What the sudden death of solar cycles can tell us about the nature of the solar interior

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ABSTRACT

We observe the abrupt end of solar activity cycles at the Sun’s equator by combining almost 140 years of observations from ground and space. These “terminator” events appear to be very closely related to the onset of magnetic activity belonging to the next sunspot cycle at mid-latitudes and the polar-reversal process at high-latitudes. Using multi-scale tracers of solar activity we examine the timing of these events in relation to the excitation of new activity and find that the time taken for the solar plasma to communicate this transition is of the order of one solar rotation - but could be shorter. Utilizing uniquely comprehensive solar observations from the Solar Terrestrial Relations Observatory (STEREO), and Solar Dynamics Observatory (SDO) we see that this transitional event is strongly longitudinal in nature. Combined, these characteristics imply that magnetic information is communicated through the solar interior rapidly. A range of possibilities exist to explain such behavior: the presence of magnetic reconnection in the deep interior, internal gravity waves on the solar tachocline, or that the magnetic fields present in the Sun’s convection zone could be very large, with a poloidal field strengths reaching 50kG—considerably larger than conventional explorations of solar and stellar dynamos estimate. Regardless of mechanism responsible, the rapid timescales demonstrated by the Sun’s global magnetic field reconfiguration present strong constraints on first-principles numerical simulations of the solar interior and, by extension, other stars.

Introduction

Unlocking the nature of the solar dynamo, the mechanism by which the Sun’s magnetic field is generated, sustained, and repeatedly cycles, remains one of the most challenging matters in astrophysics¹,². Over the past fifty years models attempting to reproduce the key ingredients of solar variability have grown in sophistication from observationally-motivated empirical models³,⁴ to fully three-dimensional magnetohydrodynamic numerical simulations⁵–⁷ with the common top-level goal of reproducing the spatio-temporal variation of sunspots over many decades. Levels of success in such modeling efforts have been mixed² as many of the key physical properties of the deep solar interior, where the dynamo action is believed to take place, remain largely unknown and incredibly difficult to observe.

Extreme-Ultraviolet (EUV) Brightpoints (BPs) are an ubiquitous feature of the solar corona and, since the Skylab era, research has focused on their origin and diagnostic potential, hinting at their ties to the magnetism of the deep solar convection zone⁵–¹¹. Recent research has solidified their connection to the scales of rotationally-driven “giant-cell” convection¹²,¹³. Subsequent work¹⁴ (hereafter M2014) demonstrated that monitoring the latitudinal progression of the number density of BPs with time¹⁵ permitted the identification and tracking of magnetic activity bands that migrate from latitudes around
55° to the equator over a period of around 20 years. These bands of enhanced BP activity presented an extension in space and time of the sunspot activity and migration pattern, known as the “butterfly pattern”, that has been observed for over a century\textsuperscript{16} and has been considered as the pattern central to the Sun’s dynamo mystery\textsuperscript{2}. As part of their investigation, M2014 noticed an abrupt reduction in the equatorial BP density that occurred in conjunction with the very rapid growth of BP density at mid-latitudes ($\sim$30° latitude). The rapid growth of BP density at mid-latitudes appeared to be occurring at the same time as the rapid increase in the number of sunspots being produced at the same latitudes—those spots belonged to the new sunspot cycle. M2014 deduced that the switch-over, transition, or annihilation of the oppositely polarized magnetic bands at the equator was a required event to trigger the emergence of new cycle spots at mid-latitudes. These events were deemed to mark the termination, or death, of the old magnetic activity bands at the solar equator, and hence were the transition points from sunspot cycle 22 to 23 (in 1997) and from sunspot cycle 23 to 24 (in 2011). M2014 inferred that the enhanced BP density bands were intrinsically tied to the Sun’s 22-year magnetic polarity cycle\textsuperscript{17} and that the interaction of those activity bands was responsible for the modulation of the sunspot pattern (see below). The “termination” events, or “terminators,” that are described in M2014 took place over a time span around one solar rotation—on the face of it, an incredibly short timescale for a process inside a star. Exploring their duration in more detail motivates this manuscript, what might we learn about the state of the solar interior by considering these “events”?

In the following we will introduce and illustrate certain concepts from M2014 and demonstrate the appearance of terminators in a host of solar features, measures, and standard indices going back nearly 140 years. Culminating in the contemporary era, we’ll revisit M2014’s terminators in the 22-year long record of coronal images taken by the Extreme-Ultraviolet Imaging Telescope (EIT\textsuperscript{18}) on the Solar and Heliospheric Observatory (SoHO), the Extreme-Ultraviolet Imagers (EUVI\textsuperscript{19}) on the twin STEREO spacecraft and the Atmospheric Imaging Assembly (AIA\textsuperscript{20}) on the SDO spacecraft in the 19.5 and 19.3nm broadband channels. While the contemporary dataset permits a more precise timing and longitudinal exploration of the most recent terminator, examination of the entire record offers possible insight into the physics of the solar interior, how it constructs the patterns of solar activity, and the possible importance of terminators in the latter.

