SOLAR ACTIVITY AND THE SOLAR CYCLE

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ABSTRACT

Solar activity prediction methods have been wide-ranging, mostly numerical, and essentially curve fitting. Thus for many years the search for physically based methods has remained elusive. Surprisingly, a new class of methods does seem to be making progress, and it relates to the structure of the field within the Sun and heliosphere. This class is now based on solar dynamo physics, but began with some surprising observations that the Sun's activity can be predicted by monitoring geomagnetic precursors, namely geomagnetic fluctuations near solar minimum. It was puzzling how the Sun could broadcast its future activity levels to the Earth! We have developed some understanding for how these methods work based on the Sun's dynamo and the structure of the magnetic field in the heliosphere. Additionally, we have expanded the prediction methods using a SODA index (SOlar Dynamo Amplitude), which monitors the Sun's buried dynamo fields. Thus the prediction methods have changed from numerical schemes to an understanding of the Sun's dynamo processes- to explain a connection between how the Sun's fields are generated and how the Sun broadcasts its future activity levels to Earth. This has led to better monitoring of the Sun's dynamo fields buried deep within the Sun, leading to more accurate prediction techniques, based on the Sun's polar and toroidal magnetic fields. We explain how these methods work and discuss solar activity predictions for solar cycles #23 and #24. At the present time the SODA index suggests a reduced amount of buried magnetic flux, hence unless dynamo processes increase dramatically, solar cycle #24 will likely be significantly smaller than cycle #23! At present, the mean smoothed F10.7 value is forecasted as 155±30, corresponding to Rz of 100±30.

INTRODUCTION

This paper will focus on long term solar activity prediction or forecasting and its relation to the structure of magnetic fields in the heliosphere. We examine the basis of solar activity forecasting, focusing on a physical method related to estimating the strength of the Sun's dynamo, the "SOlar Dynamo Amplitude" method (SODA index). This method has predicted 3 solar cycles quite well, having first been tested with 8 prior cycles of data.

Interestingly, the Sun, whose nearly constant energy source provides a very stable harbor for life on Earth, provides a very unstable environment for satellites in low-Earth orbit (LEO). The reason is that the solar UV and EUV irradiances vary dramatically with solar activity (showing changes at certain wavelengths of more than 100%), and this energy inflates the upper atmospheric layers of the Earth and planets, forming the exosphere in which satellites orbit. This exospheric behavior contrasts greatly with tropospheric behavior, where meteorologists traditionally, yet safely, ignore solar irradiance changes. The solar irradiance is called as a misnomer, the "solar constant," since its changes are about 0.1%, much smaller than the EUV variations which often exceed 100%! Let us now examine solar activity behavior and how this is predicted.

