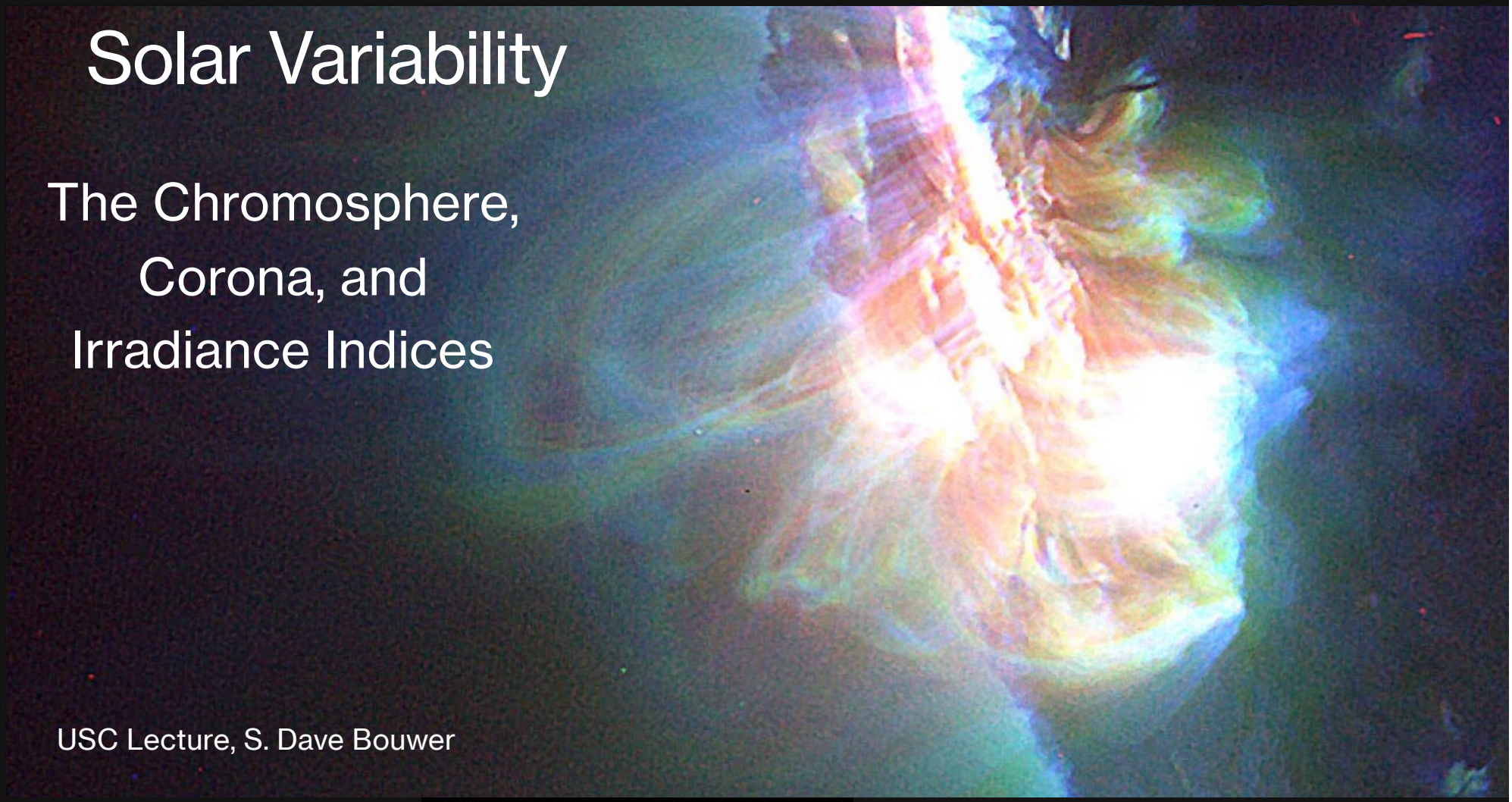
Solar Variability

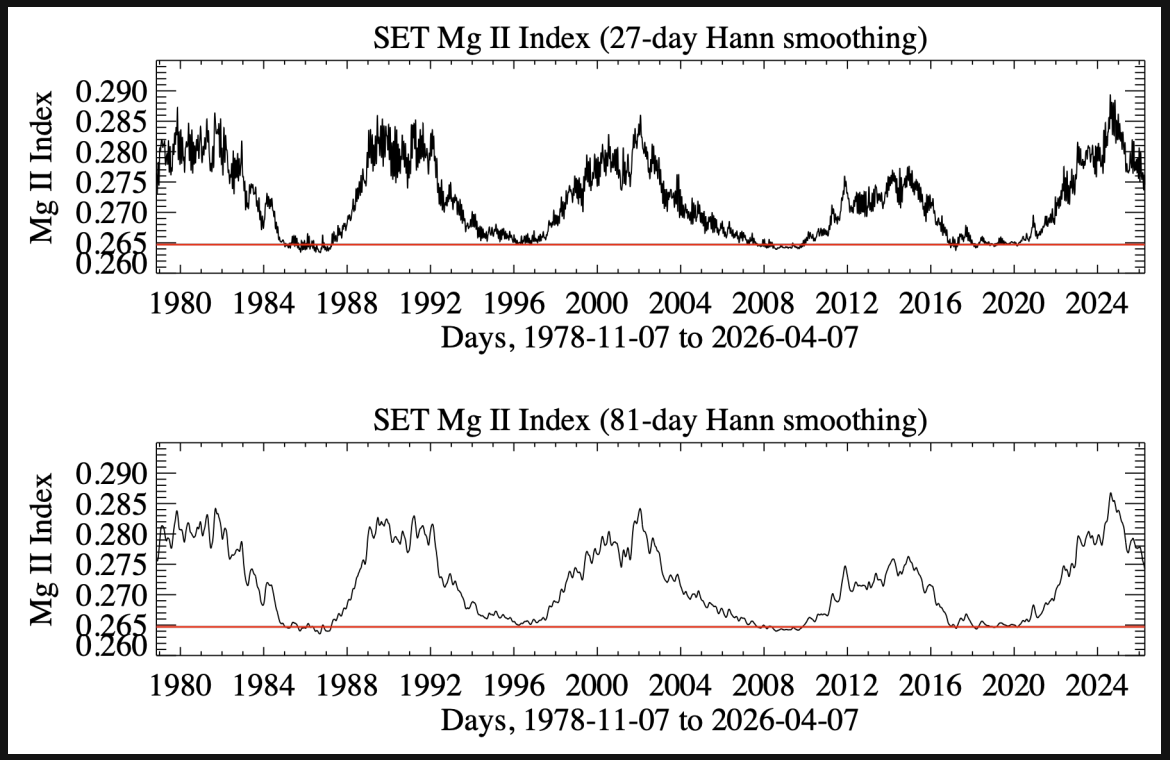
The Chromosphere, Corona, and Irradiance Indices



USC Lecture, S. Dave Bouwer

Topics

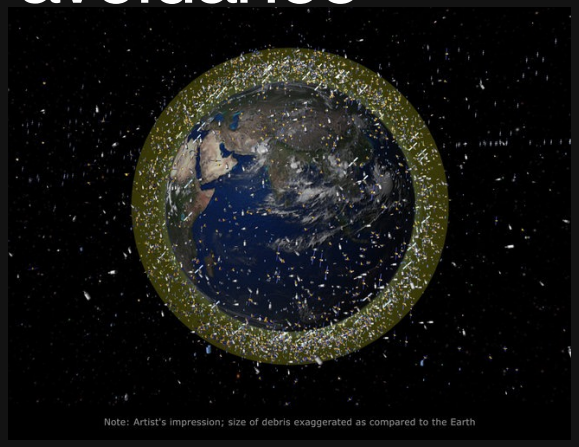
- Introduction
- Solar Physics Basics
- Mg II c/w
- Solar X-rays
- Periodicities
- ARFIRS Model
- Forecasting

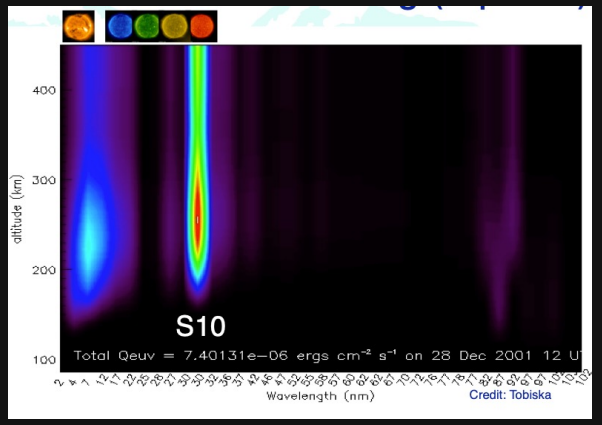


Solar Cycles 21-25

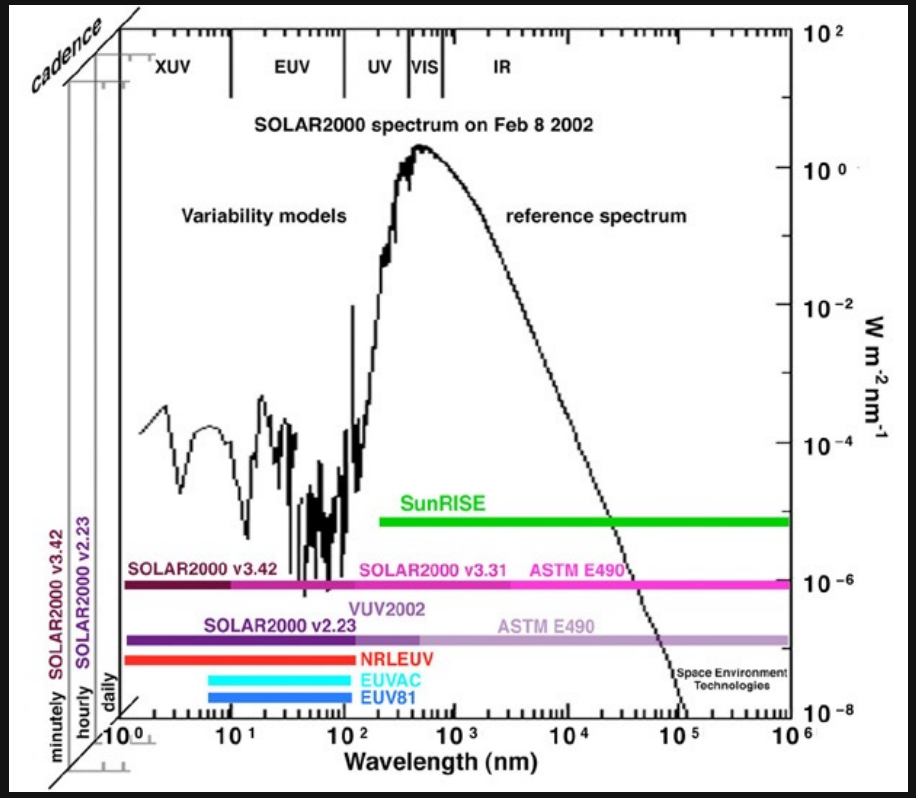
SSA - Space Situational Awareness and conjunction analysis, debris avoidance

- **Solar UV/EUV Irradiance accounts for ~80% of the daily variance of thermospheric density**
  - Approximately 11,000 Satellites in LEO
  - LEO satellites can lose ~100 m to ~2 km per day in altitude during enhanced solar activity
  - Accurately forecasting thermospheric densities can mitigate potential collisions and reducing propellant use
    - HASDM / JB2008 USSF
- 54,000 objects > 10 cm
  - 7.67 km/s at 400km, ~17,000 mph
  - ISS has made 41 debris avoidance maneuvers since 1999
    - SWIFT (Gamma-ray bursts, high energy events)
      - Launched Nov/2004, 600 km
      - Re-entry Nov/2026



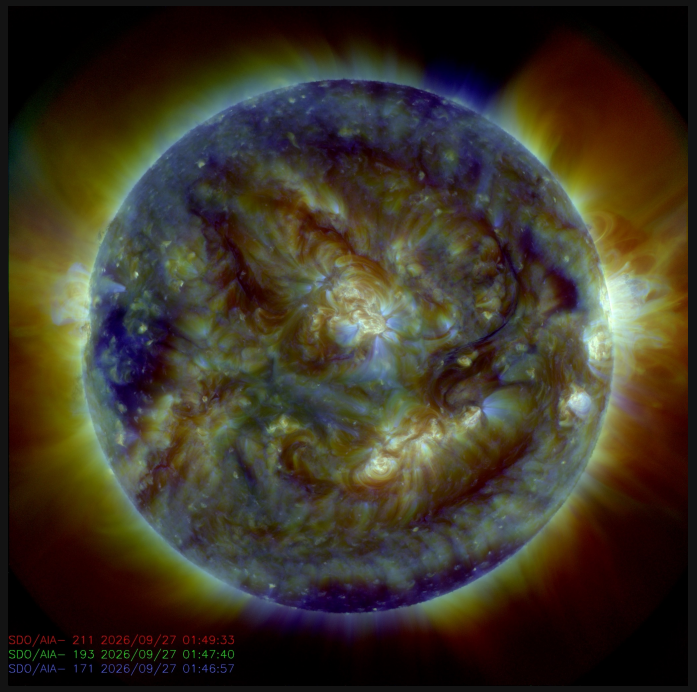


The Sun “sol”



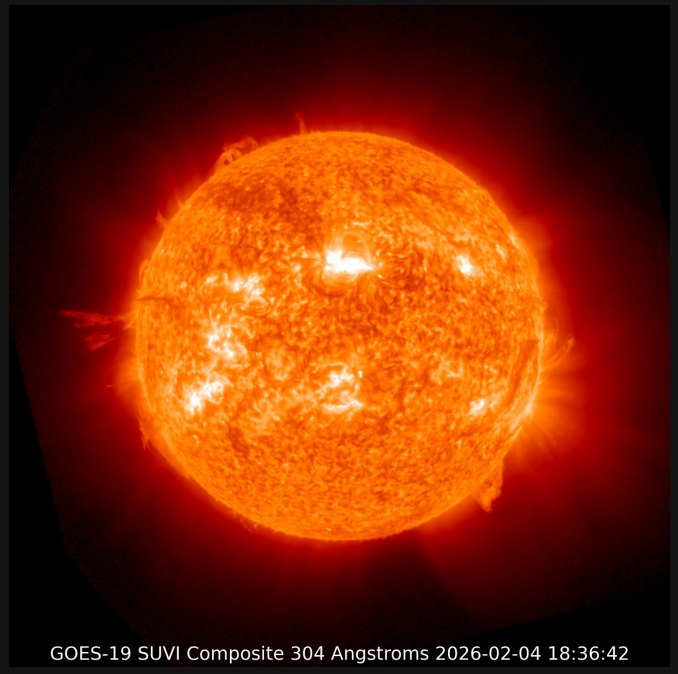
Credit: SDO/AIA, K.Tobiska

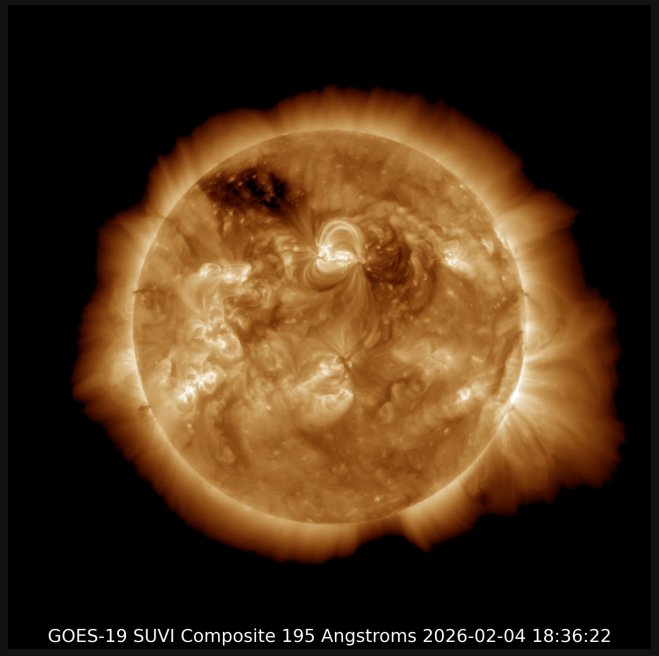
- Total Irradiance, 1361 W/m^2
  - The UV/EUV bands
    - FUV/UV 121-400 nm
    - EUV 10-121 nm



