Solar and Stellar Magnetic Fields: Origins and Manifestations
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A Clock in the Sun?

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Abstract. The sunspot cycle is quite variable in duration and amplitude, yet in the long term, it seems to return to solar minimum on schedule, as if guided by a clock with an average period of close to 11.05 years for the sunspot number cycle and 22.1 years for the magnetic cycle. This paper provides a brief review of the sunspot number cycle since 1750, discusses some of the processes controlling the solar dynamo, and provides clues that may add to our understanding of what controls the cadence of the solar clock.

Keywords. solar cycle, solar dynamo, sunspot number

1. Introduction

In the center of the Sun is a nuclear furnace that produces the heat that eventually radiates into space, producing a very habitable zone near 1 AU. The nuclear-fusion produced heat is radiated upward inside the Sun to about 0.7 solar radii, where convection contributes to the outward transport of the energy that is ultimately radiated into space. The rotation of the convection zone affects the circulation of its magnetized plasma. It enforces rotational columns of fluid similar to those that occur within a rotating sphere (Taylor 1922), but the presence of the magnetic field and the convection zone boundary introduce differences that are essential to the solar activity cycle.In particular, magnetic flux ropes produced near the bottom of the convection zone rise upward to pervade the convection zone, manifesting themselves on the surface of the Sun, as sunspots, active regions, coronal mass ejections, and a myriad of phenomena collectively known as solar activity. Figure 1a shows a cut-away drawing of the Sun's interior with an idealistic convection pattern, together with some of the related features that appear on the observed photosphere. Figure 1b shows a cross section of the Sun and contours of the period of the motion of plasma in the convection zone, here depicted as symmetric with respect to the solar rotation axis. This figure assumes that the rotation periods in the north and south are precisely identical, whereas, in fact, the sun often has two quite independent north and south hemispheres, especially in the regions above the poles. Helioseismology informs us of these motions, but only recently (Komm *et al.* 2018) has it been possible to separate the flow structure in the north and south, even though we know the north and south hemispheres can magnetically be quite different. Finally, Figure 1c shows the rotation period of the Sun versus radial distance. The core and the radiative zone are thought to share the same rotation period, but in the convection zone, this period becomes a function of latitude.

Two important phenomena associated with this circulation are manifested on the photosphere as distinctive surface features: the rush to the poles and the torsional oscillation. The global appearance of these, which arise from a combination of zonal and meridional flow features, are sketched in Figure 2a on the surface of the photosphere,

