A FORECAST OF REDUCED SOLAR ACTIVITY AND ITS IMPLICATIONS FOR NASA

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ABSTRACT

The "Solar Dynamo" method of solar activity forecasting is reviewed. Known generically as a "precursor" method, insofar as it uses observations which precede solar activity generation, this method now uses the SOlar Dynamo Amplitude (SODA) Index to estimate future long-term solar activity. The peak amplitude of the next solar cycle (#24), is estimated at roughly 124 in terms of smoothed F10.7 Radio Flux and 74 in terms of the older, more traditional smoothed international or Zurich Sunspot number (Ri or Rz). These values are significantly smaller than the amplitudes of recent solar cycles. Levels of activity stay large for about four years near the peak in smoothed activity, which is estimated to occur near the 2012 timeframe. Confidence is added to the prediction of low activity by numerous examinations of the Sun's weakened polar field. Direct measurements are obtained by the Mount Wilson Solar Observatory and the Wilcox Solar Observatory. Further support is obtained by examining the Sun's polar faculae (bright features), the shape of coronal soft X-ray "holes," and the shape of the "source surface" – a calculated coronal feature which maps the large scale structure of the Sun's field. These features do not show the characteristics of well-formed polar coronal holes associated with typical solar minima. They show stunted polar field levels, which are thought to result in stunted levels of solar activity during solar cycle #24.

The reduced levels of solar activity would have concomitant effects upon the space environment in which satellites orbit. In particular, the largest influences would affect orbit determination of satellites in LEO (Low Earth Orbit), based upon the altered thermospheric and exospheric densities. A decrease in solar activity would result in smaller satellite decay rates, as well as fewer large solar events that can destroy satellite electronic functions. Other effects of reduced solar activity upon the space environment include enhanced galactic cosmic rays and more space debris at low altitudes (from the decay of old satellite parts, etc.). The reasons are well known: namely, solar activity serves to sweep the inner heliosphere of galactic cosmic rays, and lower exospheric densities result in decreased drag on LEO debris, allowing longer lifetimes.

INTRODUCTION

This paper will concentrate on long-term solar activity predictions. In particular, these predictions are related to the present condition of the Sun's activity and how these conditions are expected to vary over the next decade. The reason for considering present and future levels of solar activity is their importance to the National Aeronautics and Space Administration (NASA) in its Low Earth Orbit (LEO) satellite programs. LEO satellites do not orbit in a total vacuum but rather in the extended components of the terrestrial atmosphere known as the thermosphere and exosphere. The scale heights of these atmospheric constituents are in a constant state of change, determined to a large extent by the ultraviolet (UV) and extreme ultraviolet (EUV) outputs of the Sun. Changes in these solar outputs affect the atmospheric drag on satellites in LEO; this strongly impacts their orbital paths and lifetimes.

The varying short wavelength solar output is affected by the Sun's activity. Therefore, predicting solar output requires methods of predicting solar activity. Recently (ref. 1), general methods for solar activity forecasting have been outlined. This paper will focus on a solar "precursor" method: the "Solar Dynamo Method" which uses a SOlar Dynamo Amplitude (SODA) index as a measure of the internal fields of the Sun. This method has a physical basis rather than a purely numerical basis. The term "precursor" has been applied to geomagnetic and solar prediction techniques using signals that precede solar activity, much as in meteorology, where low atmospheric pressure often precedes terrestrial rain.