Chromosphere & Corona

Chrom./Cor. reflect the principal properties of solar dynamics



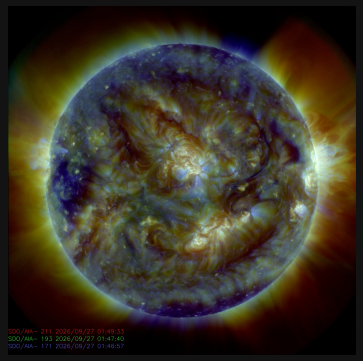


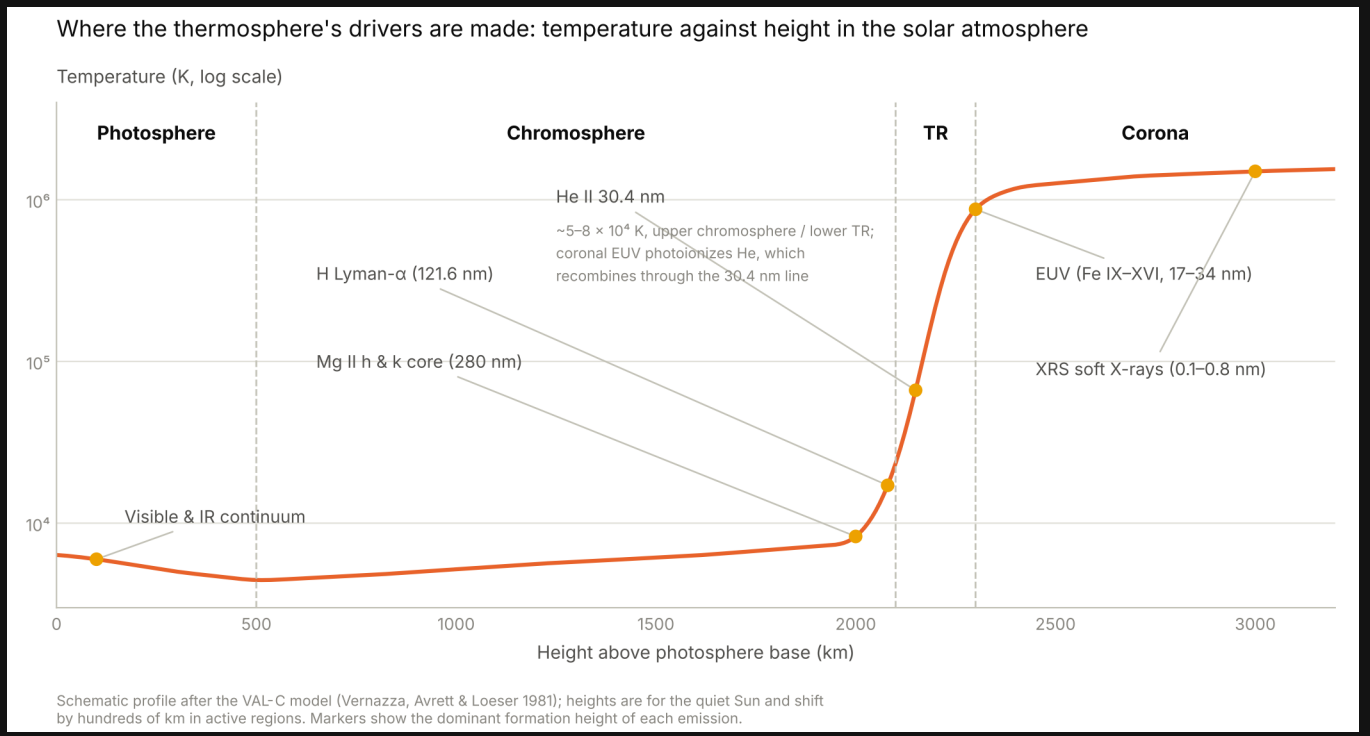
UV / EUV

- The photosphere, transition region, corona have distinct temperature profiles

- Approximate thickness:
  - Photosphere: 500 km
  - Chromosphere: 500-2100 km
  - Transition Region: ~100 km
  - Corona: 2,500 ++

- In the transition region 1-400 nm band the percentage of irradiance, 35-50%, comes from the transition region (He 30.4 nm, Ly-a 121.6 nm)

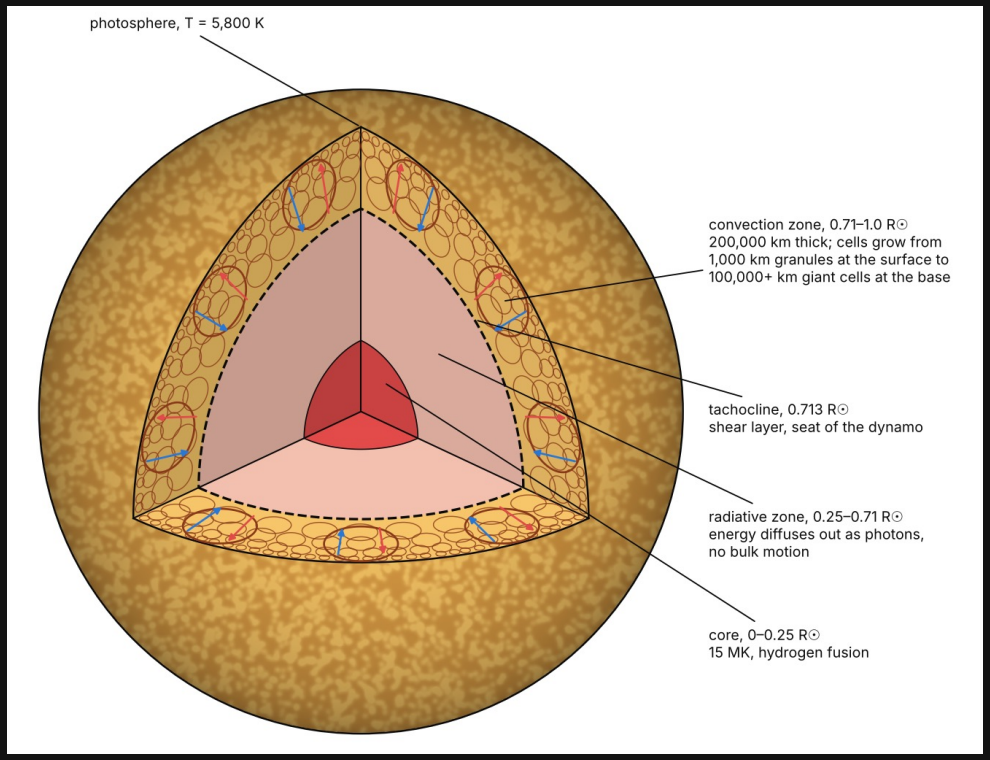


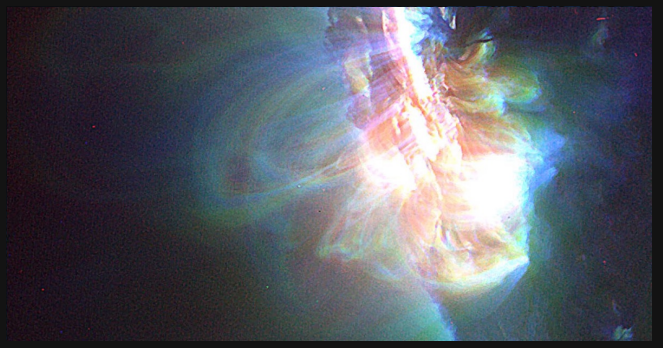


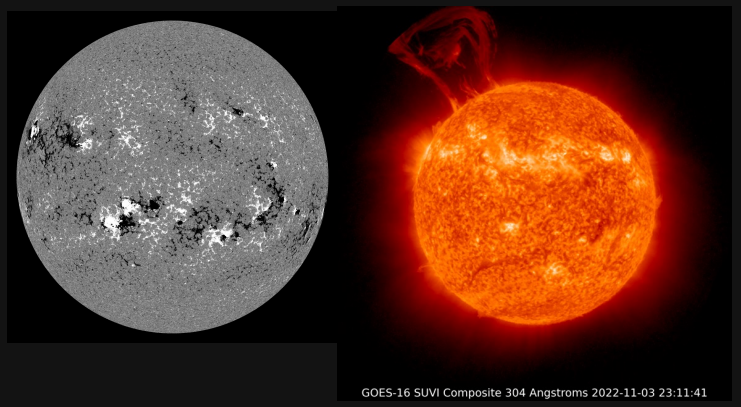
Transition region: 17.1, 19.3, 21.1 nm

The Convective Zone

The source of complex, twisting magnetic fields resulting in active regions and coronal loops





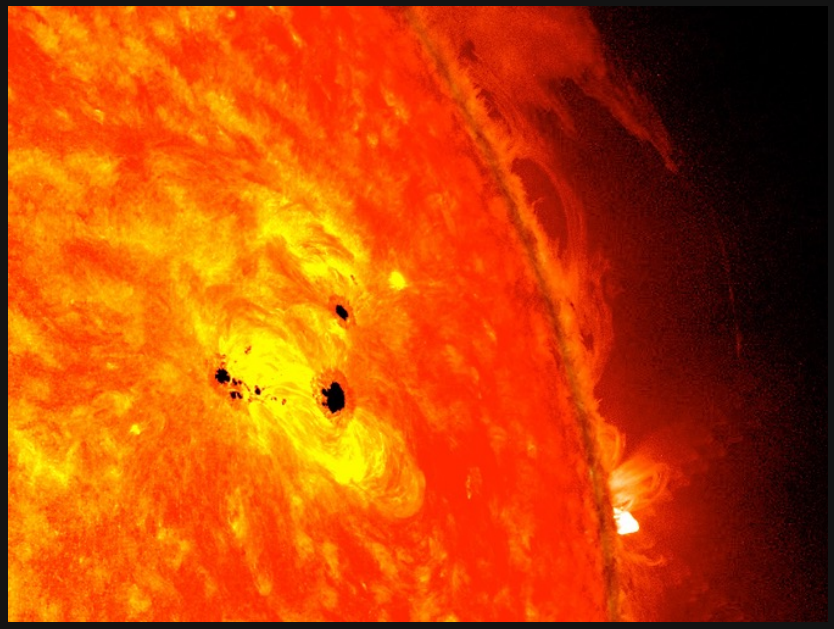


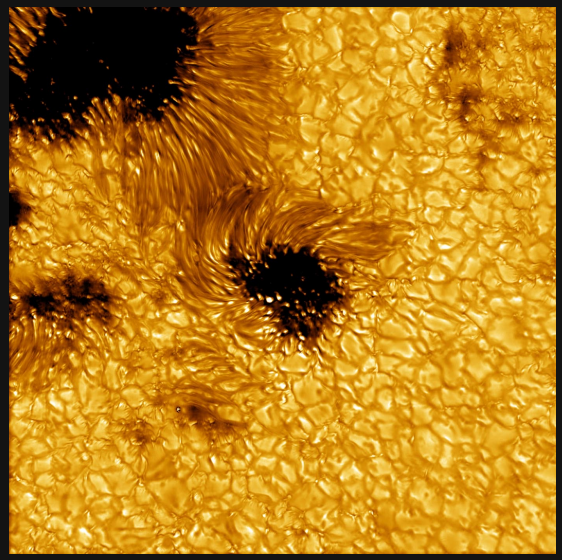
Little is known about the layers of the sun below the photosphere

Credit: NASA/SDO

Active Regions

- Changing irradiances:
  - Active Regions
    - bipolar
    - randomly appear in lat./lon.
  - Plages
  - Network



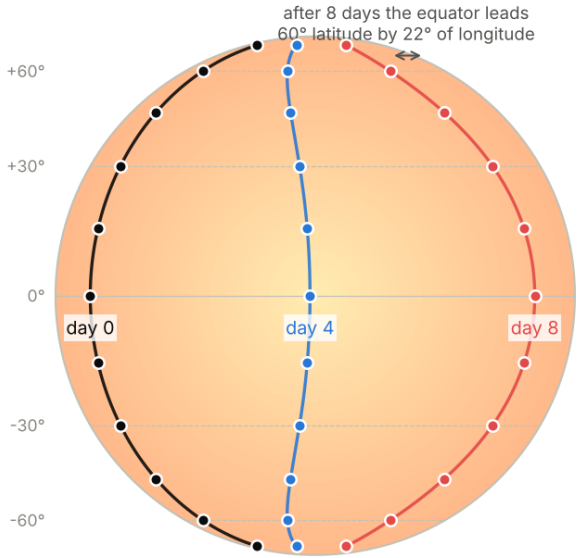


Credit: La Palma

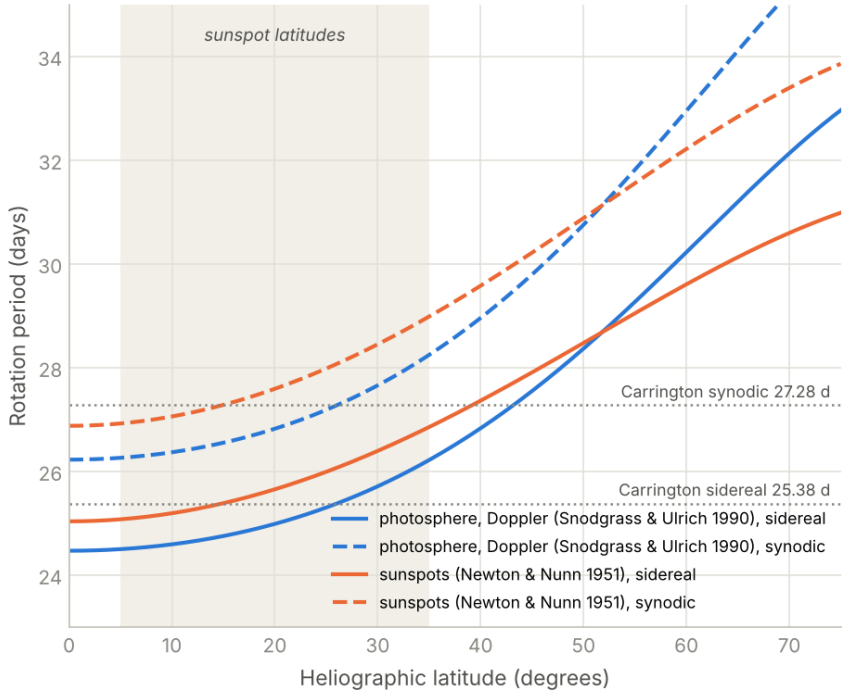
Differential Rotation

Solar differential rotation: the equator turns in about 25 days, the poles in about 35

(a) A meridian of markers, followed for 8 days (photospheric Doppler rate)

