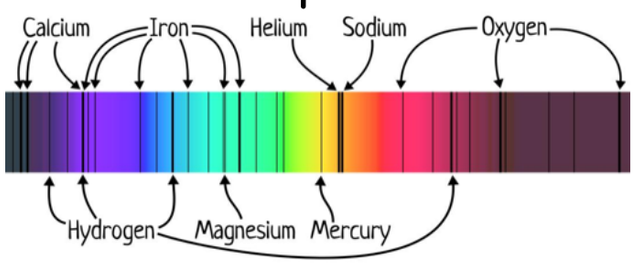
From David Hathaway, The Solar Cycle, 2015

Solar Climate Records Important for Space Climate



- Solar Irradiance
  - Our Sun as a Star (no spatial resolution)

Solar Spectrum



- **Solar Spectral Irradiance (SSI)**
  - Brightness as function of wavelength
  - Units of $W/m^2/nm$

$$\int_0^\infty SSI \; d\lambda$$

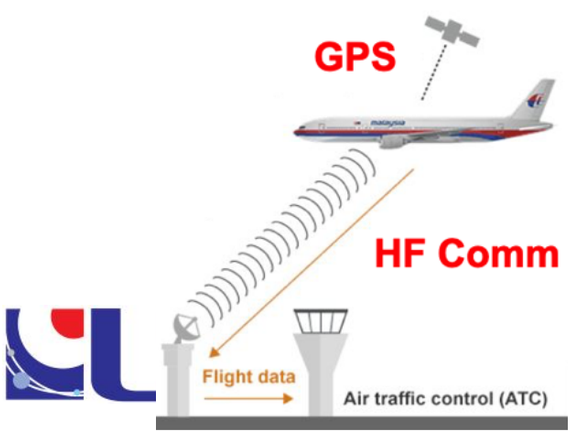
Total Solar Irradiance
1361 W/m^2

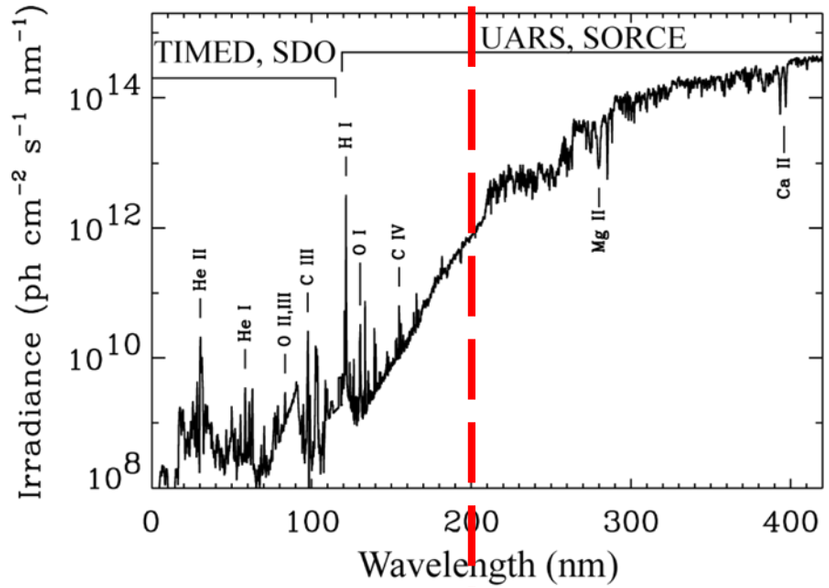
- **Total Solar Irradiance (TSI)**
  - TSI is SSI integrated over all wavelengths
  - Units of W/m^2

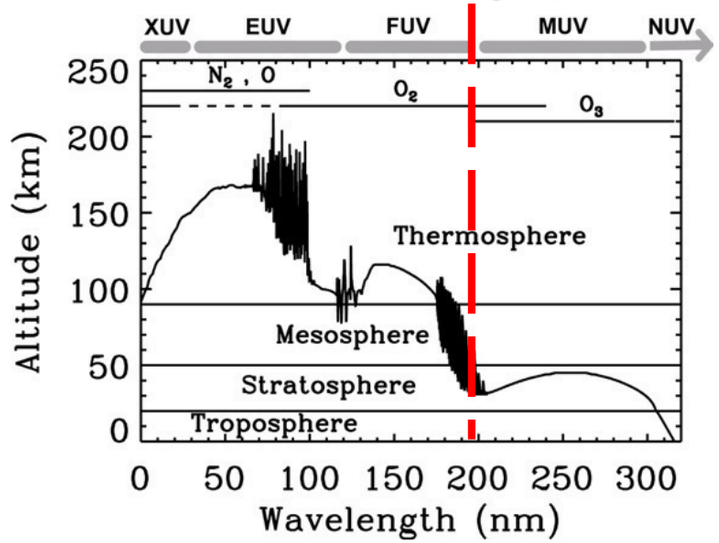
Solar Ultraviolet Absorbed in Earth's Atmosphere Affects

Space Weather

- XUV, EUV, & FUV heat thermosphere and create the ionosphere
- Space Weather impacts:
  - HF Communication
  - GPS Navigation
  - Satellite Drag (lifetime)



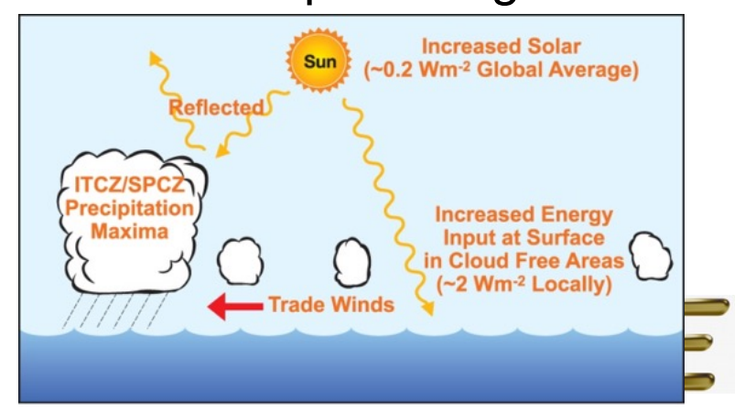




Woods – Space Climate 7 – slide 4

Climate Change

- MUV, NUV, Vis, & NIR are absorbed lower and at the surface
- Climate Change impacts:
  - Stratosphere Ozone and Water Chemistry
  - Top-Down Heating
  - Bottom-Up Heating

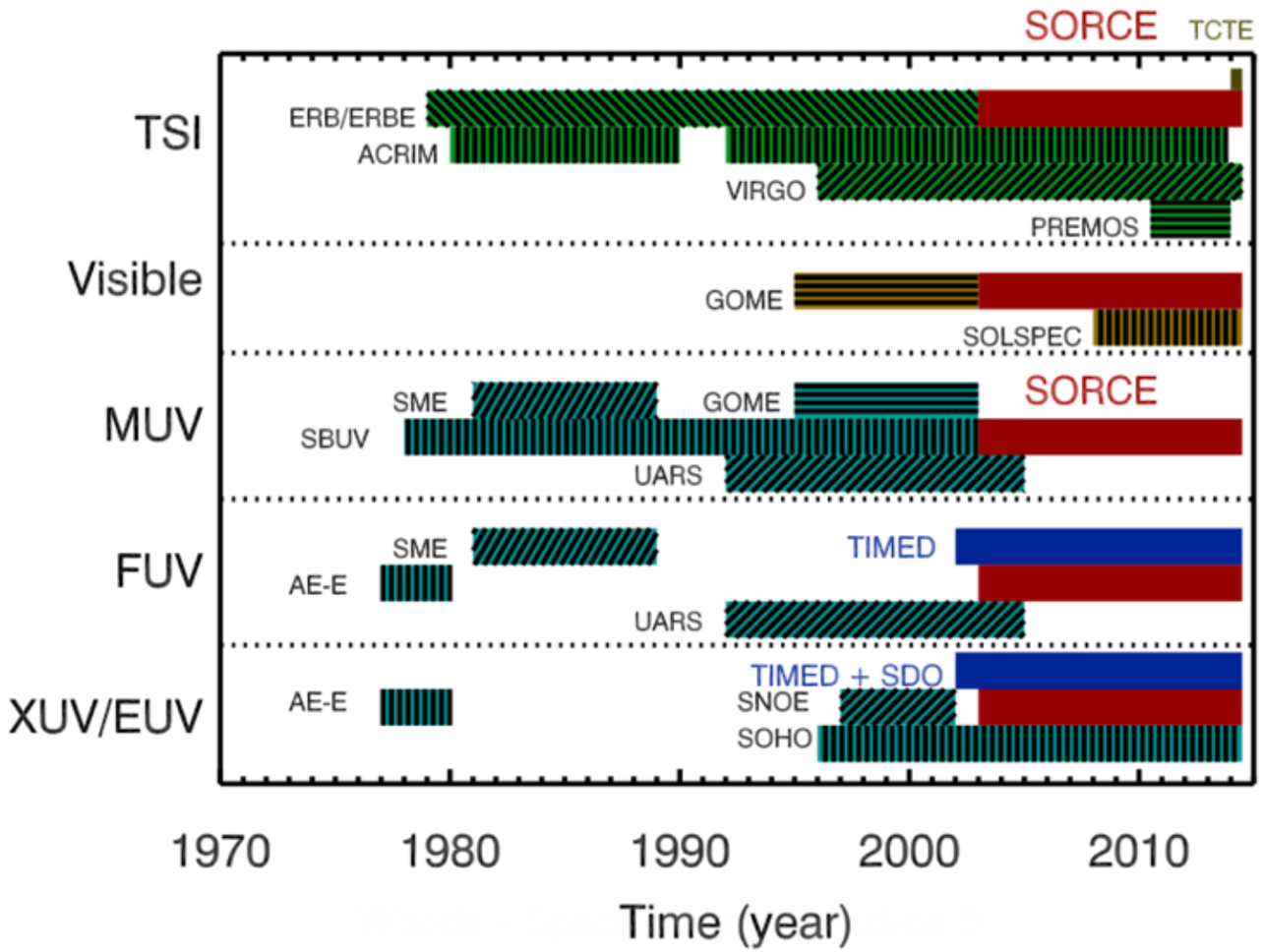


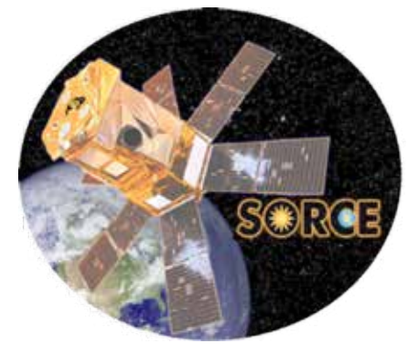
Many Satellites Provide the Solar Climate Records

- Overlapping observations are critical to accurately combine the different measurements into a composite time series.
- Many of these can obtained from http://lasp.colorado.edu/home/lisird/

TIMED/SEE
2002-present

SDO/EVE
2010-present



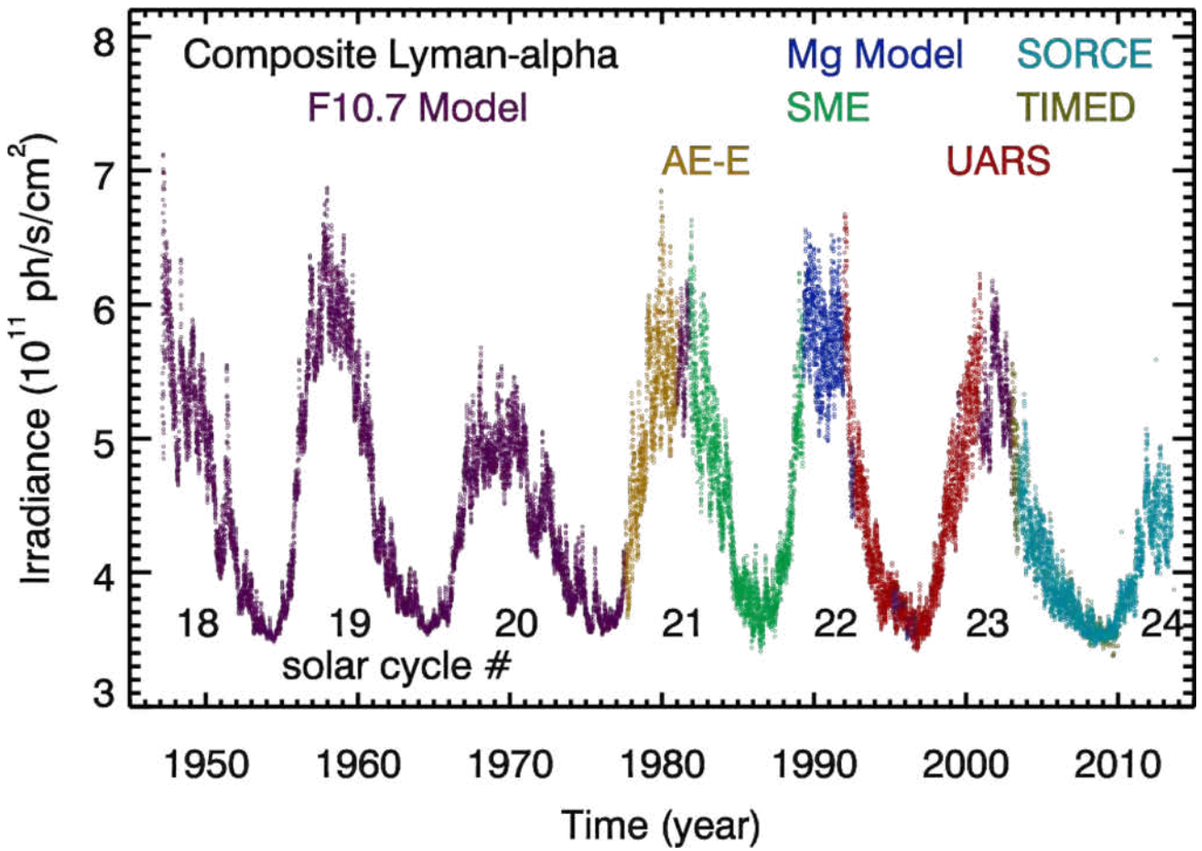


SORCE: 2003-2019

TSIS-1: 2018-present

Key Goal is Creating Long-term Composite Record

Example of SSI Composite Record at H I Lyman-α (121.6 nm)

