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The Extended Solar Cycle: Muddying the Waters of Solar/Stellar Dynamo Modeling or Providing Crucial Observational Constraints?

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In 1844 Schwabe discovered that the number of sunspots increased and decreased over a period of about 11 years, that variation became known as the sunspot cycle. Almost eighty years later, Hale described the nature of the Sun's magnetic field, identifying that it takes about 22 years for the Sun's magnetic polarity to cycle. It was also identified that the latitudinal distribution of sunspots resembles the wings of a butterfly—showing migration of sunspots in each hemisphere that abruptly start at mid-latitudes (about $\pm 35^{o}$) toward the Sun's equator over the next 11 years. These sunspot patterns were shown to be asymmetric across the equator. In intervening years, it was deduced that the Sun (and sun-like stars) possess magnetic activity cycles that are assumed to be the physical manifestation of a dynamo process that results from complex circulatory transport processes in the star's interior. Understanding the Sun's magnetism, its origin and its variation, has become a fundamental scientific objective—the distribution of magnetism, and its interaction with convective processes, drives various plasma processes in the outer atmosphere that generate particulate, radiative, eruptive phenomena, and shape the heliosphere. In the past few decades, a range of diagnostic techniques have been employed to systematically study finer scale magnetized objects, and associated phenomena. The patterns discerned became known as the "Extended Solar Cycle" (ESC). The patterns of the ESC appeared to extend the wings of the activity butterfly back in time, nearly a decade before the formation of the sunspot pattern, and to much higher solar latitudes. In this short review, we describe their observational patterns of the ESC and discuss possible connections to the solar dynamo as we depart on a multi-national collaboration to investigate the origins of solar magnetism through a blend of archived and contemporary data analysis with the goal of improving solar dynamo understanding and modeling.

Keywords: Sun: magnetism, Sun: interior, Sun: rotation, solar cycle, sunspots

The Sun is a magnetically active star. It possesses a magnetic field of complex evolving geometry that extends far out toward interplanetary space after its origin in the Sun's interior (e.g., Fan, 2009). The magnetic field of the Sun, structured in space and time over disparate scales is maintained by a dynamo that operates within the convecting plasma confined roughly to the outer 30% of the Sun's radius. The net output of that dynamo waxes and wanes in strength every 11 years (see, e.g., Usoskin, 2017). Such non-uniform distribution of sunspot activity was suspected already by Carrington (1863). Further, understanding the mechanism, or mechanisms, by which the magnetic field traps the Sun's sub-surface energy reservoir to couple the subsurface layers with those of the outer atmosphere to transport, build-up and dissipate colossal amounts of energy there poses a perennial challenge. In other words, the persistent circulative and convective forcing of that magnetic field drives radiative and particulate activity across time-scales, including what we now call "space weather" (e.g., Gold, 1959; Svalgaard, 2013). The reliance of society on space-based technology has reached a point where understanding the origin, evolution, and multi-faceted impacts of the Sun's magnetism has reached a heightened level of importance in astrophysics. Beyond this very practical issue, there is an implicit understanding that unlocking the puzzle around the origins of the Sun's magnetism could provide vital clues to the origins and behavior of the magnetic field in other stars (see, e.g., Lanza, 2010).

The variation in number of the canonical marker of solar magnetic activity, sunspots, would appear to demonstrate that the Sun's magnetic field is routinely circulated with a periodicity close to 11 years (e.g., Hathaway, 2010). The gross variation in sunspot number, and variation of the sunspot distribution in latitude exemplify this quasi-periodic variation, see e.g., **Figure 1**. There we see that, with every new sunspot cycle, a fresh set of spots takes over the Sun's surface in a peculiar pattern that starts abruptly at mid solar latitudes and slowly migrates toward the equator (over a span of around 9 years) that takes on the shape of a butterfly's wing (Maunder, 1904). In this "butterfly plot" the wing like pattern of sunspot migration repeats again, and again. The determination that sunspots were locations of concentrated (strong) magnetic field (Hale, 1908; Hale et al., 1919) and the realization that, in each hemisphere of the Sun, the butterfly's wings alternated in magnetic polarity led to the stunning realization that the Sun's magnetic field was reversing approximately every 22-years (Hale and Nicholson, 1925).

