Variations of the Bright Solar Lyman-α Emission : Estimation of the UV Decrease During the Maunder Minimum

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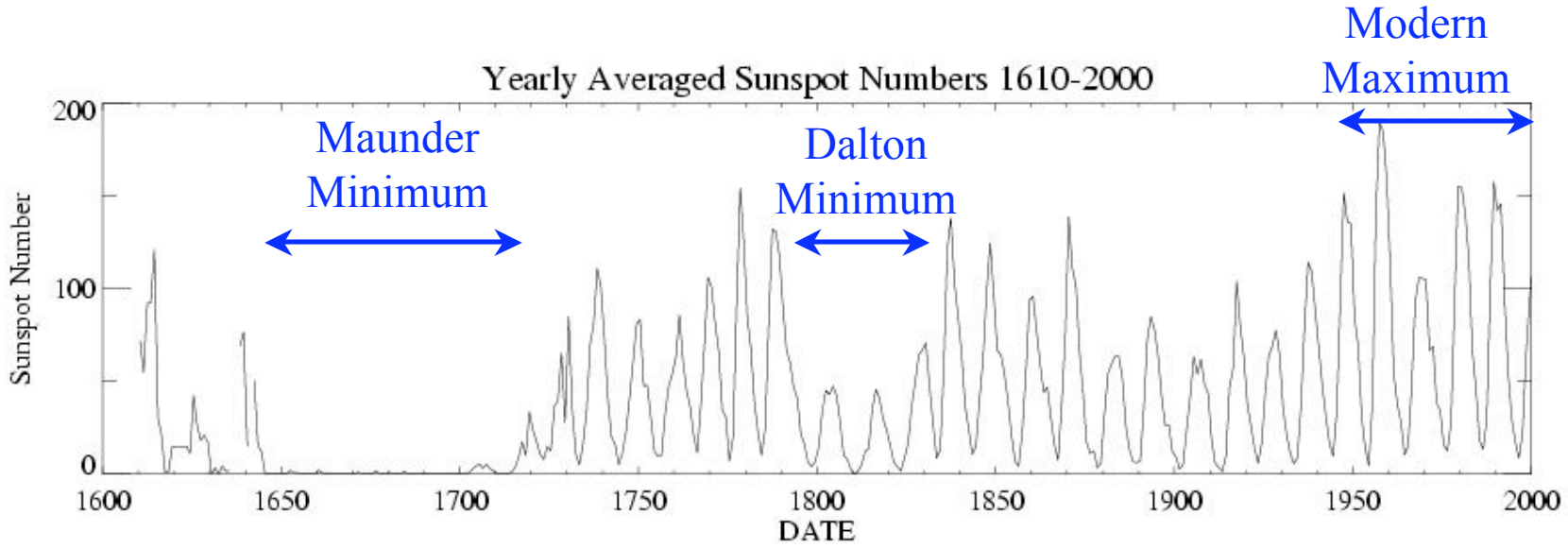
Outline

- Objectives
  - **How much does the UV radiation vary over the long-term?**
  - **What was the solar UV irradiance at Maunder Minimum?**
- Introduction of Long-term Solar Record
- Composing Solar Long-Term Lyman-α Time Series
- Estimating the Maunder Minimum solar UV irradiance
  - **Correction for active network contribution**
  - **Correction for quiet sun radiance changes**
- Conclusions

