



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

Abhishek K. Srivastava^{1*}, Scott W. McIntosh², N. Arge³, Dipankar Banerjee⁴, Mausumi Dikpati², Bhola N. Dwivedi¹, Madhulika Guhathakurta⁵, B.B. Karak^{1,2}, Robert J. Leamon^{3,6}, Shibu K. Matthew⁷, Andres Munoz-Jaramillo⁸, D. Nandy⁹, Aimee Norton¹⁰, L. Upton², S. Chatterjee⁴, Rakesh Mazumder⁹, Yamini K. Rao¹ and Rahul Yadav⁷

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*Correspondence:

Abhishek K. Srivastava
asrivastava.app@iitbhu.ac.in

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¹ Department of Physics, Indian Institute of Technology (BHU), Varanasi, India, ² High Altitude Observatory, National Center for Atmospheric Research, Boulder, CO, United States, ³ Heliophysics Division, NASA Goddard Space Flight Center, Greenbelt, MD, United States, ⁴ Indian Institute of Astrophysics, Bangalore, India, ⁵ NASA Headquarters, Washington, DC, United States, ⁶ Department of Astronomy, University of Maryland, College Park, MD, United States, ⁷ Udaipur Solar Observatory, Physical Research Laboratory, Udaipur, India, ⁸ Southwest Research Institute, Boulder, CO, United States, ⁹ Center of Excellence in Space Sciences India, IISER, Kolkata, India, ¹⁰ Hansen Experimental Physics Laboratory (HEPL), Stanford University, Stanford, CA, United States

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 $\pm 35^\circ$) 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 multifaceted 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"