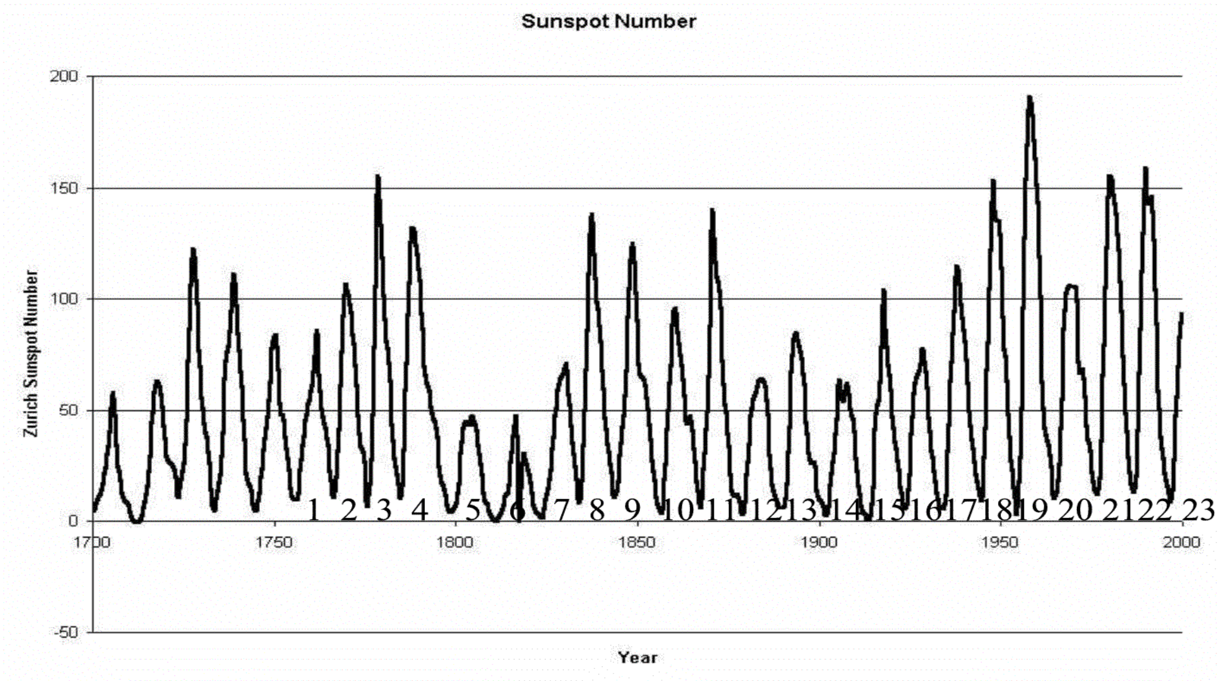


Fig. 1. Sunspot Number vs. time for the past few centuries. The figure shows "power" in a wide variety of periods beyond the famous 11-year Schwabe periodicity. Additionally, major variations exist both on longer and shorter timescales. Further, amplitudes of the cycles vary by more than 100%, in a rather chaotic manner. Epochs occur, such as during the "Maunder minimum," when solar activity dropped precipitously to near 0. The numbering on the chart shows the "Even/Odd" effect, where this century odd numbered cycles have always been larger than the previous even numbered cycle (e.g. cycle #19 > cycle #18).

Figure 1 shows solar activity as measured by sunspots for the past few centuries. Firstly, the most prominent feature is the famous 11-year Schwabe solar cycle. Additionally, there is "power" at a variety of other periods (including days, months, 80 - 100 years, and even secular variations with longer periods not seen here), however, a closer examination of these periods shows that they are not strictly periodic. They appear "chaotic;" unable to be predicted on the basis of simple spectral techniques. Additionally, even the main 11-year periodicity is not a sharp period; some cycles have been as short at 8 years, and some as long as 17 years! Further, the amplitude of the cycles varies by more than 100%, in a rather chaotic manner. This is even more striking, if one realizes that there were long periods of time (50 - 100 years), most recently in the 1600's called the "Maunder minimum" when solar activity was near 0. Hence solar scientists have developed numerous methods in their attempts to forecast solar activity. Unfortunately, a number of these techniques, although successful for some cycles, have failed in the long run.

A NOAA panel investigating these forecasting methods several years ago (see Joselyn et al., 1997) chose the following general solar forecasting categories: Even/Odd Behavior, Spectral, Recent Climatology, Climatology, Neural Networks, and Precursors suggesting solar cycle #23's smoothed peak sunspot numbers shown in Table 1. There are numerous methods, which may not appear to fall into any simple category outlined in Table 1. Perhaps one category called “other” should have been adopted. For example, Kalman filtering, which is a numerical technique, often used in weather forecasting, would lie in the category of “spectral,” although there are climatological aspects as well, and the terms provided in Table 1. are rather simplified.

TABLE 1. Technique and predicted sunspot numbers for solar cycle #23.			
Technique	Low End of Range	Smoothed Max R_z	High End of Range
Even/Odd Behavior	165	200	235
Spectral	135	155	185
Recent Climatology	125	155	185
Climatology	75	115	155
Neural Networks	110	140	170
Precursor:			
Geomag. Precursor	140	160	180
Solar Precursor	108	138	168

TABLE 1. Forecasting techniques and predicted levels (in smoothed International Sunspot Units) for solar cycle #23, based upon the NOAA panel report by Joselyn, et al.(1969). The precursor levels have been divided into the Geomagnetic and Solar Precursor methods.

For more information on the solar dynamo, the reader is referred to a review article by DeLuca and Gilman (1991). Concerning this cycle, it now appears that it has peaked near a smoothed sunspot number near 125, or an F10.7 Radio Flux of 180. The sunspot value is near the lower end of most estimates seen in Table 1. From an examination of Table 1, one sees the solar cycle behavior, for this cycle, supports the Climatology, Neural Networks, and Solar Precursor methods. The NOAA panel discussions (Joselyn et al., 1997) provide an excellent review of the various methods, and other views may be found in Holland and Vaughan, 1984, Kerridge, et al., 1989, and Hathaway, et al., 1999. We now turn to the precursor methods.