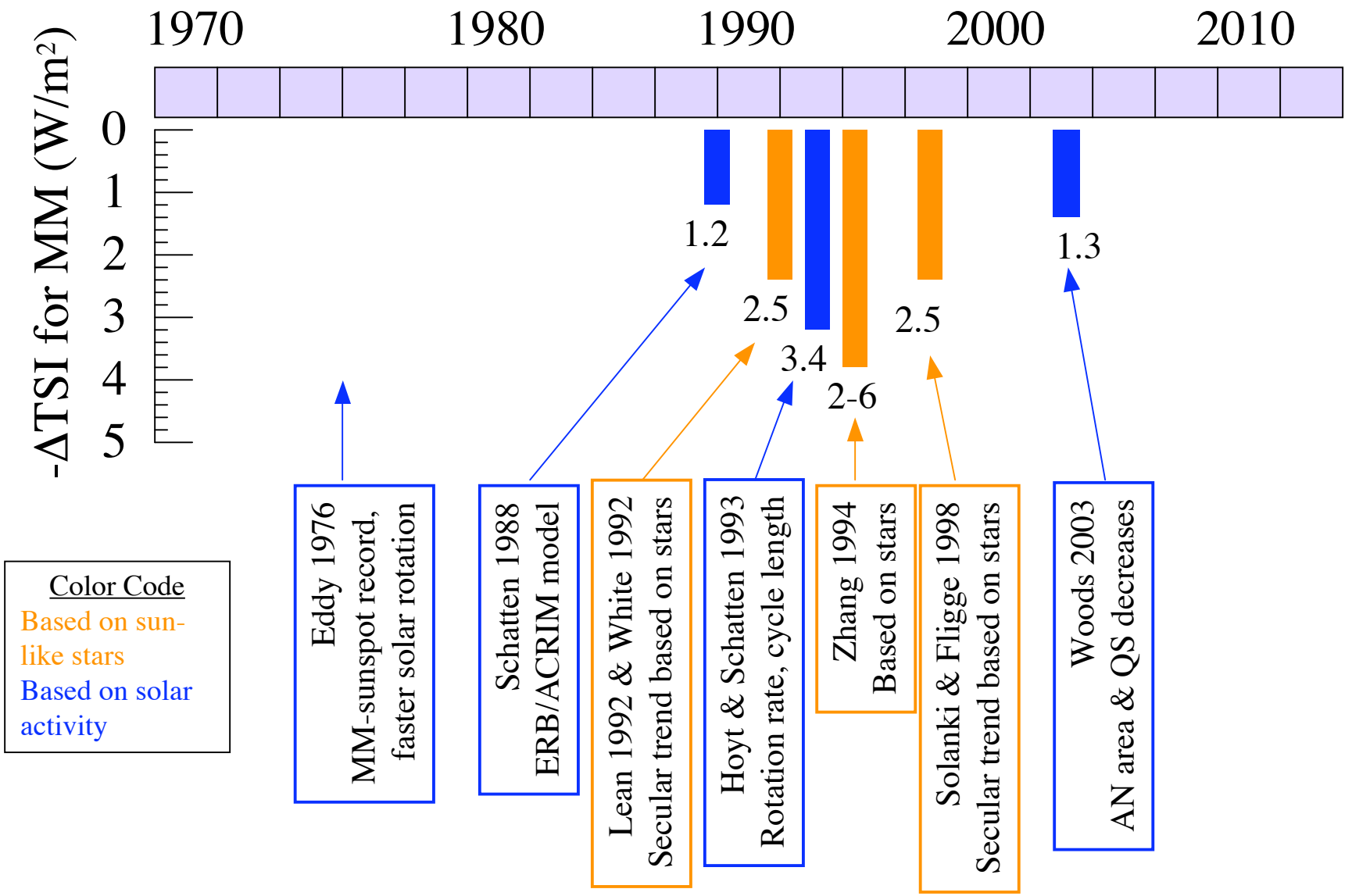
Evidence for Lower Irradiance during Maunder Minimum (MM) Period

- Sunspot record indicates little activity during MM
- Temperature records indicate colder period during MM
  - Atmospheric modeling predicts -0.45 °C with -0.25% TSI change [Rind *et al.*, JGR, 1999]
- The non-cycling sun-like stars have less intensity for the Ca II index than cycling stars [Radick *et al.*, Ap J Suppl, 1998]



[From D. Hathaway]