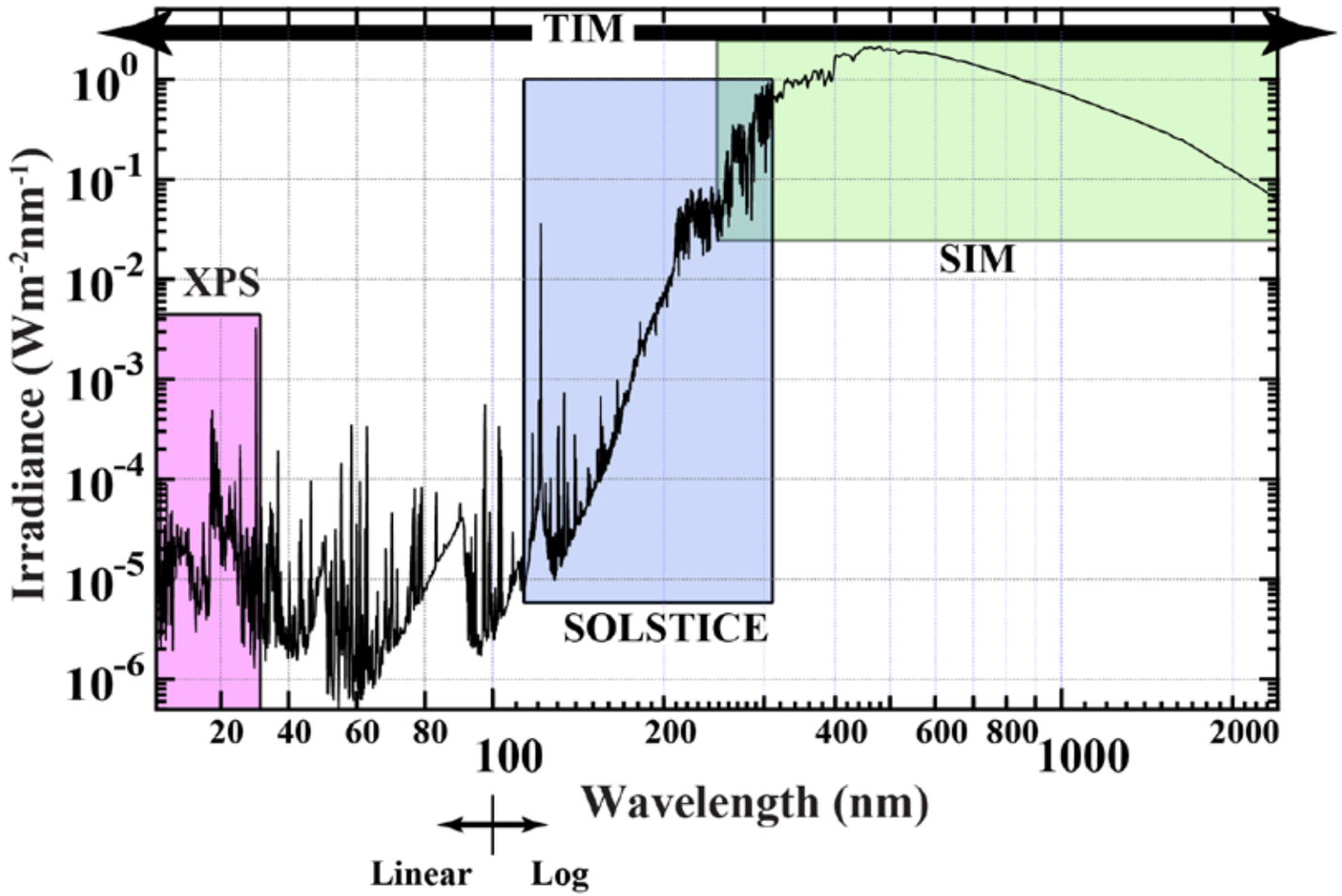


- Woods & Rottman, *J. Geophys. Res.*, 1997
- Woods, Tobiska, Rottman, & Worden, *J. Geophys. Res.*, 2000

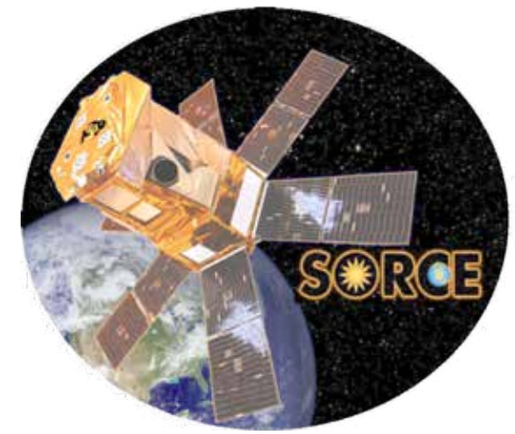
http://lasp.colorado.edu/lisird/

SORCE might be turned off on July 16, 2019

(NASA HQ decision will be made on July 11)



SORCE TIM provides TSI



SORCE SIM, SOLSTICE, XPS provides SSI

$$\int E(\lambda)\,d\lambda \approx 1324.49\ \mathrm{Wm}^{-2}$$

$$\approx 97.3\%\ \text{of TSI}$$

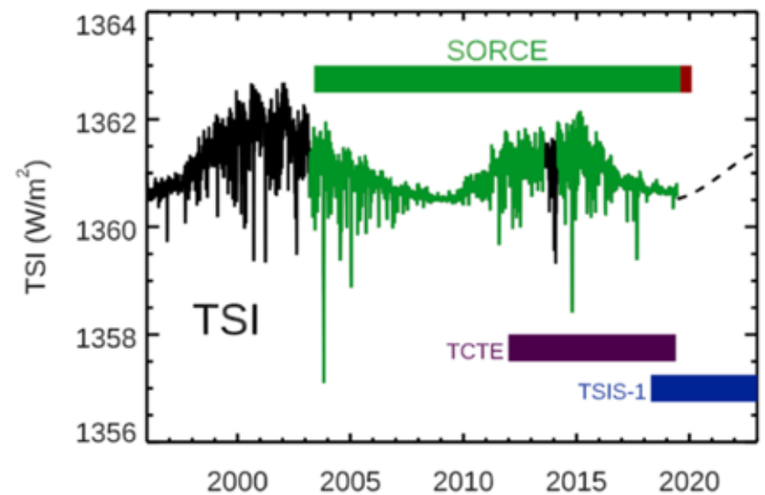
$$\Leftrightarrow\ 36.32\ \mathrm{Wm}^{-2}\ \text{missing from TSI}$$

SORCE Key Legacy Products are TSI and SSI Climate Records

SORCE Science

- **Observe the solar irradiance to create and extend the climate records of the total solar irradiance (TSI) and solar spectral irradiance (SSI: 200-2400 nm).**
- Understand the variability of the Sun's 27-day rotation period and over the 11-year solar cycle
- Model the solar variability for extending solar irradiance climate records back in time
- Explain and predict the effect of the Sun's radiation on the Earth's atmosphere and climate

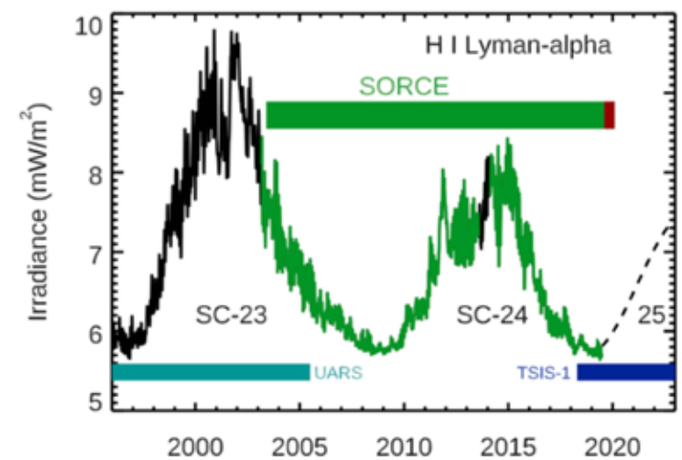
Total Solar Irradiance (TSI)



NOAA's Climate Data Record Program

NRC / NOAA defined key Climate Data Records (CDRs) in 2004, and SORCE TSI and SSI data products and SORCE-supported models of solar variability from NRL (Judith Lean) were adopted for NOAA's CDRs about TSI and SSI. [Coddington *et al.*, *BAMS*, 2016]

Solar Spectral Irradiance (SSI)
This time series is one of 2000 λs.

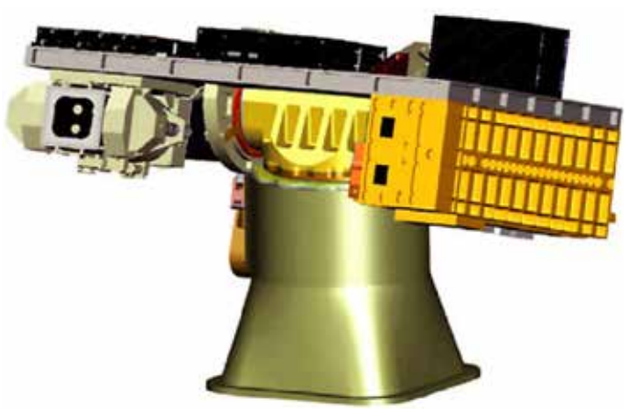


LASP

LASP's Solar Irradiance Future after SORCE are NASA TSIS, NASA CubeSats, and NOAA GOES Missions

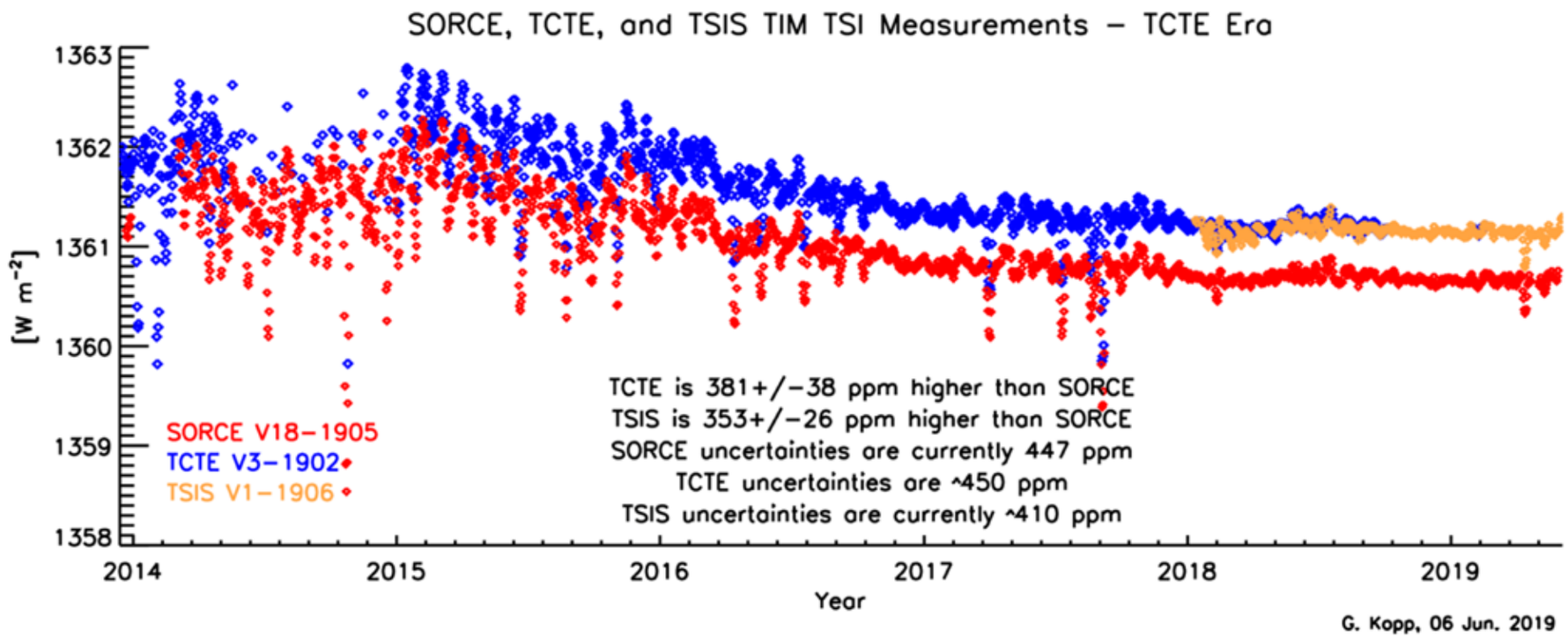
- **NASA Total and Spectral Irradiance Sensor (TSIS) has TIM (TSI) and SIM (SSI 200-2400 nm) instruments**
  - TSIS-1 launched in Dec. 2017 to ISS
  - CSIM CubeSat launched in Dec. 2018
  - CTIM CubeSat will be launched in 2020
  - Free-flyer TSIS-2 is in development

- **GOES-R EUV X-ray Irradiance Sensors (EXIS) has XRS and EUVS instruments (SSI selected lines in 0.1-290 nm)**
  - EUVS-C continues the Mg II index
  - GOES-16 launched in 2016, GOES-17 launched in 2017
  - Two more, GOES T & U, to be launched



TSIS-1 TIM and SIM are Working Great !