SOLAR AND GEOMAGNETIC PRECURSOR METHODS

As far as the geomagnetic precursors, one of the first to point out the significance of the geomagnetic Aa index in tracking long-term solar activity was Feynman and Gu, 1986. Although she never used the information for directly making predictions, it seems clear that Ohl , 1966, 1989 and other Geomagnetic Precursor practitioners used the same or similar methods to predict activity. Feynman separated the geomagnetic Aa index into two components: one in phase with sunspot number, and one out of phase. This effectively led to "active" and "quiet" components. She found that this quiet signal tracked the sunspot numbers several years in advance, similar to the Ohl results. The maximum in this signal occurs at sunspot minimum and is proportional to the sunspot number during the following maximum. How this signal propagated or why it should be present, however, was not clear.

Precursor methods were developed by the Soviet geophysicist Ohl, 1966, 1989 to make solar predictions and taken up by Brown and Williams, 1969, who later noticed an extremely high correlation (close to 1) between geomagnetic activity near solar minimum and the size of the next solar cycle. High correlations were found between the number of "geomagnetic abnormal quiet days" and the size of the next solar cycle. Although the abnormal quiet day geomagnetic index was an unusual one, later the correlations remained high when objective geomagnetic indices, such as Ap, and Aa were employed. Bartels, 1963, discusses these indices. Thompson, 1993, further improved upon the relationships between geomagnetically "disturbed" days and the amplitude of the next sunspot maximum.

Let us move on to Precursor methods by pointing out that the correlations found by the geophysicists were very puzzling because the Sun's activity might cause a terrestrial effect, but not vice versa! So the order of the causality seemed to be reversed. Additionally, the relationship of the geomagnetic storms and interplanetary ejecta has been studied by Cane, Richardson, and St. Cyr, 2000. Trying to unravel the mystery of how the Sun could broadcast to the Earth, in advance, the level of its future activity, Schatten et al., 1978, searched for a physical mechanism to understand the phenomena. To place these puzzling correlations in a physical context meant relating these geomagnetic effects somehow to solar dynamo theory. Let us examine how this is done.

SOLAR DYNAMO THEORY AND SOLAR PRECURSORS

In any MHD (magnetohydrodynamics) dynamo, there is a behavior similar to the simple "disk dynamo," explained in physics books, wherein the amplified magnetic field is proportional to the " initial magnetic field." The solar dynamo goes through more "gyrations" than the simple disk dynamo, but the previous behavior remains. Figure 2 shows the Babcock dynamo. In this model the Sun's polar fields near solar minimum are wrapped up by differential rotation to form the toroidal fields, which later float to the Sun's surface and erupt to form active regions. As these fields dissipate, they regenerate the polar field allowing the solar cycle to recur.

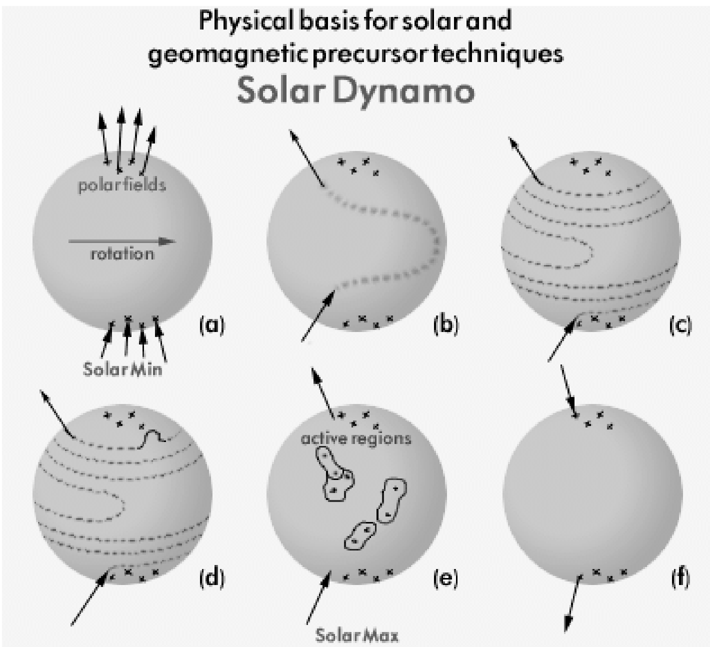
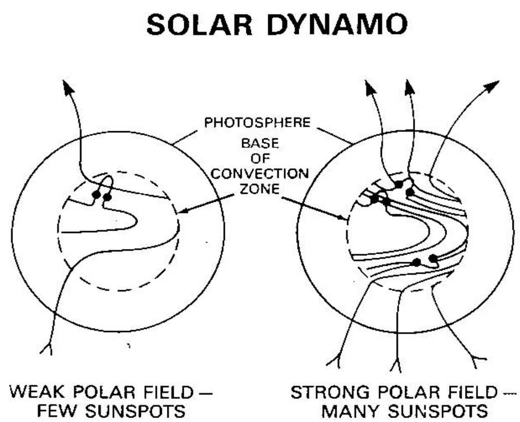