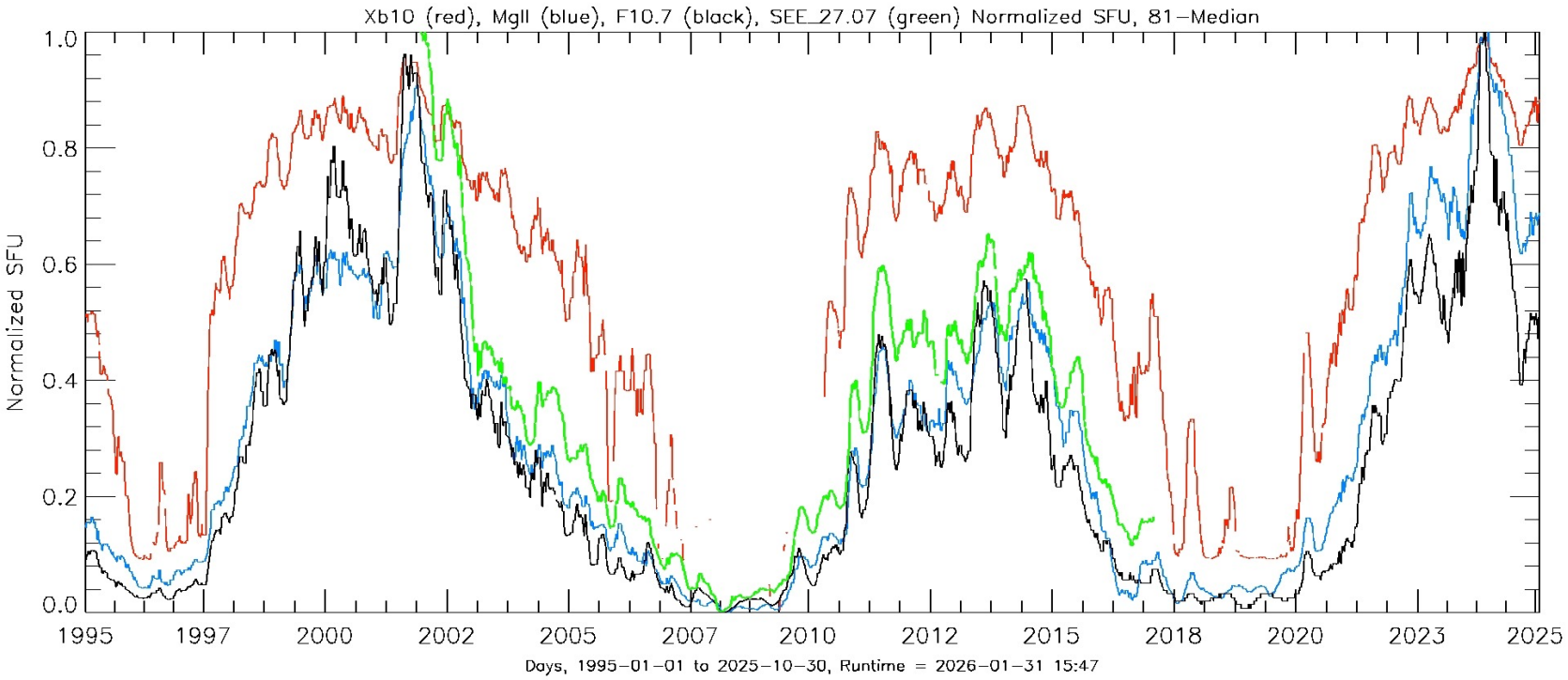


(b) Rotation period against latitude

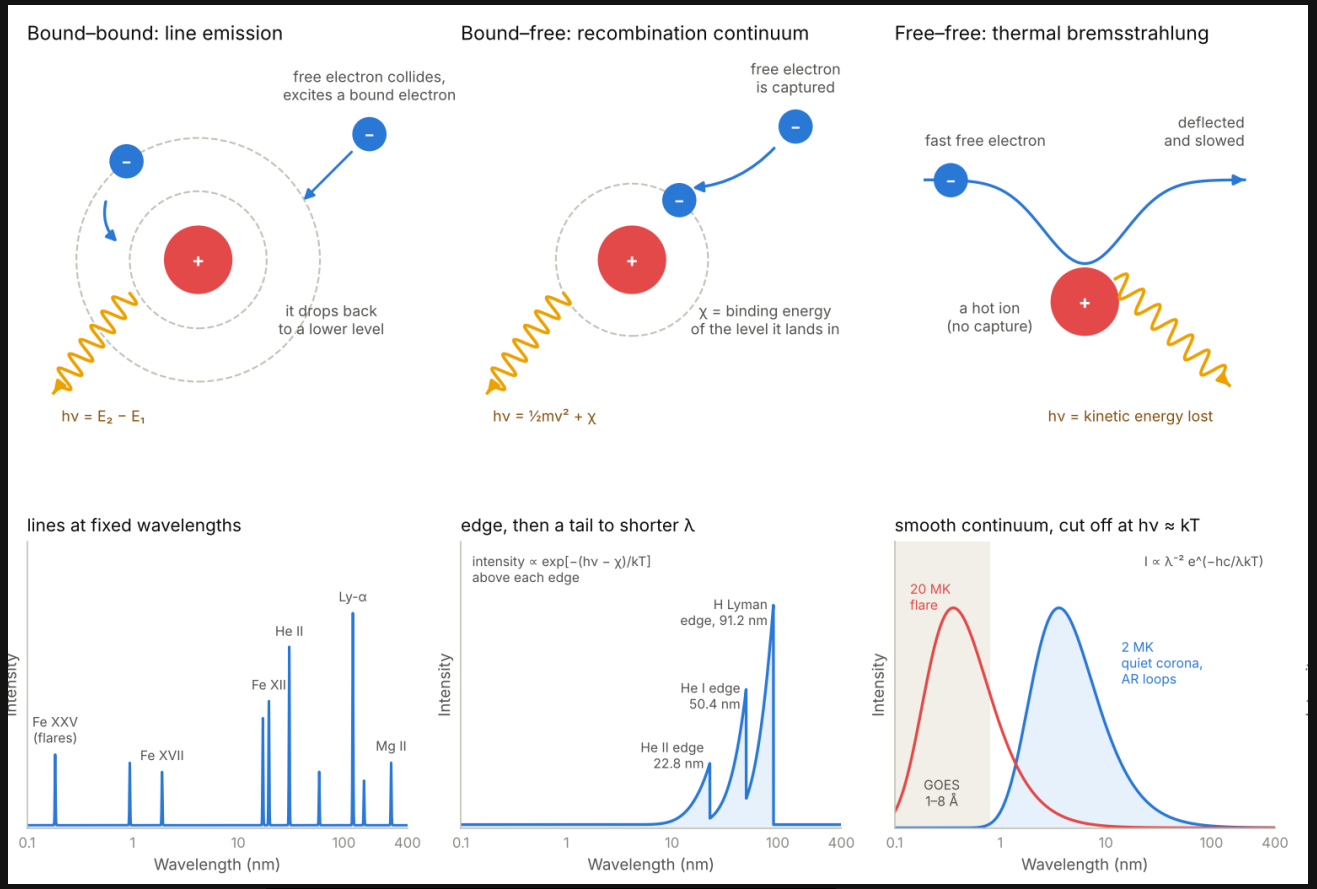


Sidereal = relative to the stars; synodic = as seen from the orbiting Earth, about 1.9 days longer. $\omega(\varphi) = 14.713 - 2.396 \sin^2\varphi - 1.787 \sin^4\varphi$ deg/day (Doppler); $14.38 - 2.96 \sin^2\varphi$ (sunspots).
Sunspots rotate faster than the surface plasma, suggesting they are anchored below it.

Solar Indices

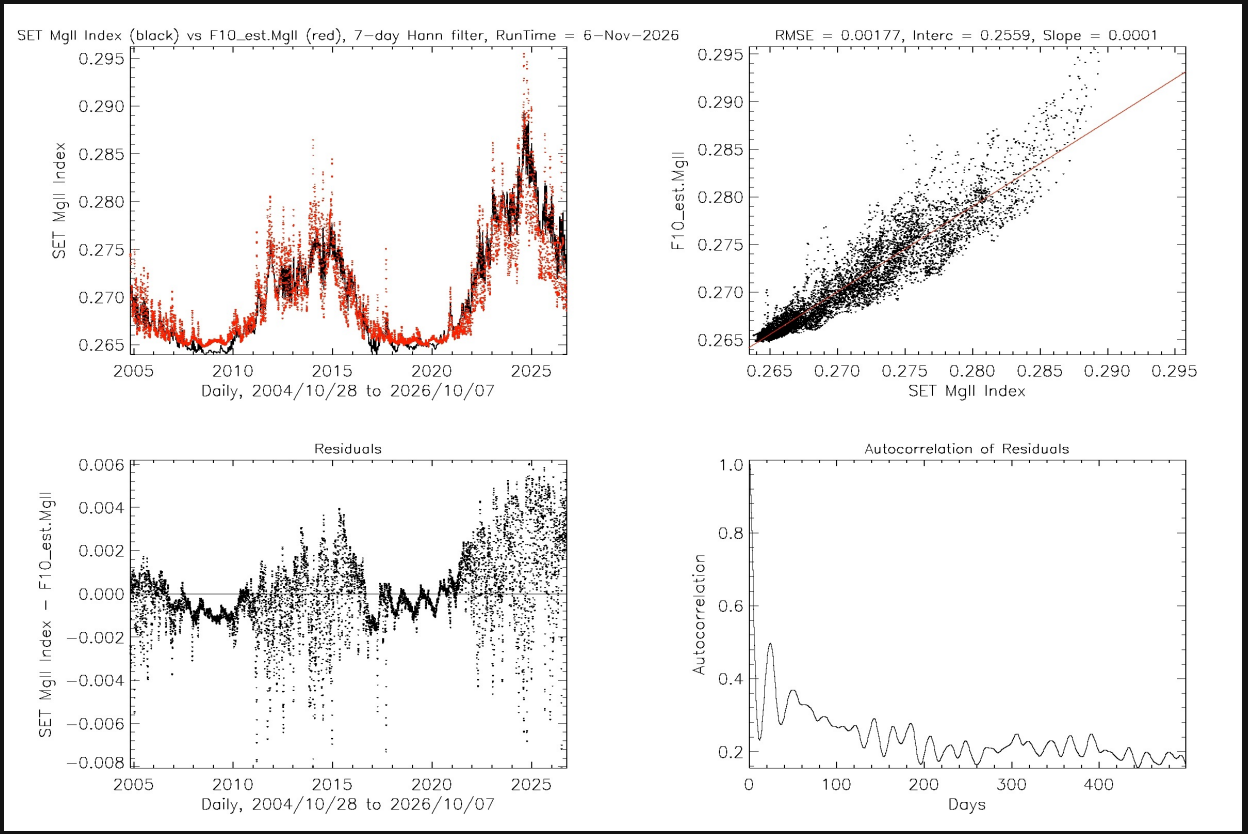


Emission Sources



F10.7 vs Mg II

- F10.7 is often used in thermospheric models, but:
  - It is a proxy, with no effect at Earth
    - Differs from UV
  - Measured 3 times a day
  - It has a significant coronal component
    - Sensitive to flares



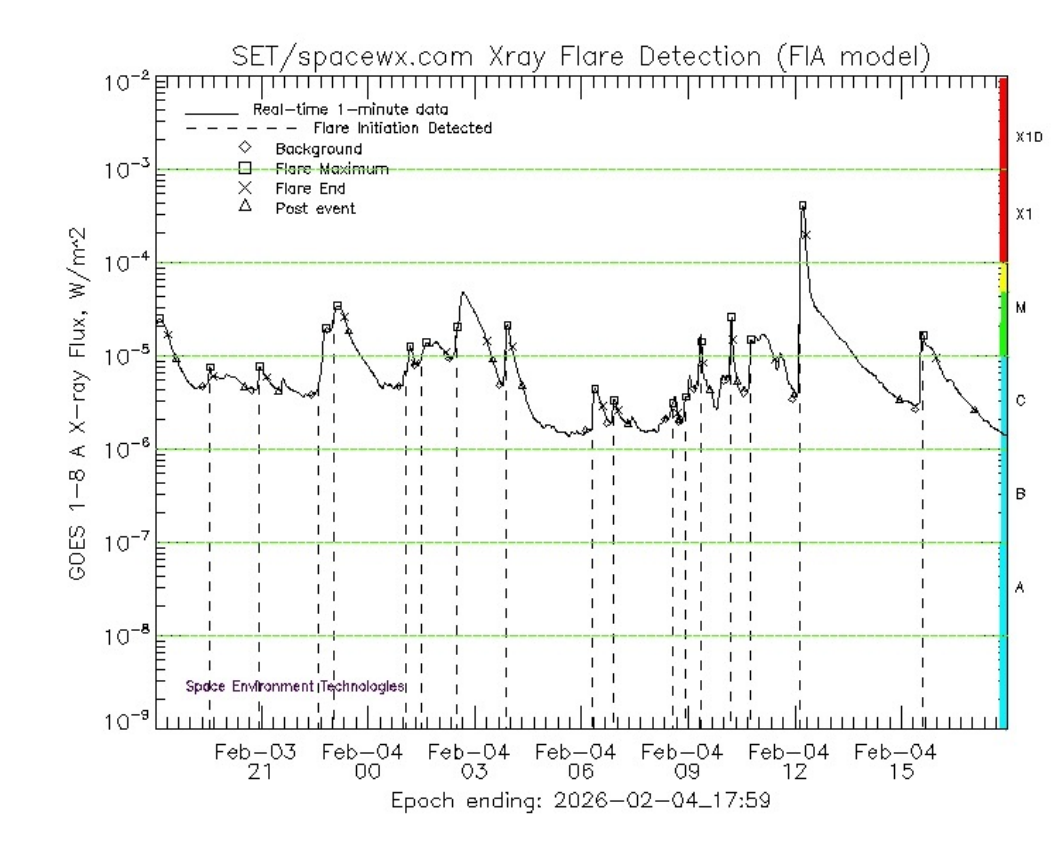
0.1-0.8 nm 1-minute “Soft” X-ray Flux

- Dominated by active regions, with impulsive magnetic reconnection heating

- HF Radio blackouts
  Frequent source of CMEs
- 1 cm – 0.3 m GNSS/GPS errors

- The problem:
  - Detect the onset of a flare
  - Separate flares from background

$$\Phi_{imp}(t) = a \bullet \Phi(t) \bullet e^{\left(b \bullet \Phi(t)\right)} + c$$