**Terminators in the Historical Record**

Panel A of Fig. 1 shows the familiar, quasi-cyclic number of sunspots present on the Sun since 1860—a modulation that has been observed and puzzled generations of scientists for over 400 years\textsuperscript{1}. As discussed above, despite decades of research, this coarsest measure of solar variability remains a quintessential enigma of astrophysics. Panel B of the figure adds to the complexity of sunspot evolution by demonstrating the evolution of spots in latitude and time. This plotting method results in the eponymous “butterfly diagram” of the Maunders\textsuperscript{16}, because the cross-equatorial group of spots presented in each solar cycle resembles the outstretched wings of a butterfly. The keen reader will note that, on each of these panels, we have drawn dashed vertical lines which fall at neither solar maximum (the peak of sunspot activity), nor at solar minimum (the bottom of sunspot activity), instead appearing, apparently, just after the start of the sunspot cycles, the “ascending phase”. These dashed lines were presented by M2014 as the times when the area of the sunspots on the disk became greater than 100 millionths of the Sun’s disk area following sunspot minimum. This designation in M2014 was motivated by their noticing the aforementioned terminator events in EUV BP density of 1997 and 2011 that were coincident with a very rapid onset of sunspot appearance and area in both solar hemispheres, on both occasions. In an effort to extend their analysis to times before EUV BPs were available, and also to compare with other recent observables, their analysis
**Figure 1.** Solar activity over the past 140 years (1860—2020) through the observed variation in sunspot number, their distribution with latitude, and the M2014 “band-o-gram”. In panel A, we show the daily total sunspot number with a 50-day running average overplotted in red. The $\sim$11-year quasi-cyclic variability is clear. In panel B, the sunspot locations are shown, and their extent is indicated by the size of the symbol. Note that the sunspot butterfly wings grow abruptly at latitudes largely inside $\sim 35^\circ$. Panel C shows the “band-o-gram,” a schematic depiction of solar magnetic activity, that is constructed largely from the information in panel B, Table 1, and the methods section. In each panel the vertical dotted lines are the termination events, or terminators, measured by M2014. In the lower two panels, for reference, we show dashed and dot-dashed lines at 35° and 55° latitude, respectively.

used a threshold, 100 millionths of the solar disk area covered by sunspots, to identify possible termination events and placed them in Table 1 of the paper. The dashed lines present in Fig. 1 are taken from that table and are provided again, in Table 1 with other climatalogical measures.

M2014 constructed the band-o-gram schematic shown in panel C (described in more detail in the methods section). The band-o-gram is constructed using only three pieces of information in each cycle, the time of sunspot maxima in each solar hemisphere and the terminator. The colors of the bands represent the polarities of the underlying magnetic system with red being positive and blue being negative. The demonstrated progression at high latitudes, above 55°, is defined by the average evolution of features (7°/yr) and was prescribed to be identical for each cycle as there was not enough information to constrain their variability. In the M2014 picture, the time at which the band departs from 55° in each hemisphere—with a poleward and an equatorward branch of the same polarity—is set to the time of sunspot maximum.
for the band at low latitudes in that hemisphere. M2014 then makes a (linear) approximation that the migratory speed from high to low latitudes is set by the hemispheric maximum and terminator at the equator (∼2.75°/yr). M2014 also identified that time between alternating hemispheric maxima — those of the same leading polarity — was approximately 21.6 years. This last point permitted the projection of the cycle 24 bands and the prediction of the onset of the bands that would give rise to cycle 25 sunspots, both recently confirmed to be following the projected path. The expectation is that the next terminator will take place late in 2019, or early in 2020, and will trigger the growth of sunspot cycle 25.

Figure 2. The 140 year record of solar filaments as observed in Hα observations from three sites—Arcetri Astrophysical Observatory (AO; 1880-1929), Meudon Observatory (MO; 1919-1989), and the Kislovodsk Observatory (KO; 1980-2018). Panel A shows the variation in the total number of filaments observed, for AO the data is provided on an annual basis, MO on a 28 day rotational basis, and KO on a daily basis. Panel B shows the composite variation of the annual filament number density as a function of latitude and time (cf. Fig. 1B) in inverted grayscale. Panel C contrasts the sunspot butterfly pattern in gray with the modulation of the highest latitude filaments present at each timestep (red—north, blue—south) and each observatory. In each figure we show the locations of the terminators as provided by M2014 as vertical dotted lines (see above). In panels B and C we also show the dot-dashed lines at 55° in each hemisphere for reference.

Records of solar features of comparable length to the sunspot observations shown in Fig. 1 are rare. Figure 2 presents a composite record of solar filaments from 1860 to the present. This composite record is constructed from observations taken at the Arcetri Astrophysical Observatory, the Meudon
Observatory\textsuperscript{24} and the Kislovodsk Observatory\textsuperscript{25}. Filaments are condensates of solar plasma suspended by complex, rope-like, magnetic structures that form at magnetic polarity inversion lines\textsuperscript{26}. Efforts to detect, catalog, and assess the variation of these features on the solar disk have been many\textsuperscript{27, 28}. Note that number density of filaments shown in panel A seldom reaches zero, but is clearly quasi-periodic like its sunspot counterpart in Fig. 1A.

In addition to the correspondence between the terminators and the rapid growth of the sunspot butterfly wings, the reader will note from panels B and C of Fig. 2 that the terminators coincide with a repeated symmetry in filament evolution on this global scale. The enhanced fingers of filament density that extend beyond 55° latitude belong to an event\textsuperscript{11, 27} known as the “rush to the poles.” This event occurs once roughly every 11 years and is part of the Sun’s polar magnetic field reversal process\textsuperscript{1}. From panel C we see that the start of the rush to the poles, as visualized in the timeseries of the highest latitude filament in each hemisphere, appears to be strongly synchronized across the equator - the feature appears to start at identical times in each hemisphere - even though hemispheric sunspot activity can often display lags of several years\textsuperscript{1, 29}. Further, it appears that the apparent synchronization at high latitudes is strongly coincident with the terminators of M2014 and the initialization of the butterfly wings. It would therefore seem reasonable to assume that the relationships observed are no fluke, the 140 year record of correlated behavior points to a (strong) coupling between these magnetized systems, and that the terminator plays a critical role, or is a bi-product of, this coupling. While we will offer no explanation in this paper, the strong repetition of the filament timeseries visible in Fig. 2C and the strong bounding of 55° latitude on filament production should provoke investigations into the underlying flow patterns at those latitudes, as illustrated in M2014\textsuperscript{*}. Note that these observations will permit tweaks, especially at high latitudes and in early years, to be made to the M2014 band-o-gram where previously only the sunspot butterfly diagram was available (Fig. 1B), but that is beyond the scope of the present work.