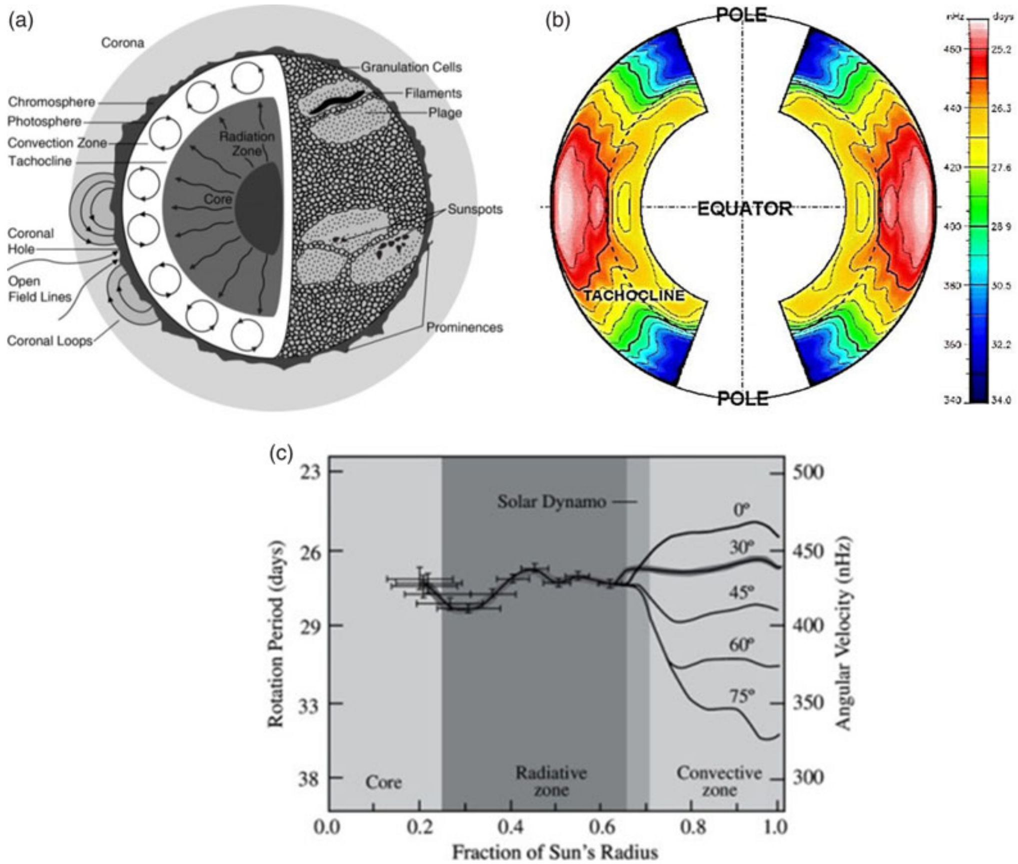

Figure 1. The structure of the Sun. The interior structure of the Sun is on the left, while the phenomena on the surface are shown on the right. Sunspots are seen equally in both hemispheres, but with opposite magnetic symmetries. Leading and trailing polarities are opposite in the two hemispheres and reverse every sunspot cycle (Russell *et al.* 2015). Internal structure of the Sun's rotation, showing the location of the tachocline where rigid rotation gives way to differential rotation throughout the convection zone. The color scales are for solar differential rotation frequency (nHz) and the corresponding rotation period (day). Figure is adapted from NASA MSFC (https://solarscience.msfc.nasa.gov/images/internal_rotation_mjt.jpg), based on the original results from helioseismology published by Thompson *et al.* (2003). Internal structure of the Sun's rotation, showing the rotation period as a function of radius at different latitudes. The latitude where the zonal velocity transitions from effective superrotation at low latitudes, to subrotation at mid and high latitudes, occurs at around 30 degrees. The torsional oscillation (see text) tends to initially appears around 55 degrees, while the associated surface magnetic activity appears with it after it has migrated to ∼30 degrees. The reasons for this behavior have yet to be determined. Courtesy of K.R. Lang, Tufts University (https://ase.tufts.edu/cosmos/print_images.asp?id=25). This figure is an adaptation of the original results from helioseismology published by the National Solar Observatory (NSF).

and 2b in the cross section, while Figures 2c and 2d show the surface manifestation of these motions over the double sunspot cycle, in a magnetogram and a zonal velocity-gram (from Kosovichev & Pipin 2019).

Figure 2e, showing the zonal velocity at two instants of time during the solar cycle, emphasizes that panel 2b does not show material motion to the pole or to the equator, but rather results from the location of bands of fast flows moving poleward and equatorward during the cycle. Figures 2c and 2d show that the solar magnetic cycle is