Maunder Minimum TSI Predictions

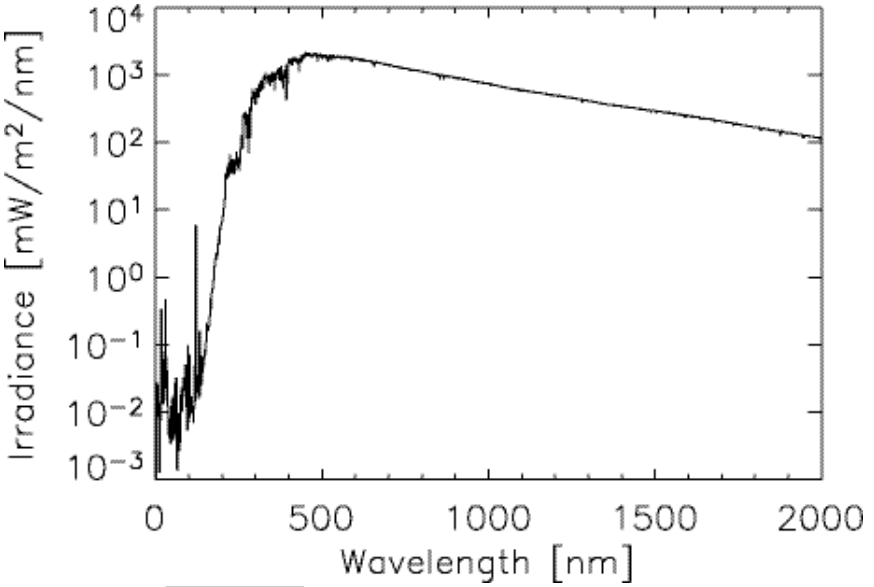


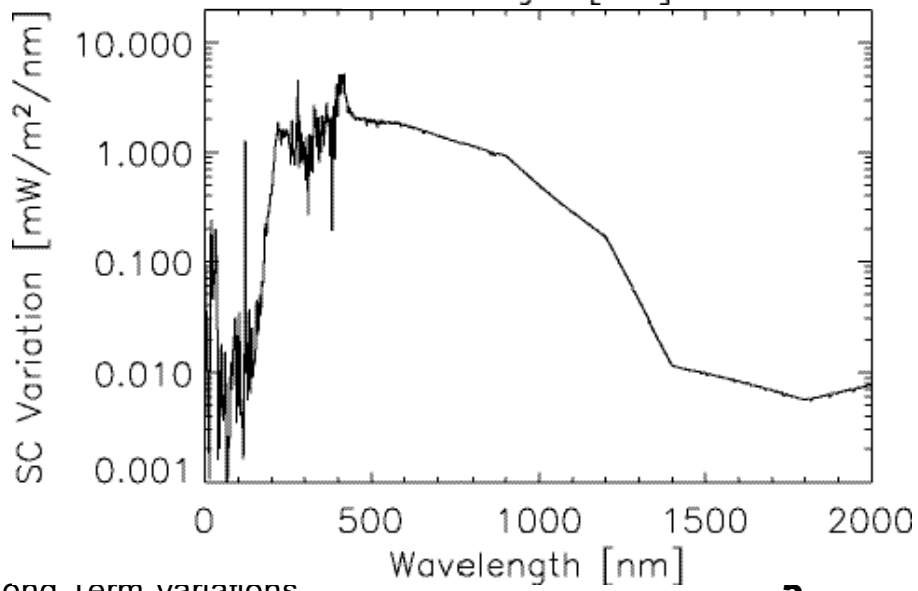
UV Irradiance Contributes to TSI

- The solar UV irradiance is an important part of the Total Solar Irradiance (TSI), especially for TSI variation

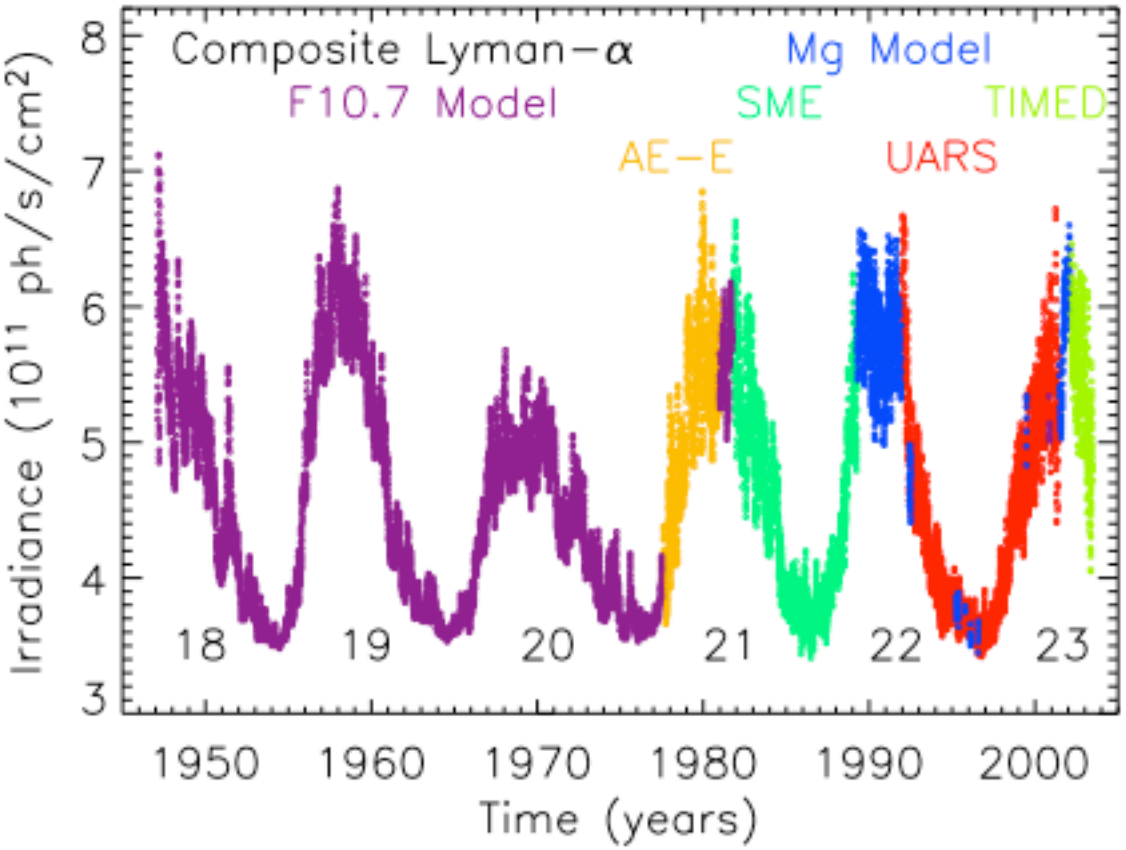
Range	Fraction of TSI	Fraction of TSI SC Variation
0-400 nm	7.7%	24%
0-300 nm	1.1%	12%
0-200 nm	0.008%	1.2%

