Relationship Between M8+ Earthquake Occurrences and the Solar Polar Magnetic Fields

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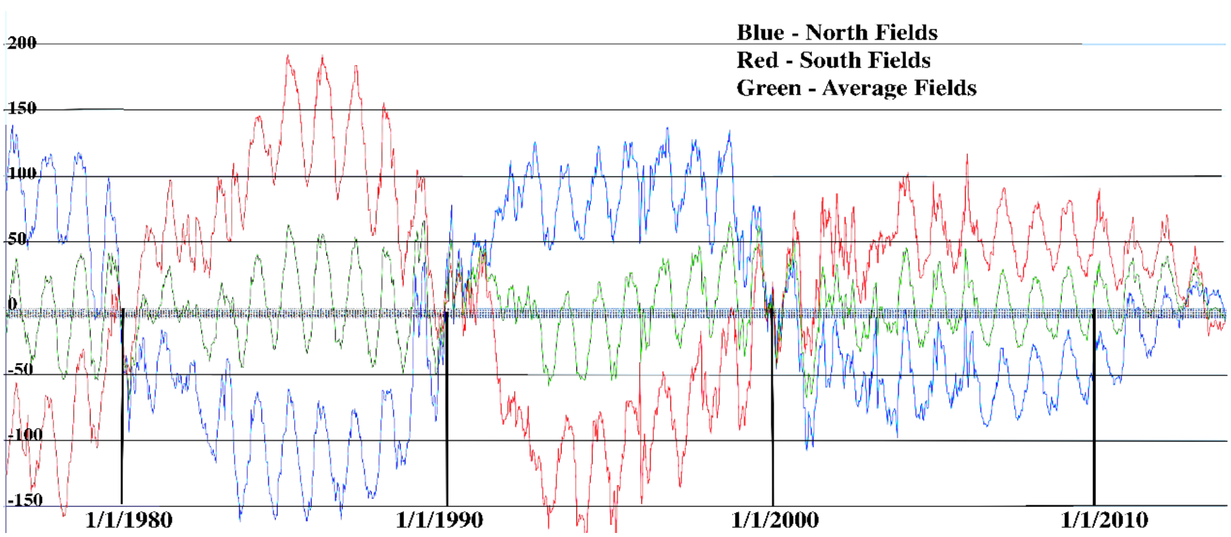
Abstract

The solar polar fields (SPF) data, as measured by the Wilcox Solar Observatory (WSO), has been studied and compared with the large magnitude earthquake record from the United States Geological Survey. The time period covers the 38 years (+13,600 days) that the WSO has collected the SPF data. This study reveals a dependence of M8.0+ seismicity on the oscillations of the SPF; the results and analysis is reported.

1.0 The Solar Polar Fields (SPF)

The sun has north and south magnetic poles that reverse every solar sunspot cycle, or every ~11 years. The SPF measured at earth also oscillate between significantly greater and lesser magnetism over shorter periods of ~1 year. The large ~1-year oscillations in magnetism (Figure 1) can be explained by changes in the heliospheric latitude of earth's orbit (Babcock 1955; Svalgaard 1978). The polar fields on the sun are persistently parallel to the polar fields of earth (Babcock 1959), which means that earth's position in the heliosphere determines which solar pole is closer to earth, and influences which of the SPF is measured more strongly. The SPF have been measured consistently since May 1976, when the Wilcox Solar Observatory (Stanford University) began collecting a running record of 10-day averages. These data can be visually represented as shown Figure 1.