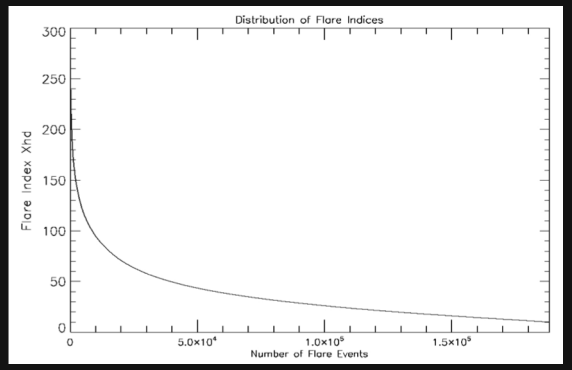


NOAA
R-scale

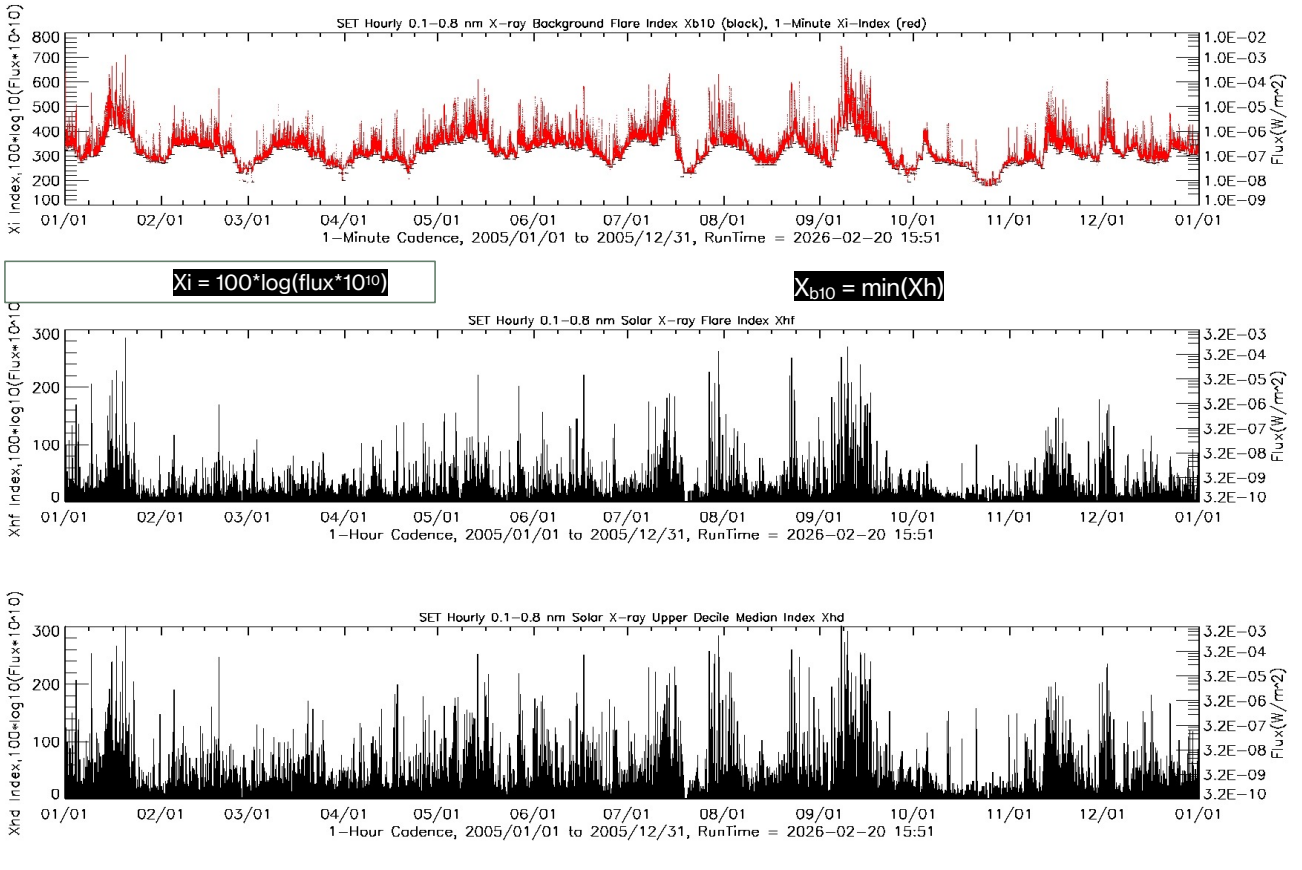
Coronal Soft X-rays Variability

Background, hourly indices

Flares occur randomly in time and magnitude

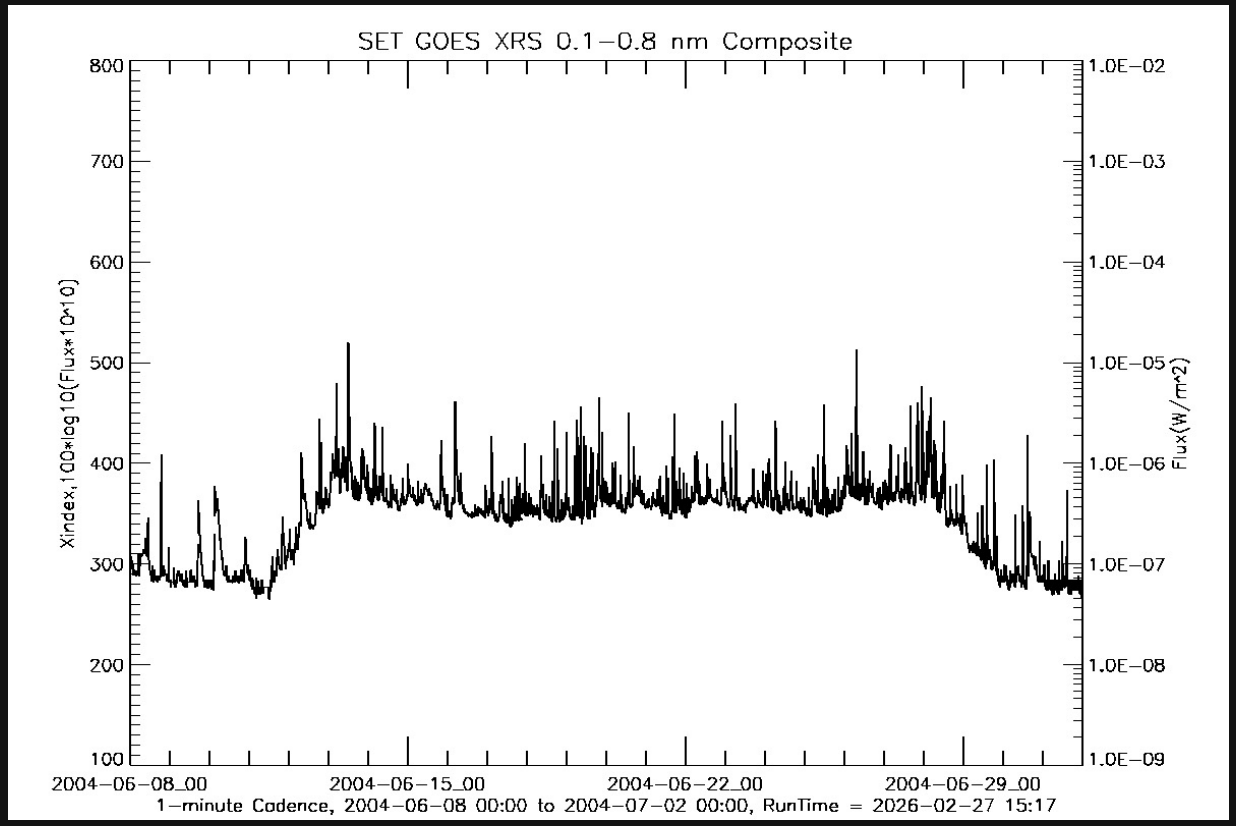


Flares mostly affects Ionosphere (~< 1-4 hours); not a major contributor to thermospheric density



X-Rays CMD/CMP

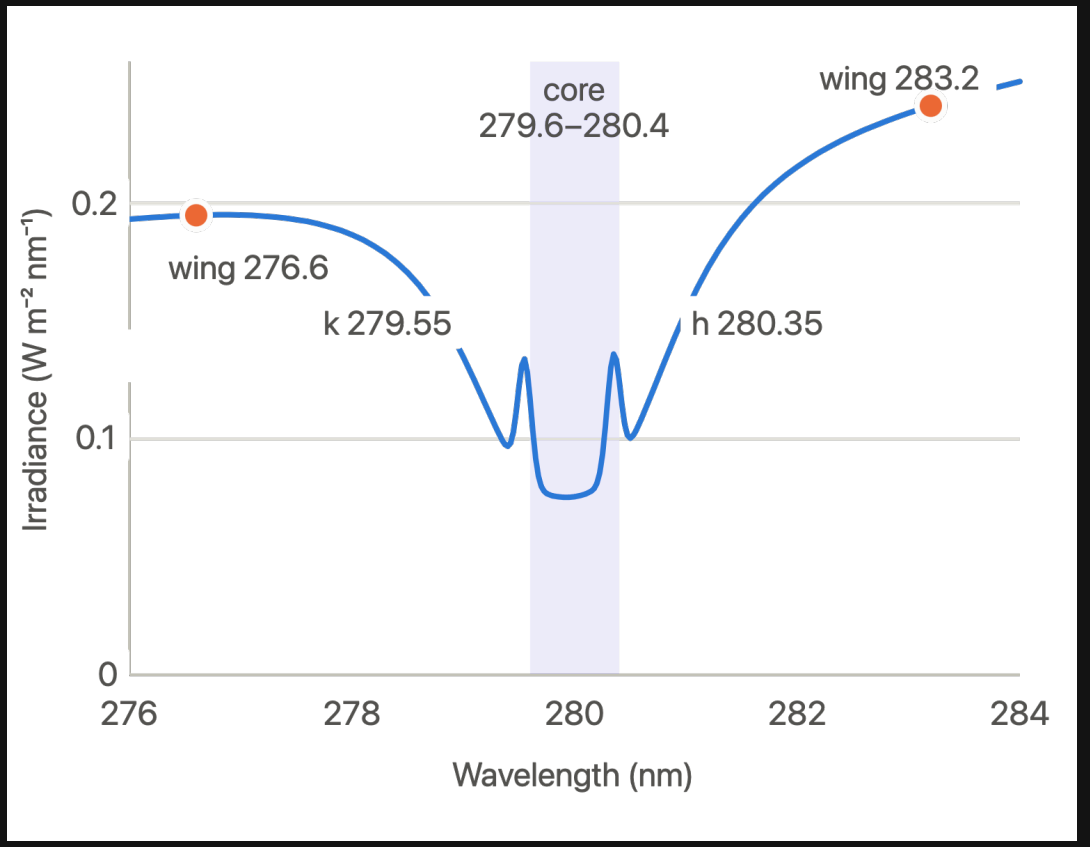
- The Sun's upper atmosphere is optically thin to X-rays, creating a step-like appearance
- Due to X-rays coming from the loops, we can see an AR ~1-2 days before it appears at the limb
- X-rays from active regions tend to peak in first rotation, UV/EUV (plages) in the 2nd rotation



Mg II c/w (Mg II Index)

- The Mg II center-to-wing ratio
  - A photometric UV chromospheric index
  - The wings stay relatively constant, the core varies with changing irradiance
  - Resistant to instrument calibrations, degradation, drift, flares

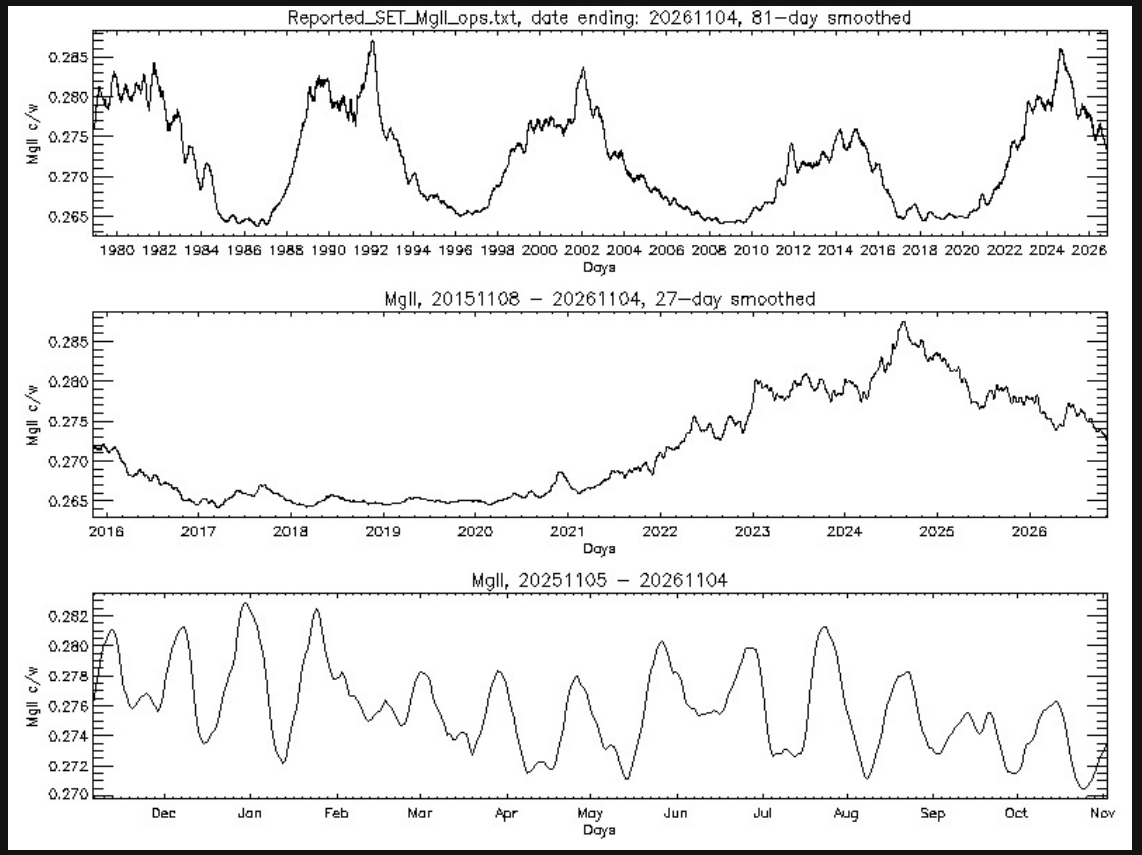
$$R_{MgII,SBUV} = \frac{4}{3}\left[\frac{I_{279.8} + I_{280.0} + I_{280.2}}{I_{276.6} + I_{276.8} + I_{283.2} + I_{283.4}}\right]$$



Mg II c/w Variability

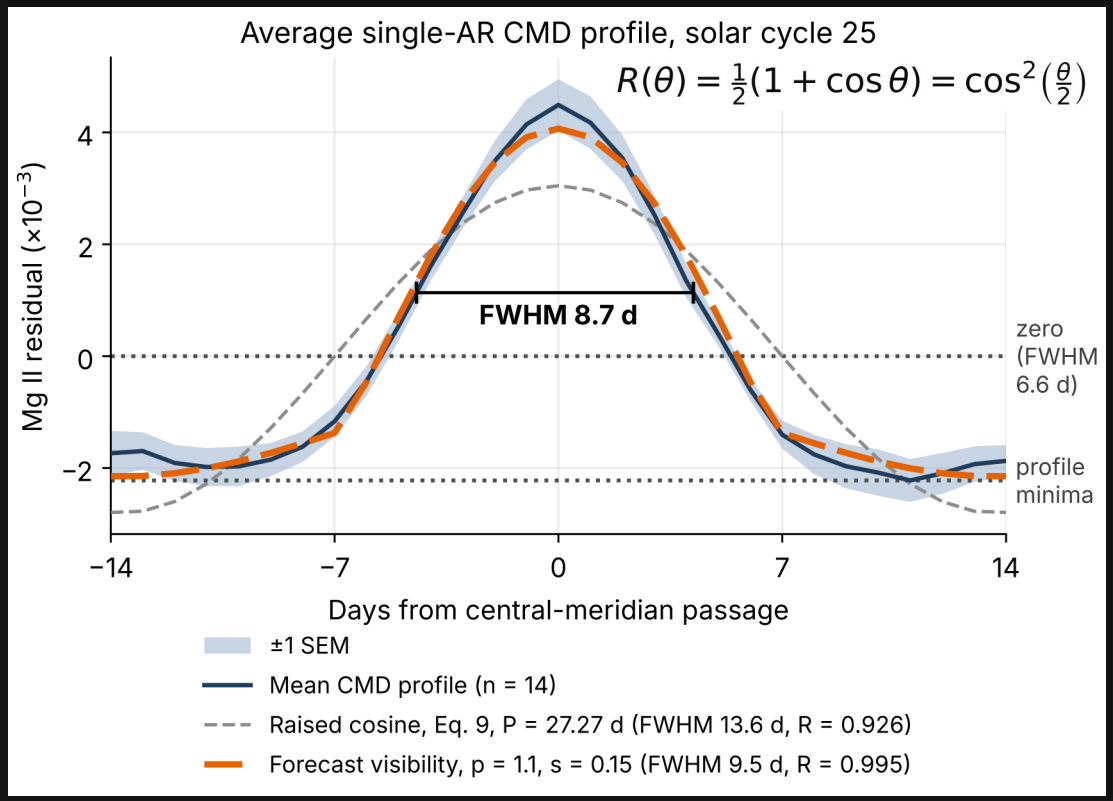
- Besides sunspot numbers (1600) and F10.7 (1947), Mg II is the longest continuous time series
- 10.6 yr mean Solar Cycle
- +- 1.4 yr SD (9.6-12.9)
- Cycle 24 was anomalous
- Predicting a cycle remains elusive