[From Woods *et al.*, SPIE, 2000]





Composite Lyman-α Time Series



Short-term (27-day solar rotation) variations are 5-35%

Long-term (11-yr solar cycle) variations are x 1.4-2.0

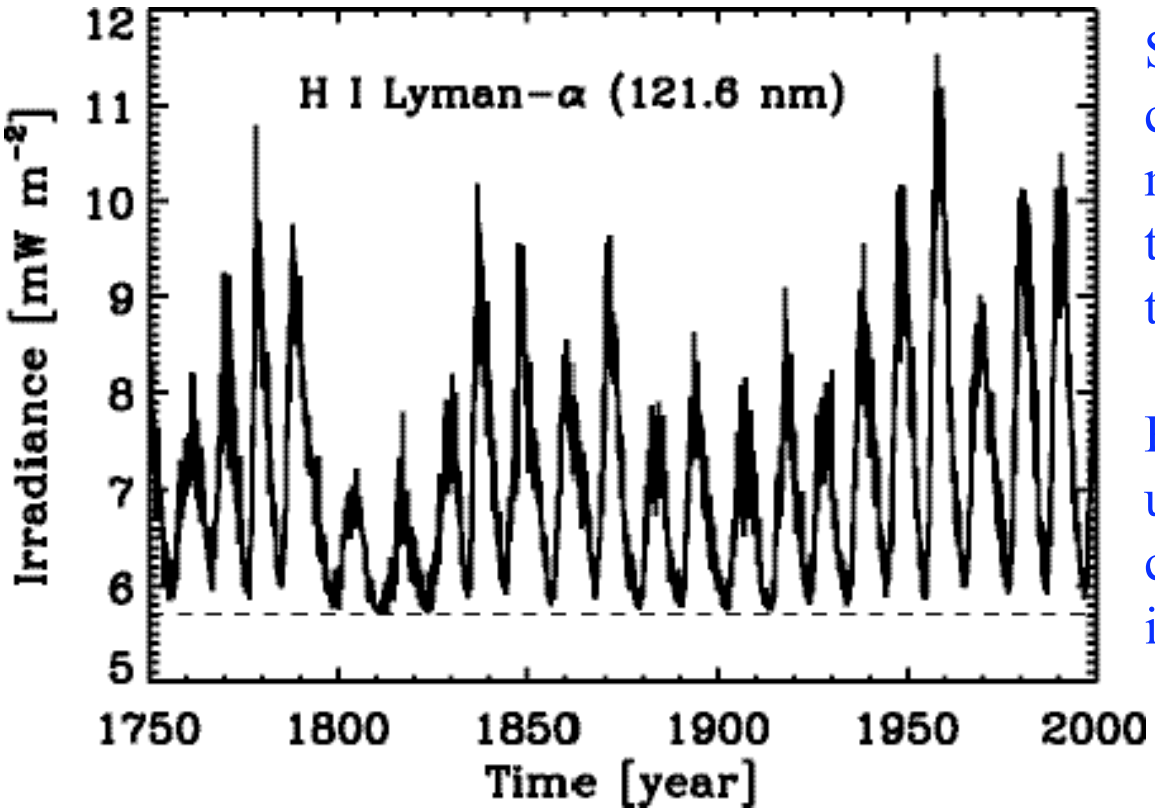
The Lyman-α time series is being extended with the TIMED and SORCE measurements.

ftp://laspftp.colorado.edu/pub/solstice/composite_lya.dat

[From Woods *et al.*, JGR, 2000]

Extending Time Series Using Sunspots

- While sunspot number is not the optimal proxy for solar UV irradiance, it is available for extending the time series further back in time



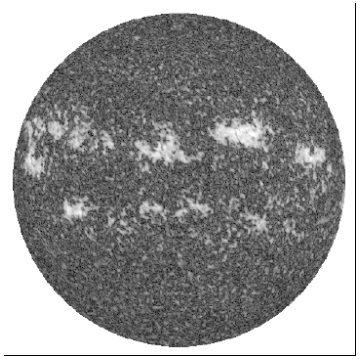
Solar cycle minimum values change slightly with this simple model, but not enough to explain the Maunder Minimum temperature changes.

