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Uniting The Sun's Hale Magnetic Cycle and 'Extended Solar Cycle' Paradigms

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ABSTRACT

Through meticulous daily observation of the Sun's large-scale magnetic field the Wilcox Solar Observatory has catalogued two magnetic (Hale) cycles of solar activity. Those two (~22-year long) Hale cycles have yielded four (~11-year long) sunspot cycles -21 through 24. Recent research has highlighted the persistence of the "Extended Solar Cycle" (ESC) and its connection to the fundamental Hale Cycle - albeit through a host of proxies resulting from image analysis of the solar photosphere, chromosphere and corona. This Letter presents, for the first time, a direct mapping between the ESC, the Sun's toroidal magnetic field evolution of the Hale Cycle. As Sunspot Cycle 25 begins to accelerate its growth, interest in mapping the Hale and Extended cycles could not be higher given potential predictive capability that synoptic scale observations can provide.

Introduction

For over four centuries solar observers have pondered the physical origins of the canonical marker of solar activity - the sunspot. It took more than 200 years after the sketching and cataloging of sunspots commenced before it was discovered that the number of sunspots waxes and wanes over an approximately 11-year period¹. A half century later, mapping the latitudinal variation of the spotted Sun yielded the "butterfly diagram," a pattern progressing from latitudes around 30° (north and south) to the equator over the 11-year period². In the golden age of solar astronomy that followed, it was first suggested³ and then demonstrated⁴ that sunspots were sites of intense magnetism protruding through the Sun's photosphere and that the polarities of the butterfly's wings alternated in sign with a period of about 22 years⁵. This alternating magnetic polarity cycle is synonymously identified with its discoverer, the eponymous (22-year) "Hale Cycle," or the (22-year) "Hale Magnetic Polarity Cycle." Understanding how the magnetic spots, their butterfly patterning, and the polarity flipping are tied together to drive solar activity has formed the keystone problem of observational⁶, theoretical⁷ solar- and astro-physics in the intervening century⁸.

For over four decades another term describing solar activity has sporadically appeared in the literature - the "Extended Solar Cycle." The extended solar cycle⁹ (ESC) was used to describe an spatio-temporal extension of the sunspot butterfly pattern to higher solar latitudes (to around 55°) and further back in time (by almost a decade). A culmination of many years of painstaking observation the ESC is exhibited in prominences and filaments^{10,11}, 'ephemeral' (small-scale transient) active regions¹², global-scale features of the Sun's corona¹³ and the zonal flow patterns^{14,15} of the 'torsional oscillation.' In effect, this assortment of observational phenomena created a set of spatio-temporally overlapping chevron-like activity patterns.

The concept of the ESC was 're-discovered' by McIntosh et al. in their study of extreme ultraviolet brightpoints and their associated magnetic scale¹⁶ [hereafter, M2014]. They identified a pattern of coronal and photospheric features that was greatly extended in time and latitude relative to the sunspot butterfly. They deduced that the activity bands observed were the (toroidal) magnetic bands of the Hale cycle, but no concurrent photospheric magnetic measurement was available to affirm their deduction. The core inference of their study was that the spatio-temporal overlap and interaction of extended activity bands observed contributed directly to the shape (the butterfly) and modulation (the amplitude) of the sunspot cycle.

Figure 1 shows the evolution of the total sunspot number, the latitudinal distribution of sunspots and the data-inspired construct introduced by M2014 that inferred the magnetic activity band arrangement and progression of the Hale Cycle and how those bands contribute to the modulation of sunspot cycles.

The Wilcox Solar Observatory (WSO) began collecting daily low spatial resolution observations of the Sun's global (or mean) magnetic field in May 1975¹⁷. A well-known feature of WSO's capability lies in its ability to isolate and study the evolution of the Sun's polar magnetic fields¹⁸. These low-resolution synoptic observations are ideal for identifying large-scale,

long-lived, patterns - reducing the effects of small-scale, rapidly changing fields of emerging magnetic regions.

