The Solar Wind over the Last Five Sunspot Cycles and The Sunspot Cycle over the Last Three Centuries

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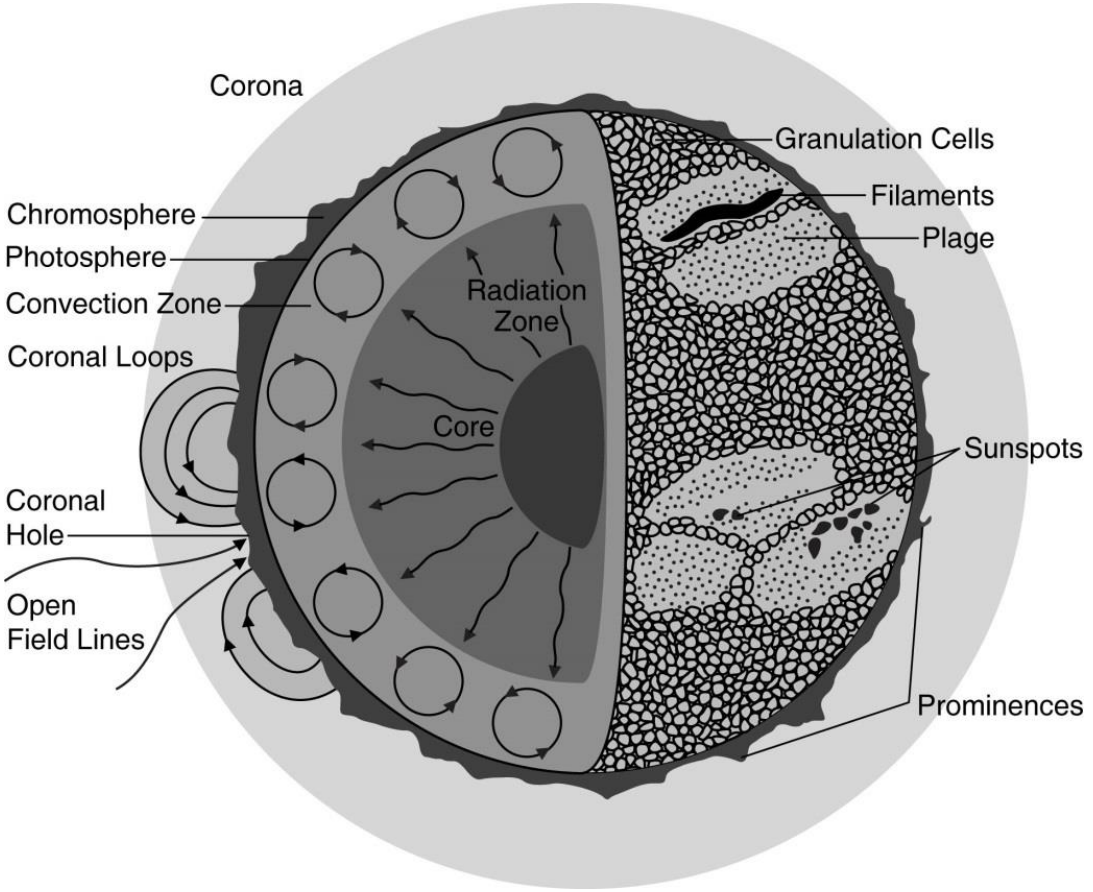
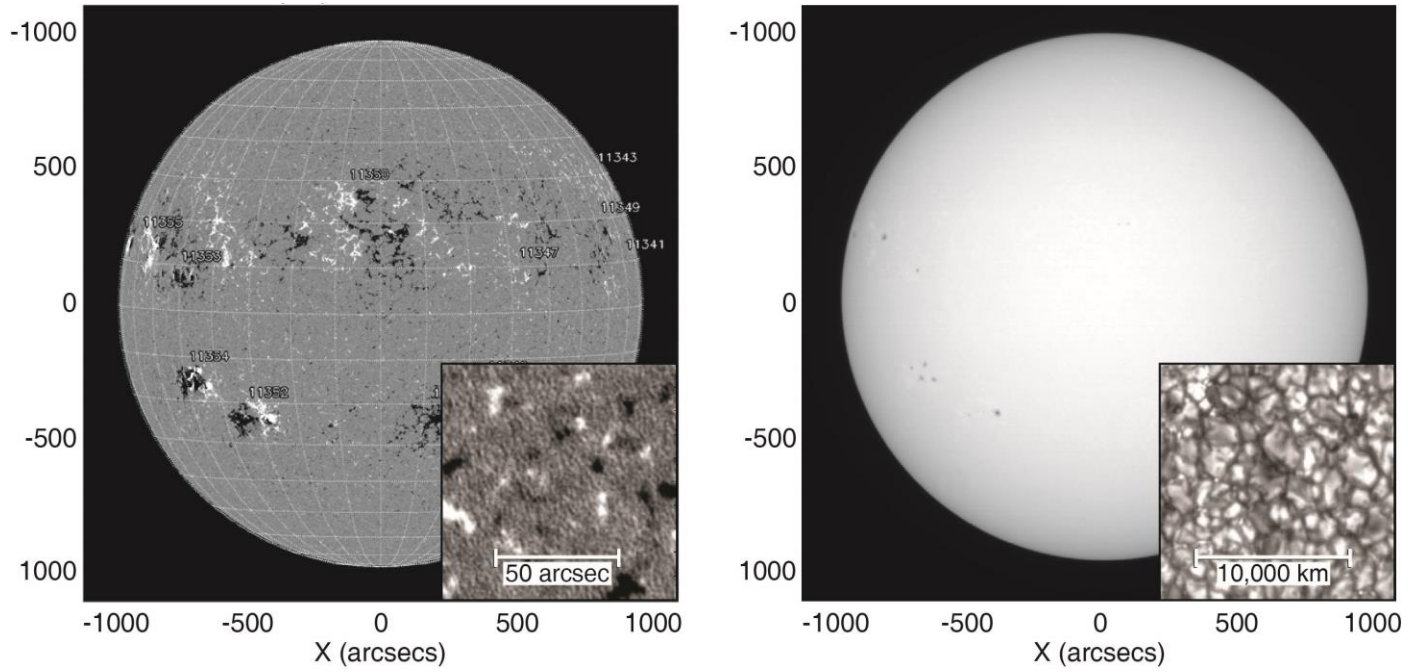
The Sun