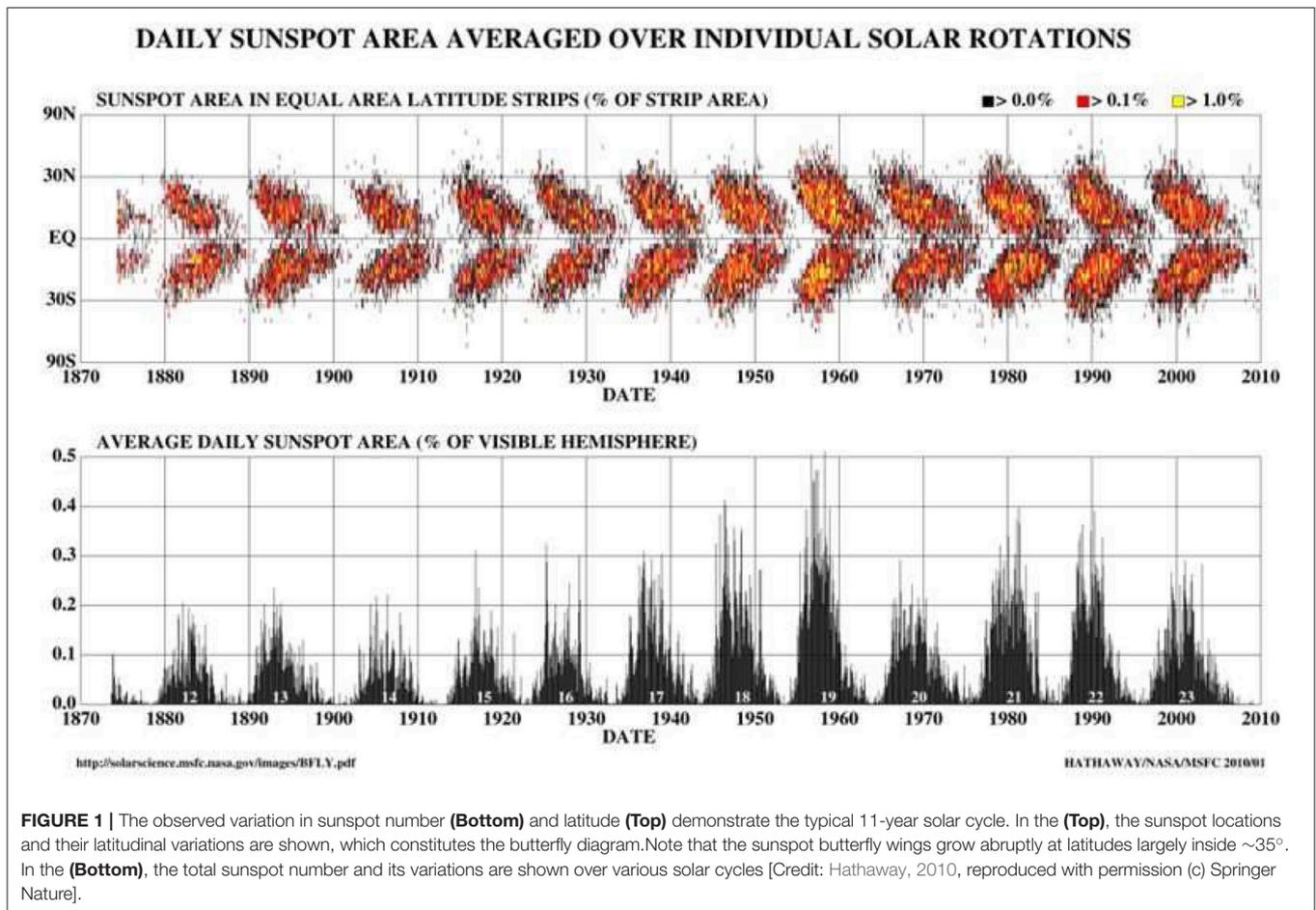


FIGURE 1 | The observed variation in sunspot number (**Bottom**) and latitude (**Top**) demonstrate the typical 11-year solar cycle. In the (**Top**), the sunspot locations and their latitudinal variations are shown, which constitutes the butterfly diagram. Note that the sunspot butterfly wings grow abruptly at latitudes largely inside $\sim 35^\circ$. 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 ($\sim 55^\circ$ 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. Altrrock (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.

1. ESC - A BRIEF HISTORICAL PERSPECTIVE

As mentioned above, observations of the ESC began three to four decades ago when Leroy and Noens (1983) analyzed coronal data obtained at Pic du Midi from 1944 to 1974 and searched for the latitude variation of coronal activity, see **Figure 2**. Similar work was conducted from a collection of ground-based coronagraphs and dedicated experiments identified the same patterns. These works collectively identified an underlying, global-scale, pattern of coronal activity that appeared to repeat over a period of about 17 years—much longer than the typical eleven-year sunspot cycle. This was consistent with an earlier work of Legrand and Simon (1981), based on the analysis of 100 years of geomagnetic indices, which inferred the presence of two extended solar cycles. These ESCs are present on the Sun at all the times in the form of spatially overlapping cycles. In these papers, the solar cycle starts every eleventh year with a total duration of 17–18 years, and during an interval of the next 6–7 years, two consecutive cycles with different levels of activity evolved simultaneously at different latitudes of the sun. Leroy and Noens (1983) demonstrated the high-latitude (rush to the poles; red-ellipse in **Figure 2**) and low-latitude (sunspot-related drift toward the equator; blue-ellipse in **Figure 2**) branches of green line (Fe XIV 5303 Å) coronal emissions.

Wilson et al. (1988), following on concentrated effort from co-authors over a number of years, reported on the appearance of a high-latitude accumulation of ephemeral active regions (e.g., Harvey and Martin, 1973; Harvey et al., 1975), the torsional oscillation (e.g., Howard and Labonte, 1980; Labonte and Howard, 1982), and the evolution of coronal emission (e.g., Bretz and Billings, 1959; Altrrock, 1988) as above in the diminishing phase of sunspot cycle 21. For example, the orientation of the magnetic polarities in those ephemeral active regions studied by Harvey and Martin was similar to the spots that emerged for the next sunspot cycle 22 *instead* of those belonging to sunspot cycle 21—this striking pattern was difficult to explain at the time. *Concerted, these observations inferred that sunspot activity was the main phase of a more extended cycle that was triggered at higher solar latitudes prior to the maximum of the given solar cycle.* It was found to progress toward the equator during the next 18–22 years while merging with the conventional butterfly diagram when it entered into the sunspot latitudes. Similar patterns of evolution were visible in monitoring the latitudinal progression of filaments and prominences over time (e.g., Bocchino, 1933; Hansen and Hansen, 1975) that are summarized by Cliver (2014).