**Terminators and Solar Activity Proxy Indices**

Since the dawn of the space age, as a means to evaluate the impact of the Sun on our atmosphere and the near-earth space environment, our community has made routine sun-as-a-star measurements. Fig. 3 shows the variation of just three in contrast with measures that we’ve introduced earlier in the sunspot number (Fig. 3A), sunspot butterfly and the M2014 band-o-gram (Fig. 3B). Panels C through E show timeseries of three canonical solar activity indices: the “f10.7” 10.7cm radio flux; the Bremen Mg II index; and the GOES 1-8Å (integrated) x-ray luminosity, respectively. Each of the these indices can be compared against the band-o-gram, the butterfly plot and the terminators, as we have above. The chromospheric MgII index shows a small jump (1–3%) at the terminators, with some being stronger/clearer than others. The two coronal measures, f10.7 and GOES, show jumps in value of order 30 and 50%, respectively. Similarly, the index can have a small up-swing in value before the step function that we might associate with the death of the last cycle at the equator. These pre-termination upswings in the sun-as-a-star indices could be caused by pulses of residual equatorial activity\textsuperscript{30} (see, e.g., the 2011 example), and/or by the small spots that occur for several rotations at the same longitude prior to the ramp-up in the butterfly wings\textsuperscript{1} (see, e.g., the 1977 example). These abrupt, step-like, changes in solar activity have been previously identified in radiative proxies and have been associated with solar-cycle start-up and solar cycle prediction\textsuperscript{31, 32}.

**Contemporary Terminators**

To this point we have dealt with measures that show the presence of terminators, and their apparently abrupt nature. Recalling the statement of M2014 that these events occur in “around one solar rotation”,

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*Editorial: that is, there’s something fundamental lurking there!*
Figure 3. Hemispheric sunspot variation, band-o-gram comparisons and the signature that terminators present in sun-as-a-star, proxy, measurements over the past 60 years. Panel A expands on earlier figures, showing the total (black) and hemispheric sunspot numbers (red—north; blue-south) with their maxima as correspondingly colored vertical dashed lines. Panel B show a comparative overlay of the sunspot butterfly diagram (Fig. 1B) and the M2014 band-o-gram (Fig. 1C) in this timeframe. Panel C shows the weekly average of the Pentincton 10.7cm radio flux from the Sun (“f10.7”). Panel D shows the variation of the composite MgII index provided by the university of Bremen (black) with the 50day running average overplotted in red. Panel E shows the integrated (1-8Å) coronal irradiance constructed from the fleet of NOAA GOES spacecraft, again with the 50day running average overplotted in red. In each panel we show the locations of the M2014 terminators as vertical dotted lines.

can we use contemporary data to investigate how quickly the transition between solar cycles might be?

Figure 4 shows a 6-month span around the 1997 (panel A) and 2011 (panel B) termination events to highlight the abrupt change in BP density occurring at the end of solar cycles 22 and 23, respectively. As above, the band-o-gram portion in panel C, illustrates the interaction and progression of the overlapping, polarized magnetic bands with latitude in the same timeframes. We see that despite the differing spatial resolutions of EIT and AIA and the lower cadence of images used (four per day for EIT, twenty-four per day for AIA), the changes to the system seem to be grossly reproduced in these events that are approximately fourteen years apart. Note that the BP densities plots shown in this article illustrate the
latitudinal distribution of BPs over the 5° wide band centered on the Sun’s central meridian relative to each spacecraft.

**Figure 4.** Visualizing the termination of magnetic activity bands. Latitude-time variation of EUV Brightpoints (BPs) for SOHO/EIT 195Å through the solar cycle 22/23 minimum (1997-1999; A) and the solar cycle 23/24 minimum (2010-2012; B) for SDO/AIA 193Å. The rapid decrease, or “termination,” of the activity related to EUV BPs at the equator is clear. The apparent termination of the bands belonging to the 22-year solar magnetic activity cycle are marked, by eye, as August 1997 and February 2011 with vertical dashed yellow lines. Panel C shows the band-o-gram of Fig. 1, reduced to the SOHO/STEREO/SDO epoch. The red and blue colored migrating bands illustrate a positive and negative magnetic polarities, respectively. The boxed regions in panel C illustrate the time-frame studied in Panels A and B and below.

Figure 5 shows the 1997 terminator in more detail, noting that the BP density plots shown are saturated to bring out weak variations. In panel A we delineate the low latitude, equatorial, region around the solar equator [± 7.5°] by green dashed lines from the northern (15° wide and centered on 22.5°) and southern (15° wide and centered on -27.5°) hemispheric mid-latitude bands using red and blue dashed lines, respectively. The central latitude and width of the activity bands (15°) in each case studied herein have been established by Gaussian fits to the latitudinal BP density distributions as illustrated in Fig. 3 of M2014. The equatorial band width was chosen to match those of the mid-latitudes. The average BP density in each region is shown in panel B by traces of the same color and introducing an average of the mid-latitude activities with a black line. We note that the solar cycle 23 activity bands are offset slightly in latitude due to the 2-year hemispheric phase lag in activity. Since we wish to study the relative evolution of the mid-latitude activity bands compared to the equatorial region, panel C of the figure shows the difference in the BP density between the equatorial and hemispheric bands as blue and red curves while the difference between the equatorial and hemispheric average is black. We note that the vertical dashed
Figure 5. The 1997 hand-off between solar cycles 22 and 23 from the perspective of SOHO. Comparing Panel A with the corresponding panel of Fig. 4 we show the latitude-time variation of EUV Brightpoints for SOHO/EIT 195Å through the solar cycle 22/23 minimum (1997–1999). On this plot three regions are identified, one equatorial (bounded at ±7.5° latitude by green dashed lines), one on the northern activity band (15° wide, centered on 22.5° latitude, bounded by red dashed lines), and another on the southern activity band (15° wide, centered on -27.5° latitude, bounded by blue dashed lines). Panel B shows the corresponding latitudinally-averaged BP density in green, red and blue while the black line illustrates the average BP density of two mid-latitude bands. Panel C shows the difference between the equatorial and northern BP density (red), the equatorial and southern BP density (blue) and the equatorial and hemispherically averaged BP density (black). Also shown is a 28-day running average of the equatorial and hemispherically averaged BP density - the smoother black line. The vertical dashed lines in each panel are drawn at August 1, 1997.

line is midnight (universal time) on August 1, 1997 and that the tick marks on the horizontal (time) axis are one terrestrial month apart. That point in time sees a 100% growth in BP density on the mid-latitude bands and a 100% decline in BP density at low latitudes within only a small number of solar-rotations. Note also that following the termination point, there is a significant increase in the variability of the signal
in the activity bands in both hemispheres—increasing the RMS of the BP density by an average of 1 BP per degree per day. In other words, the activity bands at the equator significantly decreased in activity while those at mid-latitudes saw a significant increase at approximately the same time.