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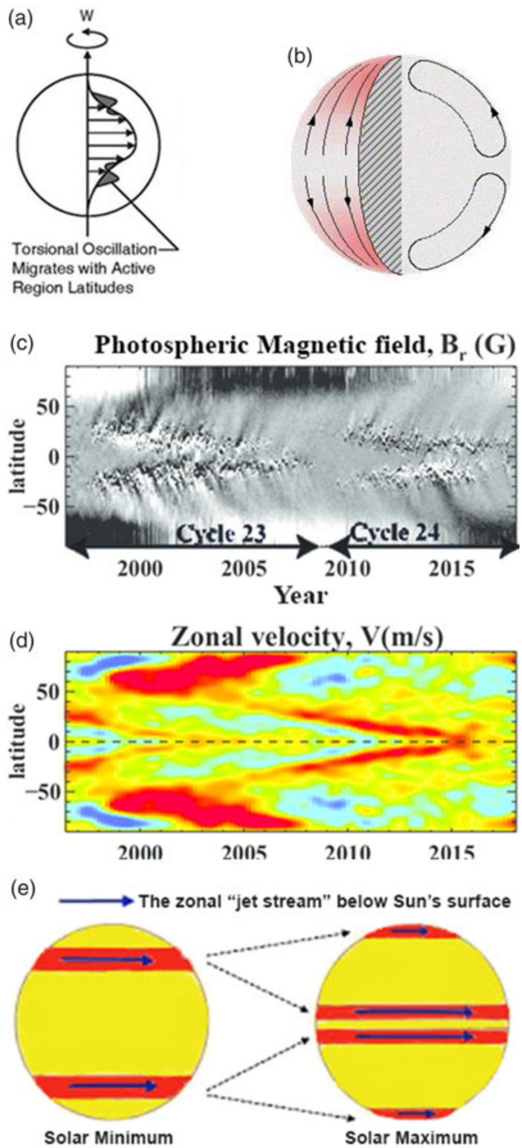

Figure 2. Illustrations of the torsional oscillations (top) and meridional circulation (bottom) described in the text. Figure adapted from Kosovichev & Pipin (2019), illustrating the cyclic behavior of the torsional oscillation velocity in the lower panel (d), compared with the solar magnetic cycle as seen in the longitudinally averaged radial surface magnetic field (c). The similarity of these patterns, with both showing poleward and equatorward branching features, suggests they are related. The zonal velocity at two instants of time during the solar cycle, emphasizes that material motion is not to the pole or to the equator, but the locations of fast flow move poleward and equatorward during the cycle.

truly 22.1 years long (on average) and that two successive magnetic cycles are always in operation with each in a different phase. Solar cycles are nested. Just counting sunspots may give an erroneous impression of the independence of successive cycles. In fact, successive cycles 'always' coexist over half their durations with the preceding and then the following cycle overlapping, as demonstrated by the zonal oscillation pattern that requires 22 years to complete.

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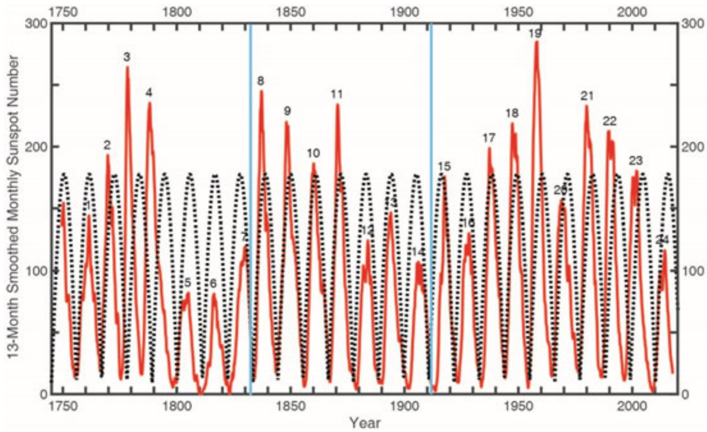

Figure 3. Sunspot record since 1749, solid line (based on Clette & Lefèvre 2016). The dotted line is an 11.05 yr period cycle with amplitude of 178.7, the average maximum SSN of cycles 1-24, for the current sunspot maxima. The 11.05-yr period is the average period for cycles 1-23.

2. The Irregularity of the Solar Cycle

Figure 3 shows the time series of sunspot numbers since 1750 (see Clette & Lefèvre 2016), as recently checked and revised for consistency across the centuries (Hathaway 2015; Svalgaard 2013). A dotted line of constant amplitude (177.8 spots) and period (11.05 yr) provides a chronometer to illustrate the variation of the amplitude and phase of the solar sunspot cycle. Two variabilities are worthy of note: the amplitude can strongly exceed the average, and the phase can differ greatly during the solar cycles shown, forming 'grand' cycles. The amplitudes are not random. They are quite variable, but they do define these 'grand cycles' quite clearly. The phase also has a large-scale variation. The sunspot number phase can change more rapidly than the chronometer phase, but when the sunspot numbers drop, the phase of the sunspot can quickly return to being in phase with our chronometer (e.g. B.J.I. Bromage, 2009, personal communication). This phase reset seems to be associated with a multiple-cycle dip in the peak cycle sunspot number. Our solar clock is irregular but not random.