2. THE CONTEMPORARY ESC

The Solar and Heliospheric Observatory (SoHO), and following space-based observatories, supplemented the long synoptic timelines provided by ground-based synoptic observing programs. Indeed, as the ability to secure the funding of the latter has become more precarious, the space based platforms, while less flexible in terms of instrumentation, have provided a uniform, high signal-to-noise platform to augment the

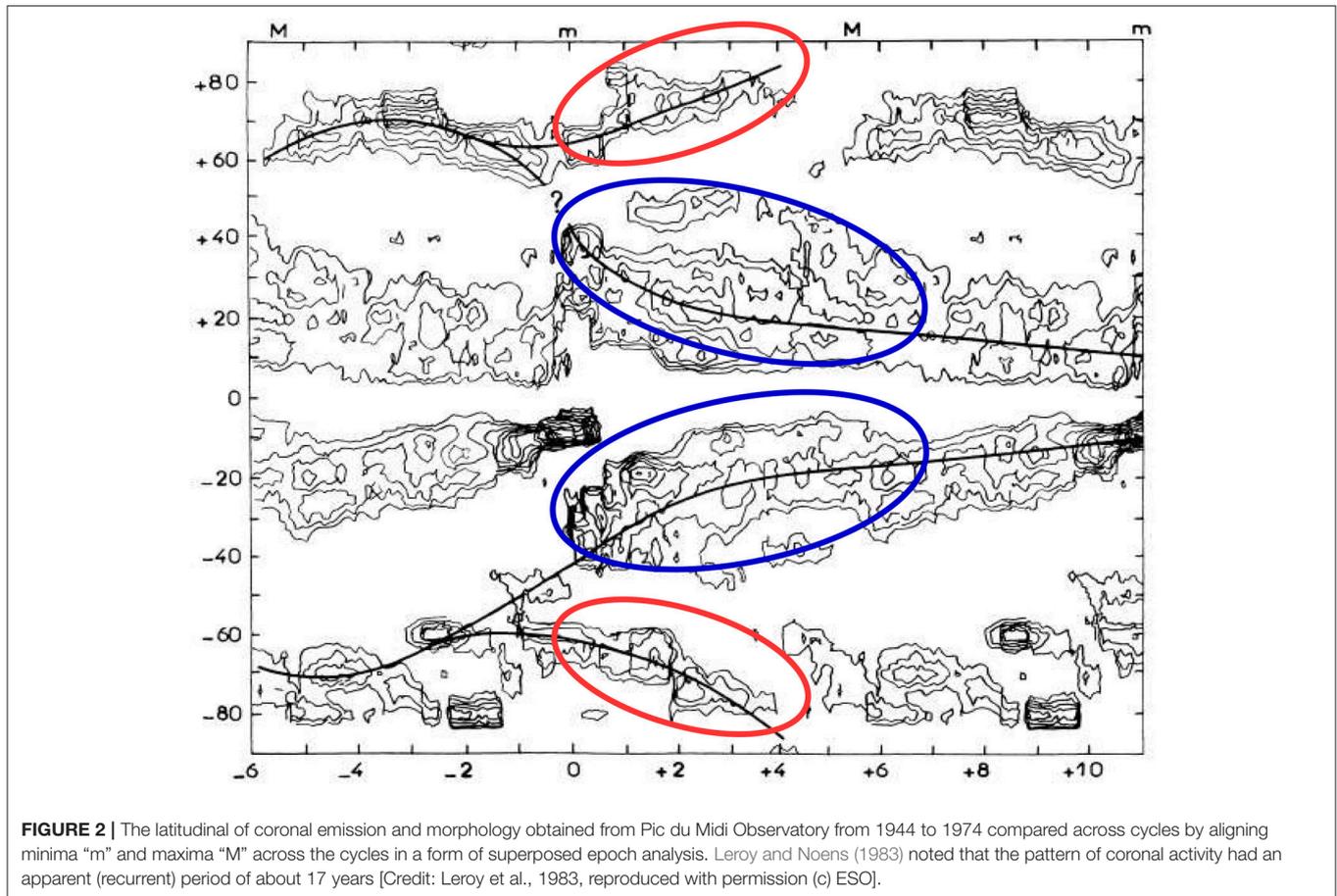
few (adequately funded) programs that exist on the ground. Although in some cases, the Satellite instrumentation does not necessarily provide better signal-to-noise ratio than ground-based instruments. For example, satellite magnetograph observations have higher noise level than ground-based observations. Several studies investigated the ESC. Offering a different perspective from those discussed earlier, Robbrecht et al. (2010) analyzed Fe XIV 5303Å green line coronal emissions using SoHO/EIT (1996–2009) and simulated fluxes (1967–2009), and studied the high-latitude coronal emissions associated with the coronal hole boundaries. They observed equatorward and thereafter poleward progressions of the activity bands of high-latitude coronal emissions and the associated polar crown filament following the polarity reversal. They found that strong underlying fields emerged in the minimum phase of the solar cycle by the poleward transport of the active region flux due to the surface meridional flow. These high-latitude structures were not the precursor of the new solar cycle, but they constitute a physically isolated U-shaped band moving latitudinally upward again as the active regions emerge at the mid-latitudes and reconnect with the polar coronal hole boundaries. Robbrecht et al. (2010) concluded that the extended ≈ 17 years cycle in coronal emission is *not* a signature of early new solar activity. Instead it was the poleward concentration of the trailing polarities of the old solar cycle caused by the meridional flow.