- The interior of the Sun contains a core where fusion produces ^{4}He from ^{1}H and releases energy.
- This energy radiates upwards until it is more efficient to transport heat by convection.
- The core and the radiation zone change slowly, but the convection zone can evolve much more rapidly and irregularly.
- The combination of convection and rotation leads to the generation of a global magnetic field that reverses about every 11 years.



The Magnetic Sun and the Visible Sun

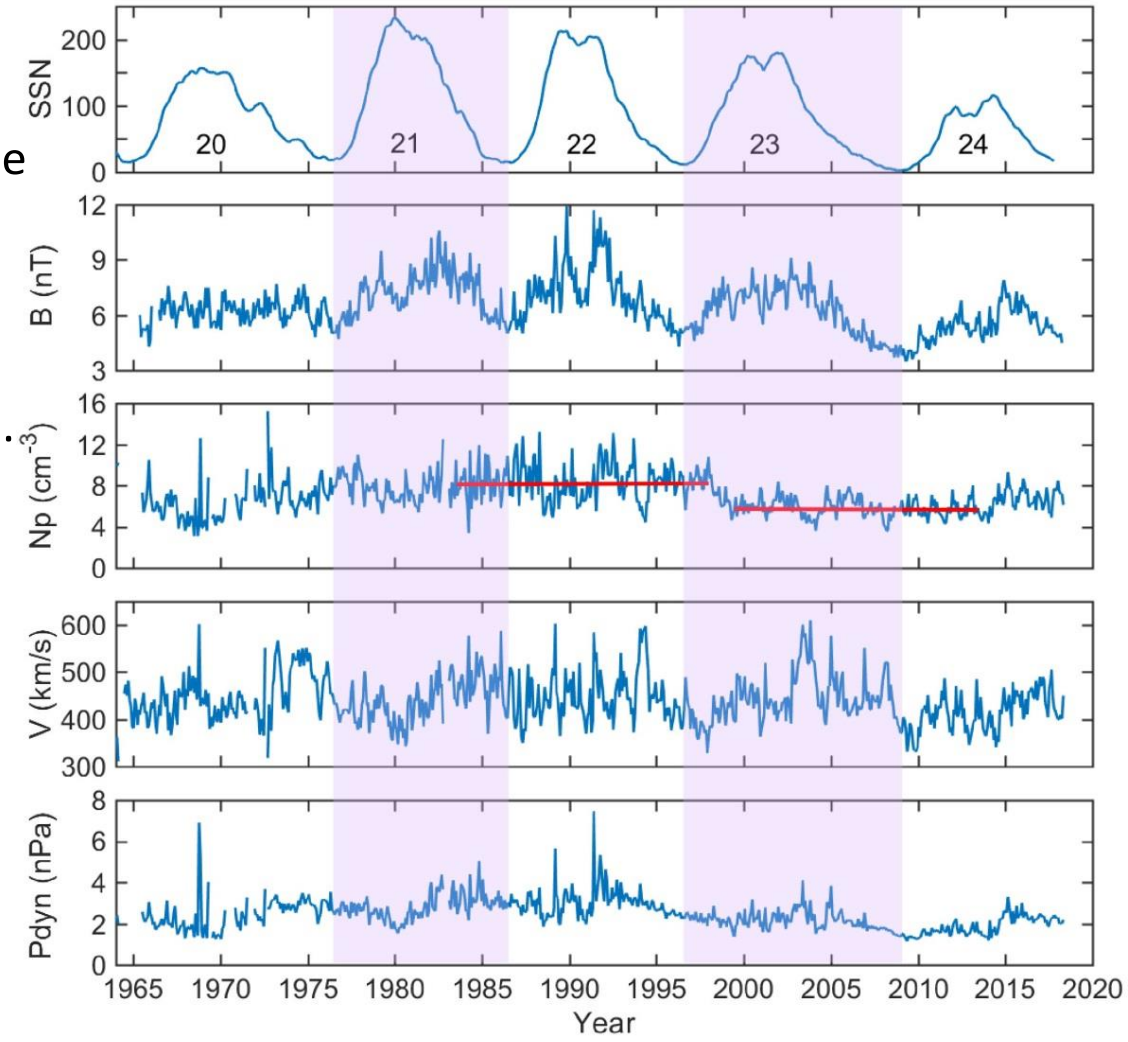


Yes, also from Space Physics: An Introduction

- Convection brings magnetic flux to the surface of the Sun and the solar wind transports the magnetic field through the heliosphere.
- The magnetic and visible suns look different. Sunspots form only when the magnetic field becomes quite strong. So the absence of sunspots does not mean that the solar wind has stopped or even weakened.
- So a good question to ask is:
  - How does the solar wind vary over the cycle?
- We have 5 solar cycles over which to examine this question.