Fig. 2. In the Babcock dynamo, the Sun's polar fields near solar minimum (a) are wrapped up by differential rotation (b) to form toroidal fields (c). These fields, later in the cycle, float to the Sun's surface and erupt (d) to form active regions containing sunspots (e). The breakup of these active region fields regenerate the Sun's polar field with a reverse sign (f), allowing the process to repeat anti-symmetrically.

Modern helioseismological studies have shed new light on the Sun's dynamo. For example, the solar community now knows that the buried toroidal dynamo field is located just below the base of the convection zone. Still, the broad view outlined by Babcock still remains valid.

Let us now see how making key observations and processing them, based on this dynamo view, will allow us to gain an understanding of the Sun's buried magnetic flux and to better predict solar activity. The dynamo process outlined is neither as simplified nor "perfect" as outlined, but rather subject to the irregularities of the individual active regions formed. Hence, over an 11- year solar cycle, the amplification sometimes regenerates more polar field and sometimes less, leading to a growth or decay in the solar cycle. If one assumes the dynamo is fairly linear, then one expects a direct correlation between the number of active regions formed in a cycle with the strength of the Sun's polar field near the prior solar minimum.



$$\Delta B \propto B_{POLAR}$$

Fig. 3. Shown is a simple schematic picture of the Babcock dynamo mechanism for two different cycles: a weak cycle (left) and a strong cycle (right). The complex picture of the temporal dynamics of a solar cycle is simplified so that the polar fields and toroidal fields of each cycle are both displayed.

Figure 3 shows a simple schematic picture of the Babcock dynamo mechanism for two different cycles: a weak cycle (left) and a strong cycle (right). The complex picture of the temporal dynamics of a solar cycle is simplified in this picture so that the polar field and toroidal field are both displayed. The main point, however, is that during a weak cycle, a weak polar field is amplified by dynamo physics below the Sun's surface into few sunspots, solar activity, etc. For a strong cycle, the reverse is true. Since the polar field of the Sun is later amplified into the sunspot fields, one can use it as a precursor or predictor of solar activity. Namely, by monitoring the observed magnetic fields of the Sun, one can use these observations to predict future levels of solar activity. This is similar to the way meteorologists monitor pressure regions to predict cloud formation. Hence it is the first "physics-based" forecasting technique.

To understand the Geomagnetic Precursor methods, we then only needed to see whether the Sun's polar field near solar minimum might be correlated with the amount of geomagnetic activity at that time. The extended solar field is called the Interplanetary magnetic field (IMF), and was found to be correlated to geomagnetic activity supporting Dungey's theory of magnetic reconnection. It was found that the southward component of the IMF (and also the total field) correlated well with geomagnetic activity. Additionally, models of coronal structure near solar minimum, when the low latitude solar fields are weak, show that the polar fields bend towards the equator to fill the low latitude heliosphere. Hence, the correlation between geomagnetic activity near solar minimum and the size of the next solar cycle seemed physically reasonable.

To test this hypothesis Schatten et al., 1996, used 8 solar cycles of historic data, and found reasonable correlations, although not as good as those found by the geomagneticians. Until recently, solar magnetic measurements could not be used directly, and instead solar "proxy" fields were used (estimated from numerous solar indices, ranged from solar polar faculae, to the shape of the Sun's corona) which were not as well measured as the geomagnetic indices. Nevertheless, the correlations were reasonable. At present we can measure directly the Sun's polar fields; Schatten and colleagues have been basing their predictions primarily from solar magnetism (the so-called "Solar Precursor method"), although geomagnetic methods were also examined to augment and check the methods (Sofia et al., 1998). The Sun's polar fields represent an excellent Sun-Earth connection to explain the correlation, as these fields are the main apparent physical manifestation of the Sun's dynamo near solar minimum.