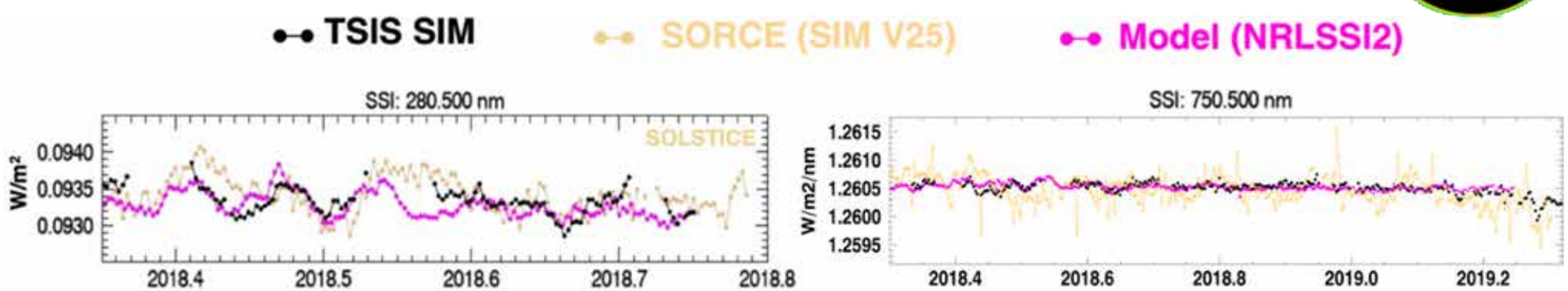
- There are some small offsets between these different TSI data sets. [Greg Kopp had TSI talk earlier in this session]

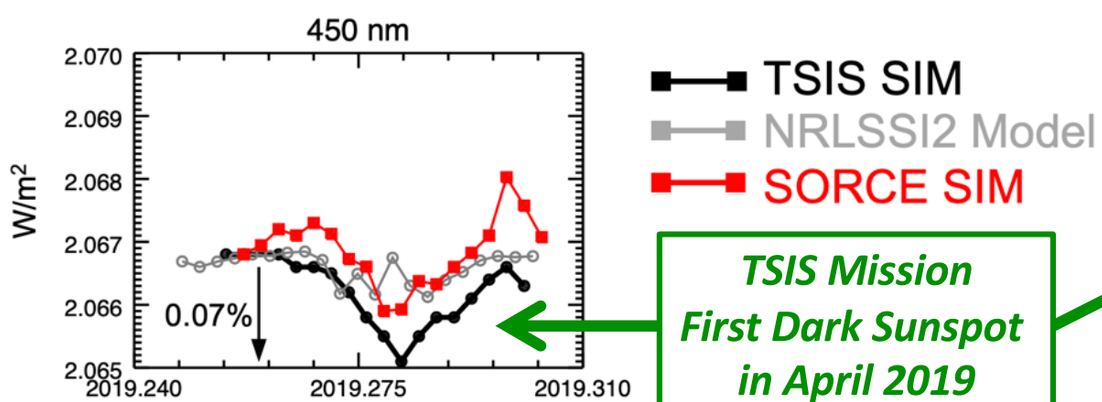


SORCE and TSIS-1 Overlap Has Been Successful

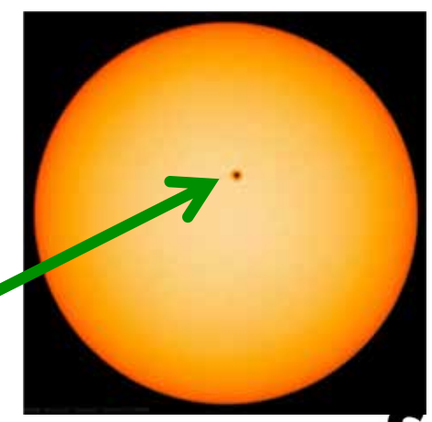
- TSIS-1 science operations began in March 2018, so *SORCE and TSIS-1 have overlap of 16 months as of July 2019.*

Solar Spectral Irradiance (SSI) Comparison



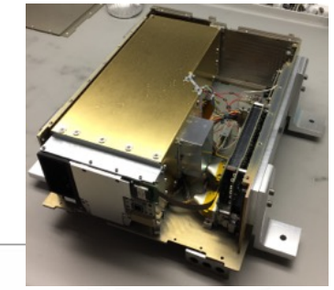


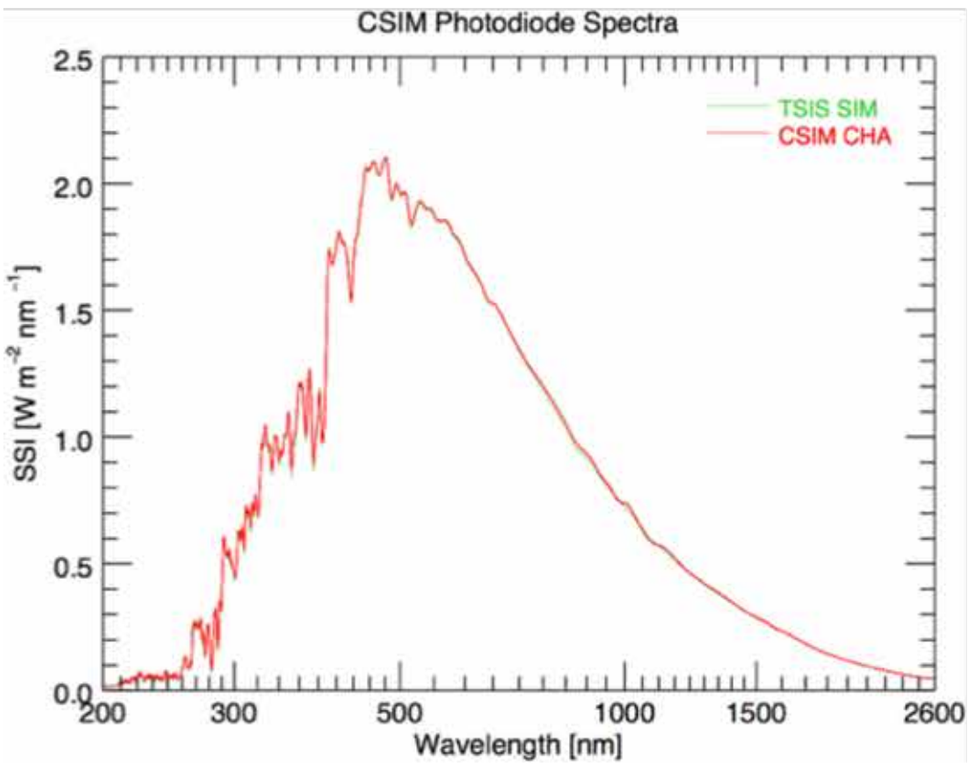
TSIS Mission First Dark Sunspot in April 2019

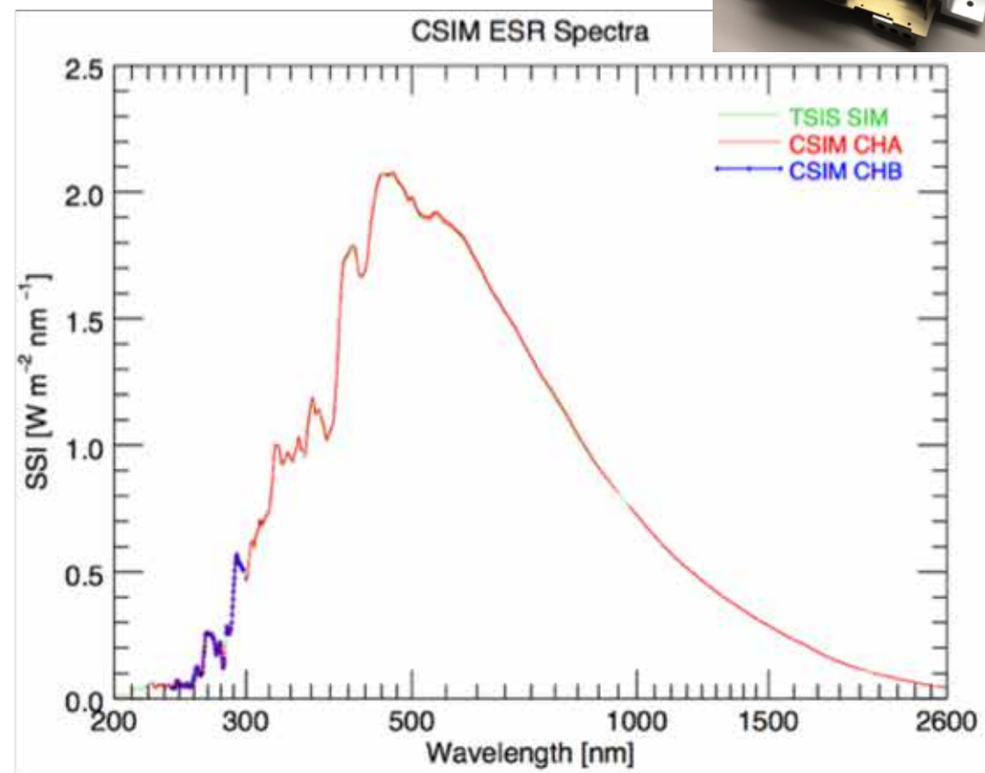


Compact SIM CubeSat – launched Dec 2018

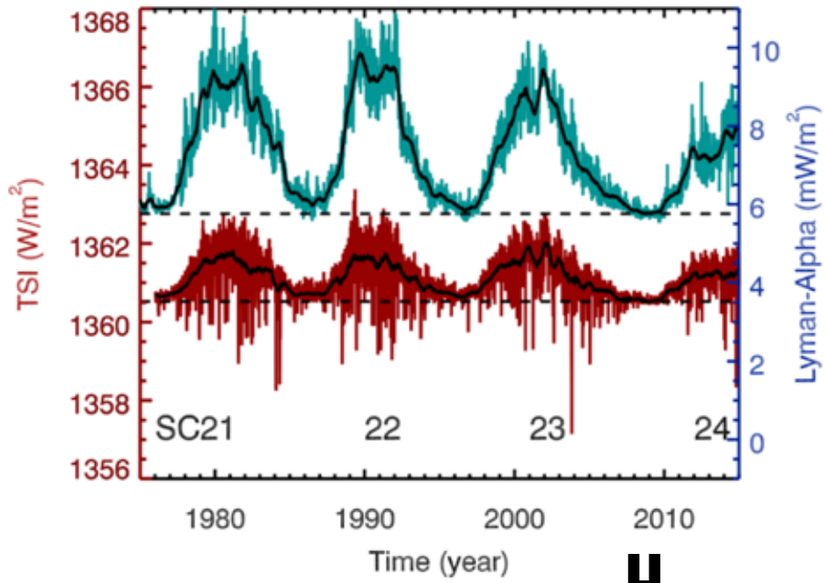
- CSIM is a 6U CubeSat in SSO at 580km
- Plots are from Erik Richard (CSIM CubeSat PI)





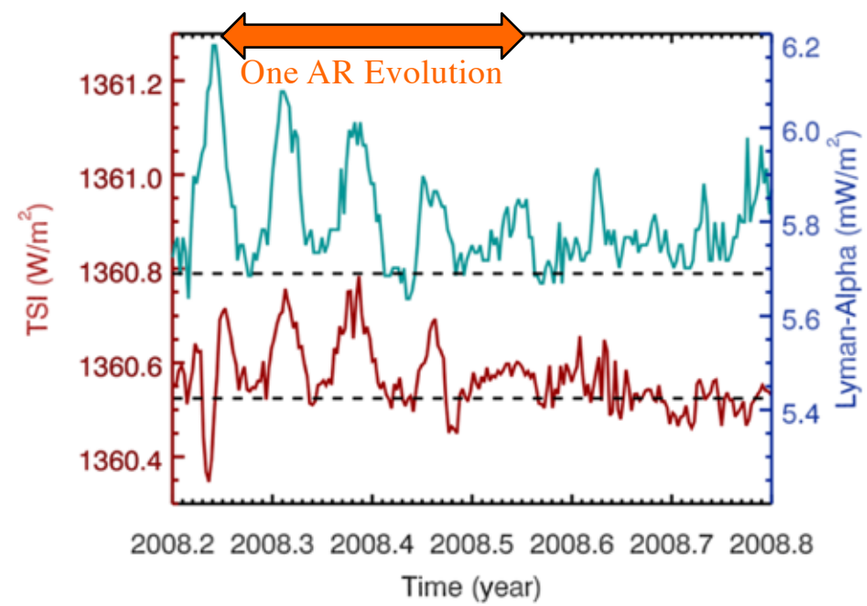


Variability Examples for TSI and H I Lyman-α 121.6 nm



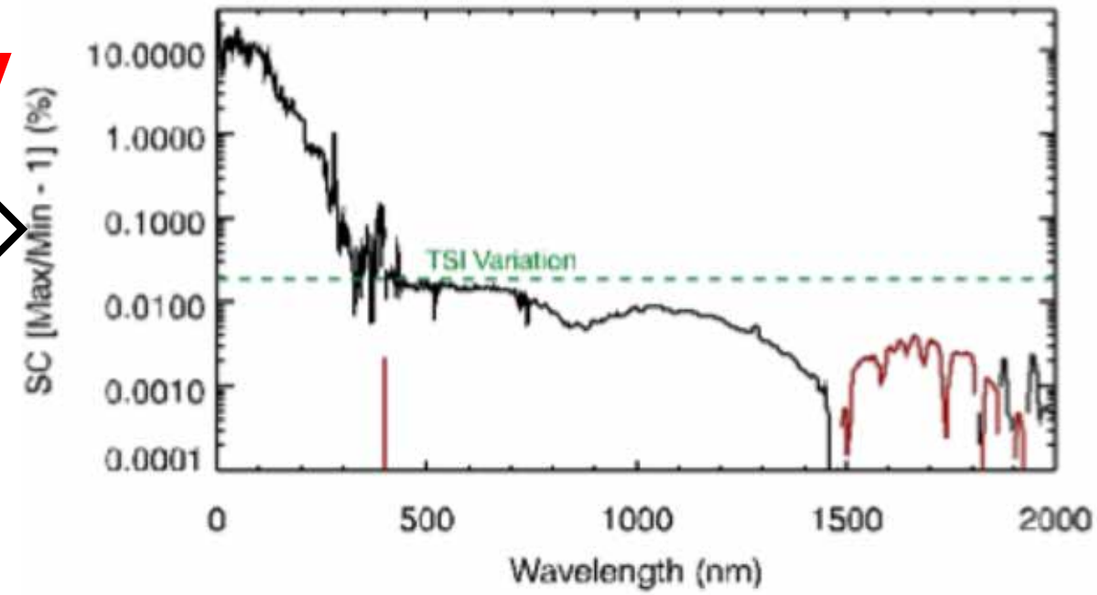
- **11-year Solar Cycle (SC)**
  - The 22-year magnetic cycle results in a 11-year intensity (sunspot) cycle.
  - The minimum in 2008-2009 may be slightly lower than previous minima.
  - The variability (Max-Min) for SC-24 is about 50% lower than previous cycles.