Figure 1: Solar Polar Magnetic Field Strength in μT



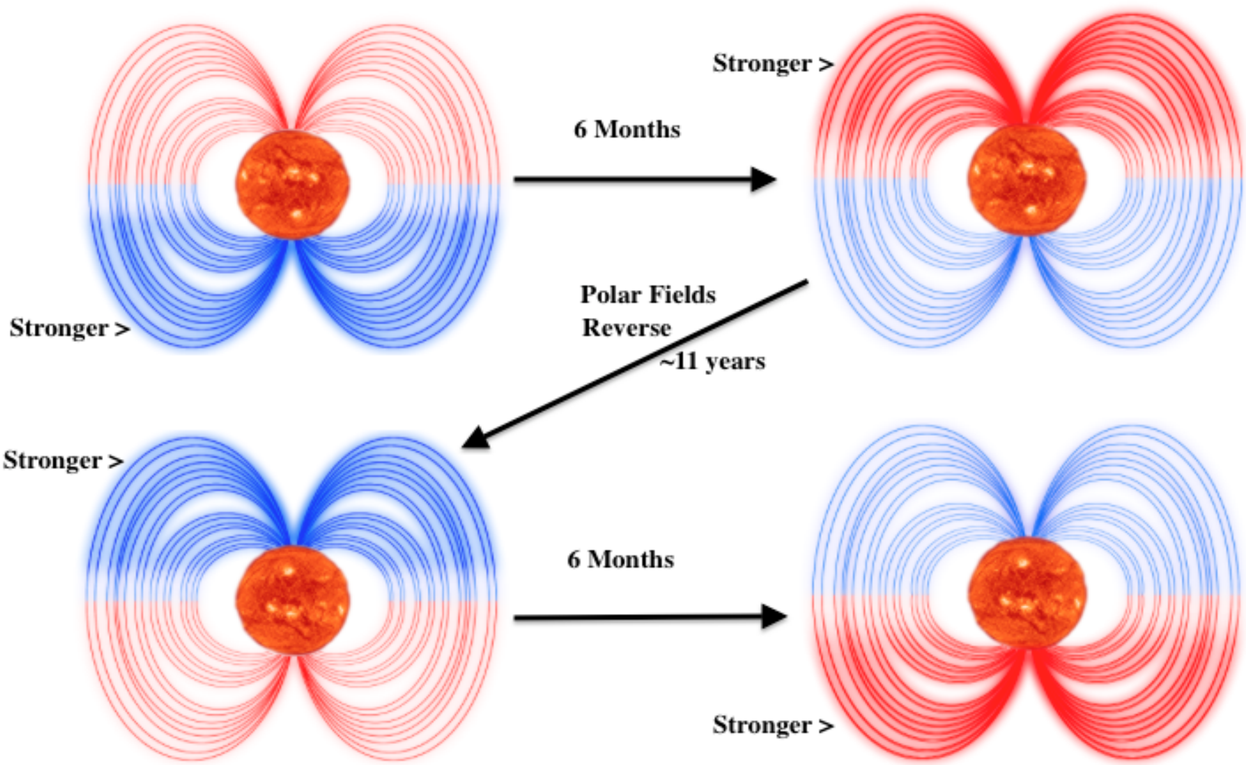
Solar Polarity Data adapted from the website of the Wilcox Solar Observatory. The Blue line is the North SPF, while the Red line is the South SPF. The Green line represents the Average Polar Magnetism of the two fields. Here we see a sinusoid on a large scale (~11 year solar cycles) and a small scale (~1 year). The baseline around which the solar poles are plotted is 0 μT. Above the baseline is positive polar magnetism, and below the baseline is negative polar magnetism - the further the line goes up or down, away from the central baseline, the stronger the magnetism.

During SPF reversals, each pole may reverse numerous times in a period that lasts more than a year. The SPF are weakest during the reversal, which occurs at sunspot maximum, and they are strongest during sunspot minimum; the cycles are inverse but in sync. Sunspot maximum occurs during the minimum magnetism of the polar fields, "Polar Minimum," while sunspot minimum occurs during "Polar Maximum."

Polar Minimum begins after both of the sun's poles have reversed their polarity once during the sunspot maximum (rarely do north and south begin reversing together) and ends after the final reversal of sunspot maximum. After Polar Minimum, the SPF begin to steadily increase in magnetism in the opposite direction (+/-) from their polarity during the previous cycle. After approximately 18 months of "Polar Recovery" (~1.5 ~1-yr oscillations) the SPF have strengthened enough to be characterized as Polar Maximum, which lasts until the next Minimum begins.