THE SODA (SOLAR DYNAMO AMPLITUDE) INDEX

When the solar dynamo method was first developed, it was only possible to assess the state of the Sun's dynamo near each solar minimum, when the Sun's buried magnetic fields poke through the Sun's surface at the poles and these fields may directly be observed. Schatten and Pesnell (1993) developed a more sophisticated method for undertaking the analysis than was done in the early days of this field. This now allows an estimation of the "magnetic state" of the Sun to be ascertained during any phase of the solar cycle, rather than only at solar minimum. As the solar cycle progresses, there is an exchange between poloidal and toroidal magnetic field as shown before in Figure 3.

This interchange is similar to the interchange between the kinetic and potential energies of a pendulum. One can measure both, and obtain a measure of the total energy of the pendulum rather than measuring only one, when that one maximizes. Expanding this idea allowed Schatten and Pesnell(1993) to capitalize on all the aspects of solar activity and magnetism to obtain a combined index, called the "SOlar Dynamo Amplitude" or SODA index. Just as with the total energy of a pendulum, use of this index can be updated during any phase of the Sun's solar cycle. Through a combined measure (the SODA index), the strength of the Sun's buried magnetic flux is obtained. Figure 4 shows the 11-year oscillations of the poloidal and toroidal field, plus their secular changes.