- **27-day Solar Rotation**
  - Rotation of active regions (AR) is like a Beacon as viewed from Earth.
  - AR eruption has only positive variability for UV emissions for ~6 months but has negative (dark sunspot) variability for the first rotation for TSI and NUV-Vis-NIR.



SSI Solar Cycle Variability

$$Variability\ \% = \left(\frac{Max}{Min} - 1\right) \bullet 100\%$$

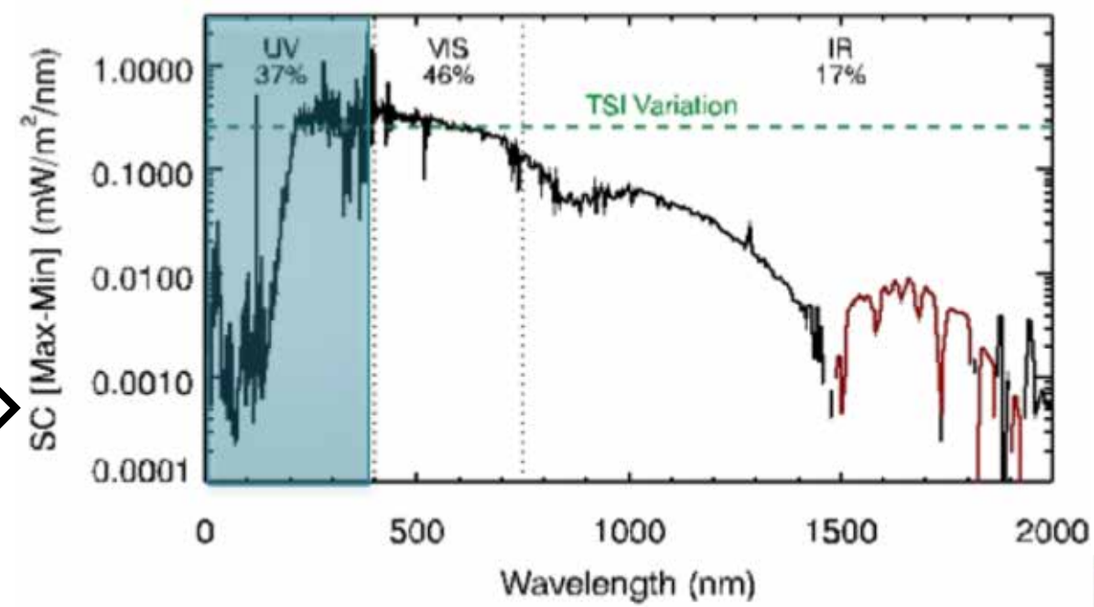


- EUV-FUV appears larger for Variability %

- The red lines in the NIR indicate negative (out-of-phase) variability.

- MUV-NUV dominate for Variability Difference

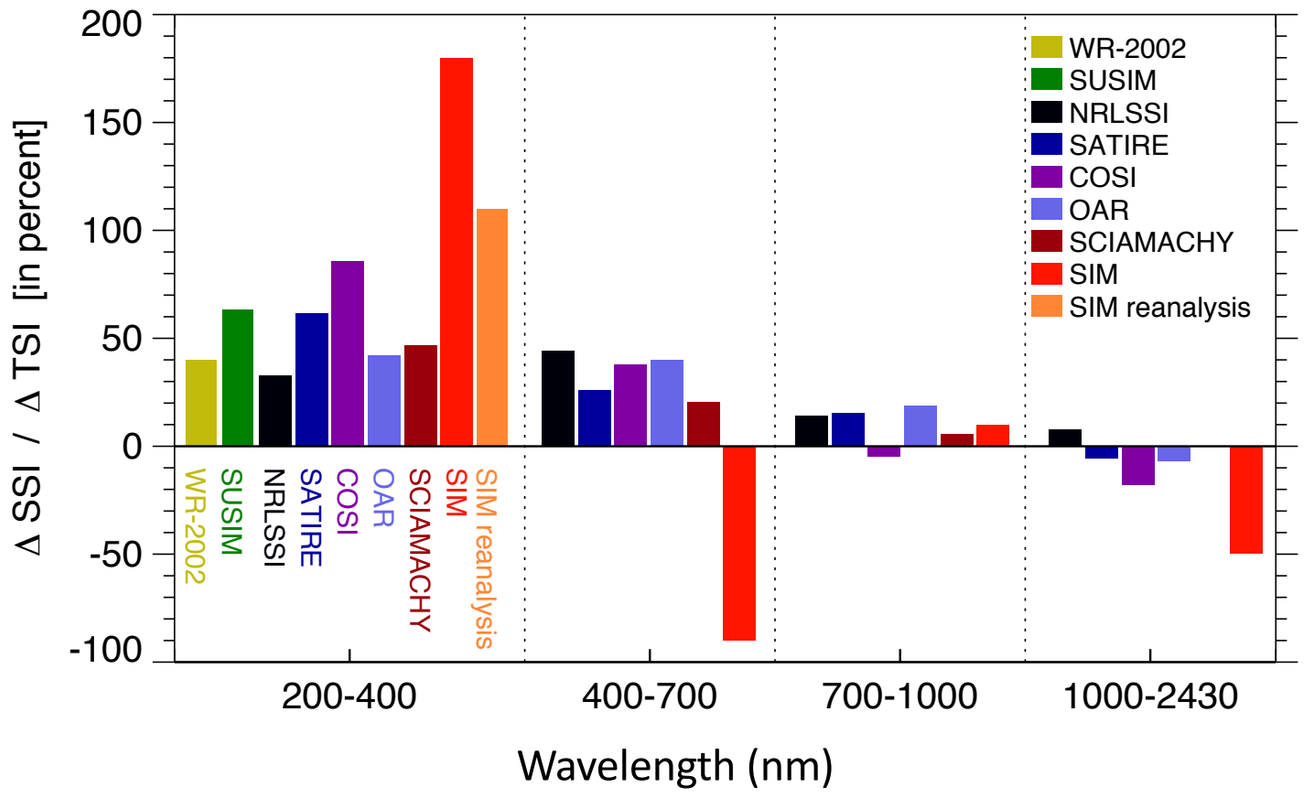
$$Variability\ Difference = Max - Min$$



Example of SSI variability from J. Lean (2012)

SORCE SIM Results for SC Variability

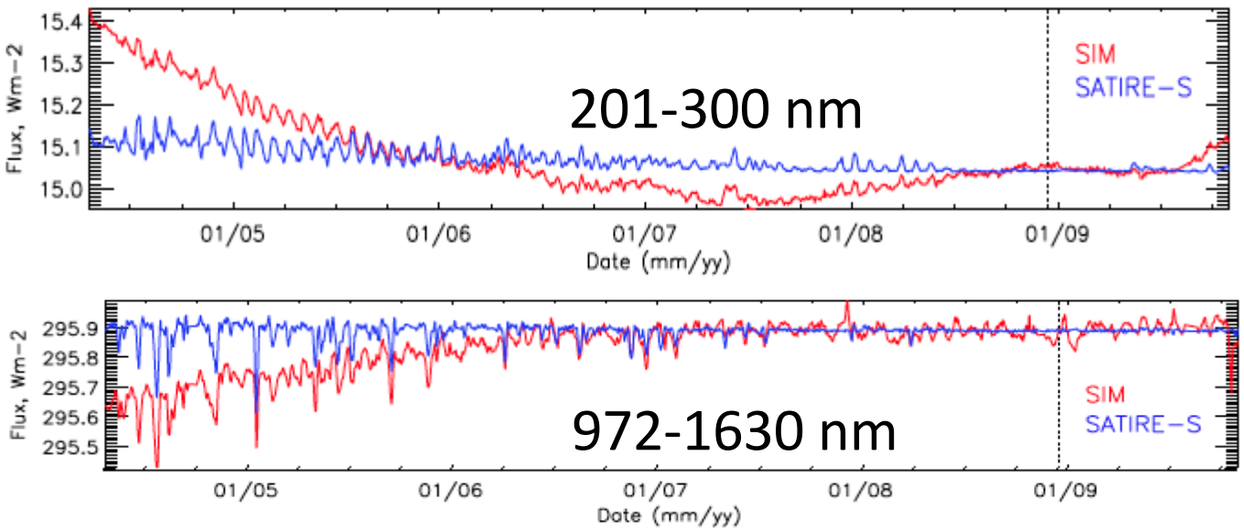
- SORCE SIM results of **out-of-phase variations** for visible and near infrared and **larger ultraviolet variations** are **<u>in debate</u>** as they do not agree with prior measurements and most solar irradiance models.



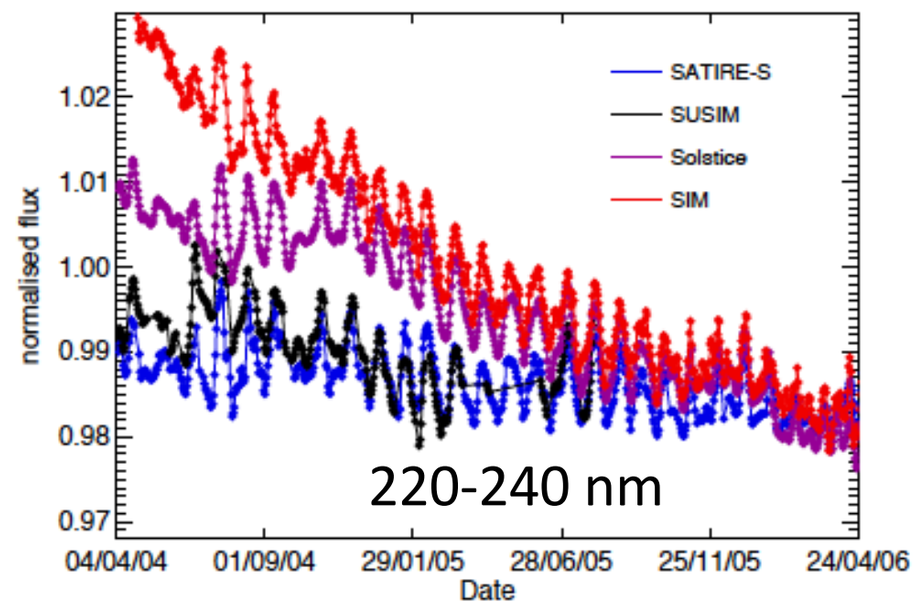
From Ermolli *et al.*, *A.C.P.*, 2013.

Example Differences for SSI Solar Cycle Variability

- Ball *et al.* (*Astron. & Astrophy.*, 2011): SATIRE model agrees with UARS results in UV but disagrees with SORCE SIM long-term variability (200-1600 nm)
  - Is SSI variability not entirely controlled by surface magnetism?
  - Are there uncorrected instrument trends in UARS or SORCE?

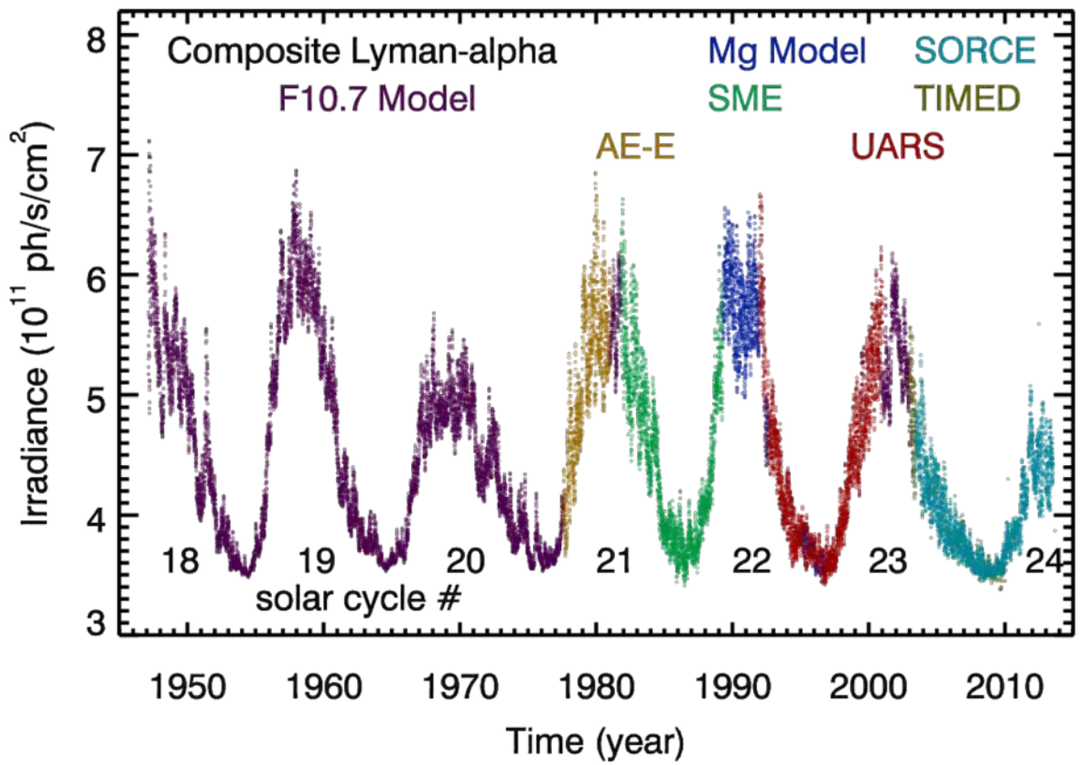


- DeLand & Cebula (*J.A.S.T.P.,* 2011): SIM versus earlier SBUV composite 170-400 nm (*but not concurrent measurements*) – concludes SORCE has uncorrected degradation based on NRLSSI model comparisons
- Unruh *et al*. (2011): Comparison of SATIRE, UARS, and SORCE for 220-240 nm shows 1% per year trend differences



Reminder: Key Goal is Creating Long-term Composite Record

What are the challenges for these solar records?