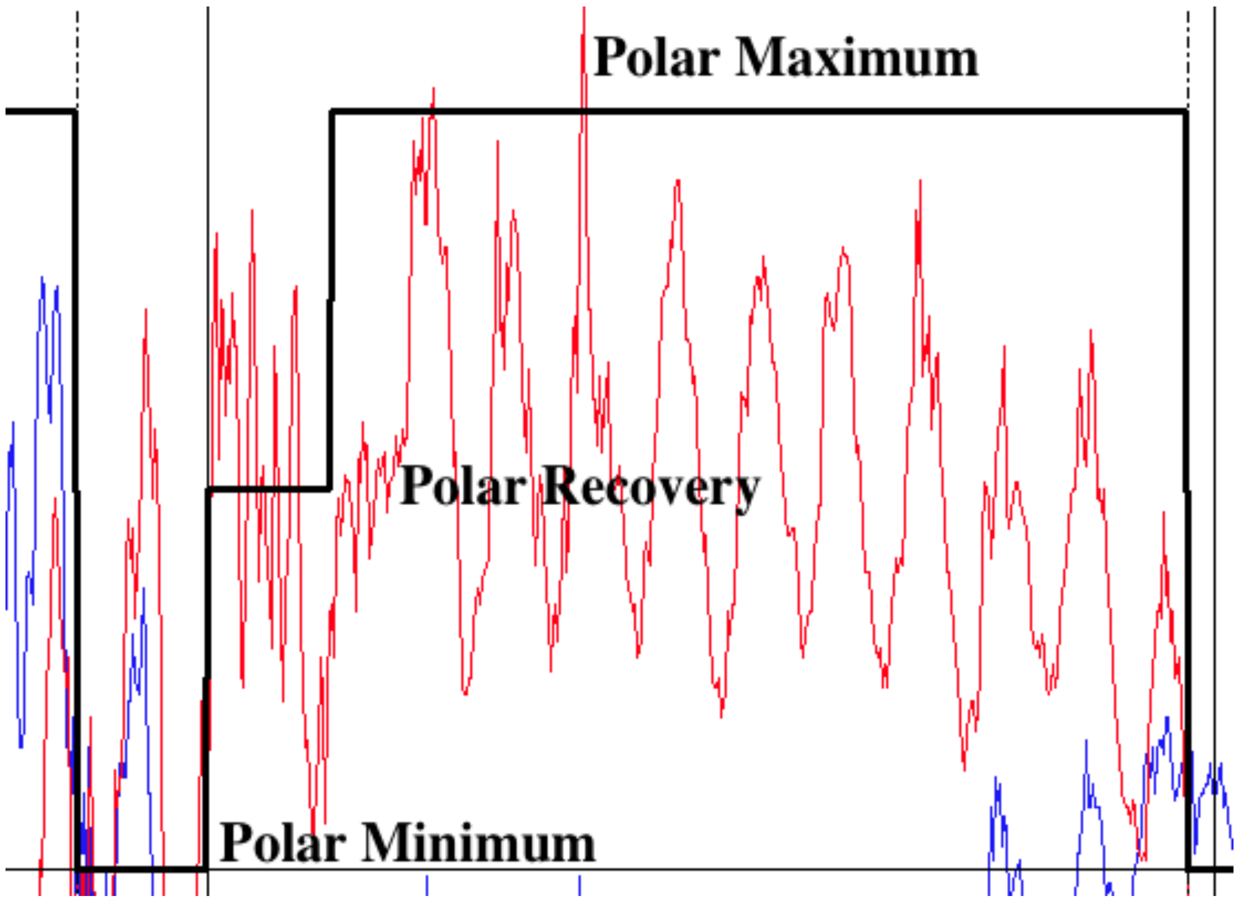
In figures 2 and 3 we see a qualitative view of the SPF cycle, and an example of Polar Minimum, Polar Recovery and Polar Maximum, respectively.

Figure 2: Visual Representation of the ~1-year/~11-year Oscillations of the SPF



The top two images represent the shifting between N and S polar field strength, usually ~6 months apart. Top left we see thicker, bolder blue lines, representing stronger force to the southern pole. Top right we see thicker, bolder red lines, representing stronger force to the northern pole. The bottom two images are after a pole reversal has taken place, which occurs every ~11 years, and represent the same pattern of magnetic force alternating between N and S. The polarity of the N and S poles has reversed but the alternating pattern of higher field strength remains.