The solar dynamo method was first tested with 8 prior solar cycles before first being published in 1978. Since then, it has predicted three solar cycles quite well. Figure 1 shows F10.7 radio flux data, in units of 10^4 Jansky or 10^{-22} J s^{-1} m^{-2} Hz^{-1}, over the past 50 years, along with the past three predictions (refs. 2-4). Cycle #23 extends from 1996 through approximately 2007, with cycle #24 starting thereafter. Examining Figure 1, one notes that the timing of earlier cycles was off by ± 1 year roughly. We have improved timing methods. Nevertheless, the stochastic nature of solar activity results in some variations that are not readily eliminated in advance.
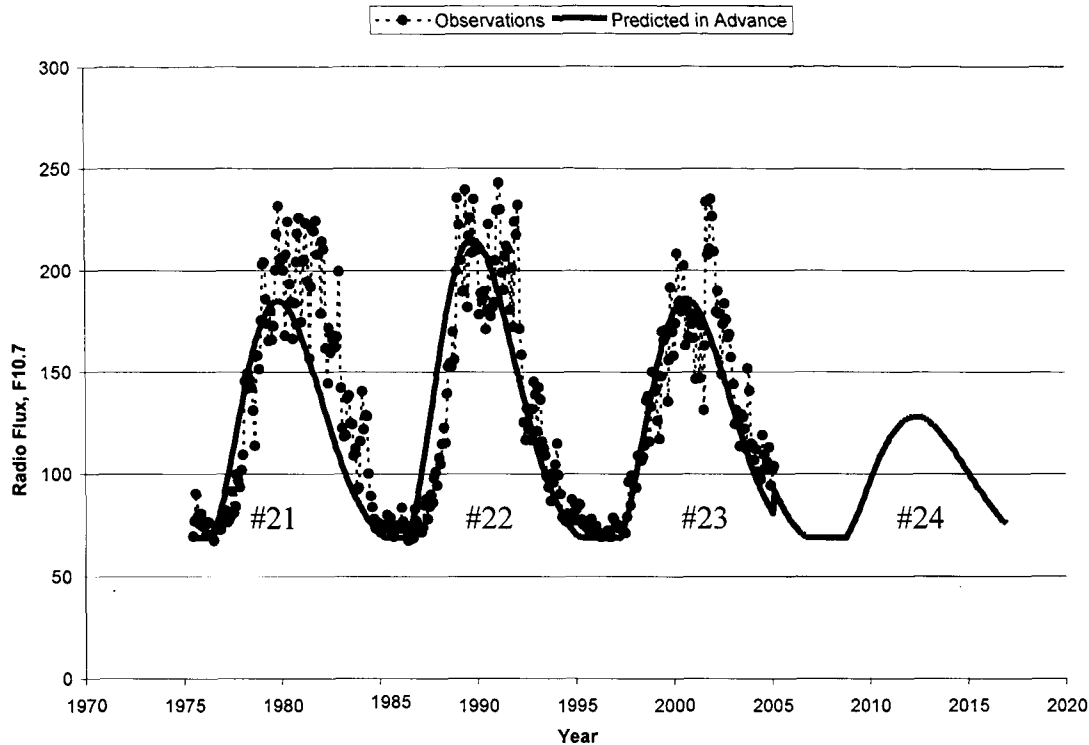

Figure 1. Observed F10.7 Radio Flux (circles) and Schatten et al. Solar Flux Predictions (solid lines) prior to each of the last three cycles. Radio Flux is in 10^{-22} J s^{-1} m^{-2} Hz^{-1}. Cycle #21 peaked ~1980; cycle #22 ~1990; cycle #23 ~2000; and cycle #24 ~2012.

The Sun-Earth Connection

The connection between solar activity and the density of the Earth's thermosphere and exosphere should be examined prior to discussing methods of solar forecasting. The Sun provides the Earth with a nearly constant energy source in visible wavelengths. This allows terrestrial organisms a very stable harbor. However, it provides a very unstable (fluctuating) environment for satellites in orbit.

The solar UV radiation ionizes oxygen, forming ozone in the Earth's stratosphere. Above this, the more intense EUV forms the hotter thermosphere and exosphere, in which terrestrial satellites orbit. Solar activity energy, as opposed to the more constant visible irradiance, inflates the Earth's atmosphere into its upper layers. These upper layers vary exponentially from the exotic solar radiation, making them particularly sensitive.

The short wavelength solar UV and EUV irradiances vary dramatically with solar activity, showing changes of more than 100%, whereas the typical visible wavelength variations are ~0.1%. Above the ozone layer, stratosphere, and mesosphere, the EUV solar irradiance forms the thermosphere and exosphere in which satellites orbit. The high degree of short wavelength variations is coupled with a low density in the upper atmospheric layers, making them more vulnerable to fluctuations.

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The orbits of satellites in LEO depend strongly upon density. The orbital effects on a particular satellite also depend upon the satellite's individual properties (ballistic coefficient, orbital properties, etc.). Although the LEO densities are primarily affected by the Sun's short wavelength output (particularly EUV), the parameter cannot be directly monitored from the ground. The reason is that the same upper atmospheric constituents that absorb this energy serve to provide a feedback loop to better shield the Earth from this dangerous radiation. Thus, what creates serendipitous circumstances for the terrestrial ground-dwellers is unpropitious for the satellites, making them more vulnerable. Because this also results in difficulty monitoring the radiation, the longer (radio) F10.7 cm wavelength radiation (which forms in the same coronal layers as the UV/EUV radiation) is often used as a proxy indicator for the shorter wavelength radiation.

Hence, overall, satellite drag is greatly magnified by solar activity, making solar activity forecasting a valuable tool for low Earth orbit predictions.