Many features of cyclic solar variability have been cataloged extensively through decades of observation, e.g., cyclic variation of sunspot number approximately every 11 years, polarity reversal of the magnetic field in 22 years (Usoskin, 2017), the slight north-south asymmetry in activity where the sunspot production of the hemispheres will lead or lag by upto a couple of years (e.g., Newton and Milsom, 1955; Vizoso and Ballester, 1990; McIntosh et al., 2013), emergence of the spot groups with east-west magnetic polarity in each hemisphere (known as "Hale's Law"; Hale et al., 1919), the emergence of active region (or sunspot pairs) with one magnetic polarity slightly more northward than the other (known as "Joy's law"; Hale et al., 1919). These observations have motivated extensive investigations and modeling efforts (too many to reference here) to explain the production of these magnetic patterns via the convective circulation of the solar interior. The most prominently recognized efforts, the dynamo wave model (e.g., Parker, 1955; Yoshimura, 1975), the "Babcock-Leighton" model (e.g., Babcock, 1961; Leighton, 1969), and the "Flux Transport Dynamo" (e.g., Wang and Sheeley, 1991). These models, and the underlying theory, based *solely* on the magneto-spatio-temporal progression of sunspots, is expertly summarized by Charbonneau (2010).

These magnetohydrodynamic (MHD) dynamo models have been considered, for the last few decades, as the most viable explanation for the process responsible for the generation, and sustenance of the 22-year magnetic activity cycle, the 11-year solar cycle, and the appearance of the butterfly diagram. At very highest level, these dynamo processes capture: (i) generation of toroidal field in the solar tachocline by differential rotation, (ii) generation of poloidal field at the surface as per the Babcock-Leighton process, (iii) advection by meridional circulation, and (iv) cycle irregularities by the fluctuations imposed in the Babcock-Leighton process (e.g., Choudhuri et al., 1995, 2007; Dikpati and Gilman, 2006; Jiang et al., 2007; Yeates et al., 2008, and references cited therein). The broadly acknowledged difficulty in forecasting/predicting sunspot cycle timing and amplitude has led some to speculate that the sunspot number and patterns do not form an adequate set to conquer the challenge of the Sun's dynamo. There is absolutely nothing to say that other stars may exhibit similar phenomena, but the presence of ESC's on other stars could significantly complicate interpretation of unresolved observations. This points to the imperative nature of exploring the ESC for the Sun,especially if it is critical for diagnosing the dynamo.

A flurry of research activity taking place throughout the 1980s, systematically studying magnetic structures with a diverse range of spatial scales, offered an enhanced picture of the Sun's magnetic evolution and extended this "butterfly" picture of magnetic activity. Volume 110 of the Solar Physics Journal in 1987 captures the breadth of this activity (Wilson, 1987). In concert, these primarily observational studies of "ephemeral"