Robert Robert Dicke (1978) long ago noted that despite first appearances, the Sun was an accurate clock. His metric was that the length of a solar cycle remained constant over the long term and varied in length for only short periods. The Sun keeps track of time internally, and reveals the correct time on the photosphere only occasionally.

3. What Is the Sun Trying to Tell Us?

Well before Dicke's seminal paper, Waldmeier noted that the faster the sunspot number rose, the higher the sunspot maximum became (Waldmeier 1935). This is illustrated in Figure 4a. This relation is obeyed in both hemispheres separately and quite independently, as shown in Figure 4b for north and south hemispheres separately. This relationship has a very simple interpretation if the Sun's convection layer is an electrically conducting medium in which the magnetic field is supported by local currents that are dissipative. The existence of the strong magnetic fields of sunspots depends on 'local' currents, and the longer they are present , the more their magnetic fields weaken. Solar cycles end with a decrease in the sunspot number, due to continued decay of the sunspot fields together with a cutoff of the supply of strong fields from below. We can use these observations to give us some insight into the workings of the solar dynamo. In Figure 5, we show the sunspot number maximum for each of cycles 1 to 24 as a function of the ratio of the duration of the declining phase when the cycle is ending, to the duration

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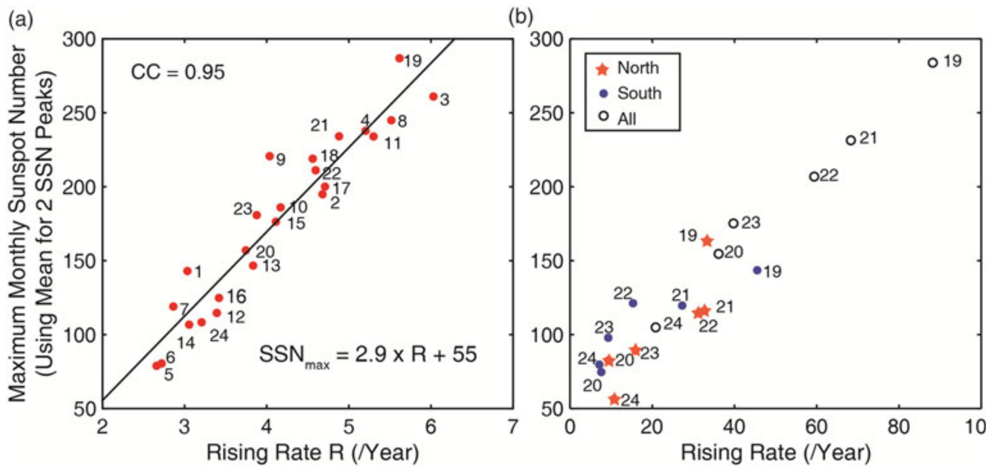

Figure 4. (a) (Left) Waldmeier effect for the solar cycles 1-25 using latest calculations. (b) (Right) Waldmeier effect for north and south hemispheres separately for cycles 19-24 when data for north and south hemispheres were available separately. Star: Northern hemisphere. Closed circle: Southern. Open circle: Combined sunspot numbers.