Figure 3: Example of the Separation of Phases in the Solar Polar Fields Cycle



Polar Minimum, Recovery, and Maximum are shown here using a portion of the SPF data. The minimum shown here is the reversal that occurred from 1999-2001, followed by ~18 months of recovery, and then the maximum period. The full SPF data, broken down into the SPF phases can be seen in Appendix B. This pattern holds true for both poles, during both positive and negative phases of their cycles.

2.0 'Significant Windows' of Solar Polarity for the Triggering of M8+ Earthquakes

"Significant Windows" cover periods of time when we hypothesized that the SPF could trigger seismic activity: (1) the extremes in SPF magnetism (either positive or negative), which are visualized as the peaks and troughs in Figures 1 and 3, and (2) the changes in polarity of the SPF, both individually and as a combined average, which are visualized as the lines crossing the central baseline in Figure 1, and the color reversal in Figure 2. The dates of extremes in magnetism and polarity reversals are surrounded by a Significant Window of days during which an M8+ earthquake would be considered 'covered' within the window.

For the extremes in magnetism, the strength of the peaks alters the length of the Significant Window, where the strongest peaks have slightly longer windows than other peaks. Some extreme periods in SPF magnetism have multiple peaks/troughs, during which times the Significant Windows were split and shared by the peaks in force. The time periods around the peaks in solar polar magnetism should be the times when the polar fields affect earth the most, and therefore are logical factors in Significant Windows. We also looked at two kinds of SPF reversals for the Significant Windows: 1) the reversal of each individual hemispheric polar fields, a "Pole Reversal," and 2) the reversal of the average polar magnetism of the sun, an "Average Reversal," derived by adding the northern fields magnetism to the southern fields magnetism, and visualized as the green curve in Figure 1. For each individual pole, the first and final reversal of each

Polar Minimum is significant, and if there are more than two reversals in such a period, the magnetism must increase beyond a threshold of minimum intensity in order for the subsequent Pole Reversal to be considered significant. For the Average Reversals of the sun, there must be adequate time between reversals for them to be considered significant; the hypothesis is that multiple short-term reversals would not allow the earth dynamo to build-up the stress requisite for a M8+ earthquake. The two types of polar reversals are significant SPF features because they are the moment when the force of the SPF changes direction; a push becomes a pull, or a pull becomes a push.

2.1 The Delay Factor

The above conditions determine whether each time point falls into an Significant Window, but the occurrence of earthquakes can reduce the likelihood of a subsequent earthquake due to the release of pressure and stress in the crust. To allow for accumulation of stress, we delay Significant Windows that occur soon after the earthquake. Each time a M8+ or series of slightly smaller earthquakes (Four M7.5+ earthquakes in a 100 day window) occurs, Significant Windows occurring in the next 100 days are delayed. For Significant Windows starting less than 30 days after the occurrence of one of these earthquake events, the window is pushed back by the lesser of either 20 days or up to the date of the factor creating the Significant Window. For Significant Windows starting between 31 and 100 days after the occurrence of one of these earthquake events, the window is pushed back by 10 days.

3.0 Analyzing the Significant Windows and Earthquake Events

The factors for creating Significant Windows are simple, but communicating them mathematically is more complex. The SPF data and the earthquake history were compared using the simple factors for Significant Windows and translated into a mathematical algorithm (Appendix A). The data analysis was performed using R code for statistical computing (Holloman 2014). The analysis probed the earthquake data for dependence on SPF measurement. Using these rules, we surveyed the +13,600 days covered from June of 1976 through mid-January 2014 to create the Significant Windows of solar polarity, which, based on the hypothesis embodied in the identification of the Significant Windows, could be proliferative to earthquake activity. The result yielded 41.6% of the days as 'significant.' For statistical testing, our null hypothesis is that the timing of occurrence of the largest earthquakes is independent of the Significant Windows of solar polarity. Under this hypothesis, one would expect approximately 41.6% of the earthquakes over the time period to fall within the Significant Windows. There were thirty-three M8+ earthquakes that were recorded on earth between mid-1976 and mid-January 2014, according to the records from United States Geological Survey. Assuming the independence of Significant Windows and earthquake occurrence, the probability of each of the 33 M8+ earthquakes of falling within Significant Windows is 41.6%. Twenty-six of the thirty-three M8+ earthquakes (78.8%) fall within the Significant Windows. Given the probability at the outset, and assuming there is no relationship between SPF and M8+ earthquakes, the probability that 26 or more out of 33 such events fall within Significant Windows is