Development of Solar Prediction Methods

A NASA-funded National Oceanic and Atmospheric Administration (NOAA) panel investigated a number of methods of solar activity prediction several years ago (see Joselyn et al., ref. 5). These methods of prediction rely upon historical knowledge of previously observed cycles of solar activity seen in Figure 2. The graph also shows the numbered cycles #s 1-23.
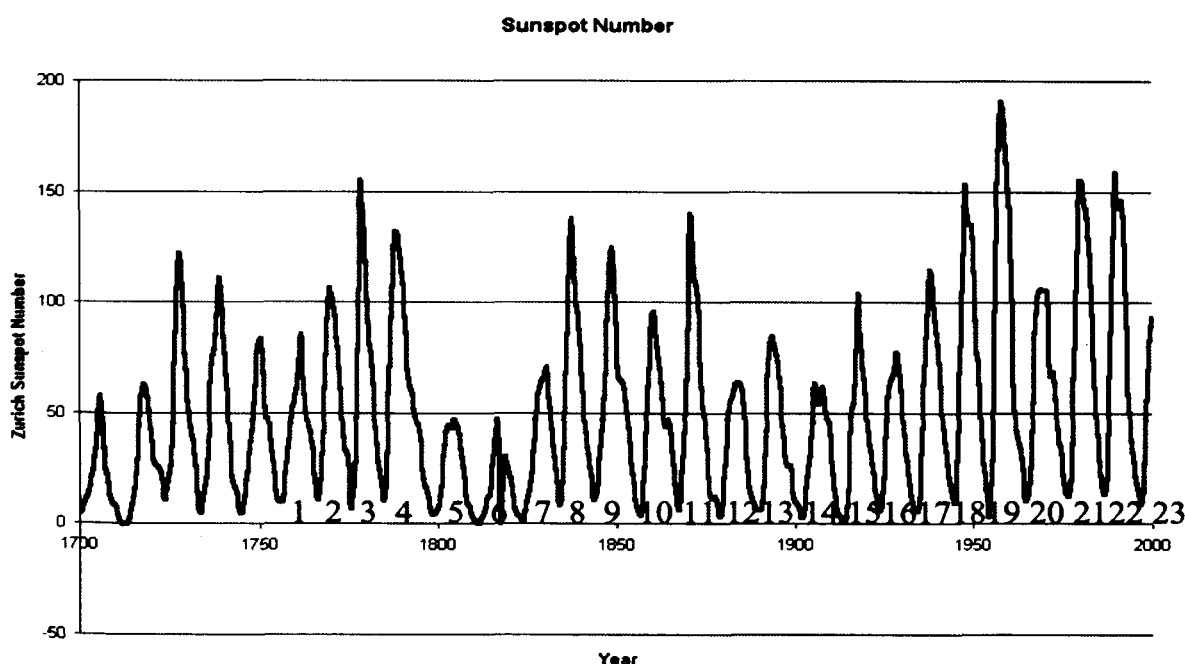

Figure 2: Sunspot Number vs. Time for the Past Few Centuries

The spectrum of solar activity 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. Even beyond this, periods exist, e.g. during the "Maunder minimum" of the 17th century (and other similar epochs), during which solar activity dropped precipitously to near 0. The numbering on the chart also illustrates the "Even/Odd" effect, where this past century's (and most of the previous century's) odd numbered cycles have always been larger than the previous even numbered cycle (e.g. cycle #19 > cycle #18).

The NOAA panel (ref. 5) chose the following general solar forecasting categories: Even/Odd Behavior, Spectral, Recent Climatology, Climatology, Neural Networks, and Precursors. "Precursors" were defined to be

observations which served as an early sign as to the size of the upcoming solar cycle. This is similar to how a low pressure in the earth's atmosphere can serve as a precursor to rain. There is a relationship governed by physical laws that can be used as a predictor. The "precursor" category is further divided into solar and geomagnetic precursors. The solar precursor method performed better than the geomagnetic precursors for this last cycle and will be the focus for the rest of this paper. It is important to note that the other methods of solar activity prediction are mostly mathematical, with little or no known physical understanding, as to how or why they might work. Being non-physical essentially means the methods were developed simply to utilize available mathematics, and for little other reason, e.g. Fourier spectra and analyses. Some methods are statistical (using the known variations from the observed solar activity over last few centuries), and these offer the same benefit that statistics offers to weather predictors. Namely, they tend to provide some estimate for the stochastic (random) aspect of the phenomenon, but little, if any, of the physical aspects. If the data were purely random, then this is probably the best that could be done. However, the solar precursor method exploits some of the physical basis for changing solar activity and the non-random variations. For more information on solar activity prediction methods, including precursor methods, the NOAA panel discussions (ref. 5) provide an excellent source.

For the past cycle, #23, the solar precursors in 1996 suggested a peak value near a smoothed sunspot number of 138 ± 30 and F10.7 values of 182 ± 30 (ref. 4). This value was more accurate than the geomagnetic predictions, which gave too high a value. The solar precursor method began as an offshoot to the geomagnetic methods. The first to point out the significance of the geomagnetic Aa index (a geomagnetic index used as a planetary index, originated by Bartels) in tracking long-term solar activity were Feynman and Gu (ref. 6). Although Feynman never used the information for directly making predictions, it seems clear that the Ohls (refs. 7-8) 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.

The geomagnetic precursor methods involved correlations found by the geophysicists. Nevertheless, they were 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. 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. (ref. 2) searched for a physical mechanism to understand the phenomena.