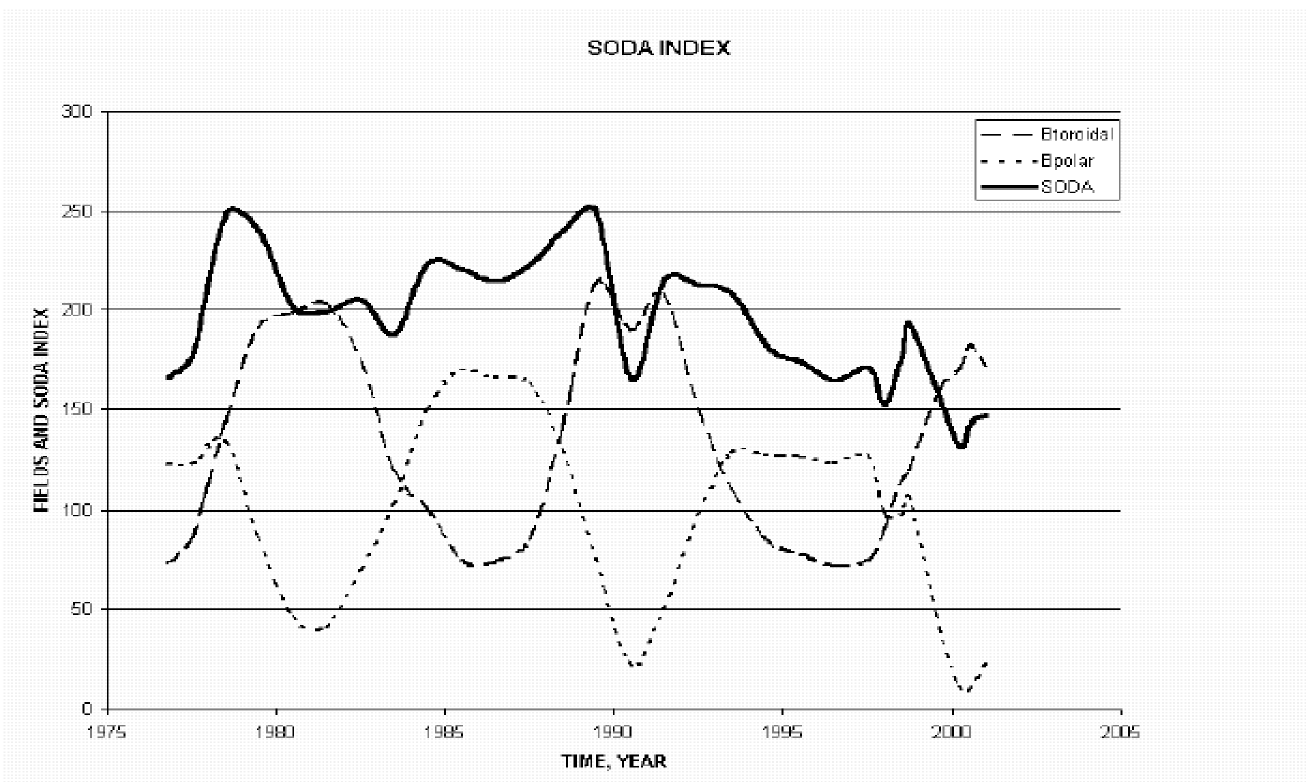


Fig. 4. The "SOlar Dynamo Amplitude" or SODA index is a composite index attempting to combine the changing toroidal and poloidal fields of the Sun. As these fields vary with time, the combined SODA index allows us to monitor the "buried magnetic flux" present in the Sun's ever-changing dynamo.

By using both indices, the combined SODA index, shows less 11-year variation, but <u>retains</u> the Sun's secular changes, thereby capturing the slowly varying strength of the Sun's dynamo fields while allowing the state of the dynamo to be monitored continuously! Note that it is important that removing the 11-year variation is <u>not</u> done with spectral filtering, as this would require having current conditions dependant upon old temporal variations, and hence would completely <u>mitigate</u> the benefits gained by updating conditions with the latest information (it would smooth the data out)!

Let us discuss other properties of the SODA index. Firstly, it provides a continuous measure of the strength of the magnetic field buried within the Sun's interior. Additionally, since the magnetic field in the interior of the Sun is "buoyant" (as the magnetic field pressure excludes plasma), the field acts like a gas in a liquid (e.g. carbon dioxide inside a carbonated drink). Hence, the SODA index terminology is not only an acronym for the "solar dynamo amplitude" measure of the magnetic field, but also as a descriptor of the amount of magnetic "fizz" inside the Sun's interior! Figure 4 shows the SODA index in recent times. It has been somewhat down from cycle #22, suggesting (several years ago) that cycle #23 would be somewhat reduced (which has been born out). This incidentally goes against the Even/Odd behavior mentioned earlier about cycles this century! Using the SODA index we predicted a value at the lower end of the Precursor methods shown in Table 1, namely a smoothed sunspot number of 138 ± 30 in 1996 and F10.7 values of 182 ± 30. This is somewhat less than the NOAA panel estimate by Joselyn, et al. Let us now see how cycle #23 has progressed.

SOLAR CYCLE #23 FORECASTS AND OBSERVED BEHAVIOR

It now appears that the smoothed sunspot number for solar cycle #23 has a mean value close to 125 and for F10.7, a value near 180. Activity would need to shoot up markedly for these numbers to be far off from the eventual smoothed average for cycle #23. Figure 5 shows F10.7 radio flux data over the past 50 years, along with the past three predictions, including cycle #23