Results

Following the method of Howard¹⁹ and Duval²⁰, the daily WSO magnetographs can be decomposed into their poloidal and toroidal components. An initial study of the slowly evolving behavior²¹ noted the potential relationship with the ESC. Figure 2 contrasts four and a half decades of WSO observations with the evolution of the sunspot number over the same timeframe. Panel B shows the latitude-time variation of the WSO toroidal magnetic field component in addition to the field strength of the northern and southern polar regions.

Several features of Figure 2 are immediately visible, but perhaps the most striking are the strong overlap in time of the toroidal magnetic systems, the short transitions from one polarity to the next - evidenced through the narrow white (very near 0G) zones, the lack of field migration across the Sun's equator, and the close association of these last two features at the Sun's equator four times in the record (in 1978, 1988, 1998 and 2011). The patterns, including a strong resemblance to the ESC, are described in more detail by Shauner²¹ and Lo²².

The last of these features, synchronized zero-crossing transitions at the lowest latitudes in each hemisphere, are concurrent with events that mark the end of Hale cycle progressions, or "termination" events, that were initially described by M2014 and again (in more detail) recently²³ [M2019]. The termination events are illustrated with dashed vertical lines in Figure 2, and mark the final cancellation of the magnetic systems that produce the last sunspot cycle at the equator and mark the period of rapid growth for the next at mid-solar latitudes. Interestingly, M2019 also noted that these termination events at the equator were co-temporal with the start of the polar magnetic field reversal process. This feature is most easily seen through the polar field strength samples as inflection points of the curves - marking the start of the zero-crossing at each pole.

In order to visually compare the WSO observations [Figure 2B] and M2014's 'band-o-gram' [Figure 2C] we convert the WSO data from sine latitude to latitude and the result can be seen in Figure 3.

Discussion

A general criticism of the M2014 'band-o-gram' is that it was based on catalogued proxies of the photospheric magnetic field through chromospheric and coronal features. Those tracked features formed by the overlapping activity bands observed were not necessarily representative of the photospheric or interior magnetic field itself. It is clear from the WSO observations that, while comparison of the observed progression with the band-o-gram is still qualitative, that there is an overwhelming correspondence of the features observed in the WSO observations with those of the highly idealized band-o-gram. We note that a similar treatment of higher spatial resolution photospheric observations from the Mt Wilson Solar Observatory over a shorter timeframe yields similar correspondence²⁴.

Conclusion

The meticulous daily synoptic scale observations of the WSO have captured almost two complete 22-year Hale cycles. These observations have permitted a mapping of the Sun's photospheric toroidal magnetic field component over that timeframe. Key features of the WSO observations compare directly to the data-inspired schematic of the ESC that was conceived to illustrate how the activity bands of the ESC can interact to shape the latitudinal progression of sunspot cycles and their amplitude. The WSO observations should unambiguously unify the Hale magnetic cycle and the ESC as being, physically, one and the same and indistinguishable. As Lo²² and M2014 inferred, there is predictive capability in these synoptic analyses through the ESC - providing strong indicators of the current progression and potential evolution of upcoming solar activity at the decadal scale, beyond those amenable through the analysis of sunspots. This result demonstrates the intrinsic power of synoptic observations at a time when it is becoming increasingly difficult to sustain such efforts.

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Author Contribution Statement

All authors conceived the experiment, P.S., L.S. and S.M. analyzed the results. All authors reviewed the manuscript.