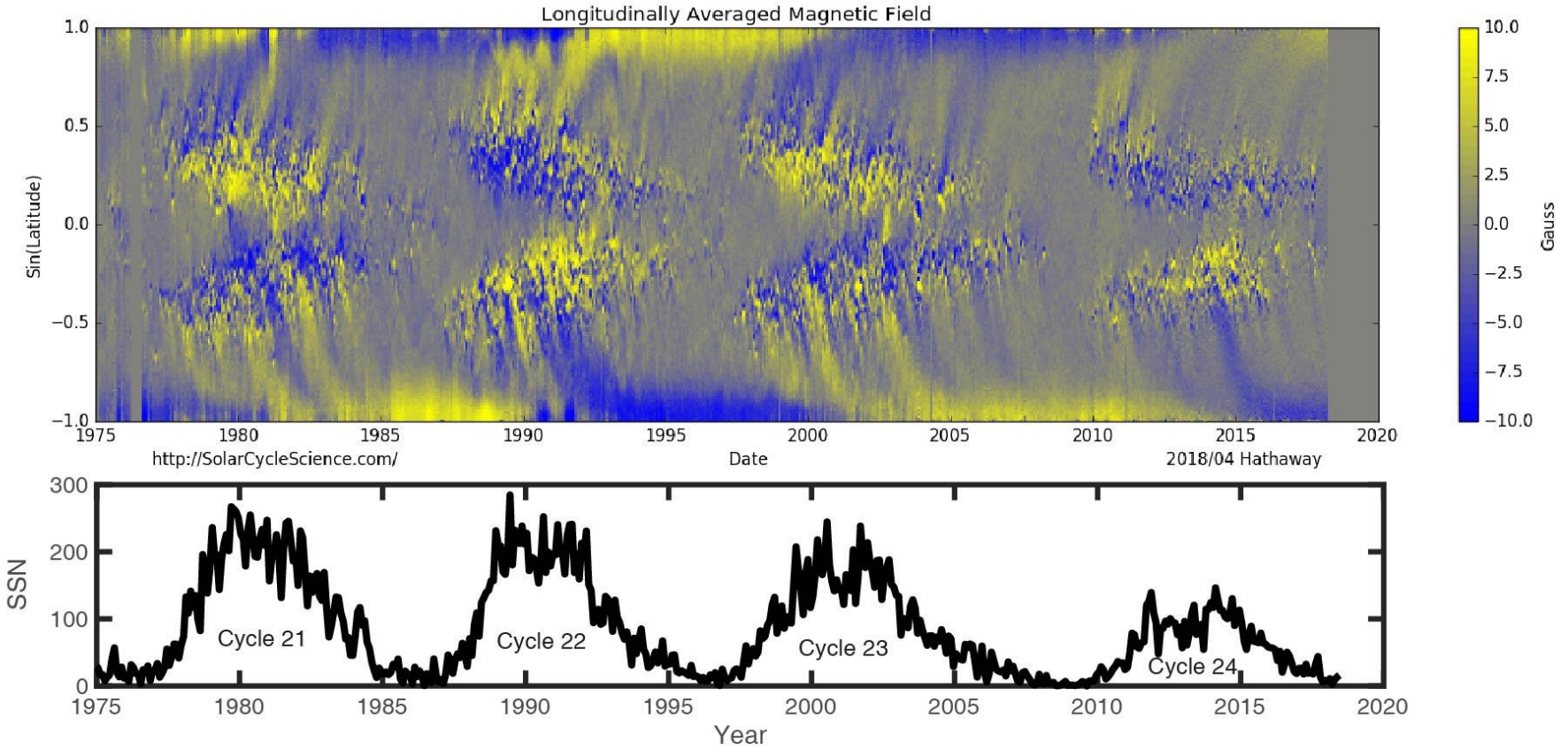
Variation of the Solar Wind with the Sunspot Cycle

- Inhabitants of Earth are most interested in the strength and orientation of the magnetic field that the solar wind carries from the photosphere to 1 AU.
- There is not a one-to-one correlation between the IMF magnitude and the sunspot number, but they do vary in phase. However, look at the lack of correlation in SPC 20.
- The number density of the solar wind is even less tied to the sunspot number. It seems to have had step changes in the declining phases of SC21 and in the rising phase of SC23.
- The solar wind speed seems to be only slightly correlated with sunspot number.