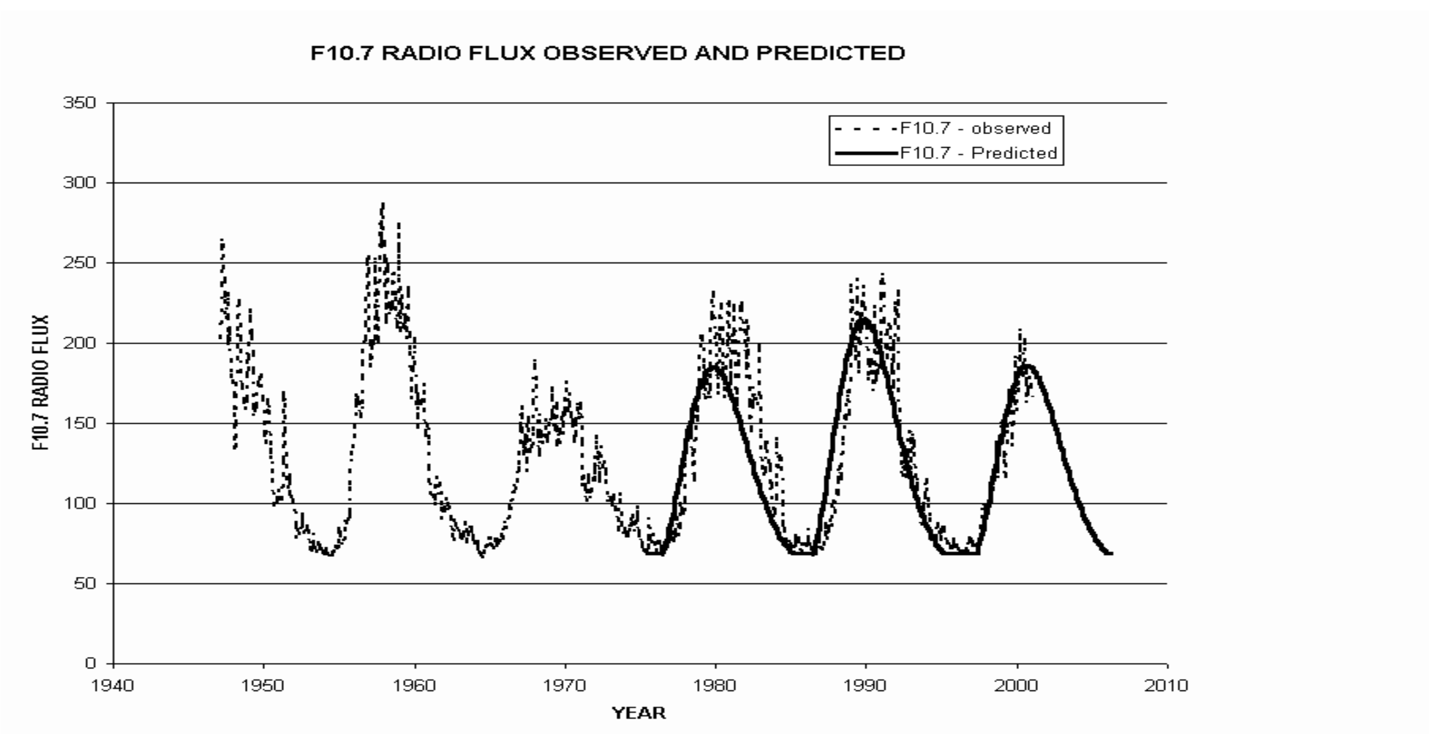


Fig 5. Shown is F10.7 Radio Flux for the past 50 years, and Schatten et al. predictions for the last 3 cycles, published in advance. Note that cycle #23, the present cycle, seems to be a better fit to the predicted values, both in timing and amplitude than previous cycles. Although this may be fortuitous, it may also be a sign that our skill level is increasing.

Examining Figure 5, one notes that timing of earlier cycles was off by ± 1 year roughly. We have, however, developed methods of improved timing this cycle seems to have been much closer to the predictions. Additionally, although perhaps fortuitously, the accuracy of the smoothed peak prediction also seems to have improved, namely cycle #23's prediction fits the observed data better than the earlier predictions.

AN EARLY PROSPECTIVE ON CYCLE #24

Let us end with an early prospective on solar activity for cycle #24 (years 2005 - 2016). Although the polar field of the Sun is just beginning its growth towards a new peak, it has already reversed sign and gone through zero from last cycle's polar field. Let us examine the polar field rise since the reversal.

Wilcox Solar Observatory polar field strength measured (Hoeksema et al., 2002) in the polemost 3' aperture shows magnetograms averaged each 10 days. They provide the following behavior: since year, 2000, the smoothed mean polar field rose from zero to 0.2 Gauss, compared with nearly 0.5 Gauss over a similar period for the last cycle, a decade earlier. Thus this cycle's polar field has not been growing as rapidly as last cycle's. Although this is a small fraction of a full solar cycle, the polar field often rises in only 2-3 years, and this stunted growth appears significant. Additionally, as MHD (magnetohydrodynamics) magnetic fields are only amplified from pre-existing fields, the slow rise may portend a small cycle #24. Nevertheless, one shall certainly have to wait for the next couple of years to see how the Sun's fields grow before one can make more definitive predictions of the next cycle. At the present time, however, we can estimate solar cycle #24 to be somewhat smaller than cycle #23, as shown in Figure 6, with a smoothed F10.7 near 155, significantly lower than the present cycle #23.