From http://lasp.colorado.edu/lisird/

Challenge 1: Different Levels of Irradiance

Satellite Measurements of the TSI

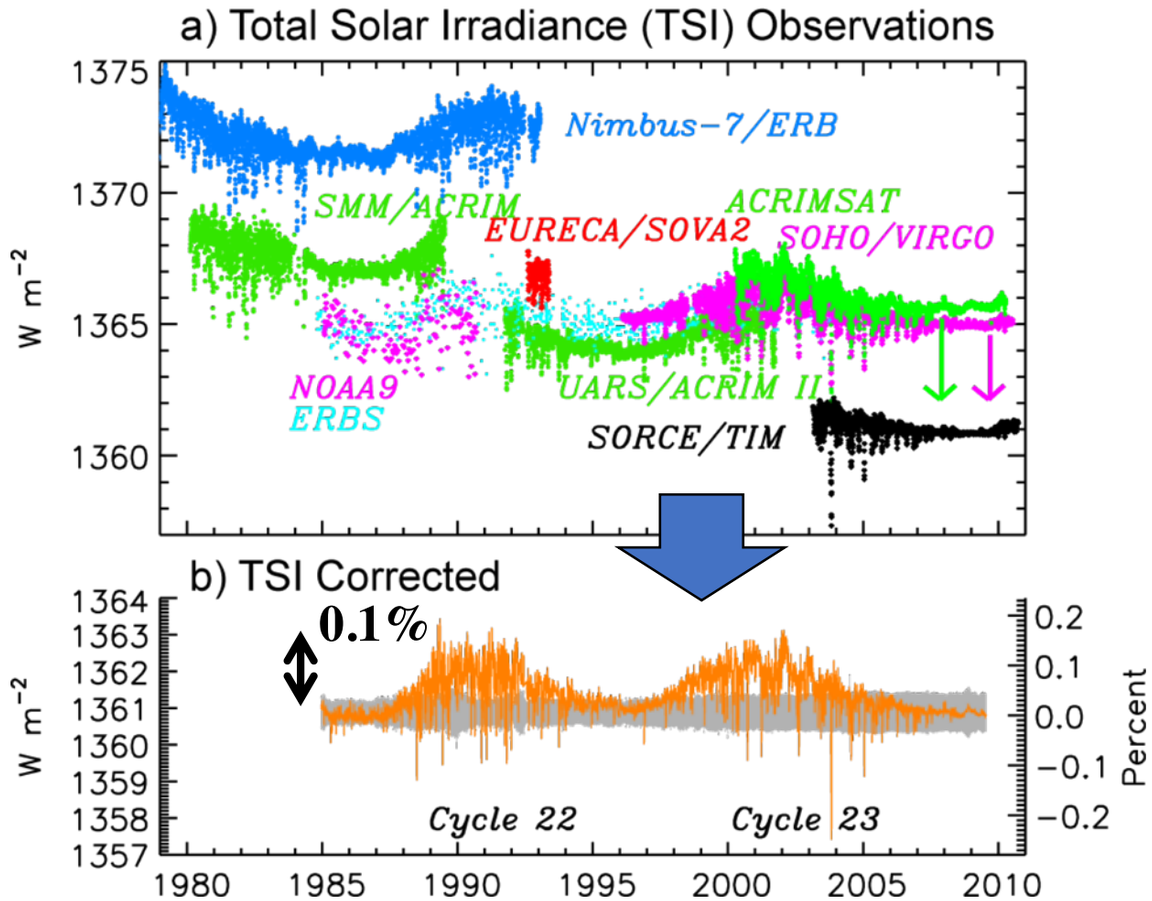


Figure adapted from Kopp & Lean, GRL, 2011

TSI = Total Solar Irradiance
(all wavelengths)

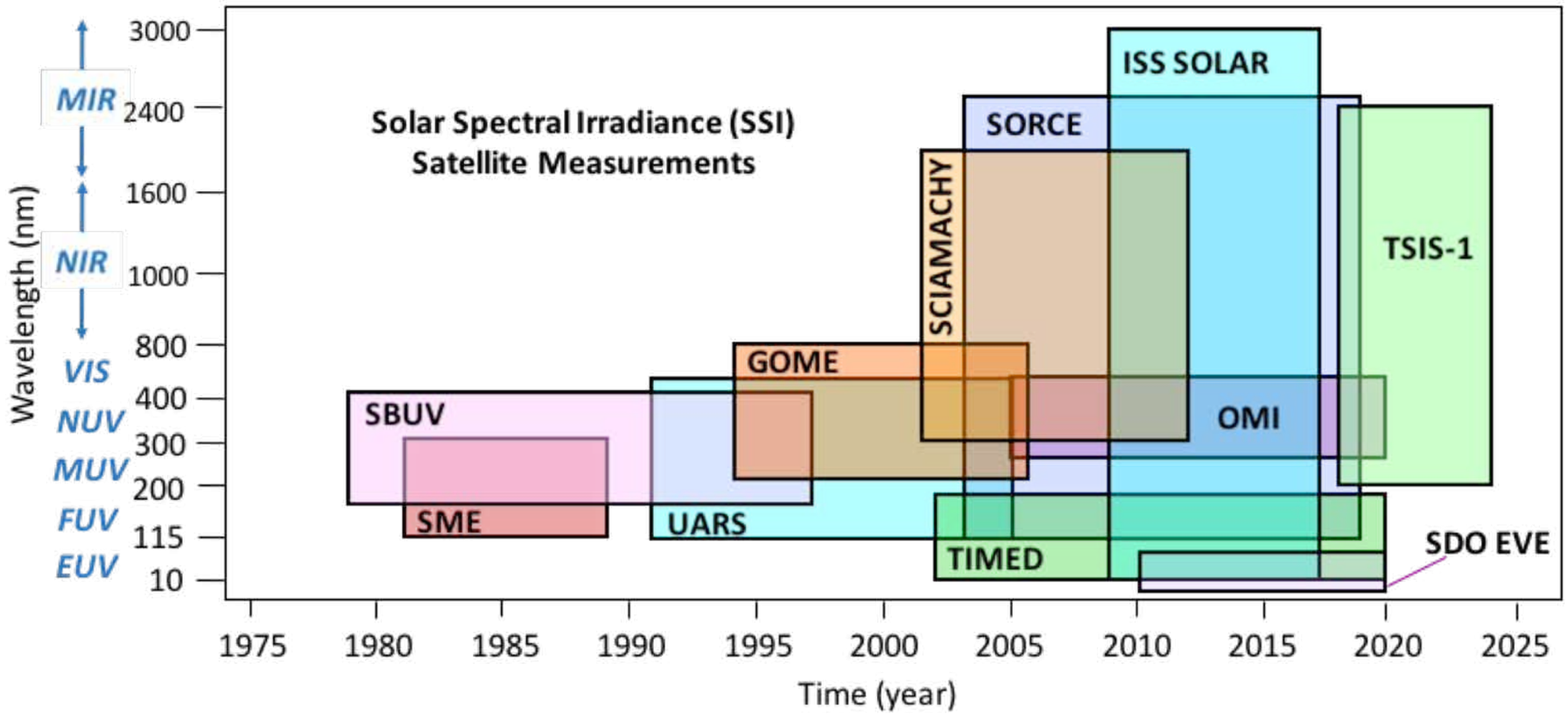
11-year solar cycle variation is about 0.1%

It is critical to combine these measurements to make a long-term TSI record for Sun-Climate studies.

There is new composite TSI by Dudok de Wit *et al.* [2017].

Challenge 2: Incomplete Spectral Coverage

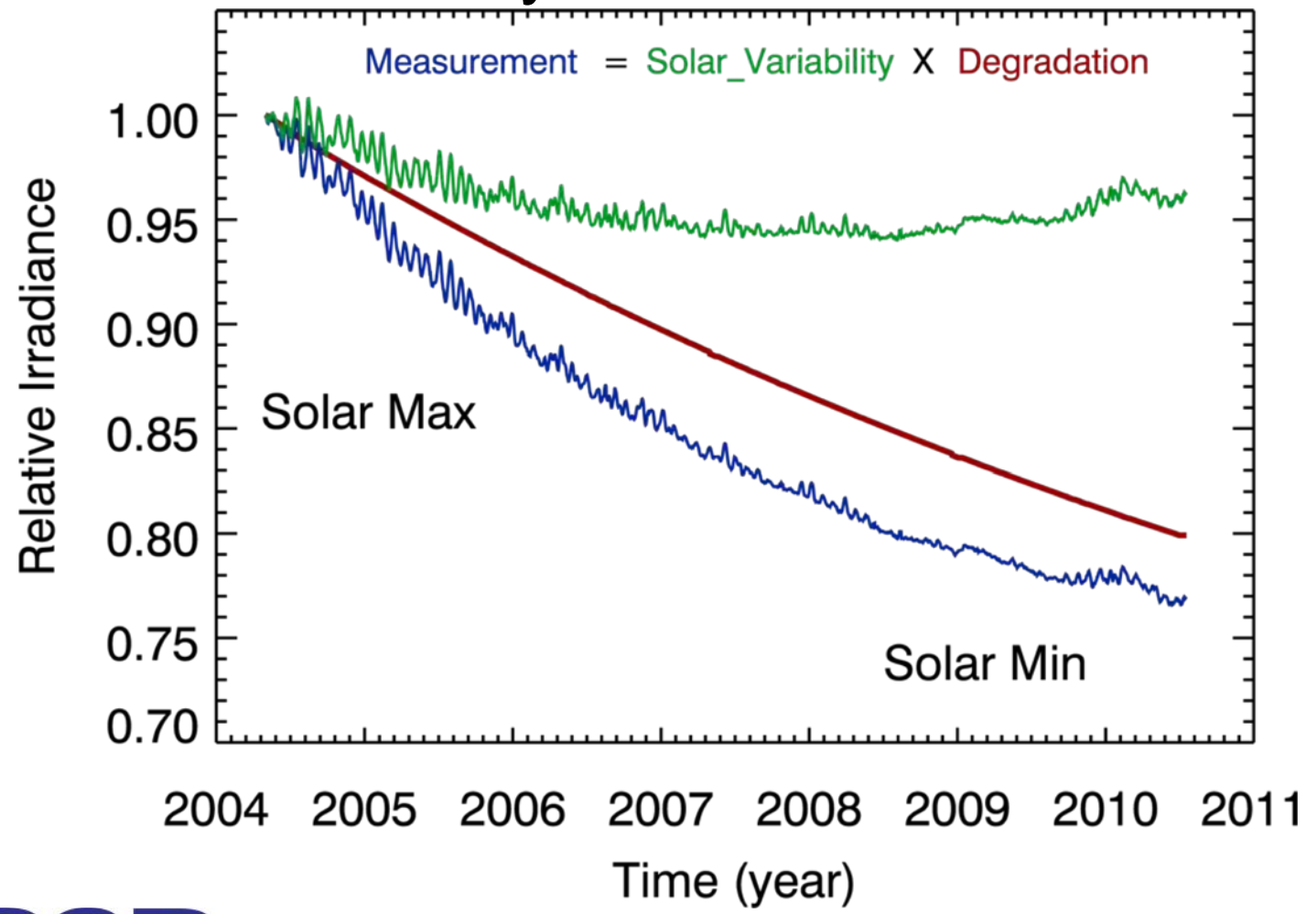
- Ultraviolet coverage is most complete since 1978



SC-21 | SC-22 | SC-23 | SC-24 | SC-25

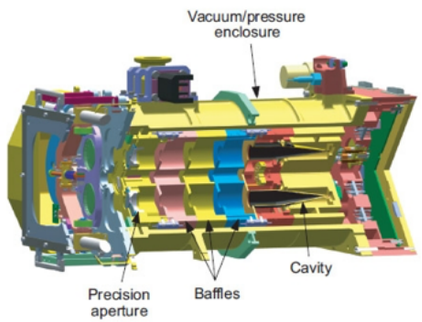
Challenge 3: Instrument Degradation Correction

- Understanding instrument degradation is critical for obtaining accurate solar cycle variations.