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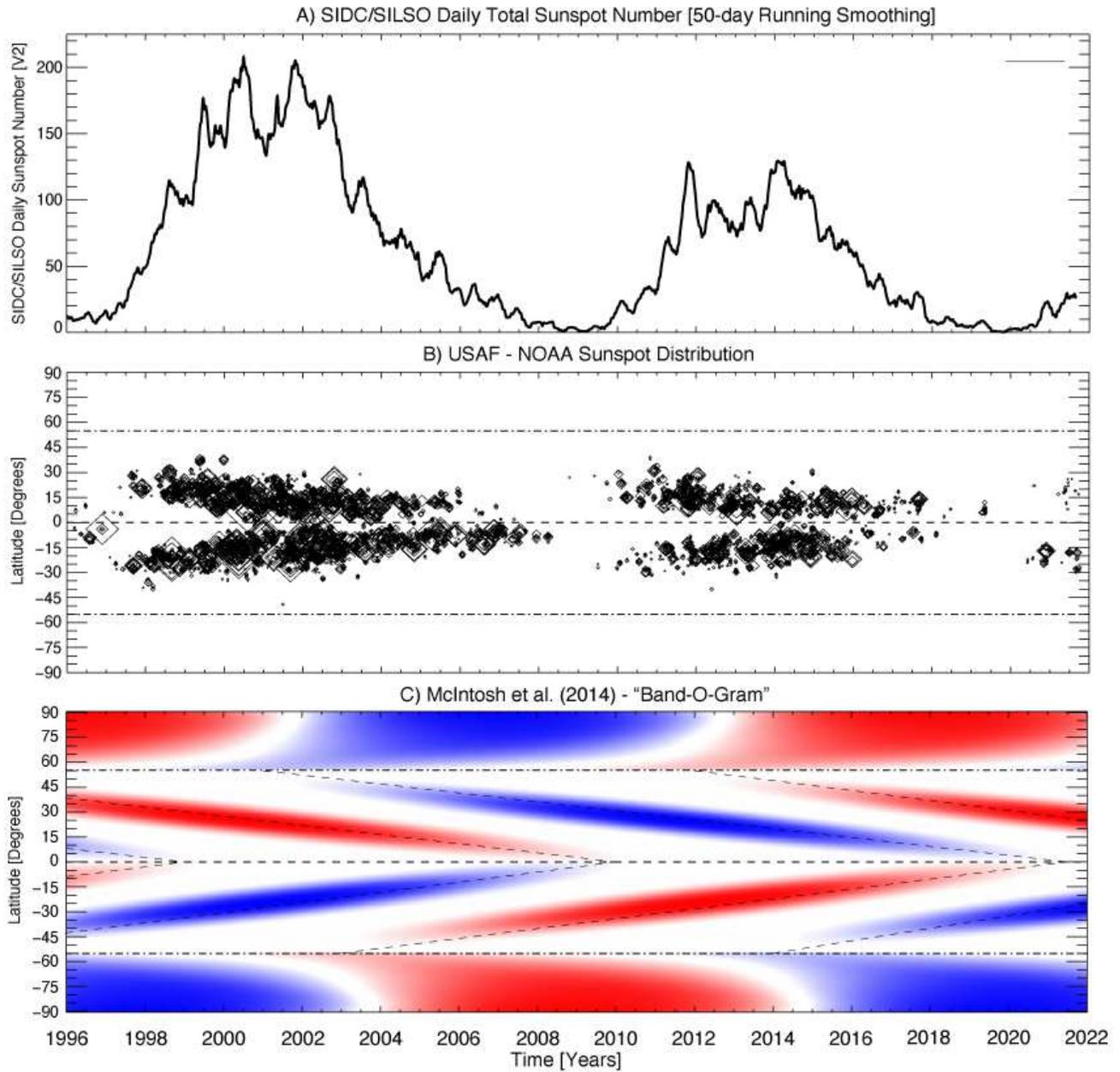


Figure 1. Sunspot evolution since 1996. Comparing and contrasting the evolution of the total sunspot number provided (panel A), the spatio-temporal distribution of sunspots provided by the US Air Force and NOAA (panel B), and a data-driven schematic of the Hale cycle evolution constructed by M2014.