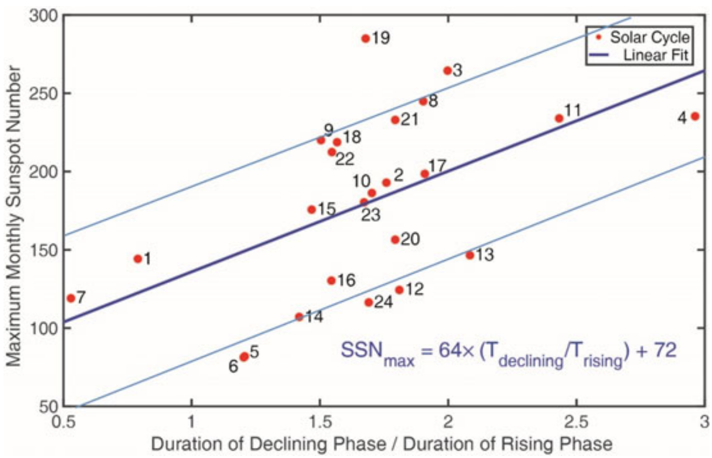

Figure 5. Maximum monthly sunspot numbers for cycles 1 to 24, versus the ratios of the duration of the declining phase divided by the duration of the rising phase.

of the rising phase when the sunspot maximum is being created. This plot shows some interesting behavior. This ratio varies over a factor of 6 from 0.5 to 3, and it defines 3 lines with distinctly different activity. There are the weak sunspot cycles 5, 6, 12, 13, 14, 16, and 24. There are the 'normal' or medium-activity cycles 1, 2, 4, 7, 10, 11, 15, 23, and the high activity cycles 3, 8, 9, 21, and 22, with cycle 19 being a clear outlier above all the rest. The low activity cycle balancing the high cycle 19 could be the Maunder minimum (not shown) which for the purposes of this discussion is a statement that the Sun does not have to produce sunspots.

A linear fit to these data is given by the center line. The two parallel lines are equally spaced parallel lines that approximate the weak maxima and the strong maxima. This gives the impression that the Sun may have different levels of internal behavior: the Maunder minimum behavior when the transport/production of magnetic flux is minimal; the weak minima pattern, the normal/median pattern, a strong transport scenario, and

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the capability of creating a very strong solar maximum. Whether these are discrete or a continuum is not clear as statistics are poor in spite of the long sunspot record used.

There is also a hint here of predictive behavior somewhat different from that provided by the Waldmeier relationship. The point farthest to the right is cycle 4. It is followed by two weak cycles 5 and 6. The second farthest to the right is cycle 11. It is followed by cycles 12 and 13, another two weak cycles. However, cycle 23 did not presage the weak cycle 24, although the recovery of the phase of solar activity occurring at the end of cycle 23, certainly was predictive, as was the phase shift at the end of cycle 4. The Sun clearly is functioning according to rules, and is not a random number generator, but as noted above we do not have a sufficient number of solar cycles to decode these rules with certainty.

4. Summary

The Sun begins with a very stable interior heat source and produces a very irregular magnetic envelope. The sunspots vary in number and strength. Rotation and convection play together to produce a very complex magnetic field. However, there are patterns in the circulation and the sunspot number that provide clues to what is happening within the Sun. While the combination of all of these factors produces complexity, it is clear that the Sun itself is keeping an accurate measure of time. For a more detailed discussion of this problem, see "The Solar Clock", a recent paper by these authors in Reviews of Geophysics (Russell *et al.* 2019).

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IAU 354: Question and Answer

Paper: A Clock in the Sun? by C.T. Russell, L.K. Jian and J.G. Luhmann

Question: Please explain in more detail why the polar, surface magnetic fields of the Sun are decoupled from the lower latitude photospheric fields.

–Chia-Hsien Lin

Answer: This effect in the Sun's magnetic dynamo is a result of the large non-convective radiative zone in its interior and the rotation of the Sun. The radiative zone contributes, at most, mimimally to the solar cycle, and acts mainly to restrict the generation of the magnetic field to the convective, electrically conducting outer 30% of the Sun. Rotating fluids, whether they are cylinders in the laboratory or spherical planetary and stellar bodies in space, form cylinders of rotating fluids, more or less parallel to the rotation axis of the body as they conduct heat to the surface of the body. This effect, combined with the spherical interior non-convecting region, divides the convection zone into three regions that weakly communicate: the northern polar zone, the mid- and low-latitude zone, and the southern polar zone. As a result, solar cycles can begin and end and behave quite independently in these three regions. The fact that they do not ever become totally uncorrelated indicates there is always some small coupling between them.