Measurement is SIM uncorrected data at 280 nm

In-flight Calibration Techniques



- Redundant Channels
- One channel is used daily, and others have low-duty cycle (weekly or monthly)
- Trending assumes exposure-related degradation
- Challenge is for non-exposure related degradation

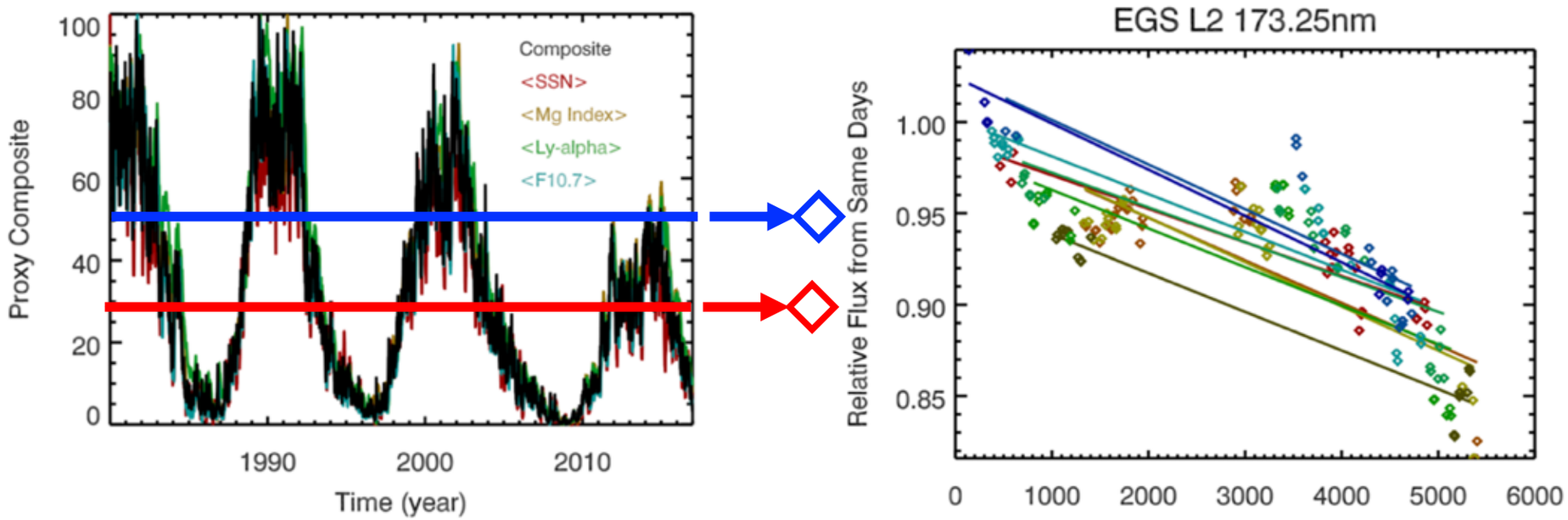
- On-board Lamps
- Calibrated lamps are used with low-duty cycle
- Trending assumes lamp is stable
- Challenge is that lamps can degrade and have often burned out in-flight

- External Sources
- e.g. stable stars (O and B stars in UV)
- Trending assumes source is stable
- Challenges are availability of target and stability of stars

- Underflight Campaigns
- Identical instrument has underflight with satellite
- Transfers fresh calibration to satellite instrument
- Limited to the EUV-FUV range because calibration accuracy (~5%) needs to be much smaller than solar cycle variability

New Technique to Validate Degradation Trends

- The Multiple Same-Irradiance-Level (MuSIL) analysis technique was developed to identify uncorrected instrument degradation trends.
- Key assumption is irradiance level repeats during rise & fall of solar cycle (SC).



Long record needed on both sides of solar cycle minimum

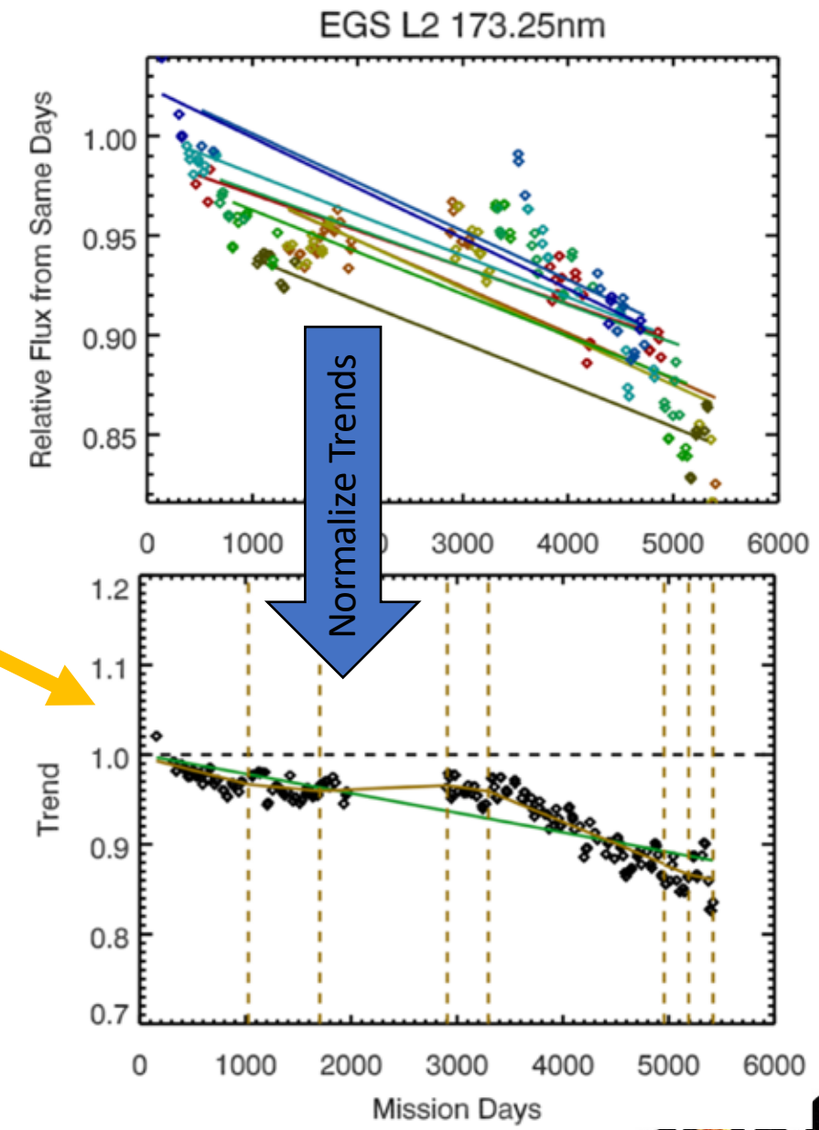
For example, TIMED/SEE from 2002-2018

Same-Irradiance-Level → solar cycle and instrument trends

Figures are from Woods *et al., Solar Phys.*, 2018

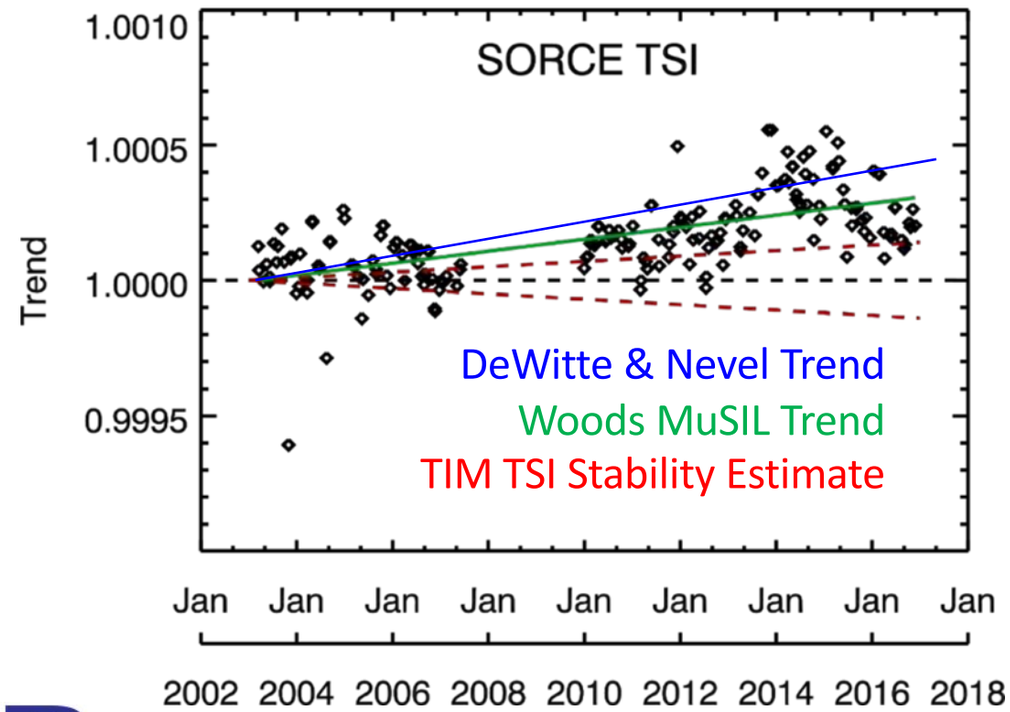
New Technique to Validate Time Series

- Combining the trends from 8 levels provides a trend that indicates an uncorrected instrument degradation trend.
- This trend is fit with piecewise linear fits (gold lines).
- Uncertainty is estimated to be 5-10% of solar cycle variability.
- *Method weakness is that it leaves gap during solar cycle minimum.*



SORCE TIM TSI has a Small Trend in MuSIL Analysis

- MuSIL analysis of TIM TSI is used to validate the MuSIL technique, but it does show an upward trend.
  - **MuSIL Trend is within 2-σ of** TIM's stability estimate of 10 ppm/year
- DeWitte & Nevel [2016] suggest there is SORCE TSI trend in comparison to other TSI records.



From Woods *et al.*, *Solar Physics*, 2018

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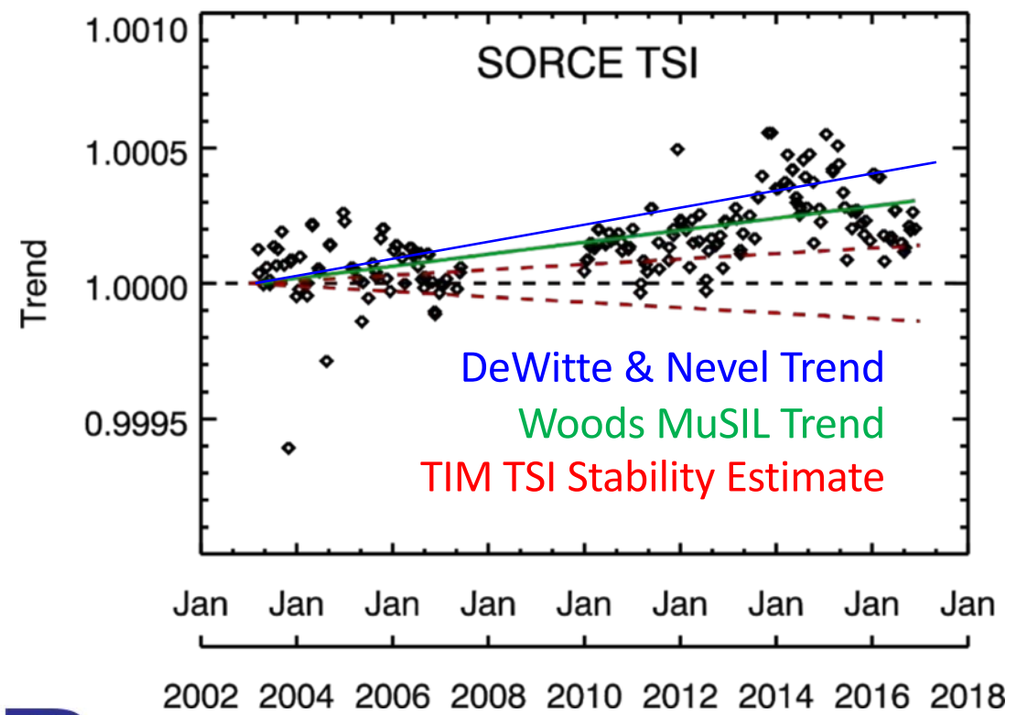
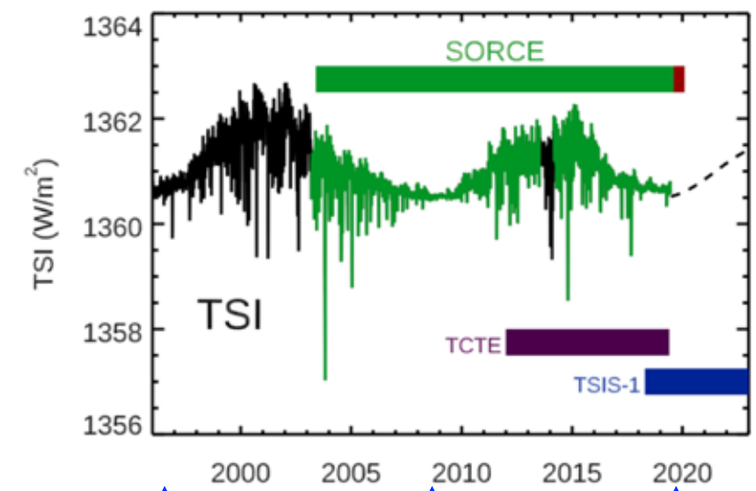