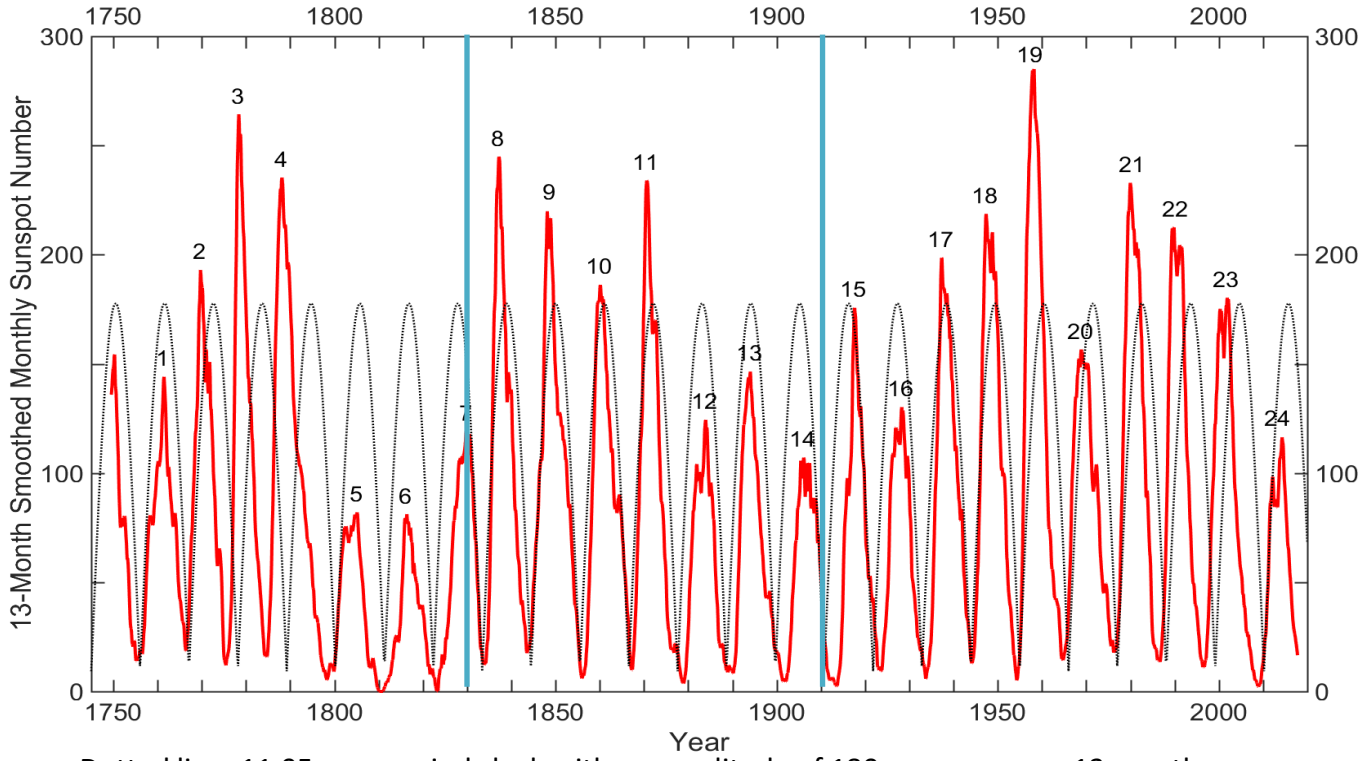
- Surprisingly, when you put the velocity and density together as dynamic pressure, a solar cycle pattern appears, as well as a long-term variation when the modulation weakens in cycles 23 and 24. Largely what happened is that stream interactions weakened.

The 22-year Magnetic Cycle of the Photosphere



- If we examine how the field in the photosphere evolved over the last 5 solar cycles, we see "motion" of the sunspots to the low latitudes and motion of the flux to the poles.
- In the present solar cycle, the flux in the polar regions is quite weak.
- We do not see this region as clearly as we should from our location in the ecliptic plane. We need to put magnetographs at high latitude.
- We need more data to study this long-term behavior. The only long-term data we have is the sunspot record. Can we learn anything useful from the time series of sunspot numbers?