**Figure 6.** The 2011 hand-off between solar cycles 23 and 24 from the perspective of SDO. Comparing Panel A with panel B of Fig. 4 we show the latitude-time variation of EUV Brightpoints for SDO/AIA 193Å through the solar cycle 23/24 minimum (2010-2012). On this plot three regions are identified, one equatorial (bounded at ±5° latitude by green dashed lines), one on the northern activity band (15° wide, centered on 17.5° latitude, bounded by red dashed lines), and another on the southern activity band (15° wide, centered on -22.5° latitude, bounded by blue dashed lines). Panel B shows the corresponding latitudinally-averaged BP density in green, red and blue while the black line illustrates the average BP density of two mid-latitude bands. Panel C shows the difference between the equatorial and northern BP density (red), the equatorial and southern BP density (blue) and the equatorial and hemispherically averaged BP density (black). Also shown is a 28-day running average of the equatorial and hemispherically averaged BP density - the smoother black line. The vertical dashed lines in each panel are drawn at February 11, 2011.

The EIT observations support the M2014 picture—one where the oppositely polarized magnetic activity
bands of the 22-year magnetic activity cycle meet and cancel at the solar equator. It would appear that the occurrence of this “event” at the equator is abrupt with the large change in the mid-latitude BP density occurring in close conjunction. Rapid growth of activity occurs on those mid-latitude bands—presumably due to a rapid increase in the rate of magnetic flux emergence therein, following the termination. Based on the EIT observations and analysis, the switch over between low and mid latitudes occurred on a timescale less than a rotational period, or 28 days, but we cannot be much more precise—better signal, and/or multi-viewpoint observations are required.

Figures 6, S1, and S2 show the equivalent plots of Fig. 5 for the termination event of 2011 from the SDO and the two STEREO spacecraft, respectively. During this time period the observations from the three spacecraft simultaneously covered every solar longitude, marking the first time in human history that such observations were available. Ordered in advancing heliographic longitude, where Fig. S1 explores the latitudinal BP density observed from STEREO “B”—behind the Sun-Earth line, Fig. 6 from SDO on the Sun-Earth line (cf. Fig. 1), and Fig. S2 shows that from STEREO “A”—ahead of the the Sun-Earth line. In each figure the vertical dashed lines mark a reference date of midnight (universal time) on February 11, 2011 and, again, that the tick marks on the horizontal (time) axis are one terrestrial month apart. Also, given the longitudinal separation of the observations, these three figures represent BP evolution centered on different longitudes - a feature we will take advantage of below. For this timeframe we delineate the low latitude, equatorial, region around the solar equator (± 5°) by green dashed lines from the northern (15° wide and centered on 17.5°) and southern (15° wide and centered on -22.5°) hemispheric mid-latitude bands using red and blue dashed lines, respectively. As above, the band thickness (15°) is established by Gaussian fits to the latitudinal BP density distributions from M2014 specific to solar cycle 24. The closer proximity of the mid-latitude active bands to the equator means that limit the equatorial region to only 10° wide to minimize the inclusion of that signal in the analysis (see below). The information in the three figures quantitatively behave in a similar fashion to that of Fig. 5; approximate order of magnitude decrease at the equator and a step-like, rapid, increase at mid-latitudes occurring on the timescale of a solar rotation. In each case we also note the relative post-termination growth in the southern hemisphere is about half of that in the North. We believe that this difference is tied to the 2-year hemispheric activity asymmetry exhibited during this epoch, mentioned earlier²⁹.

Figure 7 compares the equator to mid-latitude average BP density differences in these three cases. Comparing the three curves in panel A we can see that the signals around February 11, 2011 are longitudinally offset from one another. Cross-correlation of the timeseries (Fig. S3) indicate that the STEREO-A signal leads that of AIA by 8 days and that of STEREO-B by 15 days. Panel B shows the BP density differences time-shifted by the appropriate lag-times and we see a strong correspondence in the timeseries, especially around February 11, 2011. Note that, towards the end of the timeseries shown, those lag-time values become increasingly inaccurate due to the continued drifting of the STEREO spacecraft relative to the Sun-Earth line which slowly increases the longitudinal separation of the signals. The temporal offset between the three spacecraft would appear to indicate that the cycle termination event is strongly longitudinal and rapid in nature - possibly occurring in a fraction of a rotation. Following the termination, activity at mid-latitudes, and following longitudes, is rapidly elevated to a new level. This new plateau of activity is shown in Fig. 8 from the SDO perspective - the Sun does not appear to drop below that level for many years.

Figure 7 and 8 can be compared with the Fig. S4 that shows SDO/STEREO BP Hovmöller diagrams (longitude-time plot at fixed latitudes) of the same activity and equatorial regions as explored in Figs 6, S1, S2. Note that activity is reduced rapidly at a narrow range of longitudes at the equator before rapidly spreading across all longitudes (within one rotation). In the same epoch several longitudes are enhanced on the activity belts at the terminator with more longitudes growing subsequently, and the north notably
Figure 7. Comparing the difference in equatorial and mid-latitude average BP densities from three longitudinal vantage points. Panel A shows the equatorial-to-mid-latitude differences in BP density from STEREO-A/EUVI, SDO/AIA, and STEREO-B/EUVI are shown as red, blue, and green lines, respectively (cf. Figs 6, S1, and S2). Panel B shows the same BP density differences shifted by the maximum lag of their cross-correlation (Fig. S3). For reference in each panel we show a vertical dashed line at February 11, 2011 and dotted lines at differences of 0 and 1 to illustrate the jump in values.

within two or three rotations. This step-like longitudinal growth of activity is supported for the 2011 event by recent investigations of the Sun-As-A-Star irradiance at many wavelengths (e.g., Figs. S6 and S7) and by a host of other resolved observations from space\textsuperscript{34,35}, including the unsigned magnetic field in the activity bands (e.g., Fig. S5).