$$\text{Probability} = \sum_{i=26}^{33} \binom{33}{i} X^i (1-X)^{33-i},$$

where X represents the probability that an earthquake will fall within a Significant Window (41.6%).

Probability = 0.000015

Although the p-value is small, it is likely heavily biased since it is calculated against the dataset that was used to refine the theoretical development of the algorithm. Despite this bias, we believe it provides substantial evidence against an assumption that solar magnetism is unrelated to occurrence of M8+ earthquakes. The calculated p-value is 0.000015 (about 1 in 90,000), providing very strong evidence against the null hypothesis. Our statistical analysis demonstrated that numerical algorithms can be used to extract important features from 10-day averages of SPF indices. These extracted features can then be used to identify windows of time during which large earthquakes are more likely to occur or not occur. The features that are selected by the algorithms are relatively straightforward, consisting of the aforementioned peaks and troughs in magnetism, and times of polarity reversal. Although the results of this study are promising, it should be noted that the analysis was performed retrospectively, meaning that the model currently lacks a predictive element, and must assessed by examining how well it predicts large earthquakes in the future.

4.0 Discussion

This analysis suggests that M8+ seismicity is dependent on the variations in the SPF. Now we will discuss 4.1) the most likely ways to improve our algorithm, 4.2) a model for a explaining the SPF trigger mechanism, 4.3) how the SPF might be interacting with the earth, and 4.4) why considering the relationship between electromagnetism and earthquakes may help us better-understand these M8+ disasters.