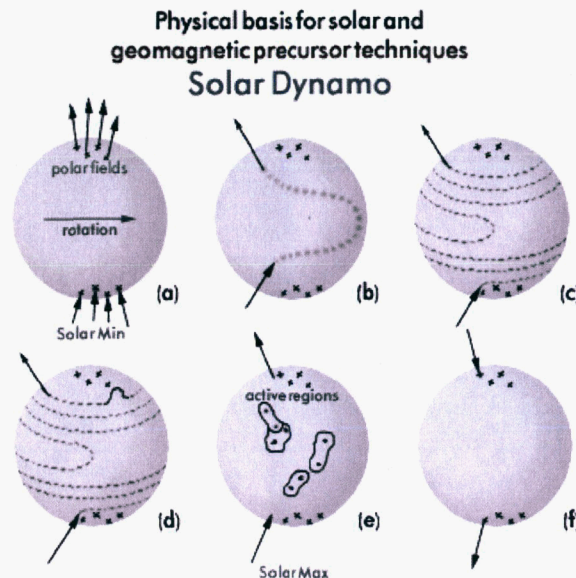**Physical basis for solar and geomagnetic precursor techniques**
Solar Dynamo

Figure 3: The Babcock-Leighton 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 regenerates the Sun's polar field with a reverse sign (f), allowing the process to repeat 11 years later, anti-symmetrically.

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Figure 3 shows the Babcock-Leighton dynamo (see refs. 9-10), a classical, generally well-accepted model for the Sun's dynamo, that explains many observed solar features. More recently, Dikpati and Charbboneau (ref. 11) have examined the detailed workings of this model, including meridional flows, as well as other improvements. Unlike a battery-generated dynamo model, where currents flow as the result of differing electron-ion behaviors, in an MHD dynamo model, the medium is regarded as a perfect fluid, with currents and magnetic fields being magnified by pre-existing magnetic fields. It is generally believed the Sun's activity results from such an MHD dynamo. Thus searching for the source of such fields can lead to understanding the nature of the next solar cycle from the pre-existing detritus field left over from the last cycle. This was essentially inherent for the Babcock-Leighton dynamo, but was not recognized as being particularly useful until Schatten et al. (ref. 2) utilized it to explain geomagnetic precursor predictions and developed their dynamo solar activity predictions.

In detail, the Sun's polar fields near solar minimum (see Figure 3) are wrapped up by differential rotation to form the toroidal fields (which float to the Sun's surface to form active regions during solar maximum). As these fields dissipate, they then regenerate the polar field, allowing the solar cycle to recur. The remnants of the last cycle thus serve as "seeds" for the next cycle. Modern helioseismological studies have shed new light on the Sun's dynamo; nevertheless, the broad views outlined by Babcock, Leighton, and others (Hale, etc.) still remain valid. Figure 3 thus shows an oscillation between the Sun's toroidal field (the East-West fields which erupt to form sunspot fields) and the poloidal field (which extends through the Sun's polar regions).

This provides the key to understanding how to estimate the Sun's buried magnetic flux, and allowing it to be utilized to predict solar activity. The dynamo process outlined is neither as simplified nor "perfect," in terms of perfectly reproducing itself, as suggested by Figure 3, but rather is subject to the vagaries of field magnification within the turbulent convection zone of the Sun. Hence, during an 11-year solar cycle, the amplification sometimes regenerates more polar field and sometimes less, leading to irregular growth and/or decay of the solar cycle. Hence, as Figure 2 shows, the cycles fluctuate in amplitude. Of particular note are the sharp downturns in activity within a single solar cycle that occurred at the end of the 18th and 19th centuries.

If the Sun's dynamo is fairly linear, then one expects a direct correlation between the numbers of active regions formed in that cycle with the strength of the Sun's polar field near the cycle's previous solar minimum. In this view, 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, for that cycle. Namely, by monitoring the observed magnetic fields of the Sun, one can use these observations to predict future levels of solar activity. As mentioned earlier, this is similar to the way meteorologists monitor atmospheric pressure regions to predict cloud formation. Hence it is a "physics-based" forecasting technique, which uses recent observations to forecast future solar activity. This is opposed to the numerical methods which sometimes use arbitrary mathematical techniques, that some times depend upon events (e.g. Fourier analysis) occurring many centuries ago. To validate the dynamo method, 8 solar cycles of historical data (ref. 2) were used to test the methods, and reasonable correlations were found. These were not "predictions" since they were not undertaken in advance. The method has now been used to make actual predictions, each one in advance, for the past 3 solar cycles (~30+ years), and now for the fourth.

The Solar Dynamo Amplitude (SODA) Index

When precursor methods of predicting solar activity were 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 reach their peak, and poke through the Sun's surface at the poles. The analysis method developed by Schatten and Pesnell (ref. 12) utilized a SOlar Dynamo Amplitude (SODA) index to provide an estimation of the magnetic state of the Sun during any phase of the solar cycle, rather than only at solar minimum. As the solar cycle progresses, there is an interchange between poloidal (polar) and toroidal (sunspot-forming) magnetic fields (see Figure 3). This is similar to the interchange between the kinetic and potential energies of a pendulum. One may measure both and obtain a measure of the total energy of the pendulum at any time rather than measuring only the maximum kinetic or maximum potential energy only at certain specific times. Utilizing this idea allowed Schatten and Pesnell to capitalize on more aspects of solar magnetism than simply the polar field to obtain the SODA index. Just as with the combined energy of the pendulum, use of this index allows it to be updated during any phase of the Sun's solar cycle. Figure 4 shows the 11-year oscillations of the poloidal and toroidal fields, often obtained with proxies, plus their secular (long-term) changes. By using both indices, the combined SODA index shows less 11-year variation, but retains the Sun's secular

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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 these authors did not use spectral filtering to remove the 11-year variations, as this would require the dependence of current conditions upon old observations, and hence would mitigate the benefits gained by updating solar conditions with the latest information (i.e. it would just smooth the data out). This has the "detraction" of not removing noise, but the benefit of allowing frequent "updating," so there are tradeoffs.