Discussion

In the preceding sections we have shown abundant examples of what appear to be significant, landmark, times in the progression of solar activity, termination points, or “terminators,” going back nearly 140 years in the observational record. First identified by McIntosh et al.\textsuperscript{14}, these events marked the transition
Figure 8. Comparing the EUV Brightpoint density butterfly plot and traces of activity over the entire SDO mission. From top to bottom, the BP density of Fig. 6 extended to the eight year mission with the best-fit activity band centroids an equatorial band shown as solid lines with only a 10 degree wide region around their center. Panels B through D show the variability along each band, north, equator and south respectively. Each plot shows the native BP density averaged over the band (black), that averaged over one rotation in blue and over four solar rotations in red. For reference the averages of the six months before and after the 2011 termination point are shown as dashed lines. Panels B and D show the “before” line continued after the termination event as a green dashed line. In these plots the step-like variation immediately following the termination event is clear. Similarly, it is clear that while the BP densities exhibit smooth variability following the terminator, they do not return to their pre-event values for many years. The equatorial region recovers first, but that is likely the result of the encroachment of the mid-latitude bands in to the equatorial range of latitudes.
from the final embers of the last sunspot cycle to the ignition of the next one as the times of significant sunspot occurrence after the quiet of solar minimum. Those events appeared to take place on a timescale close to one solar rotation. Comparing the sunspot progression with the record of the highest-latitude Hα filaments over the same epoch we see that the terminators not only coincided with the rapid growth of Maunder’s butterfly wings at $\sim 30^\circ$ latitude, but they also coincide with the initialization of the “rush to the poles” in both solar hemispheres in all examples observed—some thirteen solar cycles. Noting again the synchronization of the latter even though, in most cases, sunspot activity is asymmetric across the equator by as much as a few years.

Considering indices of solar activity that are available from the start of space age we see that the terminators demonstrate a very rapid jump in activity. The upward step in the proxy appears to grow with the apparent temperature of the region where the proxy is formed—lower in the chromosphere and significantly higher in the corona, as also pointed out in the community literature$^{31,32,34,35}$. It is beyond the scope of this article to explore in depth, but it would be a fruitful exercise to collate the various proxy measurements and algorithmically apply statistical methods$^{36}$ such as “step detection” to more precisely identify and catalog the termination events and investigate their multi-spectral magnitude.

Further, we have presented data from four contemporary spacecraft spanning the timeframes that include the termination of sunspot cycles 22 (in 1997) and 23 (in 2011) through the observations of BPs. The 2011 event, in particular, illustrates the dramatic change in solar flux emergence between the low and mid-latitudes associated with a terminator. Based on the analysis of the SDO and STEREO BP densities we deduce that the timescale for the terminator could be less than one solar rotation. The joint analysis, covering every solar longitude, indicates that the terminator is a very strong longitudinal event. Observed by each spacecraft, the transition of activity occurs very rapidly at a few longitudes before spreading to more longitudes over the next couple of rotations.

**Potential Mechanisms**

Clearly, given the broad range of signatures observed, these termination events mark abrupt changes in the Sun’s magnetic evolution. In the following paragraphs we will discuss a number of possible mechanisms for how such abrupt changes in solar magnetic output could occur.

2014 inferred that the modulation of the sunspot cycle occurred via a process that they dubbed “magnetic teleconnection.” M2014 defined this term as an analog to the term “teleconnection,” which refers to climate anomalies being related to each other at large distances on the globe$^{37}$. In short, magnetic teleconnection was proposed to describe the magnetic interactions inferred to take place between the oppositely polarized, overlapping magnetic bands of the 22-year long solar magnetic activity cycle within a solar hemisphere and across the solar equator (see, e.g, Fig. 8 of M2014, and the discussion in the methods section). In that picture, termination events signal the end of one magnetic (and sunspot) cycle at the solar equator and the start of the next sunspot cycle at mid-latitudes - acknowledging that the bands of the magnetic cycle have been present for some considerable time before the termination. Now, we have seen that they likely also relate to the start of the rush to the poles, and polar reversal process, at high latitudes. If so, the speed over which these repeated transitions occur could provide critical physical insight into coupling of the activity bands in the solar interior, if that occurs at all.

In a magnetized convecting plasma “information” can be carried in a multitude of ways. Conventionally we think of waves as the means of communication, much like sound waves carry information between humans Alfvén waves can carry magnetic information$^{38}$ in a plasma. The relationship between the measured Alfvén speed ($V_A$), plasma density and magnetic field strength ($V_A = B/\sqrt{4\pi\rho}$) gives us the ability to estimate the mean magnetic field strengths in the domain the information travels through from the transit-time estimate determined above.
An Alfvén transit time of a few days, using eight as a possible lower bound, with a transit distance of ±25° (≈219 Mm) to the mid-latitude of the new activity bands, would require the presence of magnetic fields (which can be in fibril form) with a poloidal field strength of about 50kG. Assuming an averaged tilt angle of 7 degree for the fields, this would imply a total field strength of about 400 kG, a magnitude supported by estimated rise times of strong magnetic flux elements at mid-latitudes. This is considerably larger than the 40 kG to 100 kG field strength range anticipated in that region, based on calculations of rising thin flux tubes that can produce tilt angles of solar active regions that are consistent with observations. Note that, for reference, state-of-the-art convective dynamo models are able to produce mean fields of the order of 7 kG although localized regions can reach as much ∼30 kG.