Petrie et al. (2014) gave a different explanation to the high-latitude coronal emission bands observed by Robbrecht et al. (2010), and inferred that these features may indeed have a strong connection with the main cycle under the progression, and thus the match with the torsional oscillations (distributed around 45° latitude) and photospheric ephemeral bipoles having broad latitudinal distributions. Ulrich and Boyden (2005) shows that the start of a new toroidal cycle is seen even beyond 60–70° of the latitudes in magnetic field observations.

Tappin and Altrrock (2013) studied the white light coronagraph and found that similar behavior of the global-scale corona with the historical green emission coronal observations. Altrrock (2014) analyzed the “Rush to the Poles” for solar cycle 24 finding that the solar cycle 24 displayed an unusually intermittent rush that is only well defined in the northern hemisphere. They determined that the solar maximum in the northern hemisphere has already occurred at 2011, while it was poorly defined in the southern hemisphere.

2.1. The ESC and the Sunspot Cycle

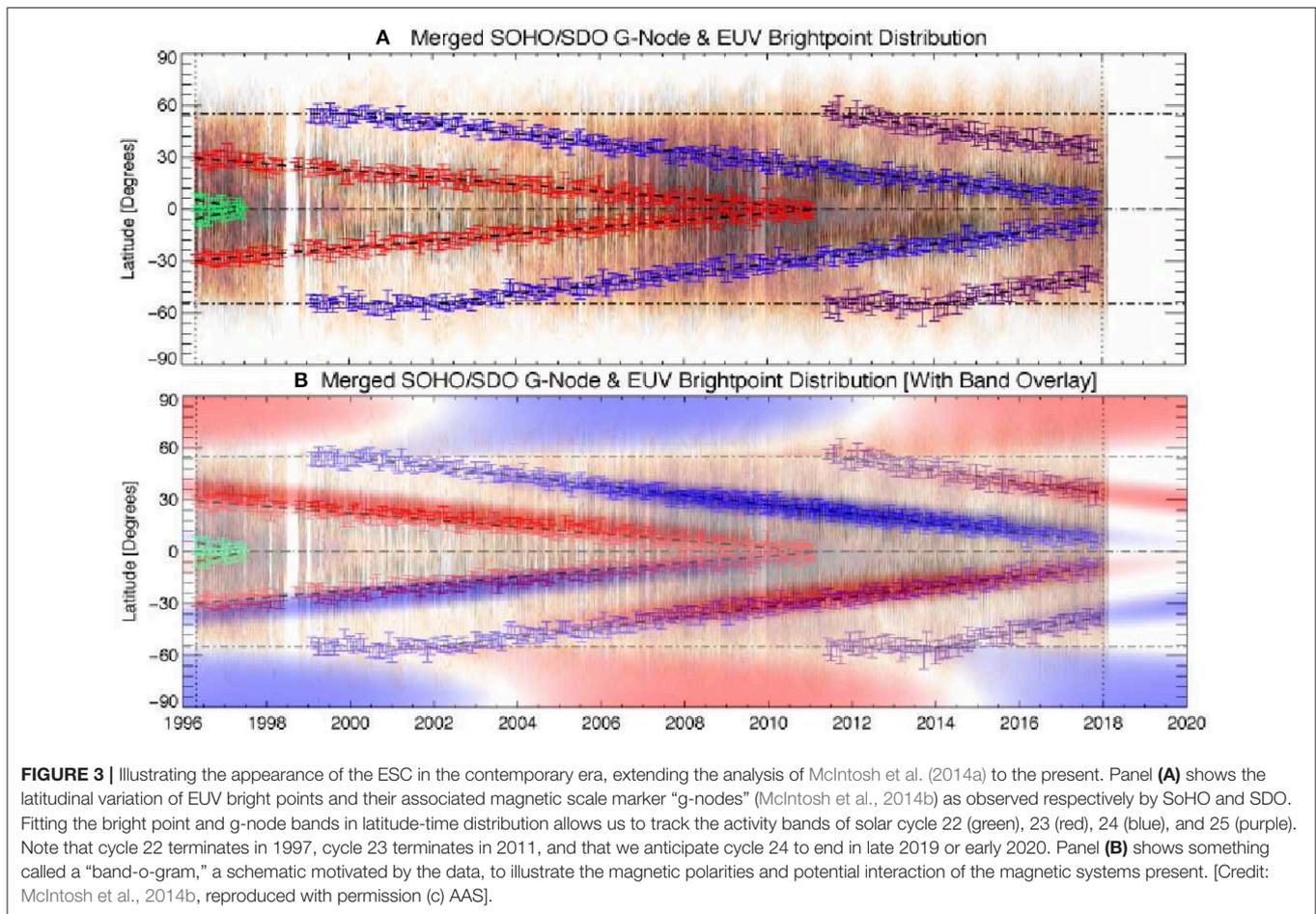
The latitudinal dependence of the solar activity markers smaller in scale than sunspots (like, for example, bright points, granulation, diffuse coronal emissions, filaments/prominences, etc.) show a narrow concentration of activity that appears at higher latitudes (around 55°) just after solar maximum. A portion of that concentration subsequently migrates toward the equator while another moves toward the poles. In a butterfly diagram this pattern gives the appearance of a “bifurcation,” or fork in activity that follows solar maximum (in each hemisphere). The former branch has been largely under-investigated with the exception of the torsional oscillation work discussed above. The latter branch has been dubbed “the rush to the poles,” and