Recent improvements in understanding solar variability can provide better MM irradiance estimate.

Active Network - probably none at MM

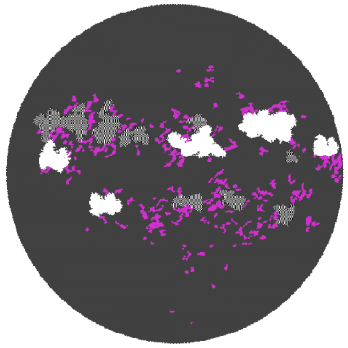
- Analysis of Ca II K images [Worden et al., ApJ, 1998] and EIT He II 30.4 nm images [Worden et al., ApJ, 1999] indicates that the active network features are present during solar cycle minimum conditions for the past two solar cycles
  - **Worden's analysis maps the images into different type of features**
  - **The Active Network (AN) evolves slowly from the decaying Enhanced Network, which in turn is from decaying Plages (associated with sunspots)**
- With very few sunspots during Maunder Minimum, then there is likely no active network during MM
  - **Adjustment is to correct the solar cycle minimum value for ZERO active network**
  - **Result for Lyman-α irradiance is x 0.80 [Worden et al., ApJ, 2001]**

Ca II K line
6/03/1992



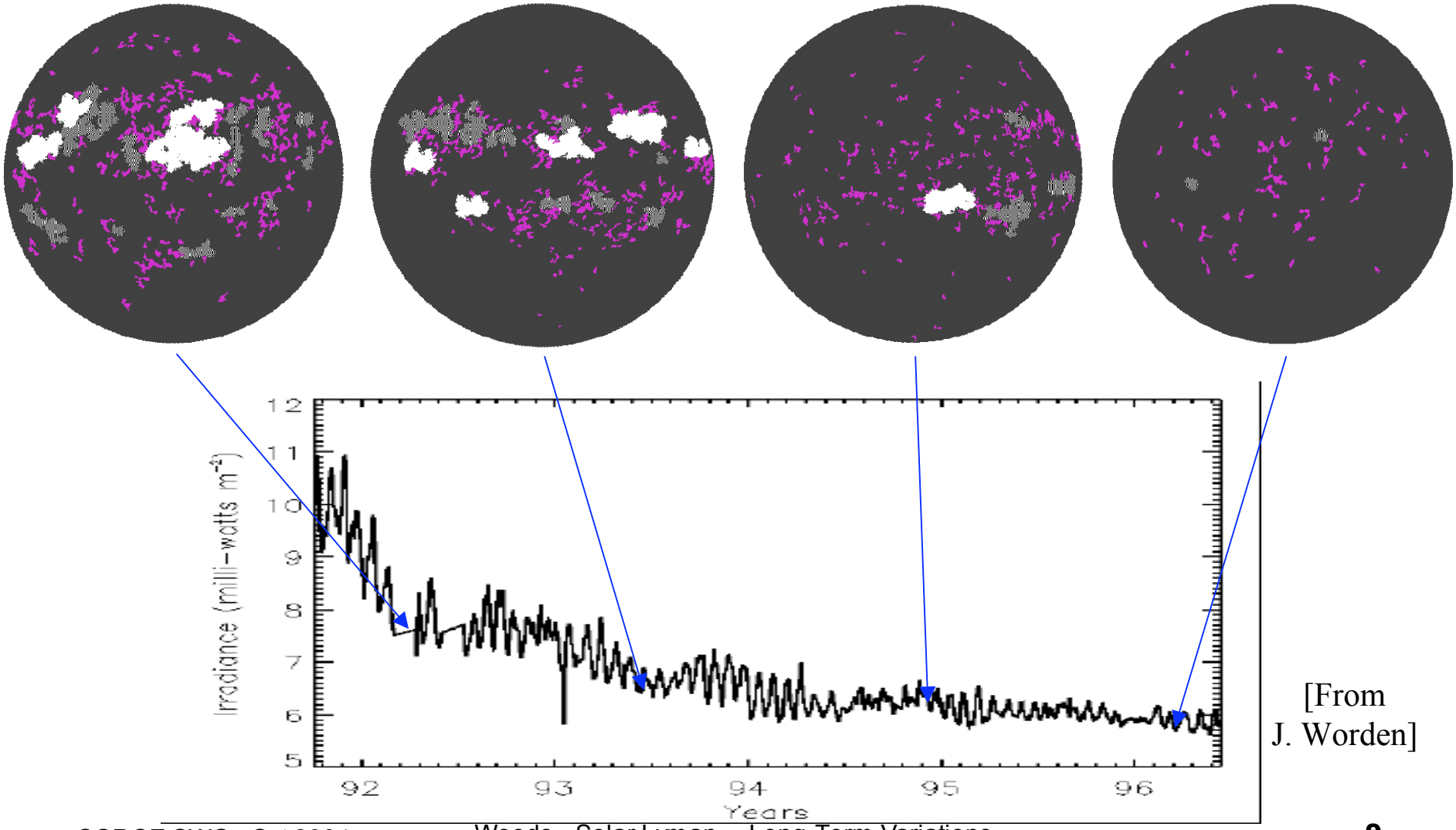
Map

- Black: Quiet-Sun
- **Purple: Active Network**
- Lined: Enhanced Network
- White: Plage