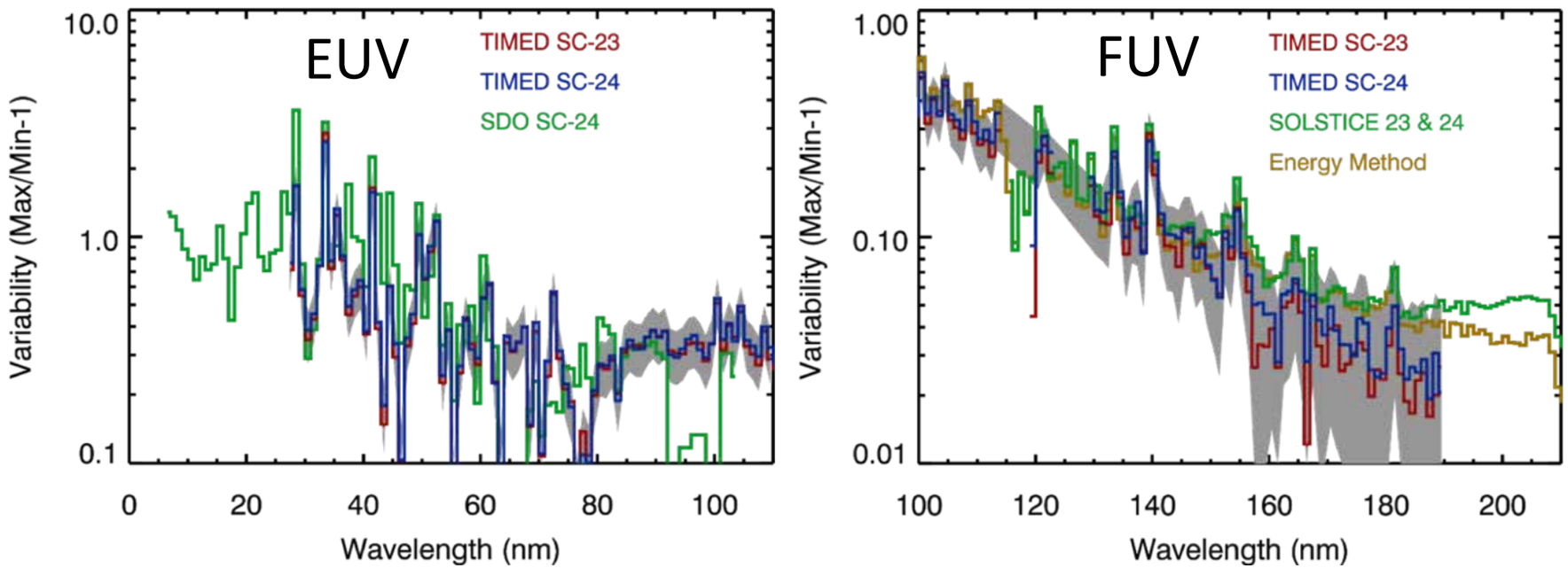
1360.623 W/m² (ref level) 1996/082

1360.507 W/m² (Δ -85 ppm) 2008/220

1360.613 W/m² (Δ -7 ppm) 2019/165

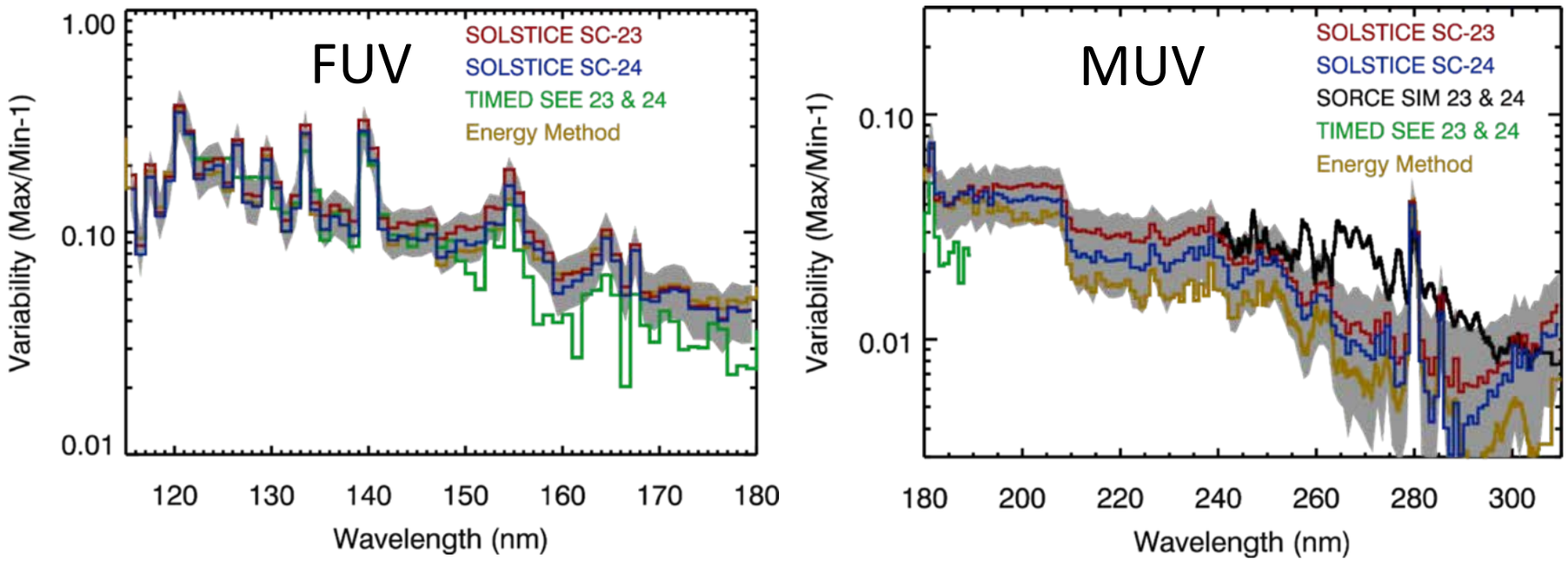
From Woods *et al.*, *Solar Physics*, 2018

New Solar Cycle Variability Results: TIMED SEE



- TIMED SEE Extreme Ultraviolet (EUV) and Far Ultraviolet (FUV) at < 150 nm are consistent with other estimates.
- **New MuSIL result has improved results for TIMED SEE solar cycle variability, primarily for wavelengths > 150 nm.**

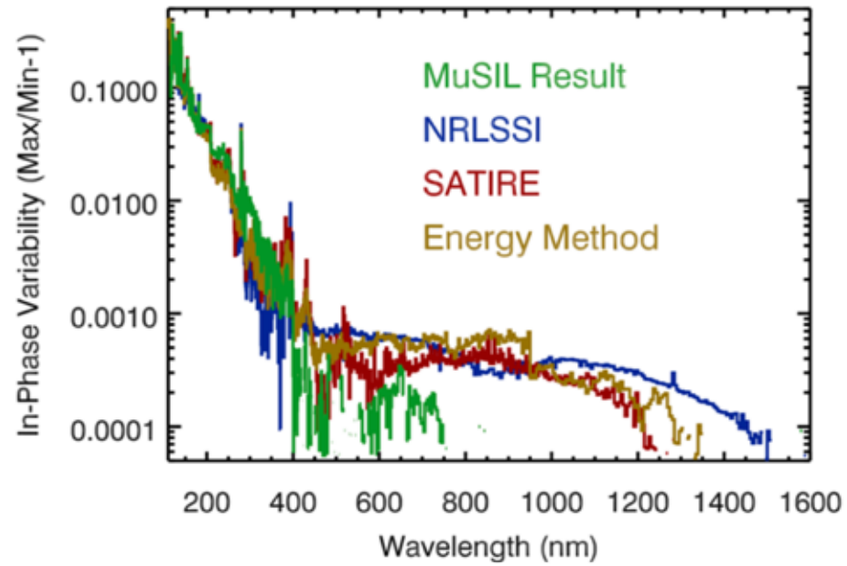
New Solar Cycle Variability Results: SOLSTICE



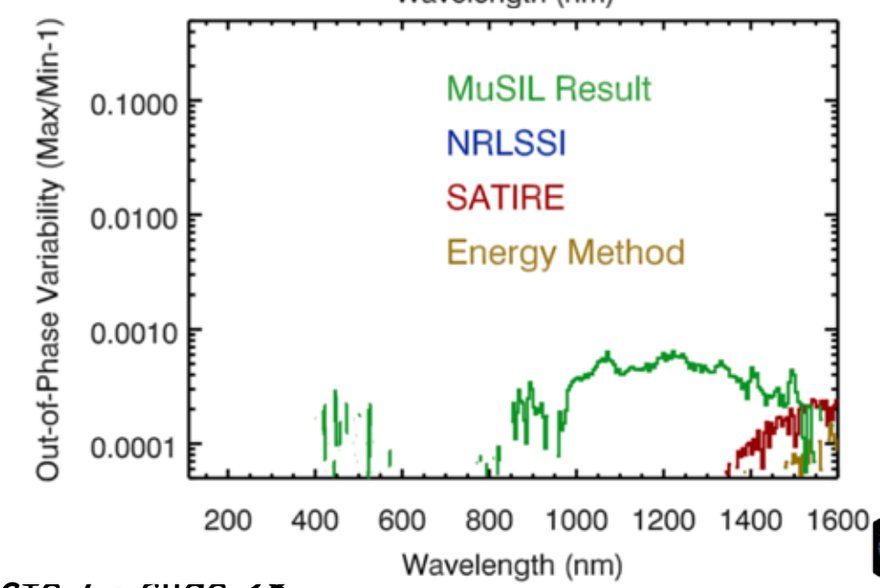
- SORCE SOLSTICE Far Ultraviolet (FUV) and Middle Ultraviolet (MUV) are consistent with other estimates.
- **New MuSIL result has improved results for SOLSTICE solar cycle variability, primarily for wavelengths > 210 nm.**

New Solar Cycle Variability Results: SORCE SIM

- SIM provides results in the Near Ultraviolet (NUV), Visible, and Near Infrared (NIR).
- The SIM NUV solar cycle variability at < 400 nm is consistent with other estimates.



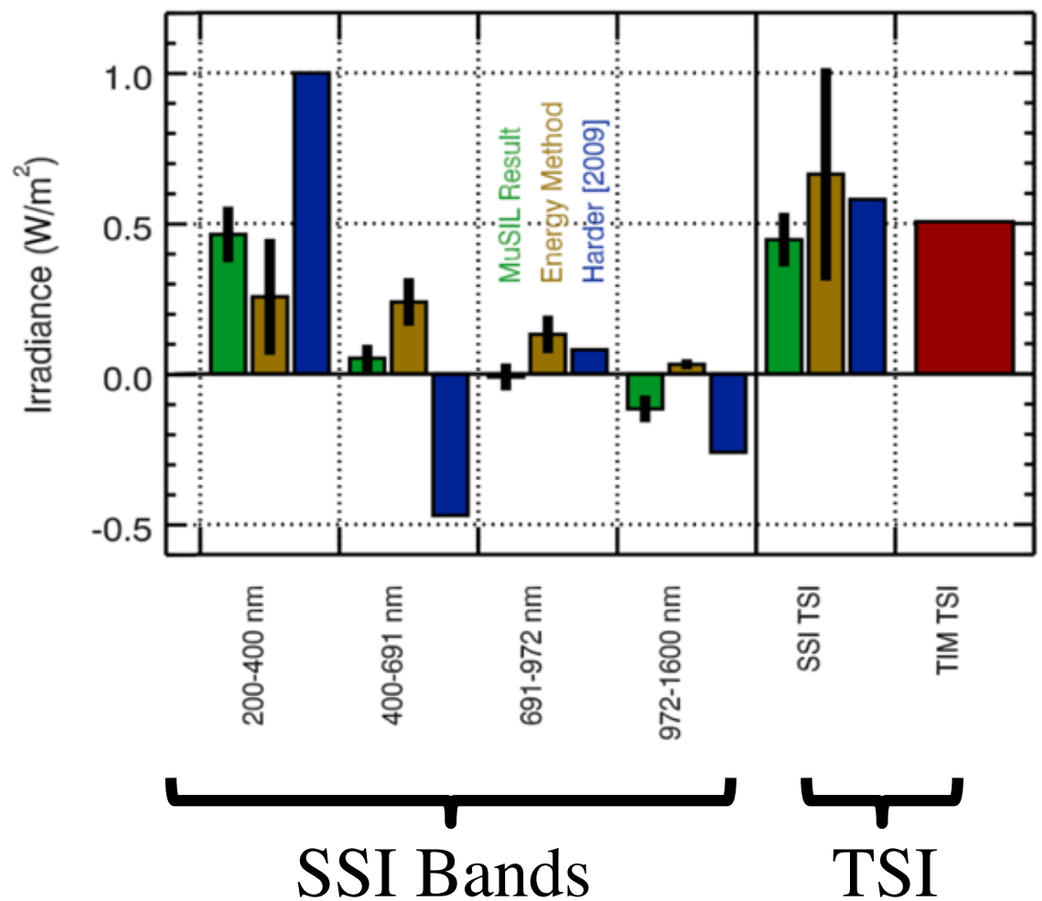
- New MuSIL result has out-of-phase wavelengths for 800 nm to 1600 nm. This is more consistent with Harder *et al.* [2009] result than the models.



SORCE SSI Solar Cycle Variability Comparison

- Harder et al. (*GRL*, 2009) Data Analysis
  - Half-cycle can be ***sensitive*** to instrument degradation
  - 4/2004 (Max) – 2/2008 (Min)
- Multiple Same-Irradiance-Level (MuSIL) Data Analysis (not modeling)
  - New technique developed to identify uncorrected instrument degradation trend
  - Woods *et al*., *Solar Physics*, 2018)
- Energy Method Model
  - SFO excess and deficit proxies fitted over 6-month periods are integrated over time (energy)
  - Modeling over 6-month periods is ***not very sensitive*** to long-term instrument trends
  - Woods et al., *Solar Phys*., 2015