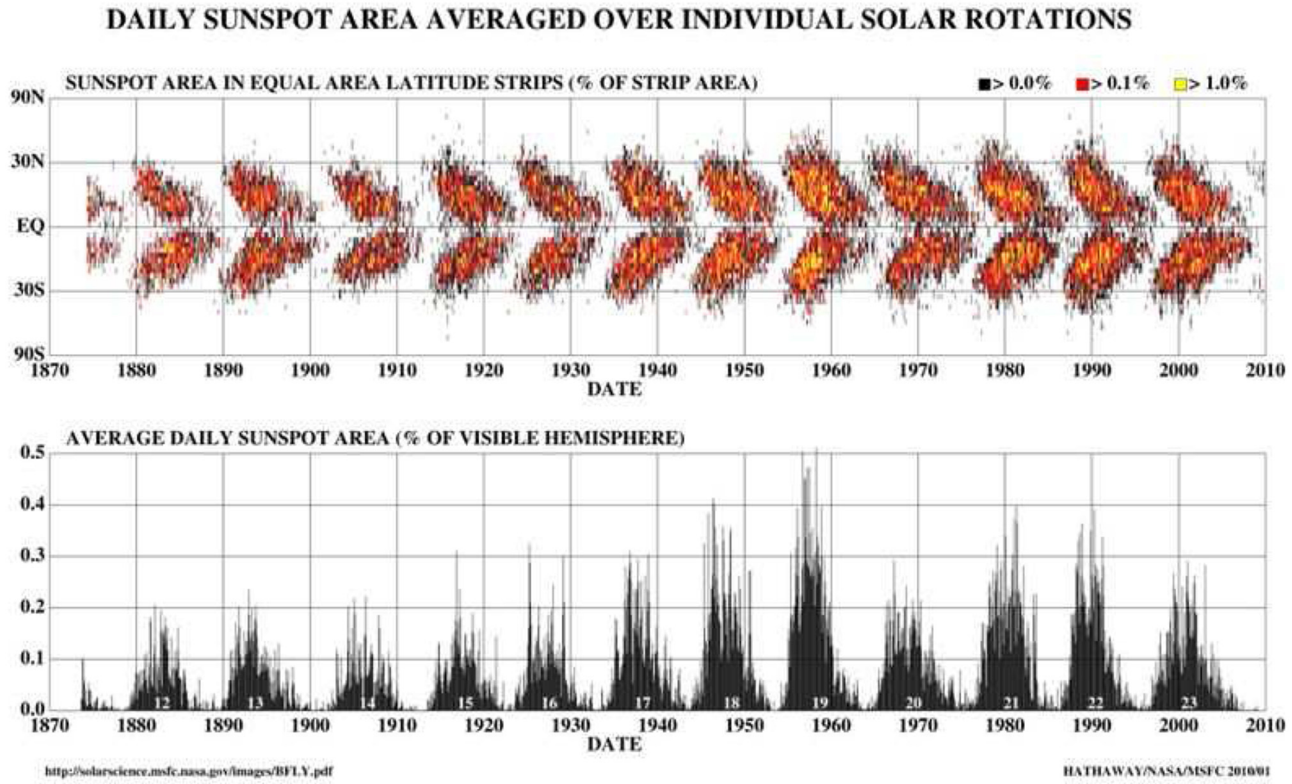

FIGURE 1 | The observed variation in sunspot number **(Bottom)** and latitude **(Top)** demonstrate the typical 11-year solar cycle. In the **(Top)**, the sunspot locations and their latitudinal variations are shown, which constitutes the butterfly diagram.Note that the sunspot butterfly wings grow abruptly at latitudes largely inside ∼35°. In the **(Bottom)**, the total sunspot number and its variations are shown over various solar cycles [Credit: Hathaway, 2010, reproduced with permission (c) Springer Nature].

active regions, XRay (and later EUV) "bright points", plage, faculae, filaments, prominences, that when combined with global-scale flow patterns and characterizations of the coronal structure above the limb characterized demonstrated a pattern that became known as the "Extended Solar Cycle"—upon realizing that the wings of the sunspot butterfly could be extended to much higher solar latitudes (∼ 55° latitude) and to earlier times (almost a decade earlier) to a degree where these activity wings form a chevron-like pattern with a strong spatio-temporal overlap in each solar hemisphere (see, e.g., Wilson et al., 1988).

A variety of observations have now asserted that the above picture of solar activity begins at higher latitudes on the Sun *years* before the emergence of the fresh sunspots of the coming new cycle, and they create new activity bands with the longer period of the extended solar cycle (Wilson et al., 1988). The ESCs are observed in many ways, all the way from sub-photospheric zonal flows to global-scale morphology of the corona. Altrock (1997) has observed the evidence of ESCs in the Fe XIV green line emissions in the solar corona, while Juckett (1998) has obtained evidence for a 17-year extended solar cycle in the IMF directions at 1 AU in the coronal hole variations and also in the planetary magnetospheric modulations. Robbrecht et al. (2010) have described that the extended cycle in coronal emission is not an early activity of the new solar cycle, rather it is the poleward concentration of trailing-polarity flux of the old solar cycle generated most likely by the meridional flows. Therefore, the signature of the extended solar cycle is present at diverse spatial scales at the Sun, combining various layers of its atmosphere. The observed coronal variation is linked with the presence of the torsional oscillations or zonal flow bands in the sub-surface layers of the Sun (Labonte and Howard, 1982; Howe, 2009).

Clearly, the ESC, magnetic activity, and sunspot cycles are intrinsically linked, but little modeling effort has been dedicated to pursuing a complete physical description of the system. In part, that is because the observational picture, and related metrics, have not been comprehensively presented for use by the modeling community.

In the following sections we'll extend the preceding historical narrative before we discuss ESCs in contemporary observations and the possible link between the ESC and the modulation of sunspots. Finally, we'll look at the outlook of our team activity and the approach that we'll take to bring observation and model together with a goal to reduce the number of free parameters on the latter, while using the former to develop a picture of the Sun's recent climatology.