Network Is Present During Solar Minimum

3/16/1992 6/03/1993 12/14/1994 2/16/1996



[From J. Worden]

QS Radiance Decreases with Activity

- SOHO SUMER results [Schühle et al., A&A, 2000] indicate that the Quiet Sun (QS) radiance changes with solar cycle activity
  - **Most models of the solar radiation assume that the QS radiance is a constant**
  - **Expect QS radiance to decrease even more for inactive periods such as during Maunder Minimum. That is, the magnetic component of the QS radiance is expected to be less and thus lower radiance values for Maunder Minimum.**
- Worden et al. [ApJ, 1999] show that the quiet network is about 15% of the solar disk, almost independent of solar cycle activity
  - **Suspect the quiet network will decay away during the Maunder Minimum**
  - **Result for Lyman-α is decrease by x 0.93**

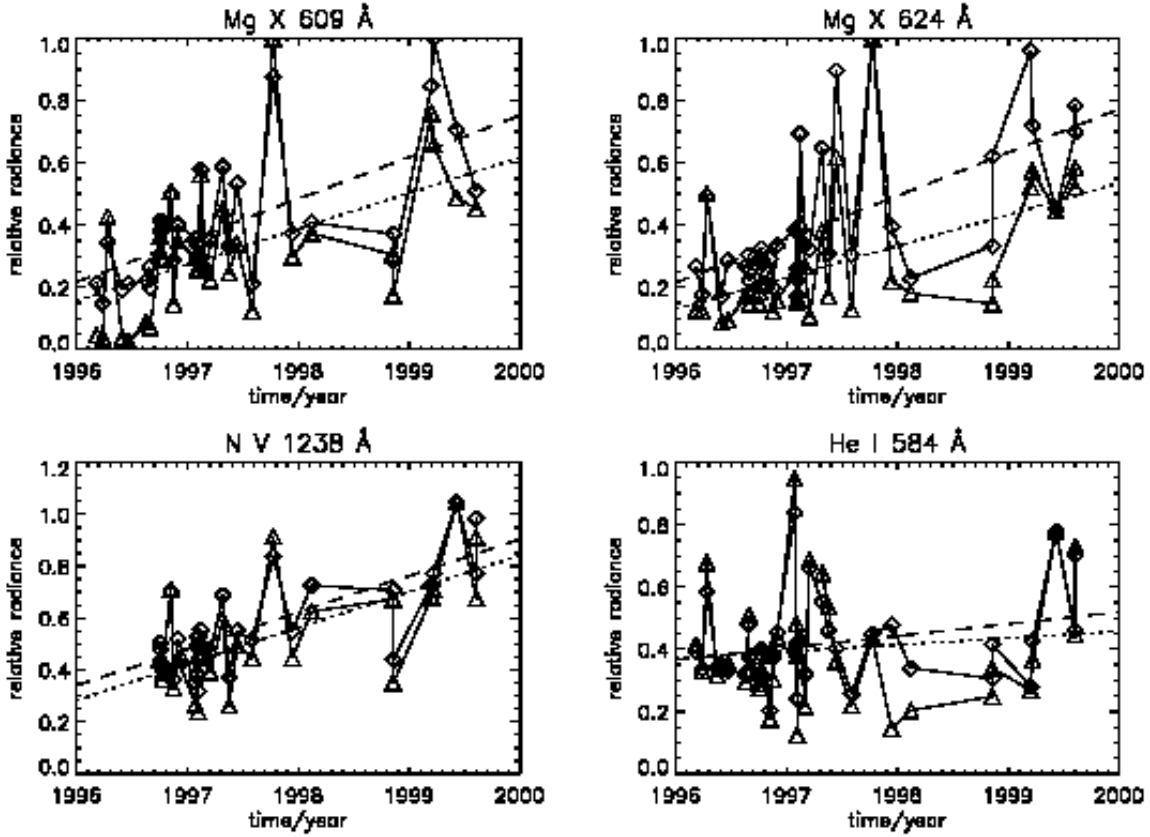
SOHO Measured QS Radiance Changes

- SOHO SUMER measurements of the QS radiance indicates solar cycle variations of 25-300% (coronal emissions more variable)

From
Schühle *et al.*, A&A, 2000.