Variability = Max - Min

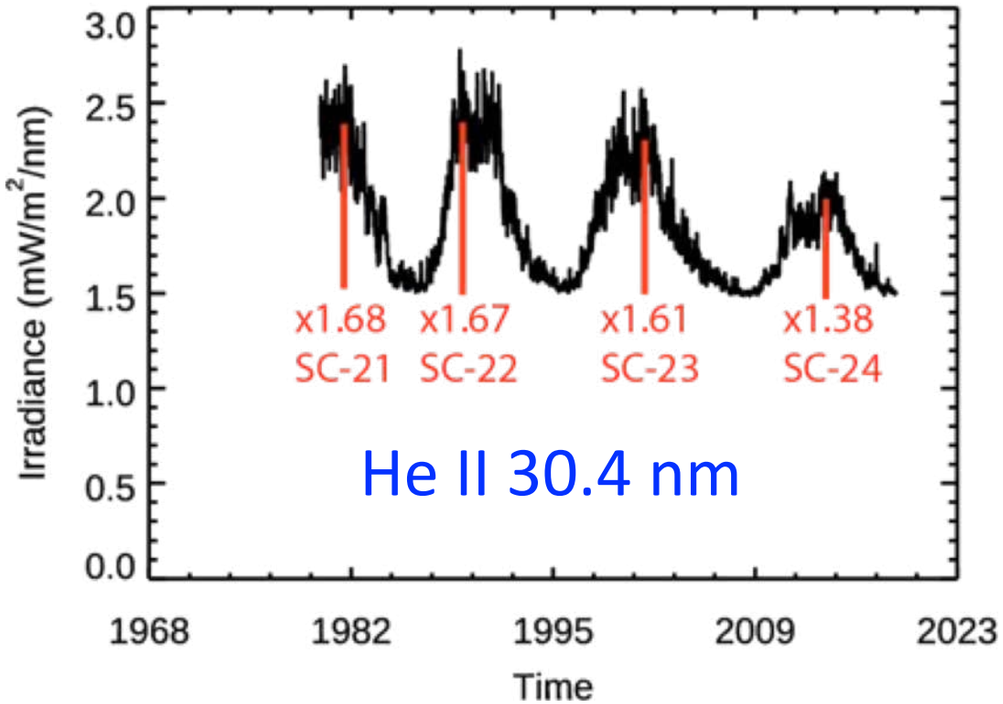


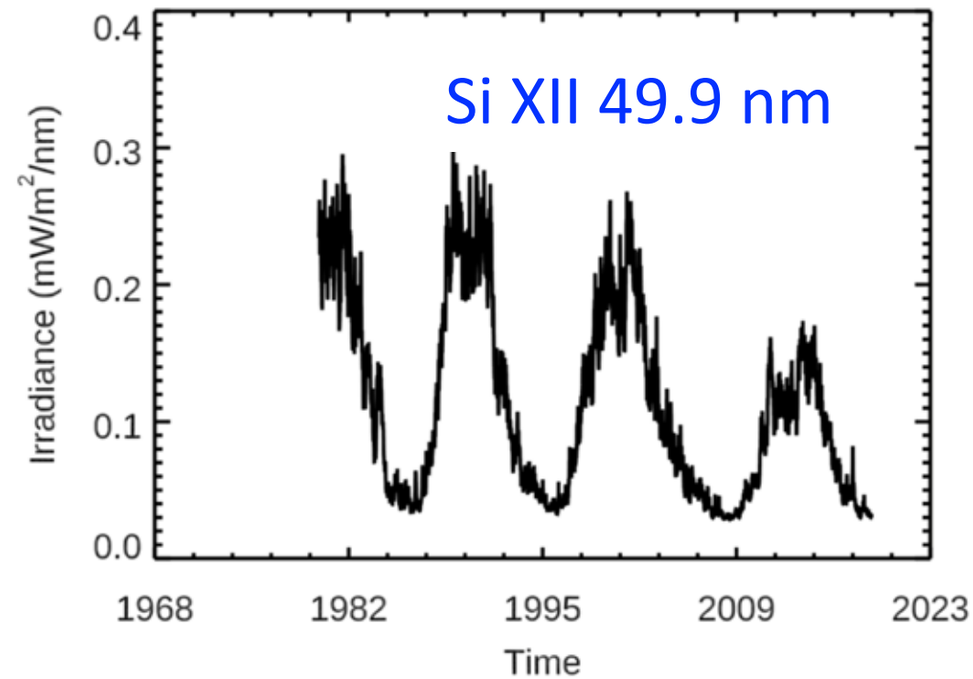
Solar Spectral Irradiance Composite 3-year Plan

- Using MuSIL analysis to assemble new composite SSI record
- Working up in wavelength to make this composite record:
  - 0.1 nm to 1600 nm
  - 1980 to present time
- Completed EUV (0.1-115 nm) range in Year 1

Mission/Instrument & Mission Years	Wavelength Range / Resolution (nm)	MuSIL Tending Analysis	Proxy Modeling	Composite Record
SORCE/SOLSTICE 2003-present	115-308 nm / 0.1 nm	Completed	Year 2	FUV, MUV Years 2-3
SORCE/SIM 2003-present	240-2400 nm / 1-10 nm	Completed	Year 2	NUV-Vis-NIR Years 2-3
OMI 2004-present	265-500 nm / 0.5 nm	Completed	Year 2	NUV-Vis Years 2-3
TSIS-1/SIM 2018-present	200-2400 nm / 1-10 nm	Year 3	Year 3	NUV-Vis-NIR Year 3
CSIM CubeSat 2019-present	200-2400 nm / 1-10 nm	Year 3	Year 3	NUV-Vis-NIR Year 3
TIMED/SEE-EGS 2002-present	27-190 nm / 0.4 nm	Completed	Completed	EUV, FUV EUV Completed
SDO/EVE-MEGS 2010-present	6-106 nm / 0.1 nm	Completed	Completed	EUV Completed
UARS/SOLSTICE 1991-2005	117-420 nm / 0.2 nm	Year 2	Year 2	FUV, MUV, NUV Year 2
UARS/SUSIM 1991-2005	115-410 nm / 0.1-1 nm	Year 2	Year 2	FUV, MUV, NUV Year 2
SME 1981-1989	115-300 nm / 1 nm	Year 2	Year 2	FUV, MUV Year 2
NOAA SBUV 1-2 1978-1997	160-400 nm / 1 nm	Year 2	Year 2	MUV, NUV Year 2

New EUV Composite Record Combines the TIMED SEE and SDO EVE Results



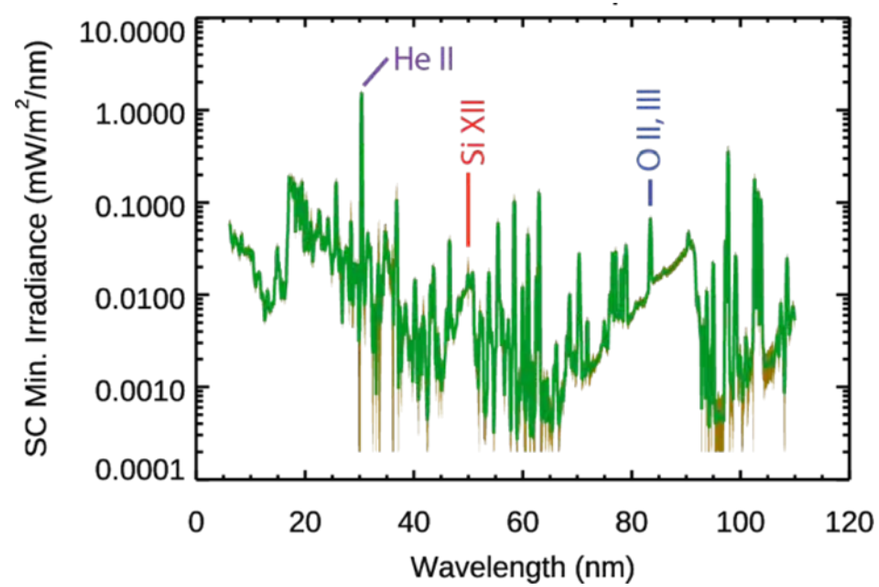


Solar Cycle #	Date of SC Max.	He II 30.4 nm SC Variability Ratio	EUV 6-106 nm SC Variability Ratio
21	1981/270	1.68	2.51
22	1991/065	1.67	2.50
23	2002/006	1.61	2.39
24	2014/070	1.38	1.89

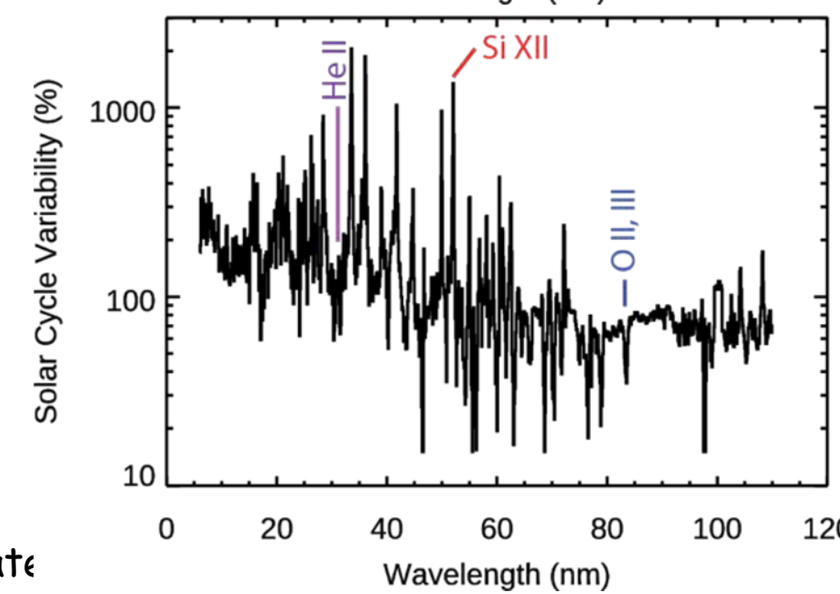
Solar Cycle 24 has significantly less variability (lower max)

New Solar Cycle Variability vs. **Wavelength**

- Three emission lines are highlighted for different layers of the solar atmosphere:
- O II,III 83.4 nm emission is typical for the ***chromosphere*** with about 30% variability
- He II 30.4 nm emission is typical for the ***transition region*** with about 70% variability
- Si XII 49.9 nm emission is typical for the ***corona*** with about 1000% variability (which is factor of 11)



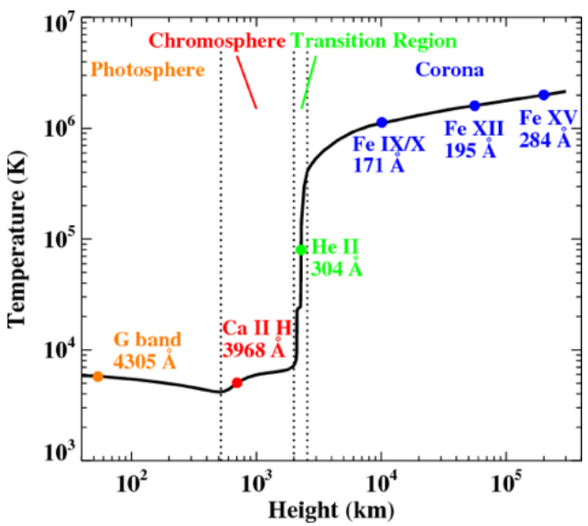
Irradiance

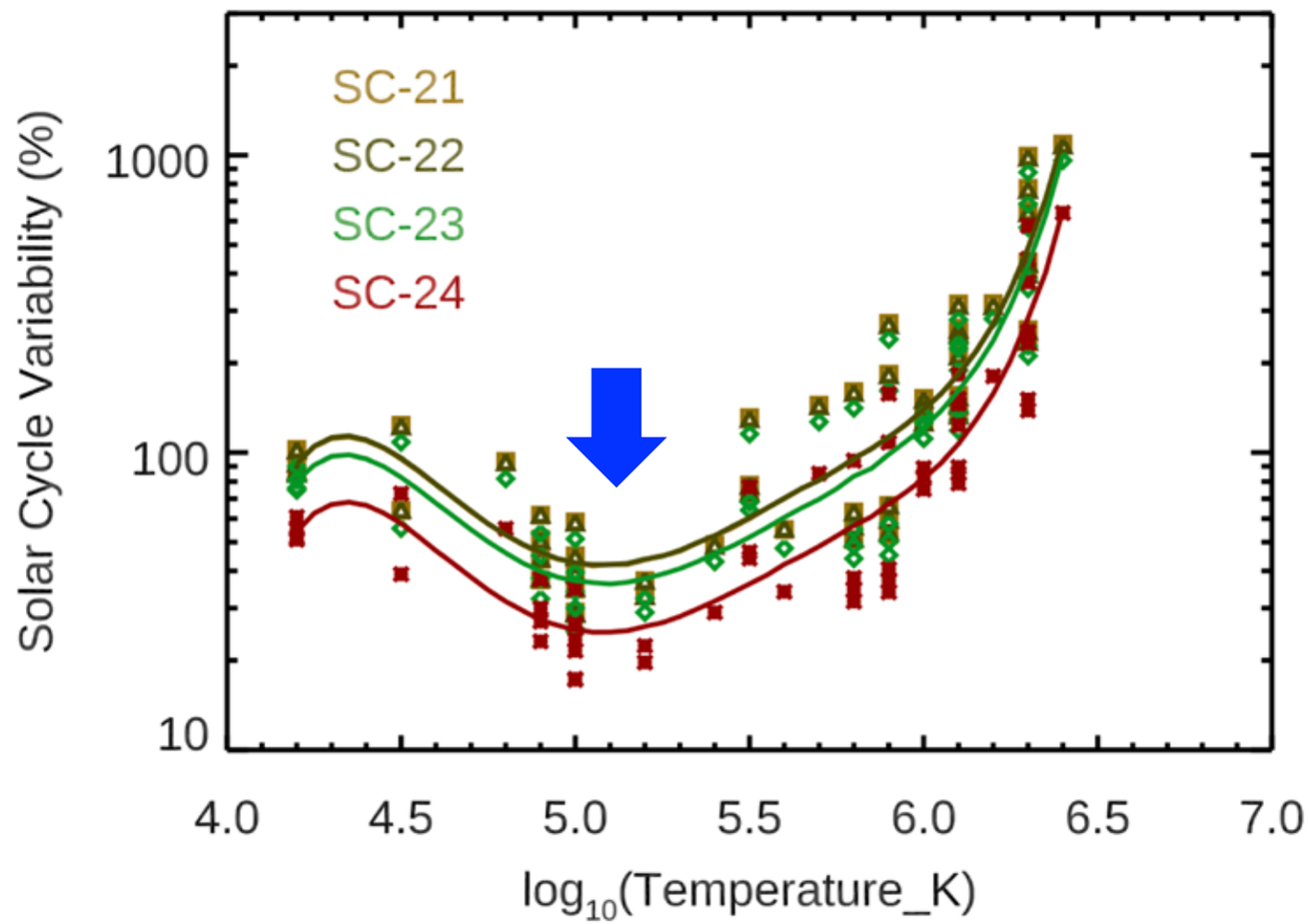


Variability (Max-Min)/Min

New Solar Cycle Variability vs. **Temperature**

- Solar cycle variation has minimum near log(Temp) of about 5.1 [0.12 MK]
- Emission temperatures indicate where the emission is formed in the solar atmosphere





Variability Minimum near log(T) 5.1 is also where there is Emission Measure Minimum [Judge *et al.*, *Ap J Lett*, 1995]

From Astron. & Astrophy.

Summary

- New solar cycle variability results show better consistency between different measurements from 6 nm to 1600 nm for 2002-2017 in Solar Cycles (SC) 23 and 24.
  - Woods *et al.*, *Solar Physics*, **293**, A76, 2018

- New solar spectral composite is currently in 0.1-115 nm range and from 1980 to present time.
  - SC-24 is significantly less variable
- Future work is to extend this composite to 1600 nm for SC 21-24

- New solar composite time series will be served from the LASP Interactive Solar Irradiance Data Center (LISIRD) in the near future
- http://lasp.colorado.edu/lisird/

LISIRD
LASP INTERACTIVE SOLAR IRRADIANCE DATACENTER