seems to be intimately involved in the reversal of the polar magnetic field. The equator-moving branches in each hemisphere can be traced using the same host of markers, and roughly stay equidistant to the lower latitude bands which are currently producing sunspots, moving slowly, before eventually reaching $\sim 35^\circ$ and giving birth to the sunspots that become the next sunspot cycle. This new cycle growth appears to coincide, in very short order, with the last vestiges of the old cycle disappearing at the equator (e.g., McIntosh et al., 2014a).

Figure 3 provides an update to the diagnostics presented in McIntosh et al. (2014a) showing the appearance of the ESC through 2017. It is due to an extension of their analysis by 4.5 years and now including the tracking of the activity bands, which will give birth to the sunspots of cycle 25 as predicted in McIntosh et al. (2014a), and documented in McIntosh and Leamon (2017). The panels of the figure illustrate the latitudinal variation of EUV bright points and Magnetic Range of Influence (MRoI) “g-nodes”, the magnetic features at which EUV brightpoints appear to re-occur (McIntosh et al., 2014b), as observed respectively by SoHO and SDO. The trails of bright points and g-nodes allowed the tracking of bands belonging to four sunspot cycles, 22 (green), 23 (red), 24 (blue), and 25 (purple). The lower panel shows the “band-o-gram,” or a data-inspired schematic of the band evolution and magnetic polarity. McIntosh et al.

(2014a) were able to fit histograms to the latitudinal distributions of these features and reported that the activity bands move at speeds around $3^\circ/\text{Yr}$. And that their start times, the times at which they leave 55° , are asymmetric in time by as much as two years while their termination point at the equator appeared to be symmetric. It was noted by McIntosh et al. (2014a) that the departure of the bands at 55° appeared to coincide with the sunspot maximum of each hemisphere. Using some seventy years of data, McIntosh et al. (2014a) noted that the hemispheric sunspot maxima of the magnetic activity cycle (those with the same leading magnetic polarity) were approximately 22 years apart. They then proposed that the bands of cycle 25 should present themselves at 55° latitude prior 2012 before leaving those latitudes offset by approximately 2 years. This is based on the hemispheric sunspot maxima of sunspot cycle 22 as the likely launch point of the activity bands that formed sunspot cycle 23. In this updated figure, at the beginning of 2012 near the maximum of solar cycle 24, the fresh activity band appears at higher latitudes (purple) and migrates toward the solar equator and was reported in McIntosh and Leamon (2017) as the first signature of the bands that will give rise to sunspot cycle 25 in late 2019 or 2020—following the expected termination of the cycle 24 bands later next year.