The SODA index provides a continuous measure of the strength of the magnetic field buried within the Sun's interior. 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, but also 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 decreasing during the past decade, suggesting that solar cycle #24 will be smaller than past cycles. Let us also examine the polar field strength levels more directly, and use them for a prediction of the next cycle, to provide some validation.
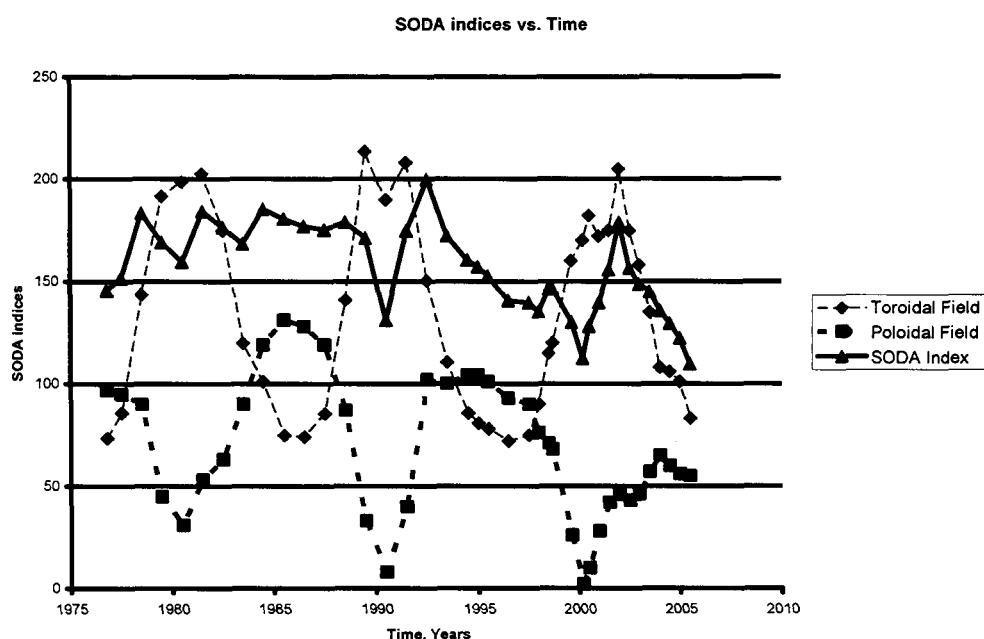

Figure 4. The SODA index is a composite index index allowing us to monitor the "buried magnetic flux" present in the Sun's ever-changing dynamo.

A PREDICTION FOR SOLAR CYCLE #24 (~2007 through 2018)

In order to predict the Sun's activity, the key component near solar minimum is the Sun's polar field. We examine this more directly, leading to the next cycle's predicted activity level. The Sun's polar field reversed near the peak activity of cycle #23 (year 2000), and began its growth toward a new peak with opposite polarity. Figure 5 shows the Wilcox Solar Observatory polar field strength measured in the pole-most 3 minute aperture approximately every 10 days, smoothed with a ~500 day low band pass filter. The figure also shows the Mount Wilson Observatory observations. Solar observatories (refs. 13-15) provide the following behavior. After polar field reversal, the smoothed mean polar field rose at about half the rate as in the corresponding portion of the previous few cycles. It has now been fluctuating at nearly half the value of these recent past cycles. Fluctuations seem to be caused by large Unipolar Magnetic Regions (UMRs), which we discuss more fully later. They are situated in unstable locations (at mid latitudes, rather than at the poles). During the current phase of the solar cycle (5 years past polar field reversal), "flux injection events," wherein the polar fields grow, usually terminate. These events are ones wherein solar magnetic flux from active regions drifts towards the Sun's poles to add flux to the new polar field. Hence although the fate of the UMRs is uncertain, they are not expected to contribute significantly to enhancing the current polar field to the magnitude seen in recent decades
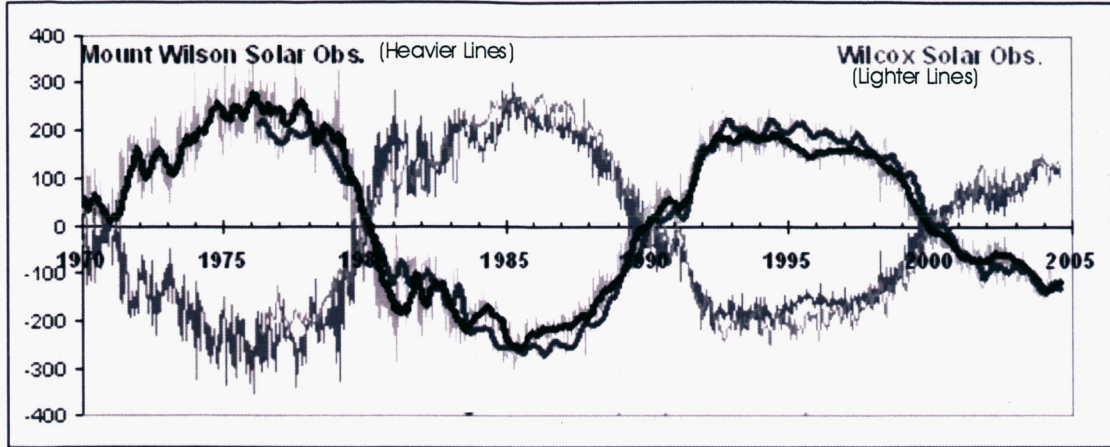
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Figure 5: The polar field (10^{-6} T) as observed by Mt. Wilson (MWO), and Wilcox Solar Observatory (WSO), after refs. 13-15. The heavier line of each pair is the MWO and the lighter line, WSO. As can be seen, the recent polar field is significantly lower than during the previous 3 solar cycles.