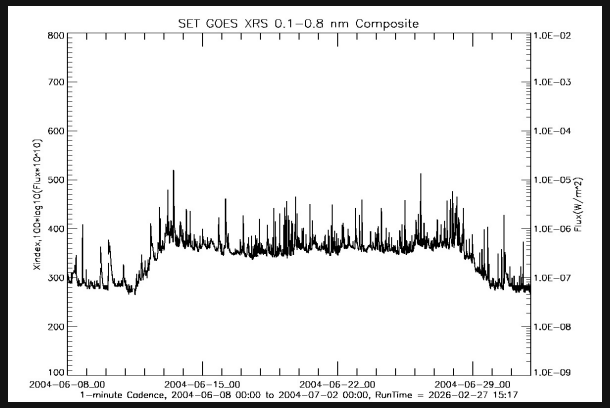
RMSE ~< 0.001

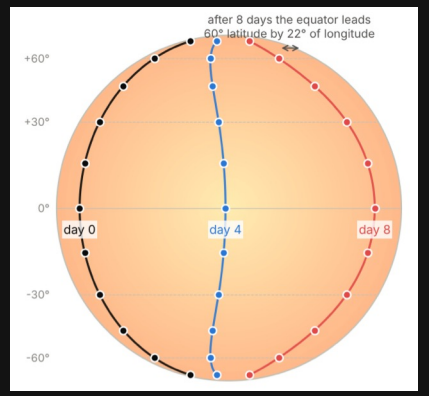


UV/EUV Central Meridian Distance CMD/CMP

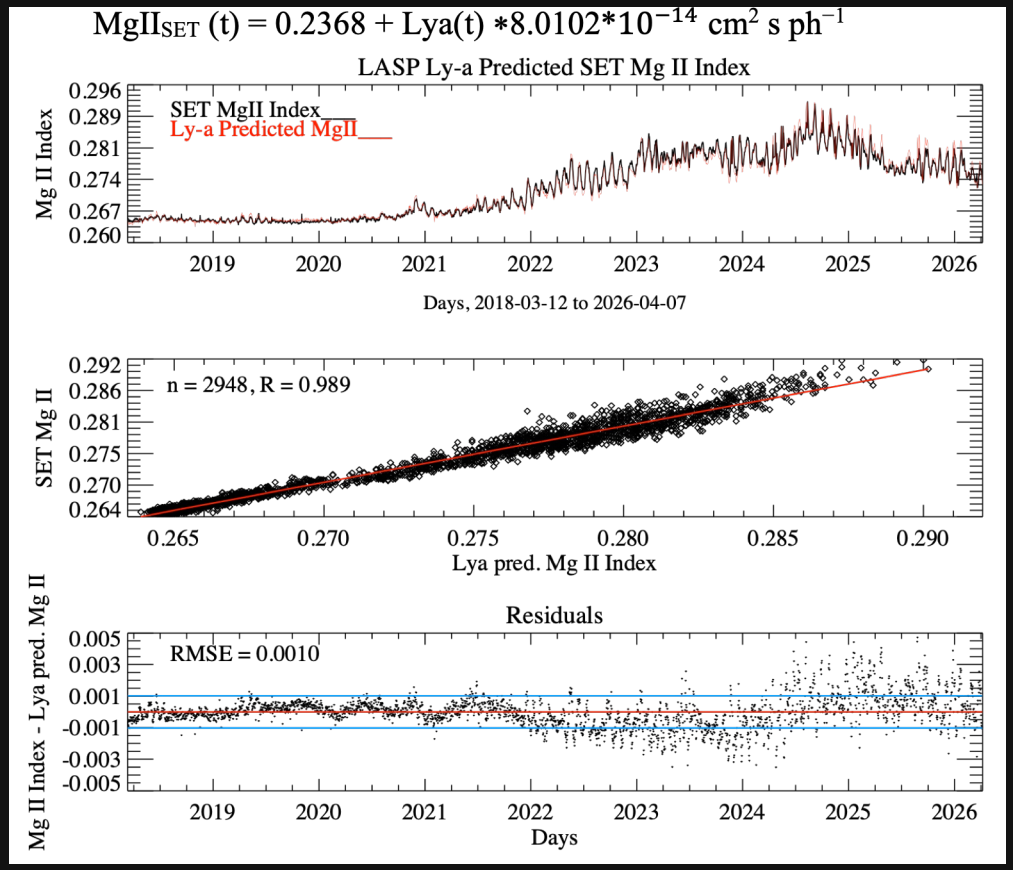
Sun's atmosphere is optically thick to UV/EUV

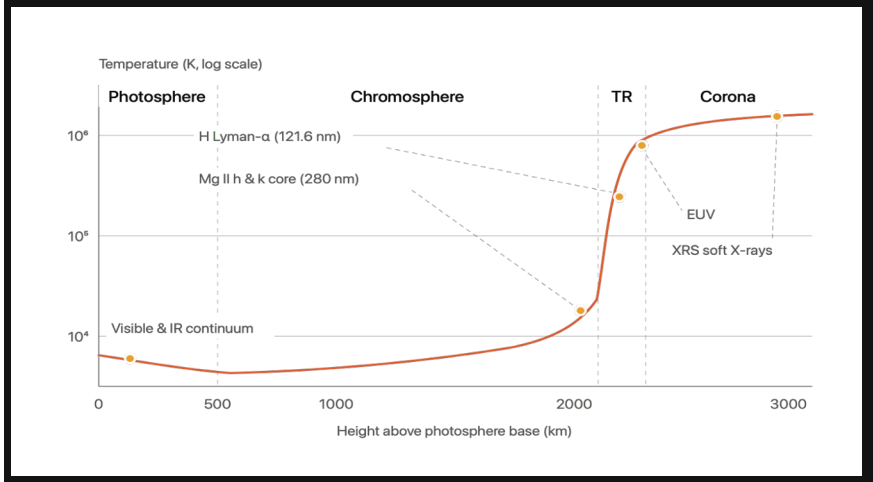






Mg II vs Ly-a

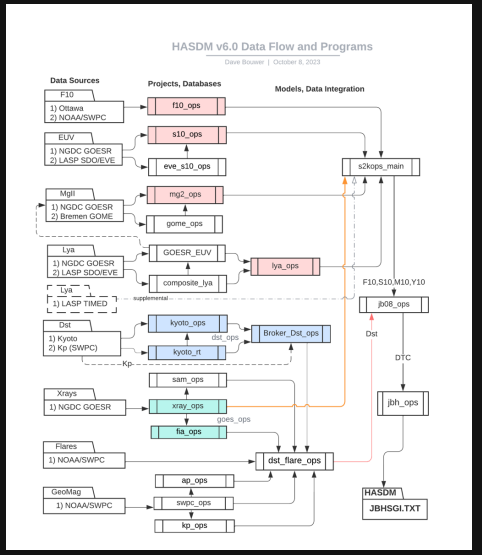

$MgII_{SET}$ (t) = 0.2368 + Lya(t) *8.0102*10^{-14} cm^2 s ph^{-1}
LASP Ly-a Predicted SET Mg II Index
SET MgII Index
Ly-a Predicted MgII
Mg II Index
Days, 2018-03-12 to 2026-04-07
n = 2948, R = 0.989
SET Mg II
Lya pred. Mg II Index
Residuals
RMSE = 0.0010
Mg II Index - Lya pred. Mg II
Days


Temperature (K, log scale)
Photosphere
Chromosphere
TR
Corona
H Lyman-α (121.6 nm)
Mg II h & k core (280 nm)
EUV
XRS soft X-rays
Visible & IR continuum
Height above photosphere base (km)

Operational Challenges

If you become involved in data operations or do research related to space-weather, there are risks in data. At SET, we have encountered many situations when data became unreliable. Despite some claims to the contrary, "30% error" is no longer sufficient in mission-critical operations

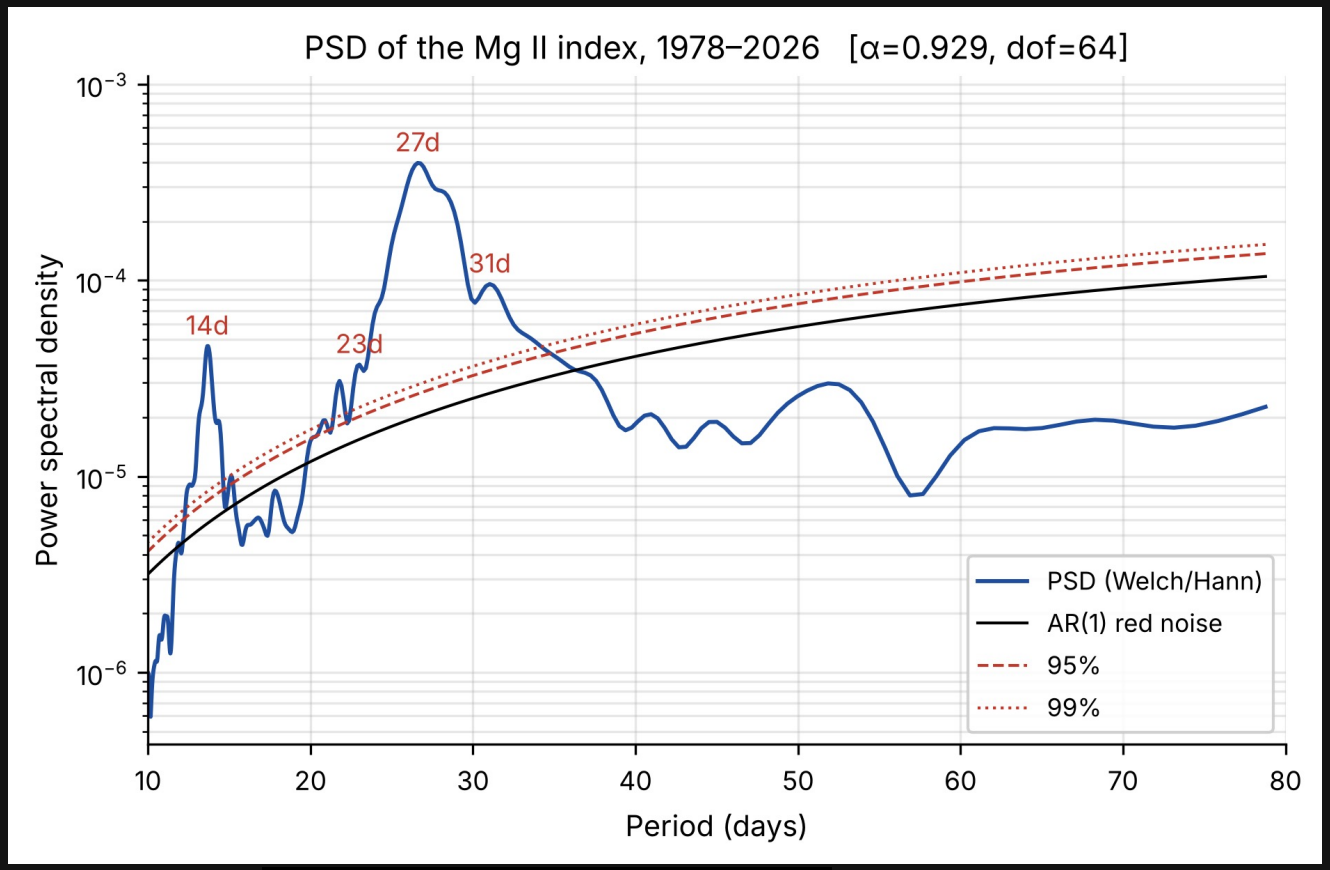
- Outages & Latency & calibrations
  - Most data providers are online with < 4 days latency about 98% of the time
    - But SET acquires ~ 50 real-time data streams
  - Websites, file names, data formats change
  - Calibrations (e.g., drift) are infrequent, with years delay
    - Poor signal-to-noise (e.g., outliers)
    - Instrument & observation limits
- SET operations mitigates these issues by:
  - redundant computer systems
  - multiple data sources
  - error-correction algorithms
  - forecasting algorithms
  - frequent monitoring of data products
- It is not as simple as "wget/readf"



Stationarity

- Stationary
  - Mean & variance do not depend on time
    - Any two windows of the record, wherever they start, estimate the same values within sampling error
  - Frequency, amplitude, phase constant over a fixed time interval
- Non-stationary
  - The statistics change within the record, whether by a trend, a changing variance, a wandering period
- **Quasi-Stationary**
  - The properties drift slowly enough to be treated as stationary within a limited window (e.g., observed solar rotations irradiance variations)

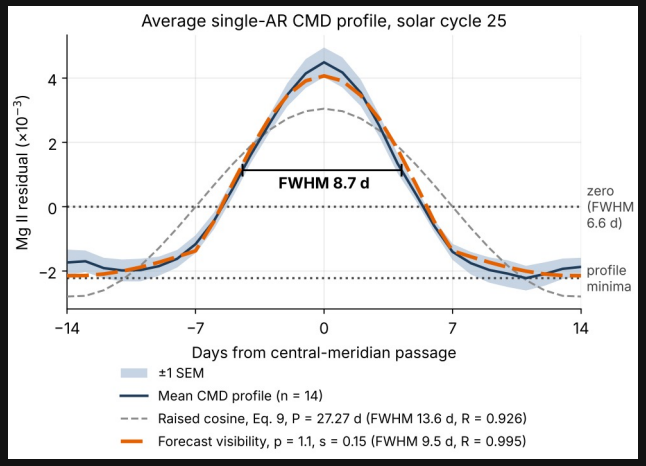
Mg II in the Frequency Domain



14-Day Period

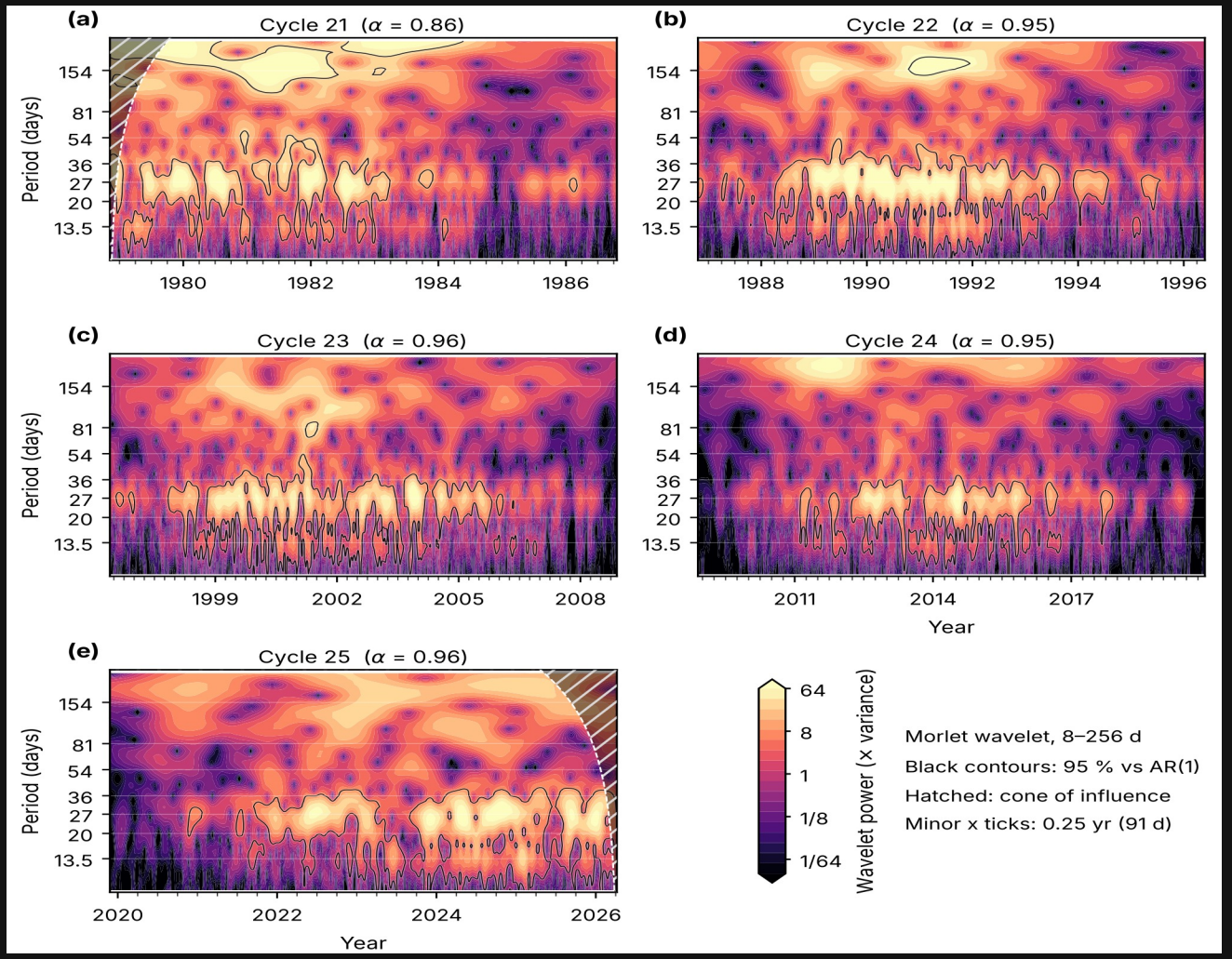
Do ARs tend to occur at 180 degrees separation?