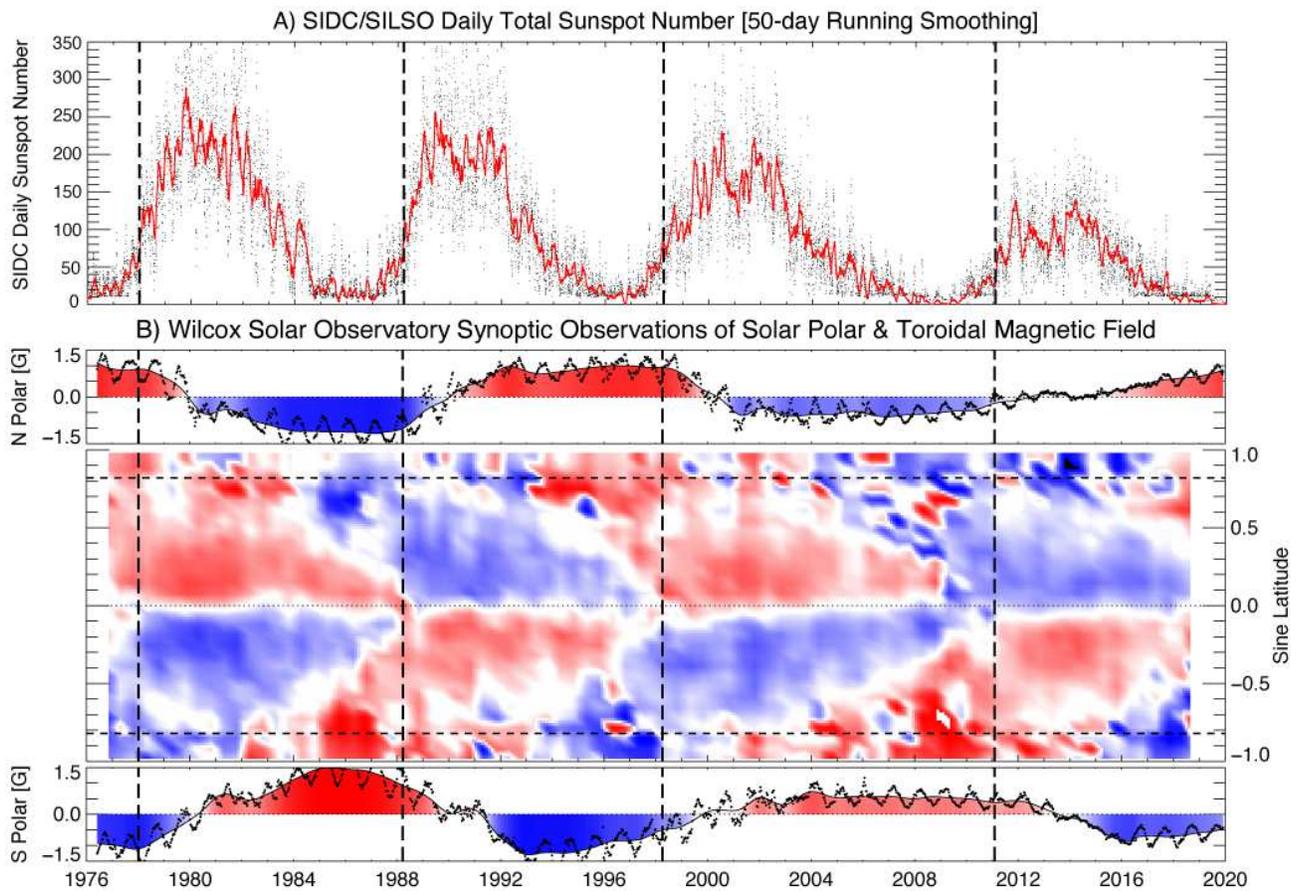


Figure 2. WSO inferred toroidal magnetic field evolution since 1976. Comparing and contrasting the evolution of the total sunspot number provided by the (panel A), with the spatio-temporal distribution of the Sun's toroidal and polar magnetic field components derived from daily WSO observations (panel B). The vertical dashed lines shown in each panel mark the times of the Hale Cycle 'termination' events.