With the polar field seen in Figure 5 significantly smaller than the peaks of the past few decades, the SODA method, sometimes referred to as the solar 'dynamo' or 'precursor' method, clearly predicts a decreased activity level for the upcoming solar cycle #24. This prediction will be further examined.
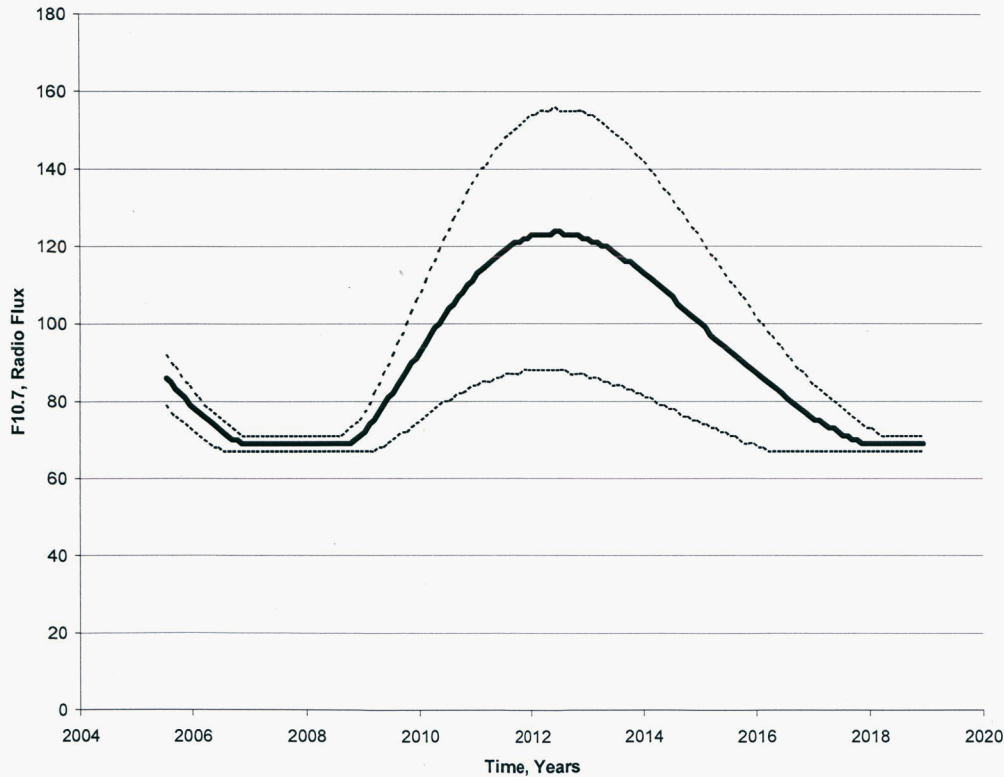

Figure 6. Prediction for the "new" solar cycle # 24 (heavy line); radio flux in units of 10^{-22} J s^{-1} m^{-2} Hz^{-1}. The light lines show the ± 2 sigma uncertainty lines. Possible timing uncertainties (of ~± 1 year) are not shown. The uncertainties shown here do not reflect the natural (daily, monthly, and yearly) variability of solar activity, which makes the actual curve of solar activity resemble a series of delta functions averaged to this approximate shape.