Note that the SUMER radiance uncertainty is 15%

QS changes are similar to solar rotation variations reported by Woods and Rottman [2002]

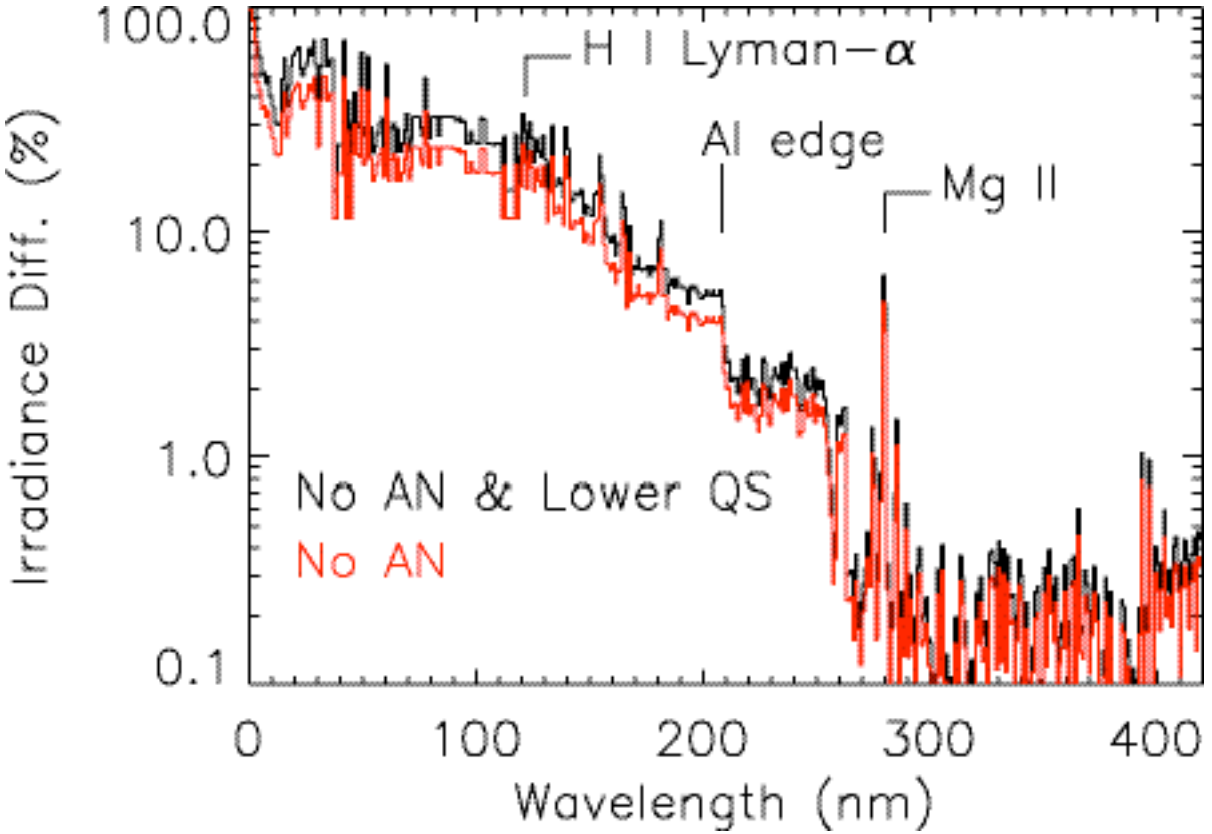


Maunder Minimum Estimate for UV

- Used these Lyman-α estimations (x 0.75) to scale the Woods and Rottman [2002] solar proxy model to obtain the difference between the Maunder Minimum irradiance and the solar cycle minimum irradiance in 1996