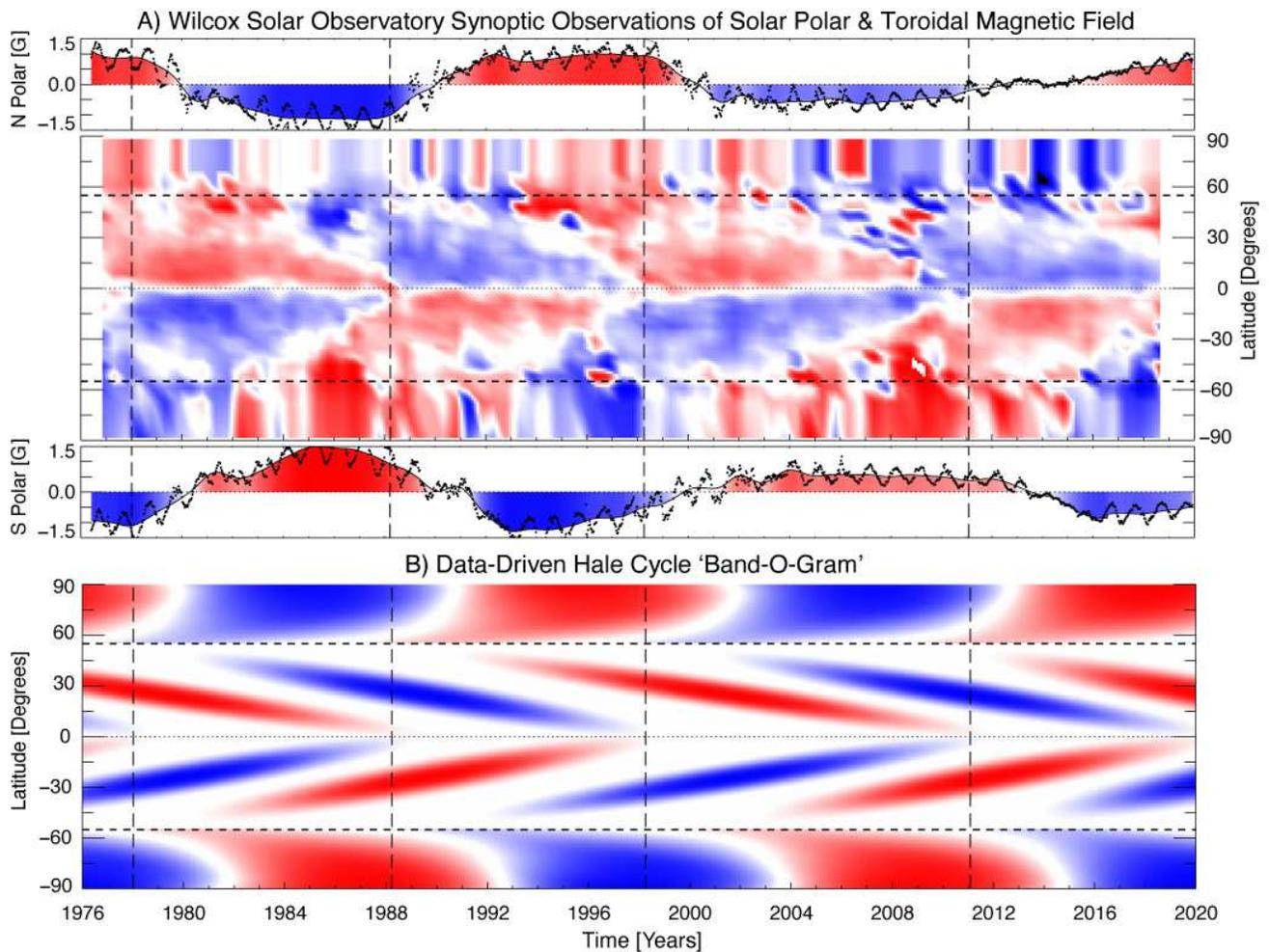


Figure 3. WSO inferred toroidal magnetic field evolution and McIntosh's 'band-o-gram'. Comparing and contrasting the WSO toroidal field measurements (Panel A, see Figure 2B) with the data-inspired 'band-o-gram' of M2014. The vertical dashed lines shown in each panel mark the times of the Hale Cycle 'termination' events studied by M2019.