Decomposition of a non-sinusoidal periodic waveform contains power at the harmonics of its fundamental period, so a ~27-day AR modulation generates power near its second harmonic (13.5 days), independent of whether any two active regions are actually separated by 180 degrees in longitude



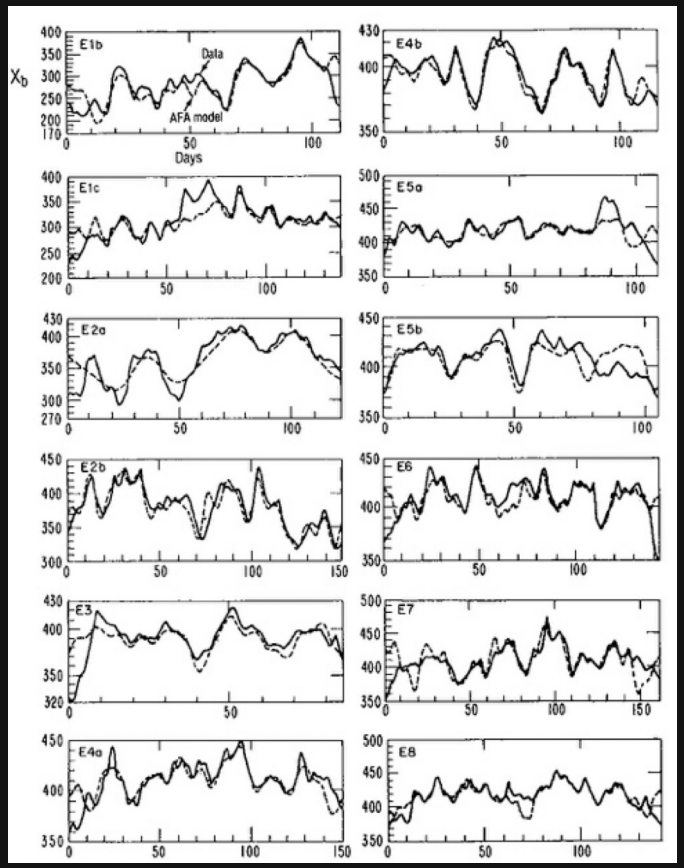
Mg II Wavelet Analysis

- Shows quasi-stationarity
  - 20-36d periods
  - ITEs ~80-190 Days
  - **Mean ITE = 128d**



Intermediate Term Epochs (ITE)

- Cycle 21 background rays (AFA, Bouwer, JGR 1983)
- Quasi-Stationary periodicities
- 4-5 Rotations
- **128-day average**



ARFIRS

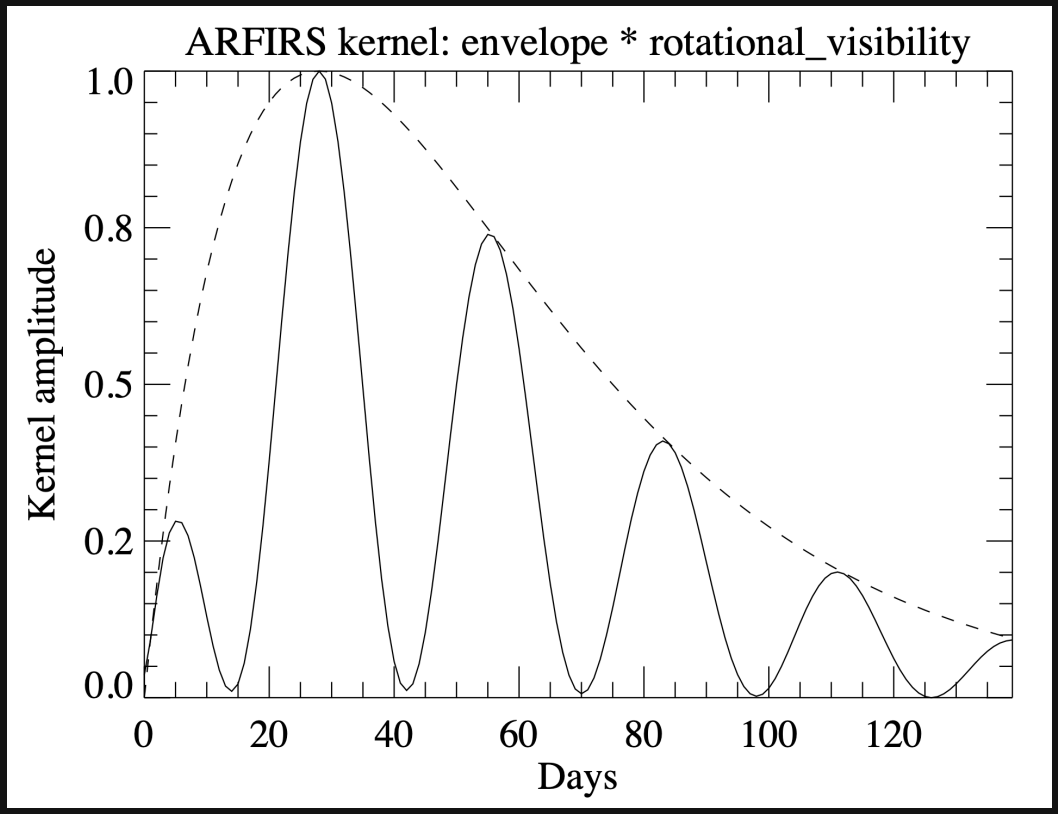
Active Region Finite Impulse Response Sinusoidal Model

A convolution of AR evolution, rotation, visibility

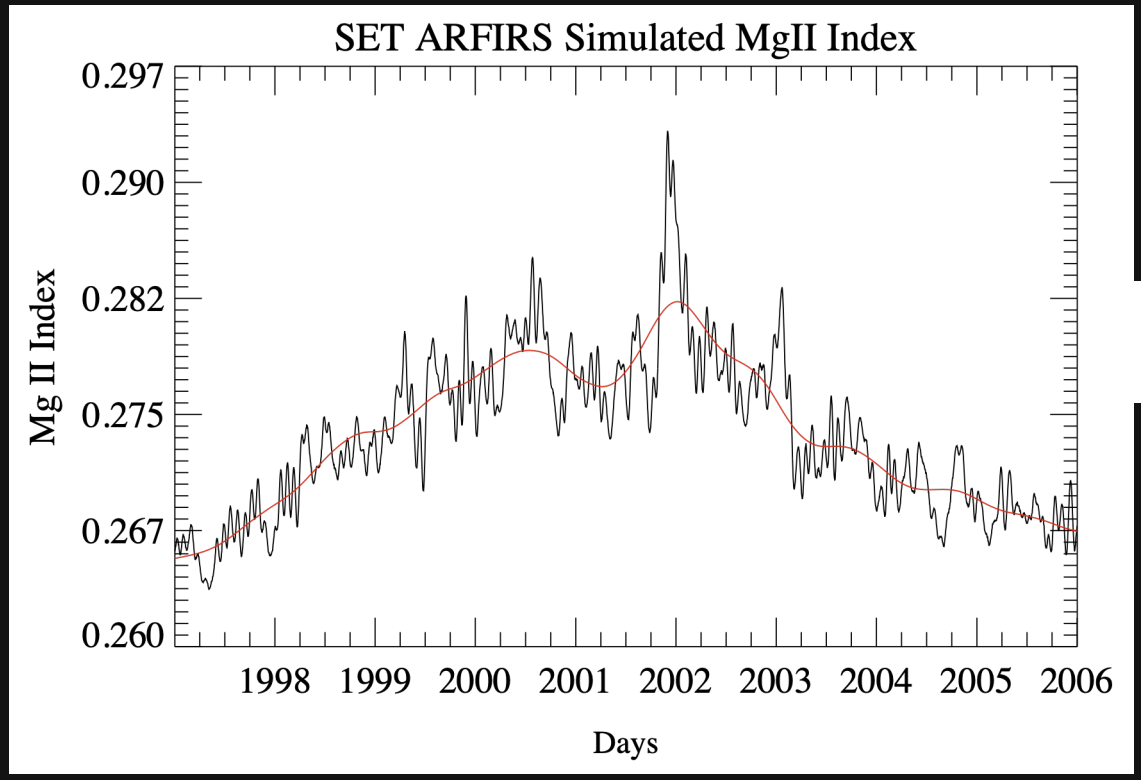
$$E_{ij}(u) = A_{ij}\left(\frac{u}{P_i}\right)^{n_i} exp\left[\frac{P_i - u}{\tau_i}\right]$$

$$R(\theta) = \tfrac{1}{2}(1 + \cos\theta) = \cos^2\left(\tfrac{\theta}{2}\right)$$

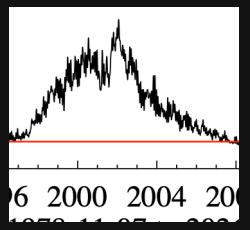
- Xb10 reaches peak within 1st Rotation
- UV/EUV reaches peak about 1 rotation later
- AR tends to last 3-6 rotations



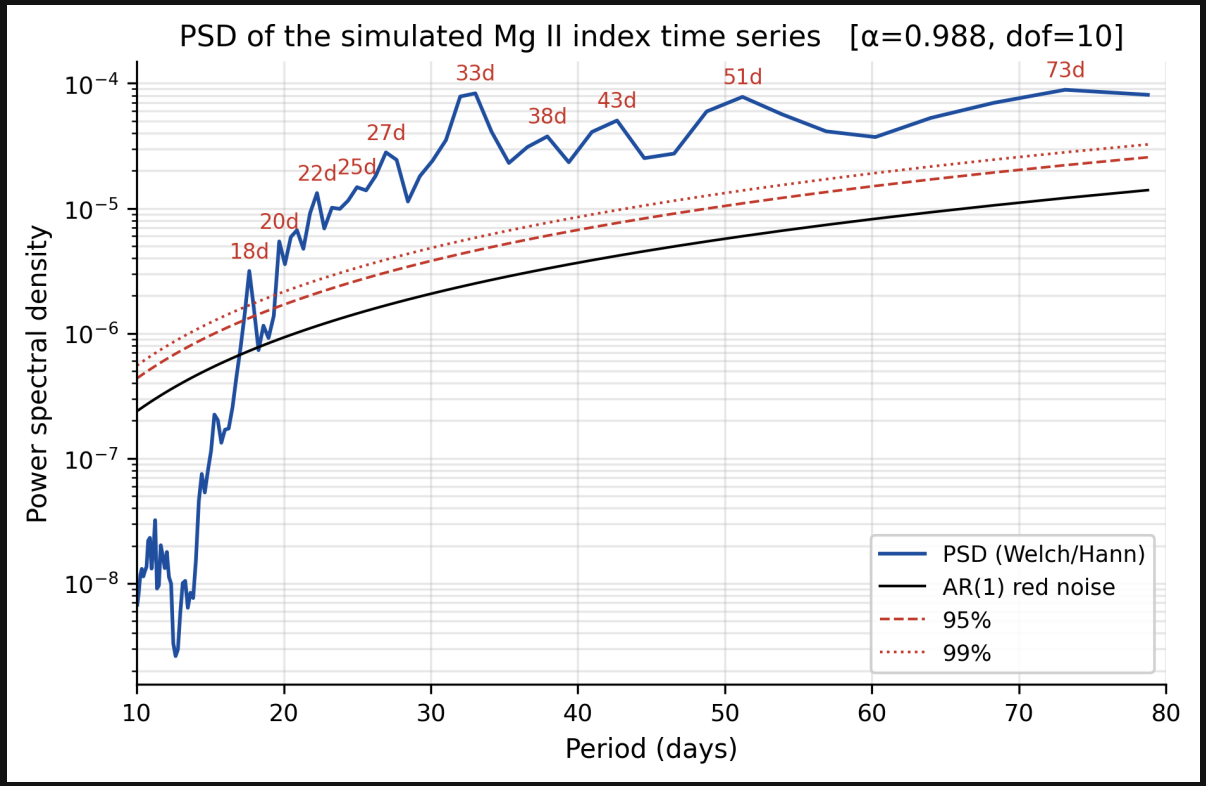
Mg II Simulation

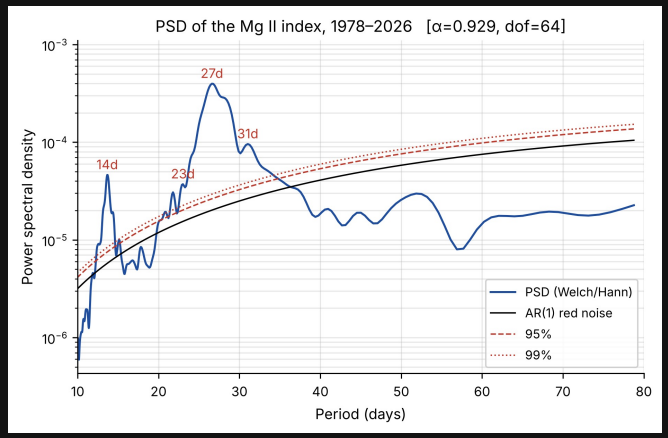


P_i days	A_i	τ_i	L_i	N_i/yr
29	0.0120	32	110	12
28	0.0278	36	137	18
27.3	0.0020	34	164	22