As shown in Figure 6, the current SODA values predict a mean smoothed Radio Flux, F10.7, for cycle #24 of about 124 ± 30 and a smoothed sunspot number, Rz, of about 74± 30. The predicted timing of the cycle has been less precise than the amplitude prediction, with uncertainties on the order of ± 1 year. More will be learned when "new cycle sunspots" of reverse sign appear on the solar disk at high latitudes. The fact that we have not seen any new cycle spots, as of June, 2005, suggests that the solar minimum between cycles #23 and #24 is probably at least a year away. This allows a rough timing, as shown in Figure 6. The cycle is expected to peak in the 2012 timeframe, although sunspot cycles typically have high levels of activity for about 4 years, making an exact timing difficult.

OBSERVATIONS SUPPORTING WEAKENED POLAR FIELDS

Several independent observations related to reduced polar field strengths provide evidence in support of the prediction of reduced solar activity during the next solar cycle. These observations, discussed in detail throughout the remainder of this section, include counts of polar faculae, examination of soft X-ray coronal holes, and coronal field calculations.

Counts of Polar Faculae

Faculae, Latin for torches, are bright features seen near the Sun's limbs. They are associated with given amounts of magnetic flux, allowing their count to serve as a rough measure of magnetic flux, when the field is not directly observed with a solar magnetograph. They are essentially a "poor man's magnetograph" and thus allow us a rough direct measurement of the solar field. Figure 7 shows the number of polar faculae for much of the last century. Although not as dramatic as sunspots or solar flares, their importance (see refs. 16 and 17) has made them an object of study for fearless solar observers who do not mind observing "quiet solar phenomena." Although the current (yr ~2000) polar faculae (ref. 17) show reduced levels, they were made by a different set of observers than ref. 16. Nevertheless, Sheeley and previous observations from Mount Wilson (ref. 16) assert that the faculae do provide a good proxy for the WSO observations. Thus the faculae do support the trend (of a currently weakened polar field) seen directly from the observatories. In addition, Figure 7 supports the reduced levels of polar fields, even if the observations cannot be well calibrated until an overlapping set of observations of the Sun is made with the two instruments used for similar time periods. To illustrate the high degree of uncertainty between the two sets of observations in Figure 7, Sheeley (ref. 16) points out that he observes both hemispheres near the poles in the spring and fall when both hemispheres become visible, due to the 7 ¼ degree tilt of the Sun to the ecliptic.
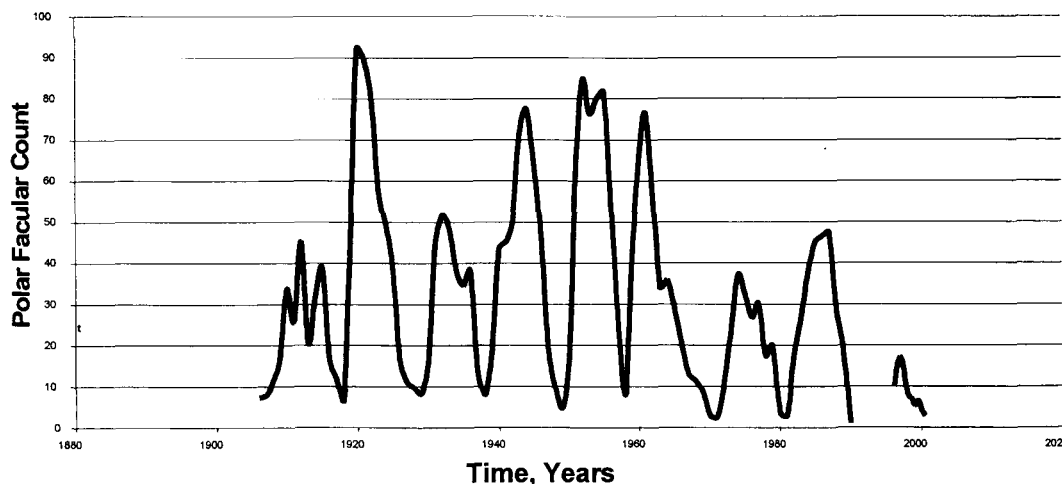

Time, Years

Figure 7: Polar facular count. The observations through 1990 were obtained at the Mt. Wilson Observatory (MWO, ref. 16), and the last decade by a "world net of polar facular observers" (ref. 17). As with all solar observations, the measurement of secular changes is difficult because observatories and observers necessarily change over the centuries.

Examination of Soft X-ray Coronal Holes

An examination of soft X-ray coronal holes was performed in an attempt to answer the question: Why and how could the Sun's field dissipate so rapidly? It raised a response suggesting that something may have occurred to the structure of the large scale solar magnetic field, different from the normal polar reversal seen in Figure 3. In the normal reversal, the field is weakened by "flux injection events" from the "following" polarity magnetic active regions at the sunspot latitudes. These flux injection events in the early phase of a solar cycle reverse the polar field, while later in the cycle they form and magnify "opposite" polarity polar fields.