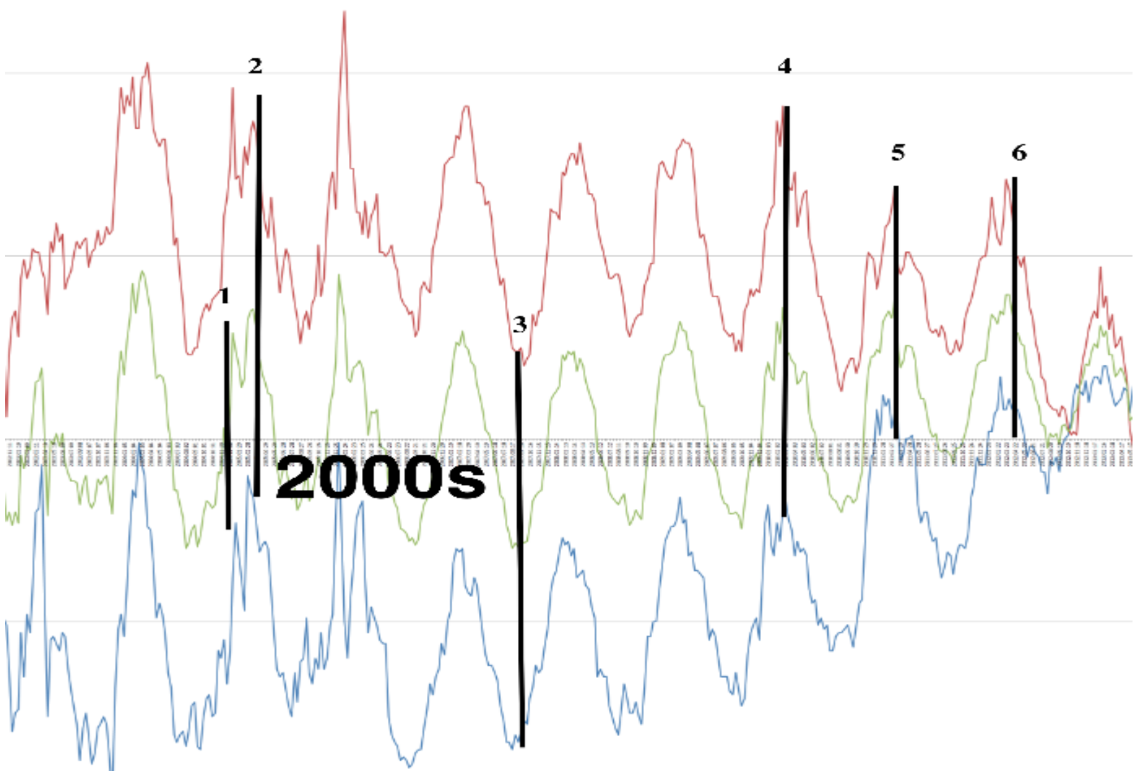
4.1 Improving this Model in the Future

This current model affords confidence in the relationship between SPF and M8+ earthquakes, but it needs to be refined. In reviewing the analysis it is clear where we need to refine this model in the future; we need to revise Significant Windows around extremes in magnetism, and reconsider the entire period of Polar Recovery.

4.1.1 The Rules for Significant Windows Around Extremes in Magnetism Should be Revisited

Among the seven M8 earthquakes that were not covered by the Significant Windows, a few were so close to being 'covered' that it suggests that we may not understand the breadth of the Significant Windows. Among those situations, none are more glaring than the only day with two M8 earthquakes on record, April 11, 2012, illuminated in Figure 4, #6. On this day, the southern polar fields had recently peaked in positive magnetism. We compare that event to the other largest events of the last few years:

Figure 4: The Six Largest Earthquakes of the Current Solar Polar Fields Cycle



A close-up of the Polar Maximum of the 2000s/2010s with black vertical lines at the 6 largest earthquakes of this the period. 5 of the 6 fell within 'Significant Windows'. (1) M9.1 Sumatra. December 26, 2004. Occurred during an "Average Reversal." (2) M8.6 Sumatra. March 28, 2005. Occurred during a positive peak of the southern field. (3) M8.5 Sumatra. September 12, 2007. Occurred during a negative peak of the northern field/positive trough of the southern field. (4) M8.8 Chile. February 27, 2010. Occurred during a positive peak of the southern field/negative trough of the northern field. (5) M9.0 Japan. March 11, 2011. Occurred during a positive peak of the southern field. (6) M8.6 Sumatra. April 11, 2012. Occurred just after a positive peak of the southern field.

In figure 4 we see #1 takes place during the Significant Window of an Average Reversal, #s 2, 4 and 5 all falling in Significant Windows of the positive peaks in southern field magnetism, #3 falls within the Significant Window around a negative peak in northern field magnetism, and only #6 fails to fall within a Significant Window. However, if you see how it closely follows the positive peak in southern fields, as did the previous two massive earthquakes, one must speculate if #6 failed to be 'covered by the Significant Windows' only because we failed to adequately understand the SPF effects. In fact, #6 looks like it *should* be covered by that peak, but it happened a few days too late according to our algorithm. Is that our error or an unrelated event? #6 actually represents two M8+ earthquakes that struck that day, so missing #6 means missing two M8+ earthquakes. Refinement of the algorithm to add a few more significant days would pale in comparison to adding 3 or 4 of the M8 events to the list of those 'covered by the Significant Windows'. If we could cover 45% of the days under significant windows and 85-90% of the earthquakes it would certainly be worth a more complex approach than the first step identified here.

4.1.2 There were No M8+ Events during Polar Recovery

We also note that there were no M8+ earthquakes during Polar Recovery, and this was not a consideration in the algorithm. This lack of large earthquakes during Polar Recovery makes perfect sense if there is a relationship between solar activity and earthquakes as the data strongly suggests; there are neither pole reversals nor strong magnetism during those times, and the Significant Windows are currently focused on those factors. The final model provides historical coverage of 41.64% of days between July 5, 1976, and January 17, 2014. However, this coverage is not uniform across the phases of the solar polar cycle. In Polar Maximum, 46.54% of the days are covered, but in Polar Minimum and Recovery, 27.89% and 25.21% of the days are covered, respectively. Simply by eliminating the period of Polar Recovery the number total days in Significant Windows would decrease a few percentage points without 'covering' any fewer M8+ earthquakes.