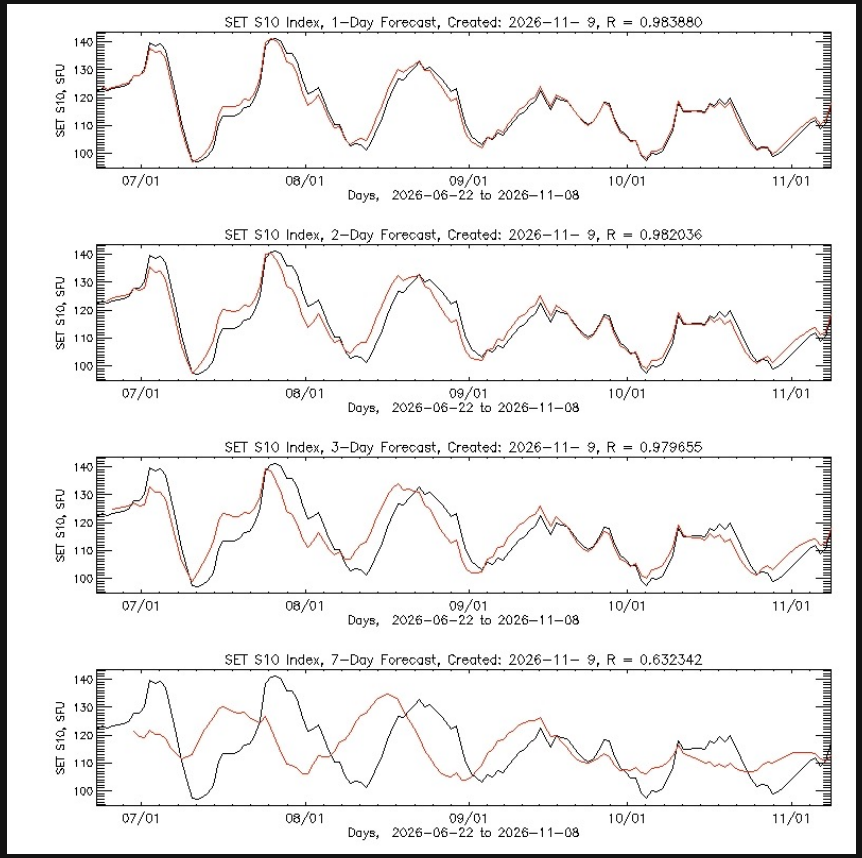
Simulation PSD





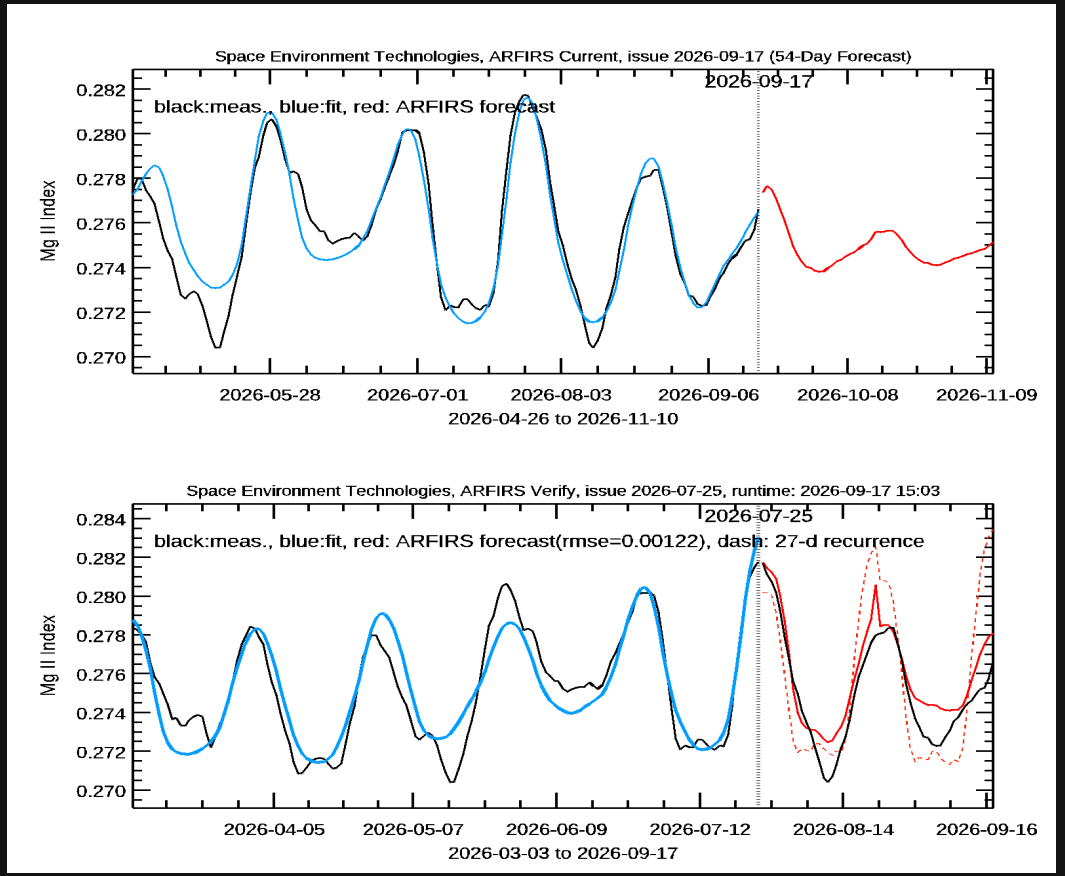
Forecasting

- EUV autoregressive forecasts breakdown after just a few days
  - Multiple ARs result in phase inaccuracies



Forecasting Mg II

- Combining what is known about AR evolution and rotation:
- Modify ARFIRS:
  - Sharpen sinusoid for CMP
  - Apply 27-day Hann filter to approximate longitudinal spreading of AR & plages
  - Use OMP/NNLS to iteratively find active regions
    - Vary envelope tau
    - Vary AR lifetime
    - Vary rot. period (26-29d)
  - Blend with Xb10, recurrence
  - Blend with Auto.Reg. days 1-6.

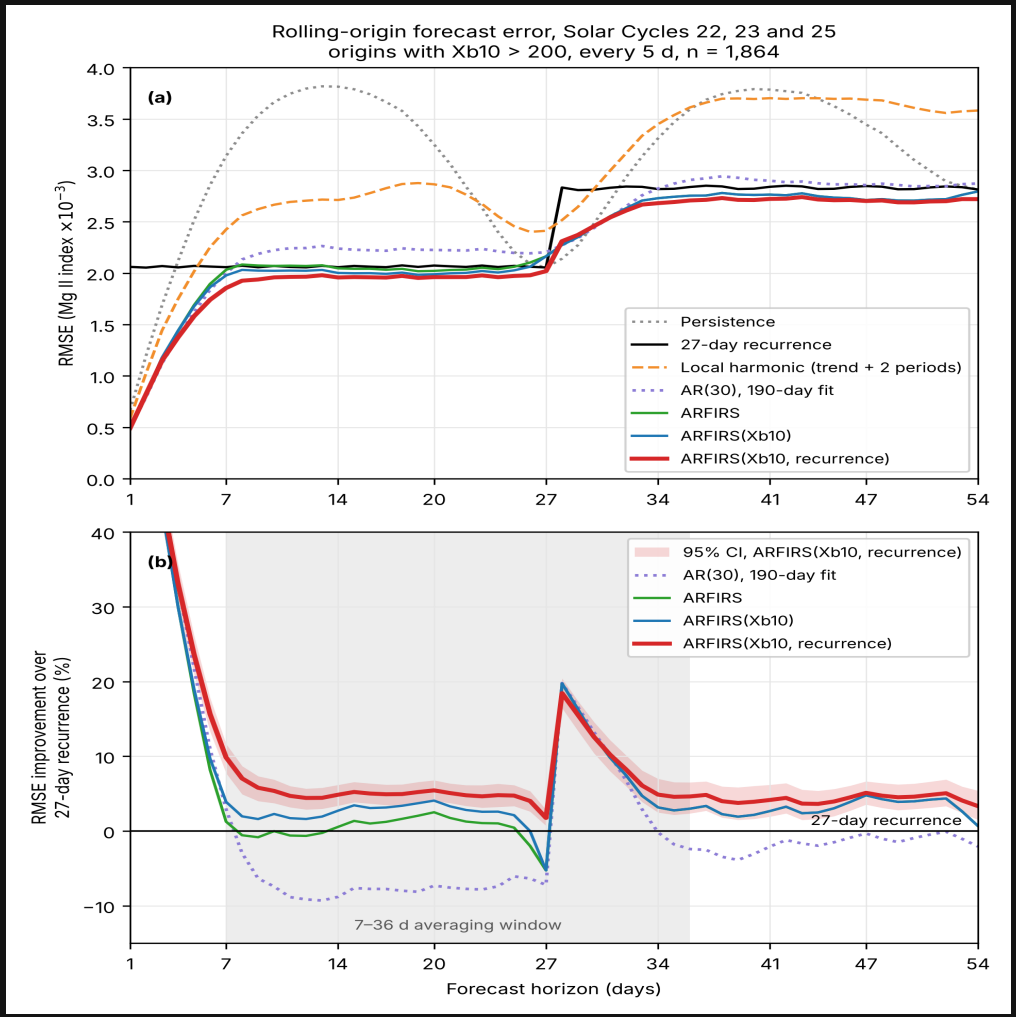


ARFIRS Forecast Skill

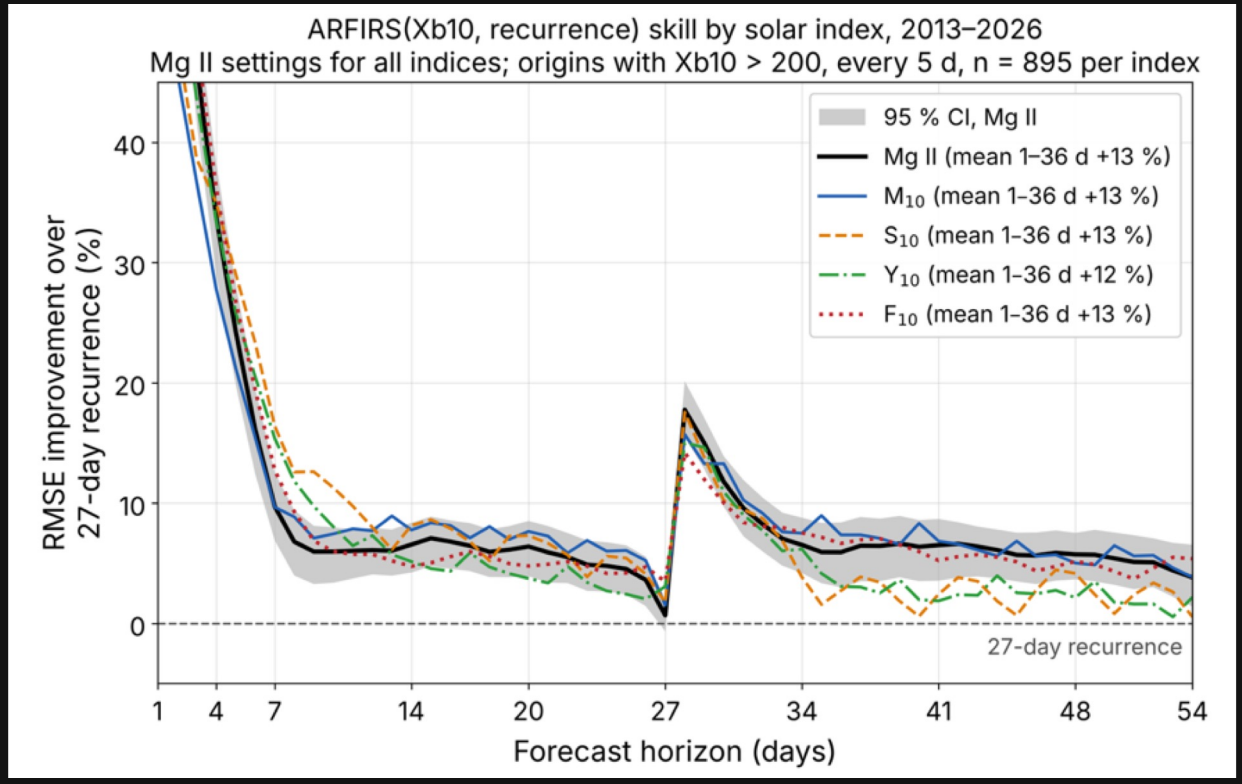
- Out-performs Persistence, Harmonic, AR(30), Recurrence *
- ARFIRS alone marginal performance
- ARFIRS(Xb10, 1-7d blend) improves RMSE
- ARFIRS(Xb10, recur.) reduces mean error vs recurrence 7% over 7-36 days

- Future work:
  - Emergence of new ARs on farside
  - Multiple ARs in AR “nests”
  - Dispersion of ARs into plage & network

*At 27d recur., persist. = last value

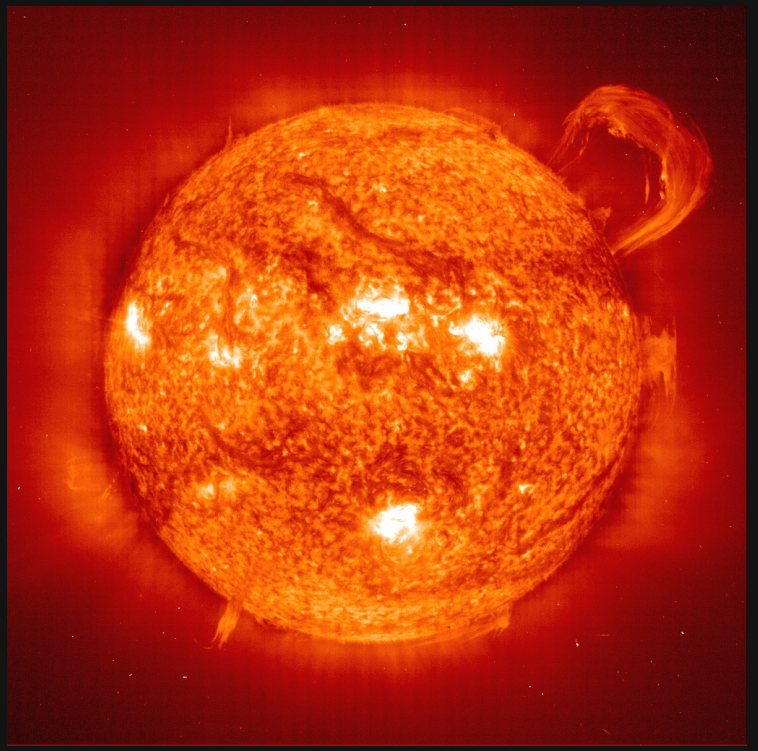


ARFIRS Applied to HASDM/JB08 Indices



Conclusion

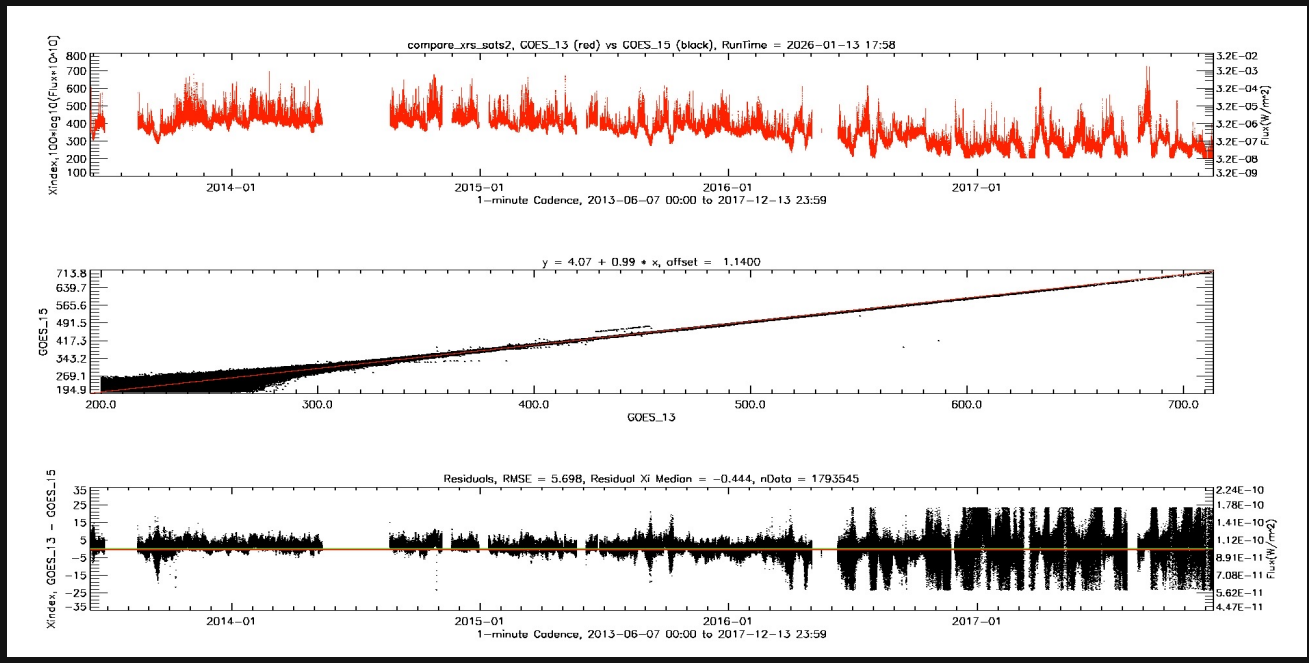
- Chromosphere/Transition Region/Corona have unique irradiance properties
- Active regions dominate solar irradiance variability
- The Mg II c/w ratio is an excellent proxy for UV/EUV irradiances
- Historical/Operational data present statistical challenges
- Solar variability is quasi-stationary over intermediate-term epochs ranging from 80 to 190 days
- An active region model coupled with rotational variations suggests forecasting up to two solar rotations is possible, with significant applications to thermospheric densities and satellite drag



Suplemental slides

Solar Indices Time Series Analysis

- Operational Challenges
- Stationary and Quasi-stationary
- Hazards in statistics
- Fourier transform & Power Spectra Density (PSD)



1995-2026 Data

https://spacewx.com ->Library -> Publications -> Tech. Reports -> SET_TR-2026-03_Tech_Memo_GOES_Xrays.pdf