Further, if Alfvén waves are responsible for carrying the information from the termination of one cycle to the ignition of a new cycle at mid-latitudes in a matter of a few days then it would appear that the Sun’s dynamo may be operating in a regime where the magnetic fields present in the Sun’s convection zone are dynamically important. That is, the magnetic field strength is in a state of “super-equipartition” relative to convection. While there have been limited theoretical considerations, there are no numerical convective dynamo models operating in that regime despite indications that considerably increasing simulation resolution sees a trend of developing small scale magnetic fields that become significantly super-equipartition compared to the convective flows.

In a similar vein, we estimate the approximate timescale for giant-cell convection to carry the information about the cycle termination from equator to mid-latitudes. Based on estimates of the turbulent diffusion time scale at a giant cell scale ($L_{GC}$) of about 400 Mm, and a typical kinetic energy density of $10^6$ erg/cm$^3$, gives a velocity magnitude ($v_{GC}$) of about 34 m s$^{-1}$. In this case, the ∼25° distance ($D=219$ Mm) via turbulent diffusion would take about $D^2/(v_{GC}L_{GC})$, or around 40 days, still longer than that observed, but not by much.

Another possible mechanism for rapid transport of information in the convective interior could come in the form of (internal) gravity waves in the solar tachocline—the shear layer between the Sun’s radiative interior and convection zone (see Fig. S8). The propagation speed of gravity waves in the solar tachocline is dependent on the thickness of the layer, the sun’s gravity at that depth, and departures of the stratification from the adiabatic state, $\delta$, such that $v_{gw} = 1.23 \times 10^7 \ \delta^{1/2} \ \text{cm s}^{-1}$. Typical values of $\delta$ of the top of the tachocline (∼0.001) and at the center of the tachocline (∼0.04) would respectively yield travel times from the equator to mid-latitudes of around 4 days and 4 hours, respectively, depending on where the wave is triggered. A sudden cancellation of toroidal fields of opposite signs on either side of the equator could excite such a gravity wave because the top boundary of the tachocline would quickly sink down in response to the loss of magnetic pressure. This depression would propagate toward higher latitudes rapidly perturbing the activity bands at mid and high latitudes. This last example would take the form of a “buoyancy” wave on the solar tachocline which could conceivably explain the rapid magnetic flux emergence at mid-latitudes and high-latitudes in a fraction of a solar rotation.

The Next Terminator

Fortunately the cyclic, and somewhat predictable, behavior of the magnetic activity bands point to a terminator occurring in late 2019 or early 2020 when the activity bands of sunspot cycle 24 reach the equator, and eventually terminate. This event should permit the growth of activity in what will become sunspot cycle 25 (see, Fig. 4C) and launch the rush to the poles that will eventually seed sunspot cycle 26. We note that the Parker Solar Probe will be ideally suited to observe this event in interplanetary space with STEREO-A while assets on the Sun-Earth line, like SDO, the Interface Region Imaging Spectrograph (IRIS) and the Daniel K. Inouye Solar Telescope (DKIST) will allow us to probe the possible excitation and transport mechanisms at play.
Conclusion

To conclude, the observations presented herein would appear to support a regime where the magnetic fields present in the Sun’s convection zone interact each other at all times, or could even be dynamically important. This result gives strong support to the idea that the manifestation of the Sun’s large-scale activity, like the sunspot cycle, is heavily modulated by the interaction and communication of the magnetic systems present in the convection zone. Furthermore, the potential of a terminator event in the next couple of years should lend itself to extensive observational study by the vast array of assets at our disposal, in addition to the array of cutting-edge numerical models attempting to explain their occurrence and phasing in increasingly realistic environments.

Methods

In the following subsections we will briefly discuss three of the guiding concepts used in the paper that were original presented in M2014: fitting BP activity bands, the data-driven band-o-gram, and the term magnetic teleconnection.

Fitting and Tracking BP Distributions

Section 2.1 of M2014 describes the multi-step process by which the activity band positions and widths are determined as they pertain to the analysis above, and Figs. 4, 5, 8, S1, and S2.

Constructing The “Band-O-Gram”

M2014 demonstrated that the sunspot cycle landmarks, the maxima of the hemispheric sunspot number and the terminators can be used to construct a schematic picture of global-scale solar activity—the band-o-gram (e.g., Figs. 1, 3 and 4). The band-o-gram is used to illustrate the progression of the magnetic activity bands that belong to the Sun’s 22-year magnetic activity cycle. Table 1 contains the basic information required to construct a band-o-gram as determined from the data presented in this paper. We note that the band-o-gram contains no specific information about the magnitude or strength of the magnetic field present in the activity bands and should not be interpreted as having any. The band-o-gram has two basic elements, that above and that below 55°.

The lower-latitude bands start at 55° and migrate linearly (a stated approximation of M2014) to the equator. The resulting pattern is one of overlapping chevrons (as per Fig. 1), where the branches of the chevron, the activity bands, in each hemisphere alternate in magnetic polarity as deduced by Hale\textsuperscript{17}. The individual activity bands are drawn using the hemispheric maxima as the starting point and the terminator as the end. The times of hemispheric maxima are determined using the monthly hemispheric sunspot number (e.g., Fig. 3) and the terminators are defined as the time when the post solar minimum coverage of sunspots exceed 100 millionths of the solar disk area. The average band migration time is \(\sim 19.5\) years (see Tab. 1), which yields an average band migration speed of \(\sim 2.8°\) per year. As seen in Fig. 3, these simply defined bands enclose the majority of sunspots observed. M2014 noted that activity bands of the same magnetic polarity start their migration very close to 22 years apart (\(\sim 21.6\) years as per Tab. 1).