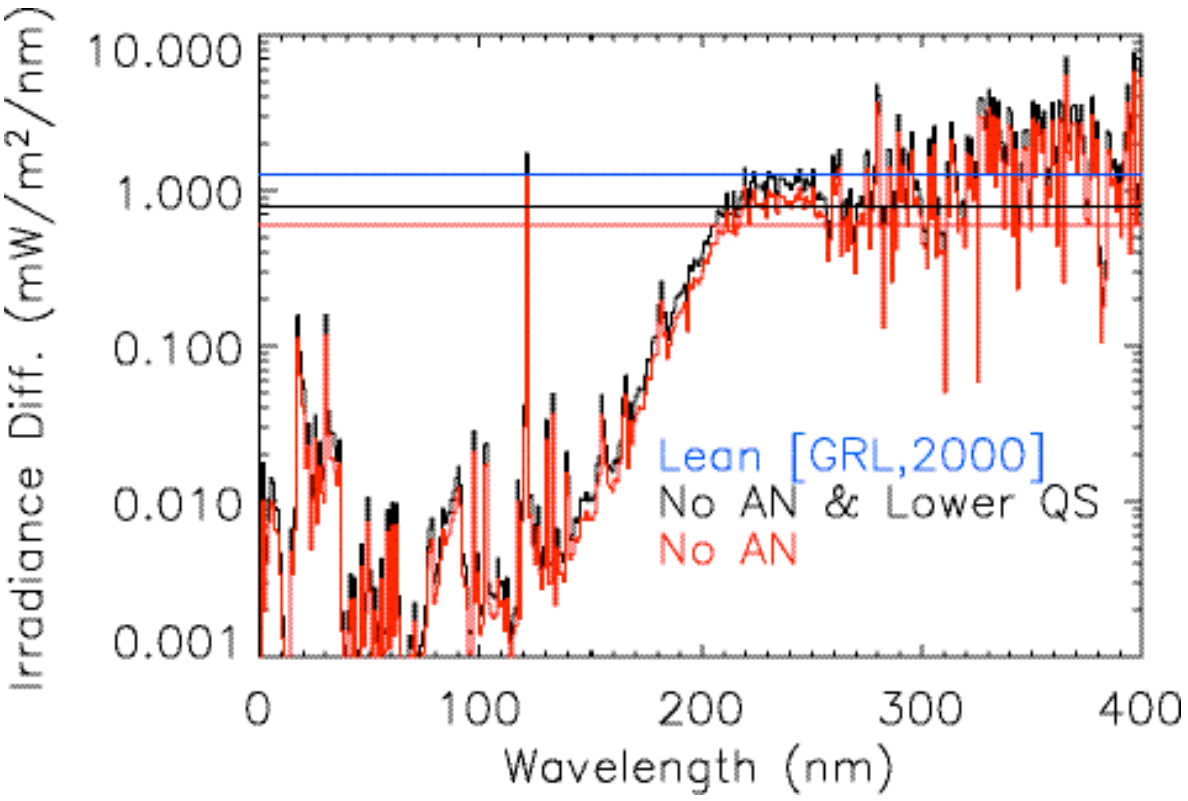
Model is based on UARS measurements in the FUV and rocket / AE-E measurements in the EUV

$$Diff. = \frac{1996 - MM}{1996} \bullet 100$$



Maunder Minimum in Energy Units

- There is a significant decrease in the UV spectral irradiance and TSI from the solar cycle minimum irradiance in 1996 to the Maunder Minimum period.



Results Below 400 nm

No AN	0.24 W/m²
No AN & Lower QS	0.32 W/m²

This estimate is ~2 times lower than the Lean [2000] predictions for Maunder Minimum irradiance below 400 nm

TSI estimate is 1.3 W/m², being about same as the recent solar cycle variation (1.2 W/m²)

This TSI estimate is ~2 times lower than other estimates for TSI during the Maunder Minimum

What's Missing in Our Understanding

- The quiet Sun radiance could be much lower during extended periods of little solar activity
  - **That is, the time frame for QS radiance changes could be longer than the 1-2 year period during our current solar minimum conditions**
  - **With the Sun being inactive for a few decades during the Maunder Minimum, the QS radiance could be even lower**
  - **Magnitude of the QS radiance change could be linked to the length of the "11-year" solar cycle**
- The solar luminosity (brightness and/or diameter) might be changing on decadal time scales
  - **Measurements during past 30 years only support luminosity changes by about 0.01% [Foukal, EOS, 2003]**
  - **Hundred-year changes in luminosity are possible**

Conclusions

- Variations of the solar Lyman-α irradiance
  - **Short-term (27-day solar rotation): 5-35%**
  - **Solar cycle (11-year): factor 1.4-2.0**
  - **Maunder Minimum / 1996 Min: factor 0.75**
- UV irradiance during Maunder Minimum (1670)
  - **Significant decrease from recent solar cycle minimum values when include adjustments for no active network and for lower quiet sun radiance during Maunder Minimum**
  - **Result of -0.32 W/m^2 for 0-400 nm is about a factor of 2 lower than J. Lean's [GRL, 2000] predictions for Maunder Minimum**
- Future improvements of the solar spectral variability are expected from the new measurements from the NASA SORCE and TIMED satellites
  - **TSI and spectral irradiance between 0-2000 nm**
  - **TIMED launched in December 2001**
  - **SORCE launched in January 2003**