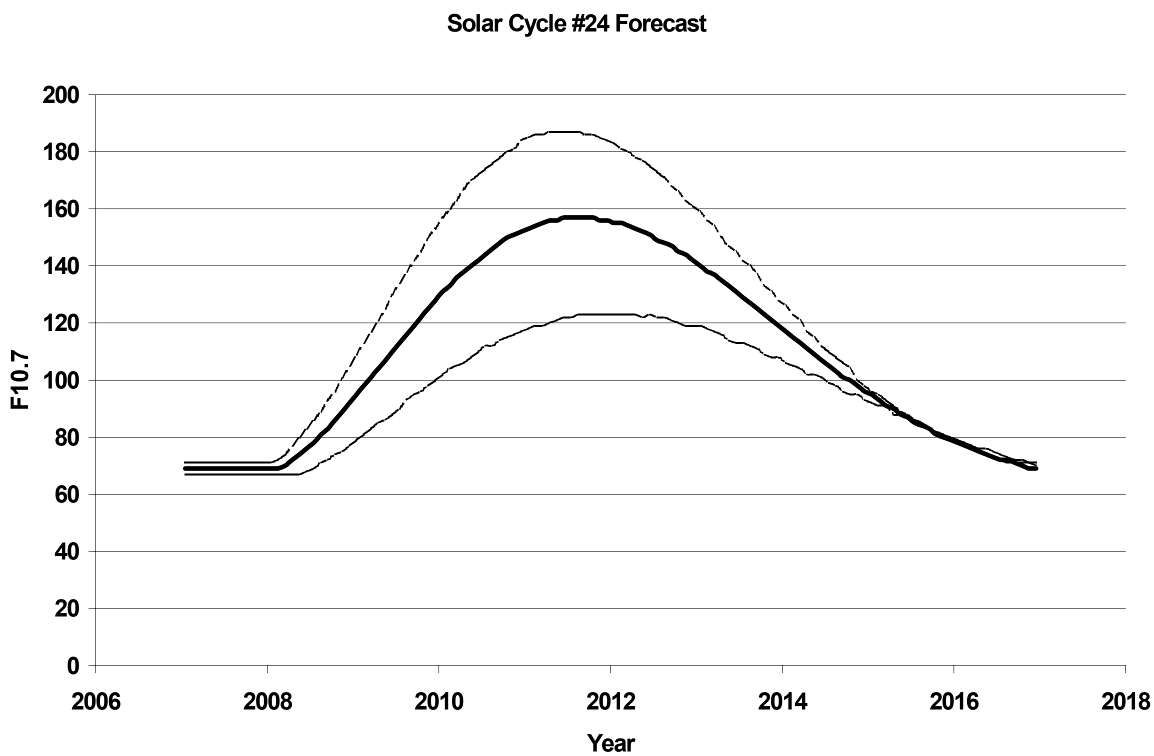


Fig 6. Shown is F10.7 Radio Flux predicted for cycle #24. The mean and ±1 sigma forecasts are shown. The mean smoothed value at the present time is forecasted to be near 155, significantly lower than the present cycle #23.

CONCLUSIONS

This paper discusses predicted levels of activity for this solar cycle, how the cycle has behaved, and where solar activity predictions may lead. Currently, solar cycle #23 seems to have reversed the trend of odd numbered cycles having larger amounts of solar activity than even numbered cycles. At present, the peak smoothed sunspot number for this cycle is near 125 and F10.7 Radio Flux near 180. For cycle #23, climatological, neural network, and solar precursor prediction methods have given reasonably good values. Additionally, the solar precursor method has been reasonably successful in two prior predictions. Further, it gains support by having a physical basis for its workings: solar dynamo theory. The SODA (SOlar Dynamo Amplitude) method went against common expectations in a couple of predictions: it predicted cycle #22 (an even-numbered cycle) would be exceptionally large (for an even numbered cycle), and also that cycle #23 would break the Even/Odd effect. At the present time the SODA (SOlar Dynamo Amplitude) index suggests little buried magnetic flux, hence this method now predicts that solar cycle #24 will likely be significantly smaller than cycle #23! At present, the mean smoothed F10.7 value is predicted to be 155 ± 30, corresponding to Rz of 100±30.

Thus, concerning solar activity predictions, just as in the early days of weather forecasting, there are both hits and misses. Yet the field as a whole is making gains both in understanding and improvements in forecasting skills. Nevertheless, one would need to better quantify solar activity to make advancements. Tobiska and colleagues (2000) are making progress in this area.

The field of solar activity predictions is interesting scientifically and practically, both for the light it sheds on the heliosphere and dynamo physics, as well as its usefulness to NSF, NASA and other agencies interested in solar activity related phenomena, ranging from power grid spikes, to communication blackouts, to satellite orbital dynamics.

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