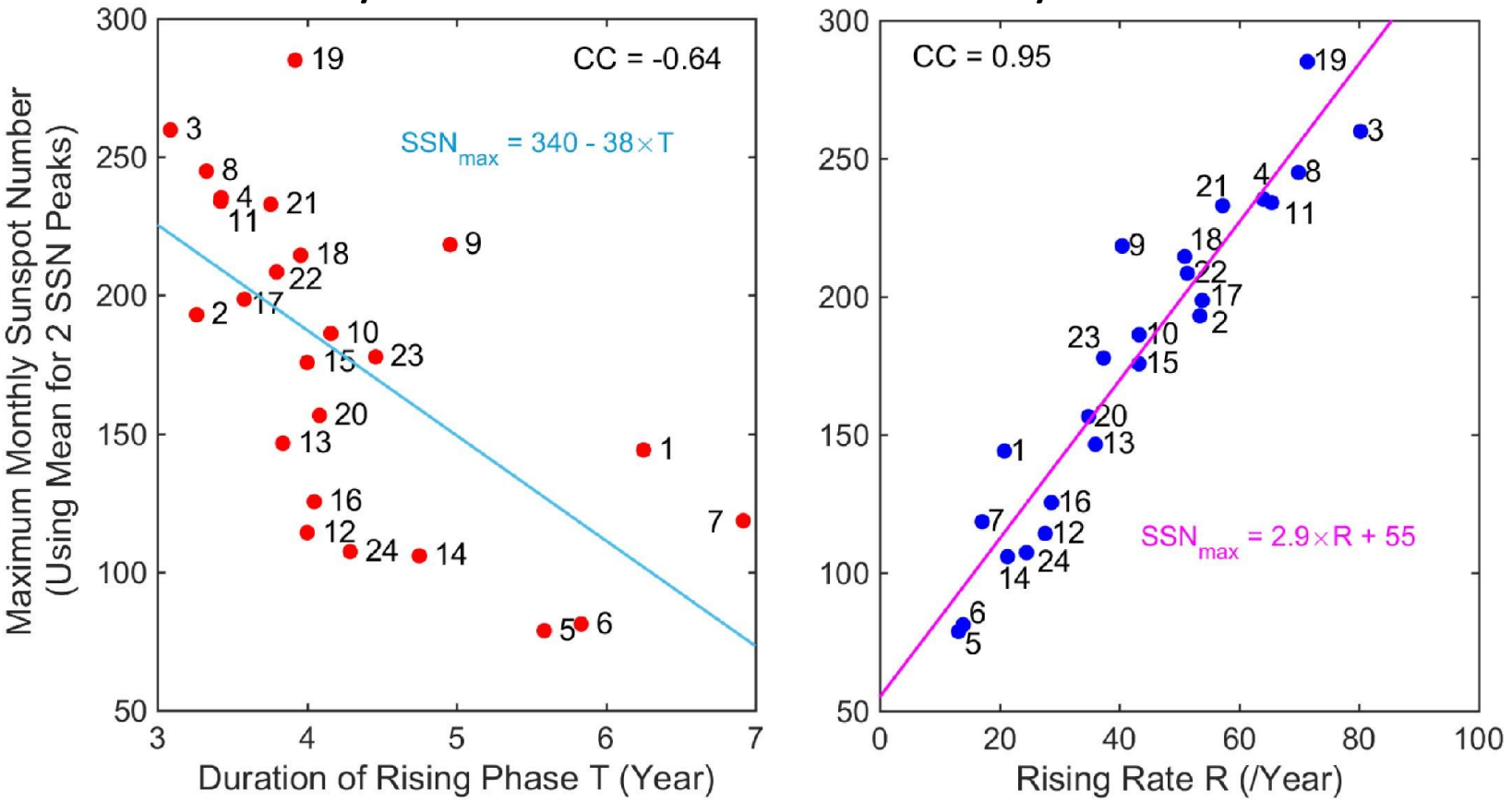
Twenty-four Sunspot Cycles on a 11.05yr Period Clock



Dotted line: 11.05-year period clock with an amplitude of 180 averages over 13 months

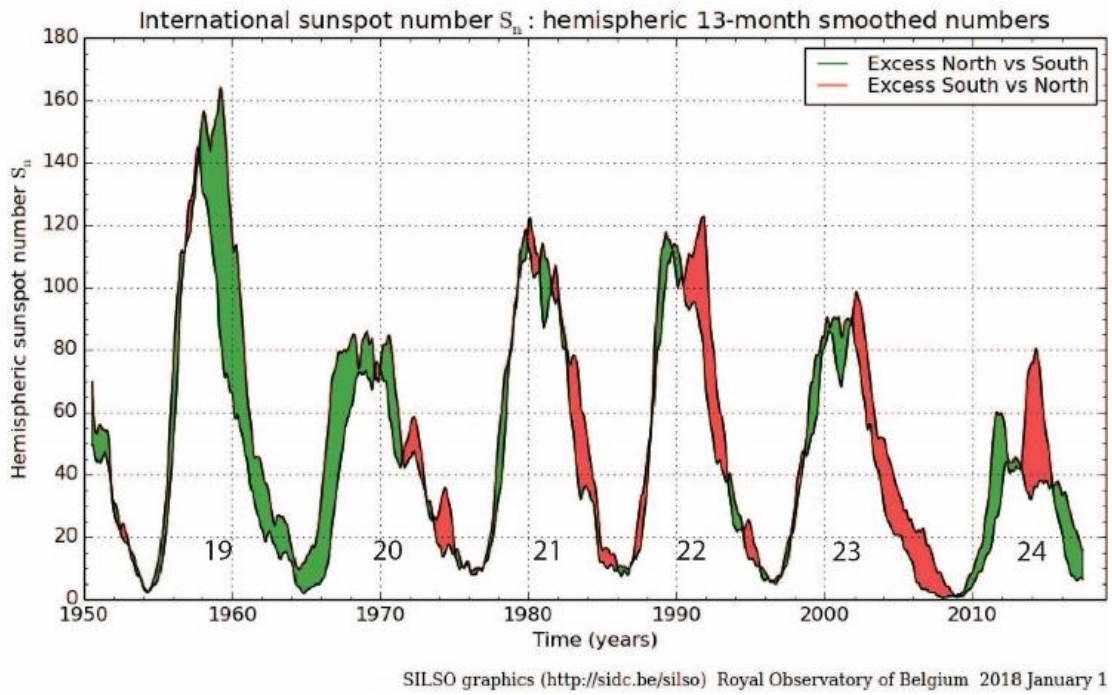
- What can we learn about the solar dynamo from these data? Is there a hope of understanding the behavior of the photosphere and possibly the solar wind over a much longer period from these data?
- My first introduction to this possibility was work that co-author Barbara Bromage showed at a conference late in sunspot cycle 23. We need to examine both the amplitude of the cycles and the phase of the cycles.
- Here we divide the time series into three segments with similar behavior.
  - Strong cycles develop a phase lead that builds up until the phase recovers in later weak cycles.
  - I divided the cycles into three groups in which the behavior occurs. We note that the modulation is not strongly periodic.
  - The phase lead builds up during strong activity and returns to “normal” during low activity.