4.2 Modeling the SPF Earthquake Trigger

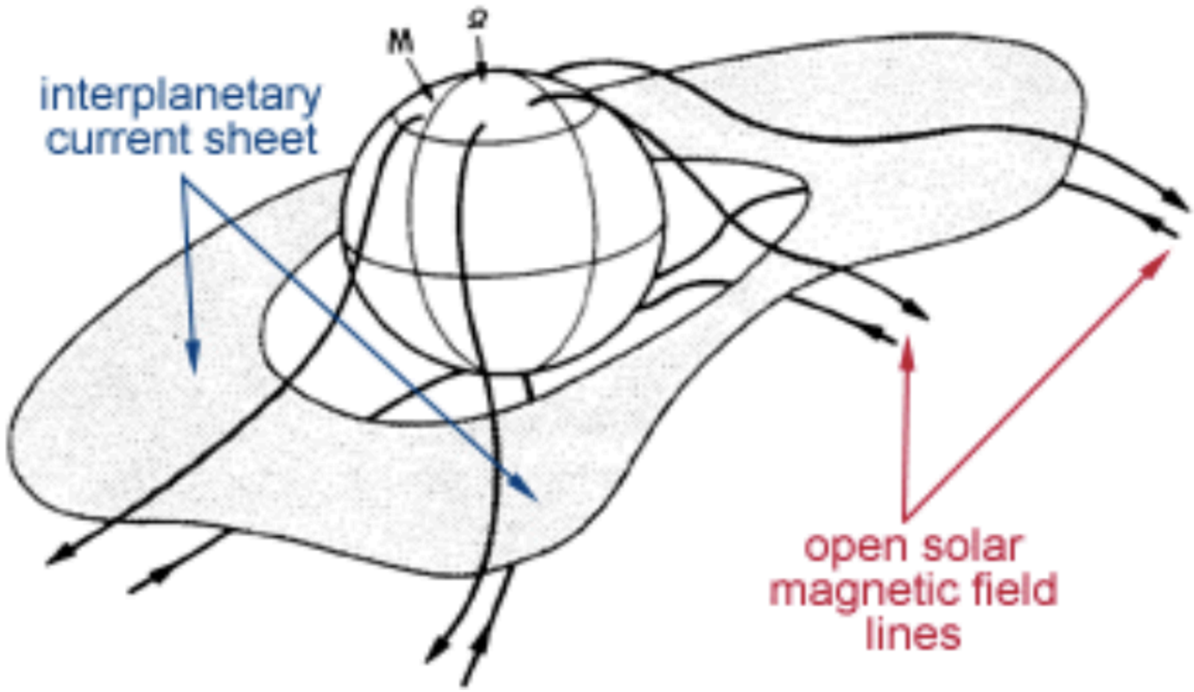
To explain the connection between earthquakes and the changes in SPF, we consider modeling the earth as a capacitor (Hill 1971; Ustundag 2005) which could temporarily store energy to be triggered later by changes in the SPF. The ionosphere, an electrically conductive layer, is treated as one plate of the capacitor while the other conducting plates exist in or below the ground. Two plates are separated by the Earth's atmosphere and mantle crust, which are treated as leaky insulations. In this model, electrical movements in the ionosphere in longitude (compression/expansion) or tangential (circulation) directions can result in significant changes in Earth's electric fields or magnetic fields which propagate into the Earth's crust, as part of the capacitor.

The field modulation (especially in the electric fields) influences the movement of global charges currently existing in the Earth's crust (Namgaladze 2013), accelerating charge diffusion toward the tectonic hot spots that already contain high charge concentration. It is also known that charges are scattered in the uniform dielectric volume and converged around cracks or contacts between two dielectric layers containing stress. As a result, a strong electric field may be locally produced amplifying the mechanical stress through piezoelectric effect (Manbachi 2011). Large displacement current and local heating have been observed during earthquakes as a result of electrical discharge in various earthquake preparation zones (Teisseyre 1997; Lovett 2013).