From M2014 the high latitude bands bifurcate at 55° and propagate poleward. However, those bands progress at slowly increasing speed with latitude. Each new band has the same polarity as that moving equatorward—the opposite polarity of the region which eventually results in the reversal of the region. The band-o-gram high latitude behavior is modeled after the Doppler measurements of the Sun’s zonal flow over several decades by Ulrich\textsuperscript{21} and the torsional oscillation\textsuperscript{11,45} such that it matches the latter over many decades, as shown in M2014. The evolution shown at high latitudes has no variability—it is an average behavior. A comparison of Fig. 1 and 2 indicates that the filament record could be used to modify the
**Table 1.** Features required to build a band-o-gram, converted from Table 1 of M2014. From left to right we provide the sunspot cycle number; the start times of the bands in each hemispheric (the time of the previous hemispheric maxima); the difference between hemispheric maxima ($\delta = T_N - T_S$) where red indicates north leading and blue for the south; the time between hemispheric maxima of the same magnetic polarity ($\delta_N$ and $\delta_S$); the terminator; the time elapsed since last terminator ($\Delta$); and the hemispheric high–low latitude transit time ($\tau$) for Each Hemisphere. As a reminder, $T_{N,S}$ is hemispheric sunspot maximum and, as per M2014, is also the first incursion of the band that becomes the upcoming sunspot cycle.

| Cycle # | $T_N$ (yr) | $T_S$ (yr) | $\delta$ (yr) | $\delta_N$ (yr) | $\delta_S$ (yr) | Terminator (yr) | $\Delta$ (yr) | $\tau_N$ (yr) | $\tau_S$ (yr) |
|---------|------------|------------|---------------|----------------|----------------|----------------|-------------|--------------|--------------|
| 12      | ...        | ...        | ...           | ...            | ...            | 1891.30        | ...         | ...          | ...          |
| 13      | 1884.00    | 1883.83    | 0.17          | ...            | ...            | 1904.75        | 13.45       | 20.75        | 20.92        |
| 14      | 1892.50    | 1893.58    | -1.08         | ...            | ...            | 1915.05        | 10.30       | 22.55        | 21.47        |
| 15      | 1905.75    | 1907.08    | -1.33         | 21.75          | 23.25          | 1925.67        | 10.62       | 19.92        | 18.59        |
| 16      | 1917.58    | 1919.50    | -1.92         | 25.08          | 25.92          | 1935.75        | 10.08       | 18.17        | 16.25        |
| 17      | 1925.92    | 1926.08    | -0.16         | 20.17          | 19.00          | 1945.75        | 10.00       | 18.83        | 19.67        |
| 18      | 1937.50    | 1939.67    | -2.17         | 19.92          | 20.17          | 1955.75        | 10.00       | 18.25        | 16.08        |
| 19      | 1949.17    | 1947.17    | 2.00          | 23.25          | 21.08          | 1966.50        | 10.75       | 17.33        | 19.33        |
| 20      | 1959.08    | 1956.83    | 2.25          | 21.58          | 17.17          | 1978.00        | 11.50       | 18.92        | 21.17        |
| 21      | 1968.00    | 1970.08    | -2.08         | 18.83          | 22.92          | 1988.50        | 10.00       | 20.50        | 18.42        |
| 22      | 1979.67    | 1980.33    | -0.66         | 20.58          | 23.50          | 1997.75        | 9.25        | 18.08        | 17.42        |
| 23      | 1989.08    | 1991.08    | -2.00         | 21.08          | 21.00          | 2011.20        | 13.45       | 22.12        | 20.12        |
| 24      | 2000.50    | 2002.58    | -2.08         | 20.83          | 22.25          | ...            | ...         | ...          | ...          |
| 25      | 2011.80    | 2013.95    | -2.15         | 22.72          | 22.87          | ...            | ...         | ...          | ...          |

Means: 21.44 21.74 10.85 19.67 19.04
Std. Dev.: 1.74 2.40 1.40 1.71 1.88

High-latitude evolution of the band-o-gram: the timing of the rush to the poles is related to the terminator, not the hemispheric maxima, and that there is considerable variability in the speed of poleward migration about the average. Similarly, the highest latitude filament traces out the path of the polarity inversion line between the old polar field and the new and so it could be used to more accurately represent the migratory speed in that part of the system. Such alterations are beyond the scope of the present paper.

**Magnetic Teleconnection**

“Magnetic Teleconnection” is the phenomenological process proposed by M2014 to describe how the large-scale magnetic systems of the solar interior of the Sun’s 22-year magnetic activity cycle might interact to produce the 11-year modulation of sunspots and the butterfly diagram (see Fig. 1). The interested reader can refer to Fig. 8 of M2014 which pictorially describes the process, but can refer also to Figs. 1, 3 and 4.

Our use of the term draws from the meteorological equivalent—teleconnection$^{46}$—where atmospheric low-frequency variability (like planetary waves) over timescales of several weeks to several years, are temporally correlated between physical locations that are geographically separated. The North Atlantic Oscillation (NAO) and the El Nino Southern Oscillation (ENSO) are examples of teleconnection phenomena. It is accepted that (internal) gravity waves play the role of moderator between the various circulatory patterns and planetary waves.
We are describing the possible band-to-band interactions between strong oppositely polarized magnetic flux systems that are born out of the 22-year magnetic activity cycle inside, and outside of, a solar hemisphere. Taking the example of Fig. 4 as an example, and noting that the band-o-gram pattern is replicated approximately every 22-years, the bands giving rise to sunspot cycles 22, 23, 24 and 25 are present. Between 1998 and 2001, following the 1997 terminator, the principal interactions are between the positive and negative bands $30^\circ$ either side of the equator—sunspots are growing rapidly in this two band system. M2014 noted that the incursion of the $55^\circ$ bands in each hemisphere, of opposite polarity to the main band at low latitude, was at the time when sunspot production started to decrease, defining sunspot maximum and, correspondingly, the onset of the descending phase. M2014 interpreted this downturn in the sense that the presence of the oppositely signed band inside each hemisphere created more magnetic connections for the low-latitude bands, reducing their amount of available free flux and hence buoyant ability to make sunspots. Entering into the late descending phase and into solar minimum between 2006 and 2009 all four bands in the system below $55^\circ$ are within $35-40^\circ$ of the equator and the number of spots being produced rapidly declines to zero due to the apparent mutual cancellation of the four magnetic systems. This epoch is broken by the termination of the low latitude bands at the equator in 2011 whence we return to the two band system and sunspot growth in the ascending phase of sunspot cycle 24.