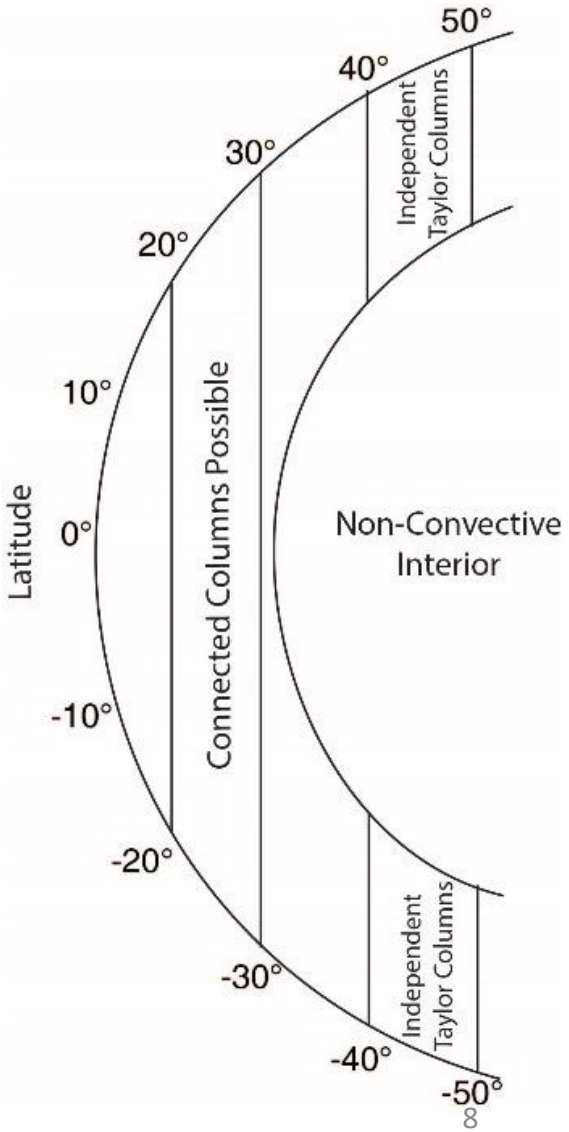
Are the Solar Cycle Maxima and the Solar Cycle Duration Linked?



- There is a weak inverse correlation between the duration of rising phase and the maximum SSN.
- However, if you plot the rate rise of sunspot numbers per year, you get a nearly perfect correlation. There is a minimum value of 55 sunspots each solar maximum and then a cycle-dependent rising rate for some duration.
- The rising phase of solar cycles does hold information for the present and for the subsequent sunspot cycle.