McIntosh et al. (2014a) was the first work to phenomenologically connect the sunspot cycle, and its temporal landmarks (minimum and maximum), with the phasing of the ESC. Noting that, in this picture, sunspot minimum is a time when there appear to be four magnetic bands within 40° of the equator and there is an appearance of mutual cancellation that is only broken (finally) by the termination of the equatorial bands.

3. CURRENT RESEARCH ON ESC AND ITS PHYSICAL IMPLICATIONS

It should be noted that, as an observational induction, the peculiar behavior of sunspot progression in different latitudinal zones on the Sun was documented in the 19th century by keen observers such as Carrington. This early work laid the foundation for the discovery of the ESC when those results were summarized later (e.g., Clerke, 1903). However we do note that, despite the considerable observational effort spent, and the connection of the various features (from small to global scales) with an evolutionary path that is eventually populated by sunspots, very little effort has been spent on addressing the nature of the ESC in relation to the Sun’s

dynamo—our focused team hopes to do that. As mentioned in the Introduction a class of dynamo model, so-called the Babcock-Leighton dynamo model has become a popular model in recent years since the pioneering work of Wang and Sheeley (1991), Choudhuri et al. (1995), and Durney (1995). These models produce some basic features of the solar cycle reasonably well and some of these models also produce some properties of the extended magnetic cycles starting from high latitudes (Dikpati and Charbonneau, 1999; Yeates et al., 2008; Jouve et al., 2010; Munoz-Jaramillo et al., 2010; Karak and Miesch, 2018). Global MHD convection simulations, although operating in a completely different parameters regimes, do produce extended magnetic cycles (Charbonneau, 2014; Augustson et al., 2015; Featherstone and Miesch, 2015; Karak et al., 2015; Hotta et al., 2016; Kopyla et al., 2016). However, it needs to be explored whether the extended magnetic cycles obtained in dynamo simulations correctly reproduce the observed extended solar cycle. In the remainder of the this focused review, we’ll discuss some of the questions and approaches required to close the (considerable) gap between observation and model.

While these efforts using space-borne EUV imagers, coronagraphs, and first-generation ground-based observations tried to shed new light on the behavior of extended solar cycles,

dramatic changes have occurred in past ten years with the advent of new-generation high-resolution observatories, and associated more advanced computational and image-processing techniques. The availability of a wealth of high-resolution observations from ground and space about small-scale features (e.g., EUV bright points, g-nodes, etc.) have enabled the study of the properties of ESCs in greater detail, their possible linkage with the sub-surface dynamics, and inherent physical implications. Apart from the classical solar cycle markers, e.g., sunspots, plage, filaments, etc., in the last few years, the new observational markers have been discovered and utilized to understand the behavior of solar variability, e.g., EUV bright points, g-nodes associated with the evolution of the rotationally driven giant convective scales (McIntosh et al., 2014b). In concert, all of these features provide the opportunity to track the progression of solar activity bands beyond the traditional eleven-year solar cycle.

The perspective of our team is first to develop and then deploy a consistent approach to the analysis of the space and ground-based data available to us. All in all we have data that spans back from the present day to the dawn of H_{α} photography in the late 1870s. From that we will be able to assess key features such as band onset times, times of bifurcation, latitudinal migration speeds, termination points, etc that can then be used to develop an enhanced set of boundary conditions for model developers. Stand-alone, these numbers over some 140 years, a dozen sunspot cycles, form an important benchmark, and their averages form a climatology can become a consensus set of parameters describing the ESC. The task for the modeling part of our team is then to try and incorporate these markers, timescales, etc into the framework of the contemporary models. Which of the contemporary models can and which cannot describe the ESC? Can they help us understand why the region around 55° is so important (apparently) to the evolution

observed? Can the incorporation of the ESC information help to improve the numerical forecasting of sunspot cycle timing and amplitude?

4. CONCLUDING REMARKS

The extended solar cycle has been readily observed for many decades. Our team will bring together the various observational datasets and apply a consistent approach to their analysis. We will then publish a consensus climatology for the ESC over the 140 years of observed evolution. The (considerable) challenge is then to understand, via modeling activities, how the ESC helps to better understand the interior of the Sun and constrain models of the solar dynamo. Maybe, following that last step, we can begin to explore how the activity of stars with different luminosities, interior structure, and rotation rates may be understood using our new solar basis as a “Rosetta Stone.”

AUTHOR CONTRIBUTIONS

All authors have contributed in an equal manner. All the member co-authors of Indo-US (IUSSTF) Joint Networked R&D Center team have worked, read, and edit the manuscript.

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