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Author contributions statement

S.W.M. conceived the experiment, S.W.M. and R.J.L. conducted the experiment, Y.F. M.D. and M.R. consulted on physical implications of the result. All authors reviewed the manuscript.

Additional information

The authors declare no competing financial interests.

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**Figure S1.** The 2011 hand-off between solar cycles 23 and 24 from the perspective of STEREO “Behind”. We show the latitude-time variation of EUV Brightpoints for STEREO-B/EUVI 195Å through the solar cycle 23/24 minimum (2010–2012). On this plot three regions are identified, one equatorial (bounded at ±5° latitude by green dashed lines), one on the northern activity band (15° wide, centered on 17.5° latitude, bounded by red dashed lines), and another on the southern activity band (15° wide, centered on -22.5° latitude, bounded by blue dashed lines). Panel B shows the corresponding latitudinally-averaged BP density in green, red and blue while the black line illustrates the average BP density of two mid-latitude bands. Panel C shows the difference in between the equatorial and northern BP density (red), the equatorial and southern BP density (blue) and the equatorial and hemispherically averaged BP density (black). Also shown is a 28-day running average of the equatorial and hemispherically averaged BP density - the smoother black line. The vertical dashed lines in each panel are drawn at February 11, 2011.

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**Figure S2.** The 2011 hand-off between solar cycles 23 and 24 from the perspective of STEREO “Ahead”. We show the latitude-time variation of EUV Brightpoints for STEREO-A/EUVI 195Å through the solar cycle 23/24 minimum (2010-2012). On this plot three regions are identified, one equatorial (bounded at ±5° latitude by green dashed lines), one on the northern activity band (15° wide, centered on 17.5° latitude, bounded by red dashed lines), and another on the southern activity band (15° wide, centered on -22.5° latitude, bounded by blue dashed lines). Panel B shows the corresponding latitudinally-averaged BP density in green, red and blue while the black line illustrates the average BP density of two mid-latitude bands. Panel C shows the difference in between the equatorial and northern BP density (red), the equatorial and southern BP density (blue) and the equatorial and hemispherically averaged BP density (black). Also shown is a 28-day running average of the equatorial and hemispherically averaged BP density - the smoother black line. The vertical dashed lines in each panel are drawn at February 11, 2011.

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**Figure S3.** BP density difference cross-correlation functions. We show the cross-correlation functions of the equatorial-to-mid-latitude differences in BP density between SDO/AIA and STEREO-A/EUVI (red), SDO/AIA and STEREO-B/EUVI (blue) and the twin STEREO instruments (green). In each case we demonstrate the peak cross-correlation lag by a vertical dotted line. For reference the vertical dashed line shows a lag of zero days.

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Figure S4. The longitudinal evolution of the BP density around the 2011 terminator for the northern activity band (A), equatorial region (B), and southern activity band (C) as observed by SDO and the twin STEREO spacecraft. Compare these “Hovmoller” diagrams with Figs. 6, S1, S2, Fig. 9.3 of Wilson, and Fig. 3 of McIntosh et al. (2017) who first identified magnetized Rossby waves in the solar interior. The BP density is constructed using a 28-day running average of instantaneous BP density observed by the three spacecraft - as introduced in the aforementioned paper. The horizontal dashed lines on each panel designate Feb 11, 2011 and the colored dots on those lines indicate the longitude of the central meridian as seen by each spacecraft on that date. Panel D shows running 50-day averages of the daily total and hemispheric sunspot numbers. The gray shaded box outlines the timeframe shown in the upper panels. It should be used by the reader to relate longitudinal surges of solar activity on the activity bands and the gross reduction of activity in the equatorial region that follow the termination with standard candles of solar activity.

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Figure S5. Comparing the absolute value of the average solar magnetic flux in the activity bands of Figs. 6 and S2 used above. The red, green and blue shared regions respectively show the mean value and one standard deviation of variability across the band in each case. The vertical dashed line indicates February 11, 2011 at 00:00UT. The horizontal lines indicate respective average activity levels over the three months before and after February 11, 2011.

Figure S6. The evolution of coronal emission seen from Sun-As-A-Star SDO/EVE spectral irradiance measurements. In the main body of the figure We show the variation of the Fe XIV 211Å coronal emission line as a function of time. The vertical dashed line indicates February 11, 2011 at 00:00UT. The data are normalized such that a large tick mark indicates 100% change after that date. The horizontal lines indicate average activity levels over the three months before and after February 11, 2011. TheInset panel shows the same radiative variability over two solar rotations before and after February 11, 2011. Again, the vertical dashed line indicates February 11, 2011 at 00:00UT and the dotted vertical lines are placed 8 days before and after. One can readily compare the shape of this radiative profile with the EUV BP Density plots in Fig. 7.

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Figure S8. Gravity waves produced in a shallow-water\textsuperscript{49,50} tachocline model are shown in two perspective views. This illustrative case is for the stratification parameter ($\delta=0.001$), characteristic of overshoot tachocline. Left panels represent gravity waves viewed along longitude, and right panels along latitude. Red-orange-yellow denotes the crest of the wave (red denoting the highest part and yellow the lowest part of the crest); indigo-blue-skyblue denotes the trough. Green is neutral. Time goes from top to the bottom. Tachocline gravity waves propagate from the equator to the pole. The vertical white line is overlaid on the right panels to show the propagation of the wave: in the topmost panel the line coincides with the top part of a crest and in the bottommost panel the line coincides with the trough of the next wave. The time difference between the topmost and bottommost frames is about (0.5-1) days in this example. Therefore it should take about 2.5 to 5 days for a gravity wave signal to propagate from the equator to mid-latitudes. Note that in these tachocline dynamics simulations, longitudinally propagating non-axisymmetric modes appear together with gravity waves propagating in all directions. For simplicity, all non-axisymmetric modes (Rossby and gravity waves) have been extracted out, so that the latitudinally-propagating gravity waves are clearly visible.

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