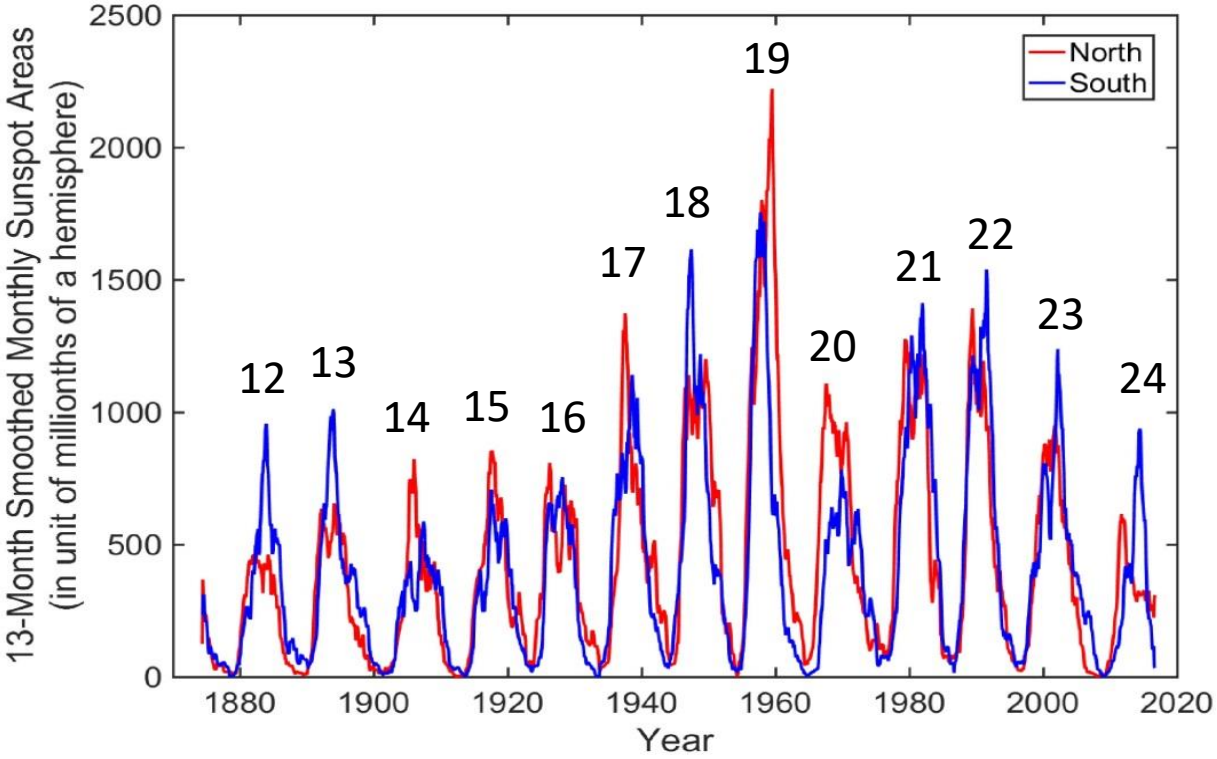
The Independence of Two Hemispheres





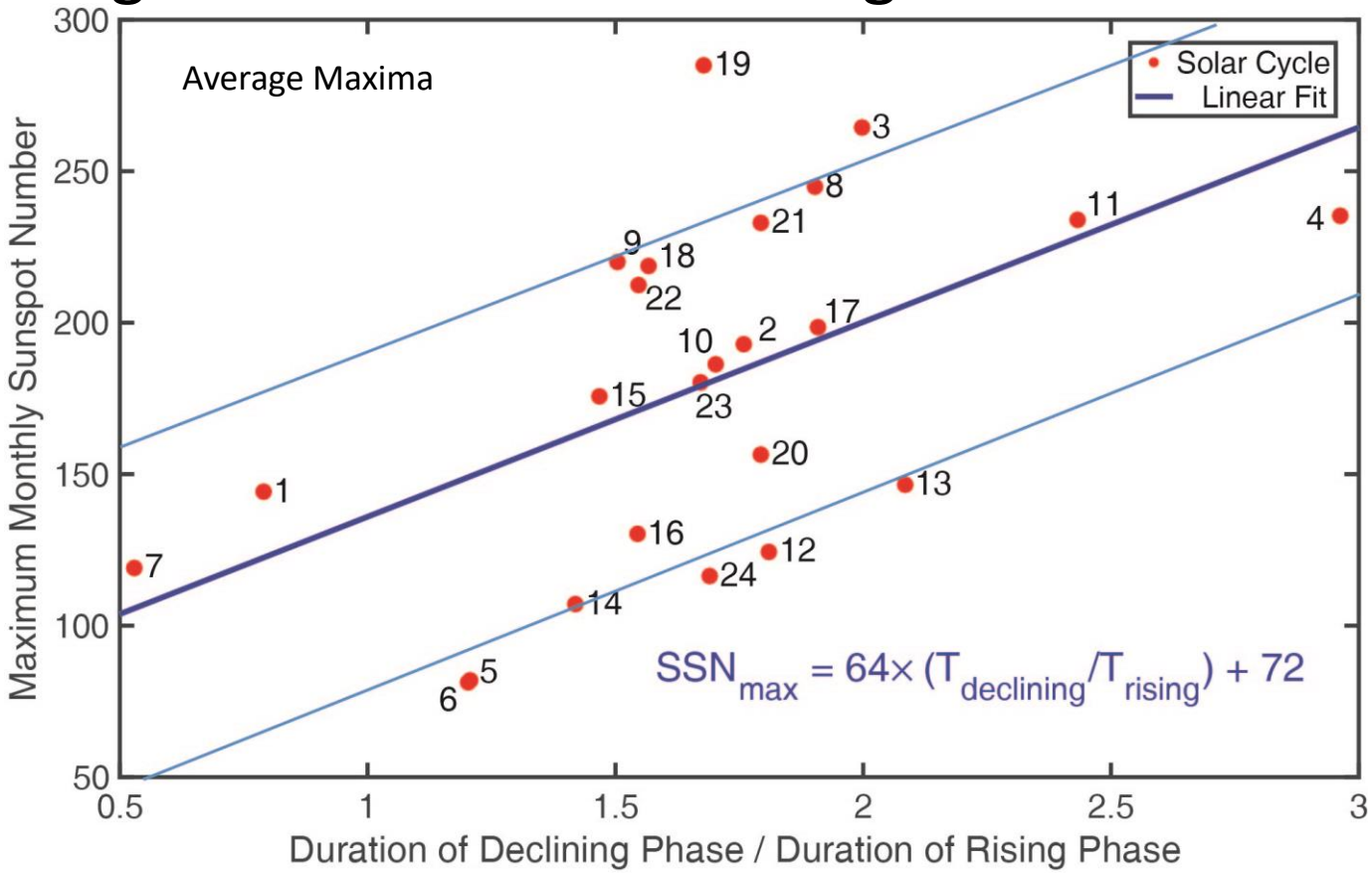
- The two hemispheres of the Sun produce sunspots with different polarities so we can easily distinguish them.
- How different are they? They certainly can peak at different times, but they seem to have very similar rise and fall times.
- Perhaps the delivery of the new magnetic flux in the new cycle may differ from north to south, but the delivery system seems to be working at the same rate in the two hemispheres.