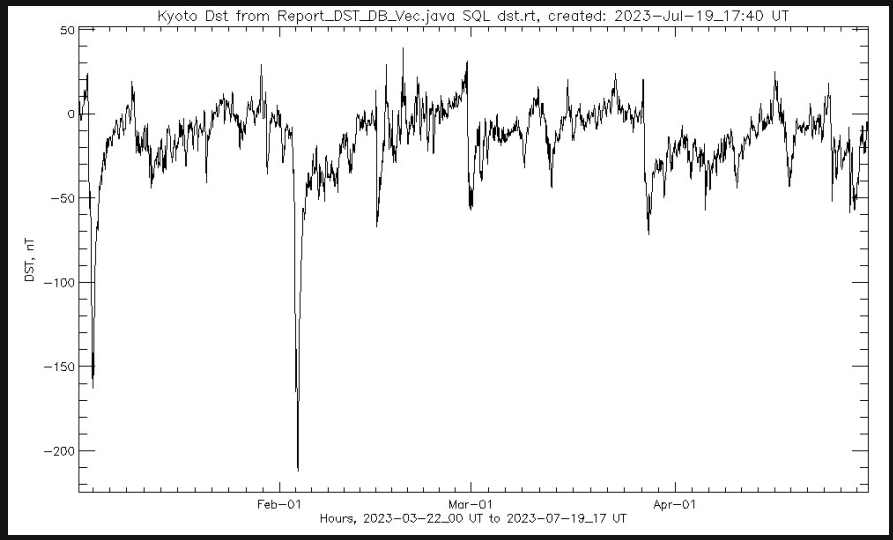
Stochastic vs Deterministic Processes

- Stochastic
  - Random: white/red noise
    - Solar flares, AR emergence, onset of geomagnetic storms
  - Individual events unpredictable
- Deterministic
  - Predictable, given initial conditions
    - e.g., Thermospheric density driven by a stochastic sun

- **White noise:** a random sequence in which each value is independent of all the others, so its power is spread evenly over all frequencies.
- **Red noise:** a random sequence in which each value is correlated with the one before it ($x(t) = \phi\, x(t-1) + \text{noise}$), so its power is concentrated at low (periodic) frequencies

Hazards in Time Series Statistics

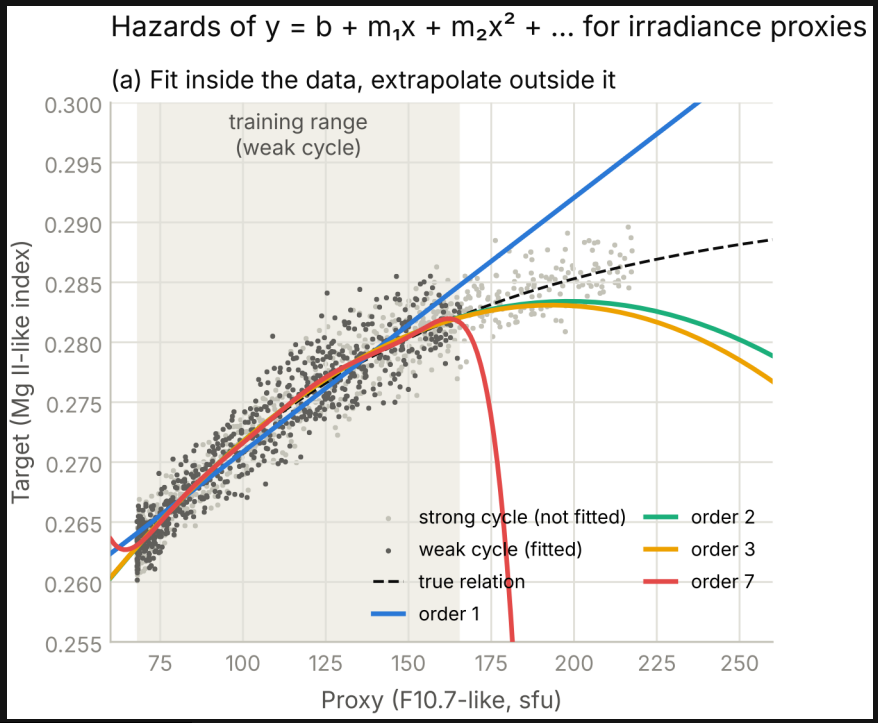
- Mean vs. median
  - If E. Musk walks into a homeless shelter, what is the average annual income?
- The hazards of y = mx + b (or y = mx +mx^2 + b or y = mx + mx^2 + mx^3 ... etc)
- Interpolating
- FFT/PSD harmonics



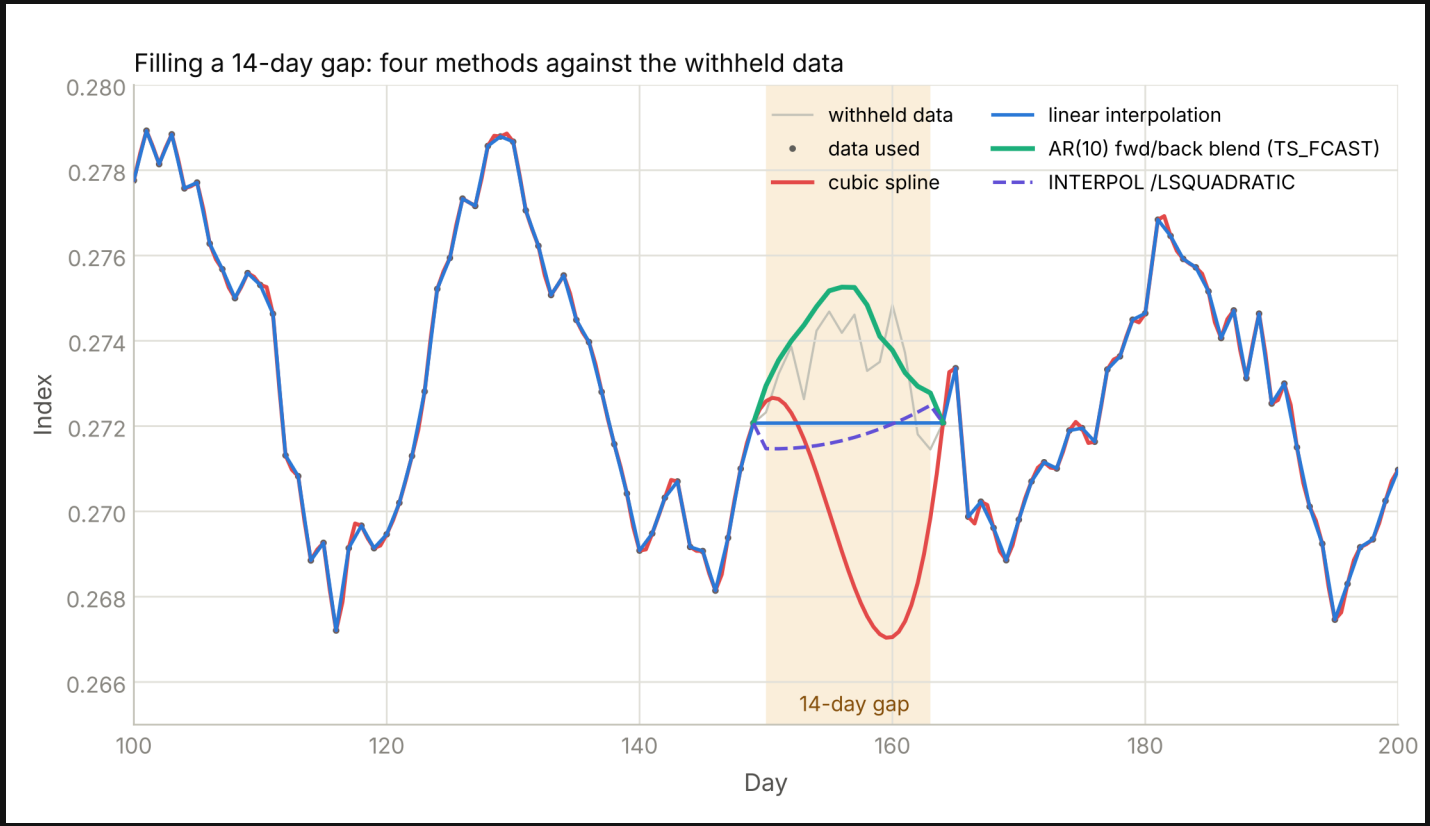
Autoregressive fitting & prediction

The hazards of y = mx + b (or y = mx +mx^2 + b1 + b2, or y = mx + mx^2 + mx^3 ..., etc.

Adding more terms to an autoregressive function does not improve prediction skill



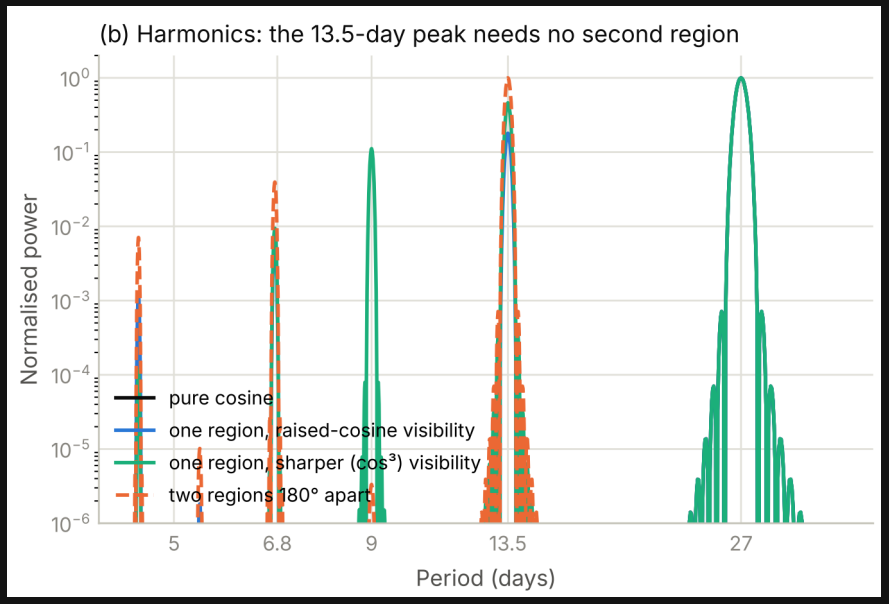
Interpolations

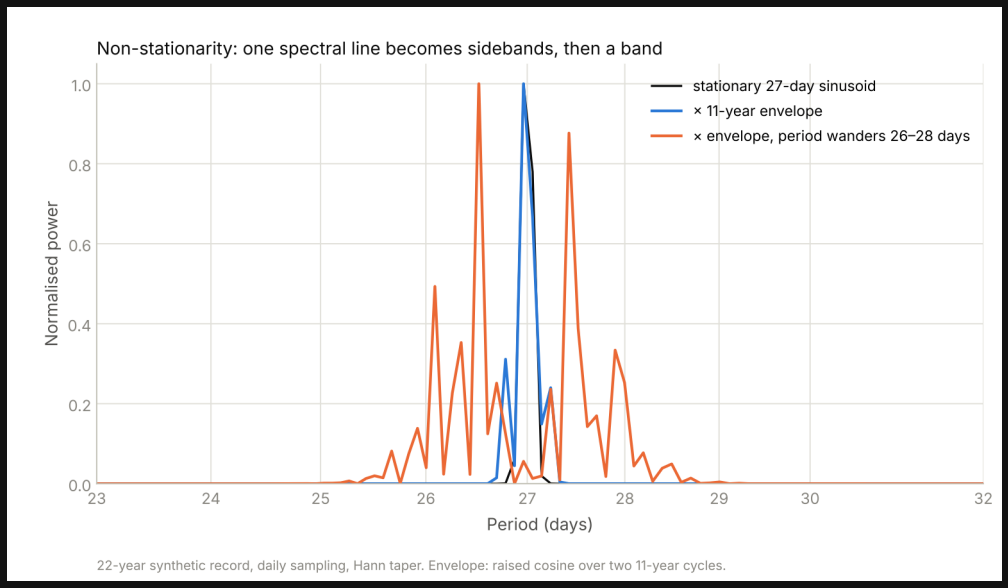


Evaluating solar periods

Fourier Transforms (FFT & PSD)

Periodicities can mislead

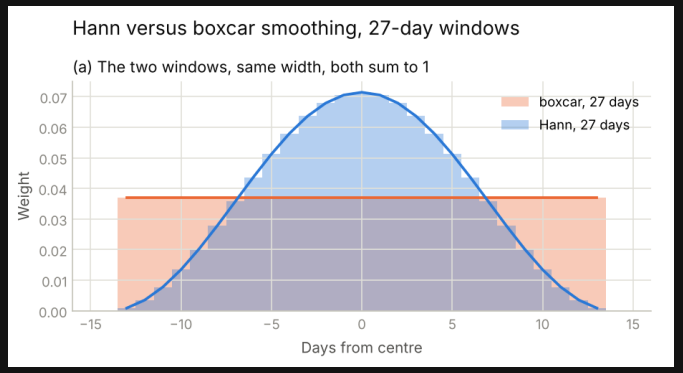


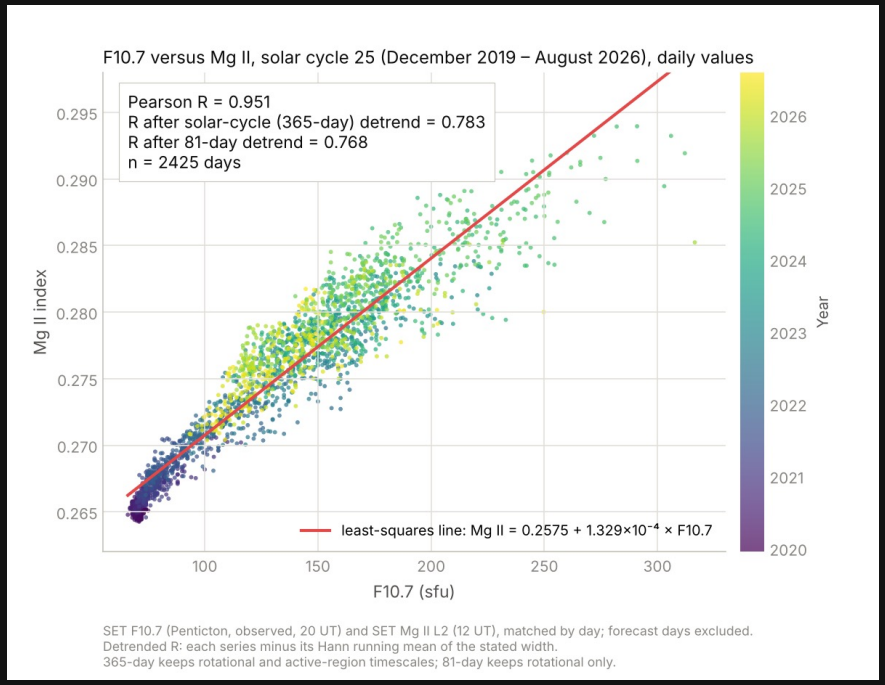


RMSE & Correlation Coefficients

RSR: The RMSE of the model residual / std. dev. of observation:
RSR of 27-day Hann filtered Mg II vs F10 = 0.21 (SS), = 0.56 (Rot. Band)

Hanning Filter vs. Boxcar averaging: its tapered endpoints suppress sidelobe leakage from adjacent frequencies





Introduction: “Space Weather”

Solar-Terrestrial Geophysics



- The Sun’s 11-yr solar cycle & solar rotation
  - ***UV/EUV/X-rays Irradiance***
  - (Solar Wind: geomagnetic disturbances)
  - Nearly all irradiances (W/m^2,must be measured from satellites
- Operations: NOAA SWPC (swpc.noaa.gov)
- Data: NCEI (ncei.noaa.gov)
- Space weather data providers, modelers
  - ~20 regional,
  - ~50 institutes,
  - ~100 Research: NASA/ESA/LASP/CCMC/Bre*men, etc.(SDO, ACE, TIMED, GOME)
  - ~10 commercial (spacewx.com:SOLAR2000, HASDM / JB2008)
  - Most rely heavily on NOAA/SWPC &NASA
- NOAA/SWPC Space Weather Workshop, 582 attendees in 2026



Thermosphere