4.3 How might the SPF interact with earth?

The earth orbits the sun in an electric field of charged solar wind known as the heliospheric current sheet or interplanetary current sheet. Space weather events such as sector boundary crossings are partially dependent on the polar fields (Svalgaard 1974), which can stream away from the sun near the north and south boundaries of the current sheet itself (Figure 5). The earth may be directly interacting with these fields, or nearby currents and fields induced by the SPF, as the changes in earth's heliospheric latitude take our planet up and down through the current sheet.

Figure 5: Lowest-Latitude Polar Fields Interact With Solar Wind



The lowest-latitude polar fields are interacting with the current sheet, and the earth's orbit takes it through the north/south expanse of the sheet. "The cartoon showing the tilted current sheet and open solar magnetic field lines is adapted from Smith et al., Observations of the interplanetary sector structure up to heliographic latitudes of 16 degrees: Pioneer 11, J. Geophys. Res., 83, 717, 1978. The artist's conception of the heliospheric current sheet was obtained from J. Todd Hoeksema, Stanford University." xuv.byu.edu/docs/previous_research/euv_imager/documentation/part3/3IMF.html

Studies confirm that the SPF also influences the solar wind; the solar wind is primary in the solar-terrestrial interaction and its modulation is dependent on space weather parameters at the star itself and in the interplanetary magnetic field, both of which are also highly dependent on the SPF (Svalgaard 1978; Wang 2009). The fluctuation in magnetic fields observable at the sun is directly related to the fluctuation of space weather surrounding the earth, often having direct integration into earth's systems through magnetic portals (Phillips 2008). The SPF reversal and the poleward migration of the neutral magnetic line described by Makarov et al. (1982) have significant effects on sunspot position and solar/geomagnetic indices. The same study found that solar prominences are tied to the movement of the SPF. The strength of the polar fields also modulate the appearance of equatorial coronal holes (Gibson 2009). These are all potential pieces to the larger puzzle of how the SPF might interact with earth to trigger the release of underground stress.

4.4 Electromagnetism and Earthquakes.

The SPF are solar-system-scale magnetic fields generated by the sun, so electromagnetic exchanges are a worthwhile avenue of investigation for a mechanism explaining how the SPF trigger earthquakes. This is especially true since there is precedent for looking into the electromagnetic aspect of earthquakes. Scientists have documented magnetic field fluctuations before and during seismic events (Johnston 1994, Scoville 2014). "Earthquake lights" and strange clouds preceding earthquakes have spurned investigations into atmospheric and ionospheric precursors to those events (Pulinets 2004; Namgaladze 2009; Freund 2009). Significant variations in energetic indices like the total electron content (TEC) or critical frequency of the ionosphere, preceded the great earthquakes of China/Haiti in 2008/2010 (Zolotov 2010), Chile in 2010 (Yao 2012) and Japan in 2011 (Kamogama 2013). There is *extensive* research that describes potential coupling mechanisms between the ionosphere, the atmosphere and the ground, where electromagnetic interactions play an important role in the earthquake triggering process. (Sorokin 2005; Sorokin 2006; Rycroft 2006; Pulinets 2011; Pulinets 2014). The sun may play a significant role in total electron content variations and other ionospheric-atmospheric interactions. (Mende 2004; Liu 2009).

At a meeting of the American Geophysical Union in December 2012, Tom Bleier described the electric currents associated with large earthquakes as “lightning underground,” often exceeding 1 million amperes, and he states that static electricity is the key to predicting earthquakes (Lovett 2013). Some have pegged the trigger for these currents, and the resulting seismic and volcanic events, to be solar activity (Odintsov 2007; Khain 2007/2008; U-yen 2014). Studies have shown that penetration of the L = 2.0 force line into seismic areas can be proliferative of earthquake activity, and the genesis of the earthquakes themselves may be electric currents flowing into the global electric circuit (Zhantayev 2014, Khachikyan 2014).

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