Sunspot Areas: North and South Separately



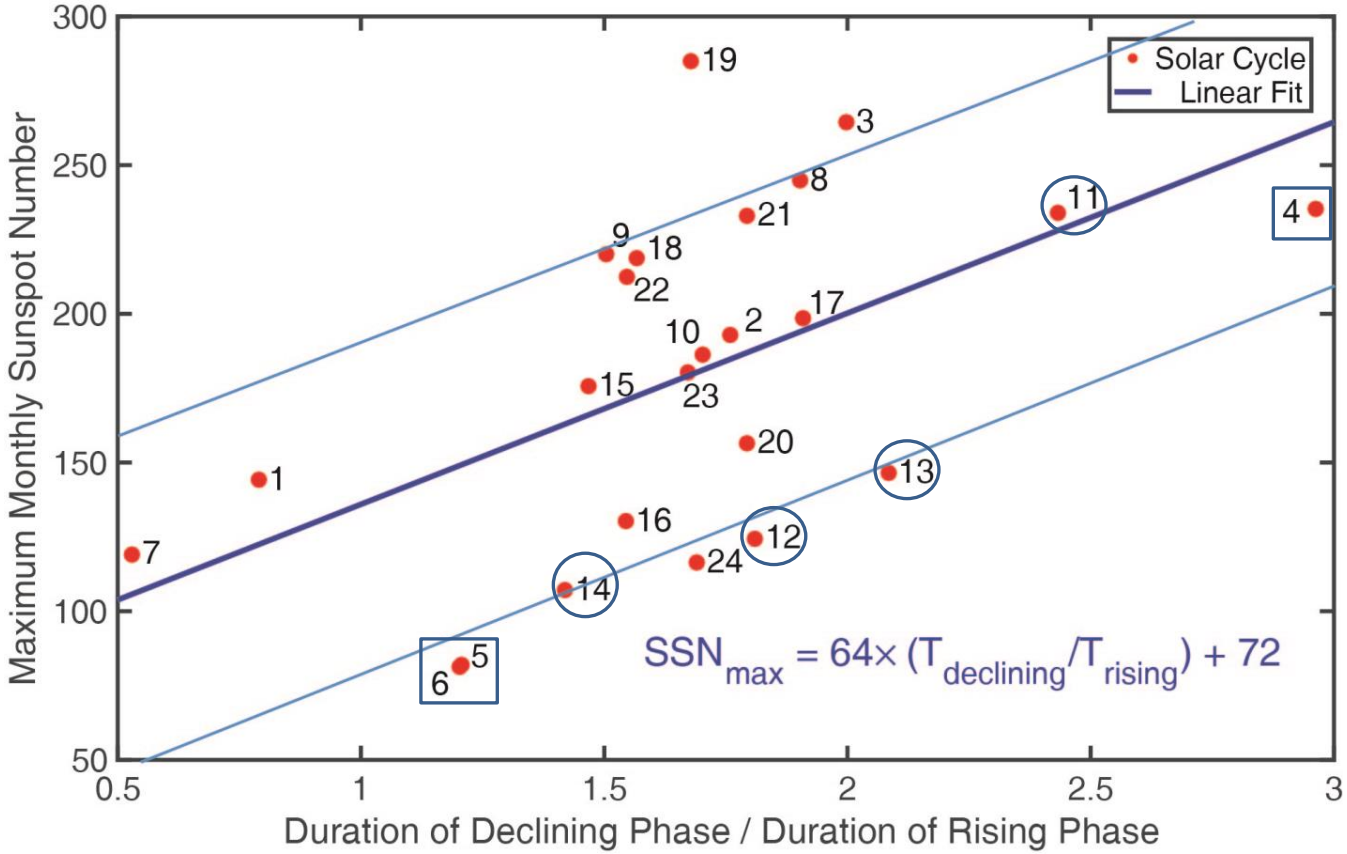
- This shows the smoothed sunspot area for north and south separately.
- The rise times and the fall times are about the same in the two hemispheres, but the timing and the peak values are different.
- The sunspot numbers and the sunspot areas divided by hemisphere tell the same story.

Correlation of Maximum SSN with Ratios of Declining Phase Duration to Rising Phase Duration (T_d/T_r)



- If transport of flux were variable and the magnetic flux available were fixed, then a more rapid transport of flux to the surface would produce a shorter rising phase and a larger maximum SSN.
- If the rate of return of flux to the interior did not increase or if it lessened, T_d/T_r would become larger.
- The correlation of T_d/T_r and the maximum SSN is good, consistent with a variable flux transport rate. However, there are clearly other factors governing activity.
- The thick line here is the best-fit correlation. The two thin lines are parallel but offset to represent subsets of higher and lower activity that appear to have a similar trend line to that of the full set.
- Used average time of maximum sunspot number to define rise and fall times.

Predictive Power of T_d/T_r



- If we examine T_d/T_r, we find that cycles 4 [square] and 11 (circle) had high ratios. They presumably brought much flux to the photosphere in a short period, producing high SSN.
- The following cycles 5 and 12 had a delayed start and low activity.
- The next cycles 6 as well as 13 and 14 also had low activity.
- The low maximum sunspot number of cycle 24 was not predicted by this ratio.
- The three trend lines suggest that the Sun has three different operational states, producing low, medium and high solar maximum field strengths. Cycle 19 and the Maunder minimum raise this to five states.

Summary

- The solar wind density does not change with the solar cycle. Still it can undergo significant changes and can maintain that change over more than one complete solar cycle.
- The interplanetary magnetic field is responsive to the sunspot cycle. The solar wind velocity changes, possibly due to the evolving magnetic structure.
- The sunspot number may peak in different parts of the solar cycle, but the rates of solar activity increase seem often to be similar (same slopes).
- The best predictor of the maximum sunspot number is the rate in rise of a new cycle.
- The duration of solar cycles is variable, causing the solar cycle phase to change relative to a fixed clock. This behavior may have both diagnostic and predictive power.
- The Sun returns to the phase of the constant clock and weak sunspot number maximum after a prolonged solar minimum.