Once a polar field forms, it is normally readily identified in "soft X-ray" photos seen from space, where it forms a "coronal hole." The reason there is a "hole" in soft X-rays, is that the energetic particles empty from "open" field lines, and hence they are dark. Figure 8 shows a drawing from Karen Harvey, based upon the He 10830 line (left), as well as recent images of the sun based upon soft X-rays and the He 10830 line from ref. 18. For the present time period, we see that few or no large scale polar coronal holes have formed. This is atypical of coronal holes near solar minimum. The coronal holes seen here are floating around the solar disk, with only weak holes located at the safe harbors of the Sun's polar regions.
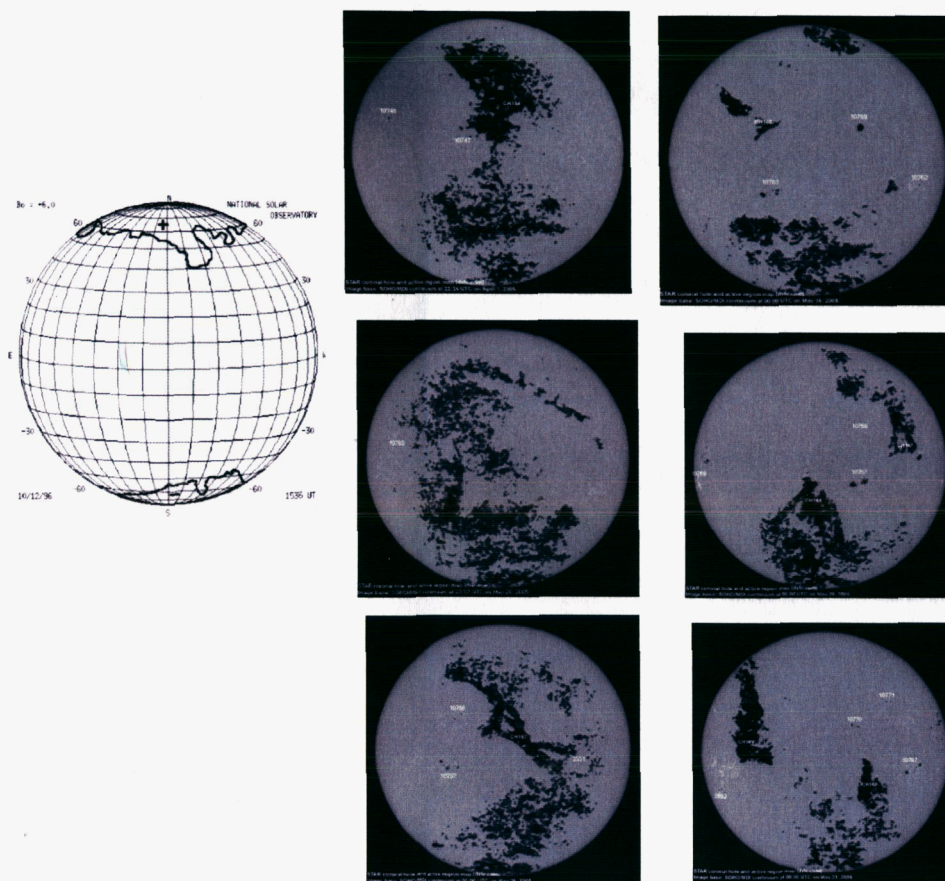
October, 1996 Coronal Hole Drawing,
Karen Harvey, using Kitt Peak He 10830 line

April, May, 2005 STAR SOHO/MDI Coronal Hole Map

Figure 8. (Left) Drawing of coronal holes near the solar minimum of 1996 by Karen Harvey. Each pole shows a large scale coronal hole, very typical of solar minimum conditions. (Right) Shown are a number of views of current coronal hole maps (based on soft X-rays), with six different views of the Sun over two months in the April-May, 2005 time frame.

The current reduction in polar field may have been the result of the unusual behavior of low latitude unipolar magnetic regions (UMRs, see ref. 19). The UMRs are like polar fields, which are one form of UMR, but large-scale unipolar magnetic fields can also reside on the Sun at equatorial and mid latitudes. The UMRs, although sometimes located at low latitudes, are most common at the poles, where they are stable since no surface differential rotation (DR) occurs there. In soft X-rays, UMRs become evident as coronal holes, and also can be seen in the line of He 10830 (see ref. 18), with both features formed on open field lines in the Sun's corona. It is believed that the UMRs did not drift to the "opposite poles" rapidly this cycle, and this unusual reduced motion of UMRs and coronal holes prevented the "normal reversal" of the Sun's polar field.

Coronal Field Calculations

One last method to examine the strength of the Sun's polar field utilizes coronal field calculations based on the "source surface" model. Hoeksema et al. (ref. 13) have improved these calculations from their early days and provide frequent updates. Field calculations during two periods just before solar minimum are illustrated in Figure 9. The top drawing in Figure 9 is from May 1994, prior to solar minimum of the last cycle. The lower drawing is recent, May 2005. A decade ago, flattening of the "heliospheric current sheet" to about ± 10 degrees is observed. This indicates a strong polar field, enabling it to suppress significant undulations in the sheet. At present, the undulations are about 3 times the range, or ± 30 degrees. This supports weak polar fields or polar fields which have not fully formed. They are insufficient to suppress significant current sheet curvature.
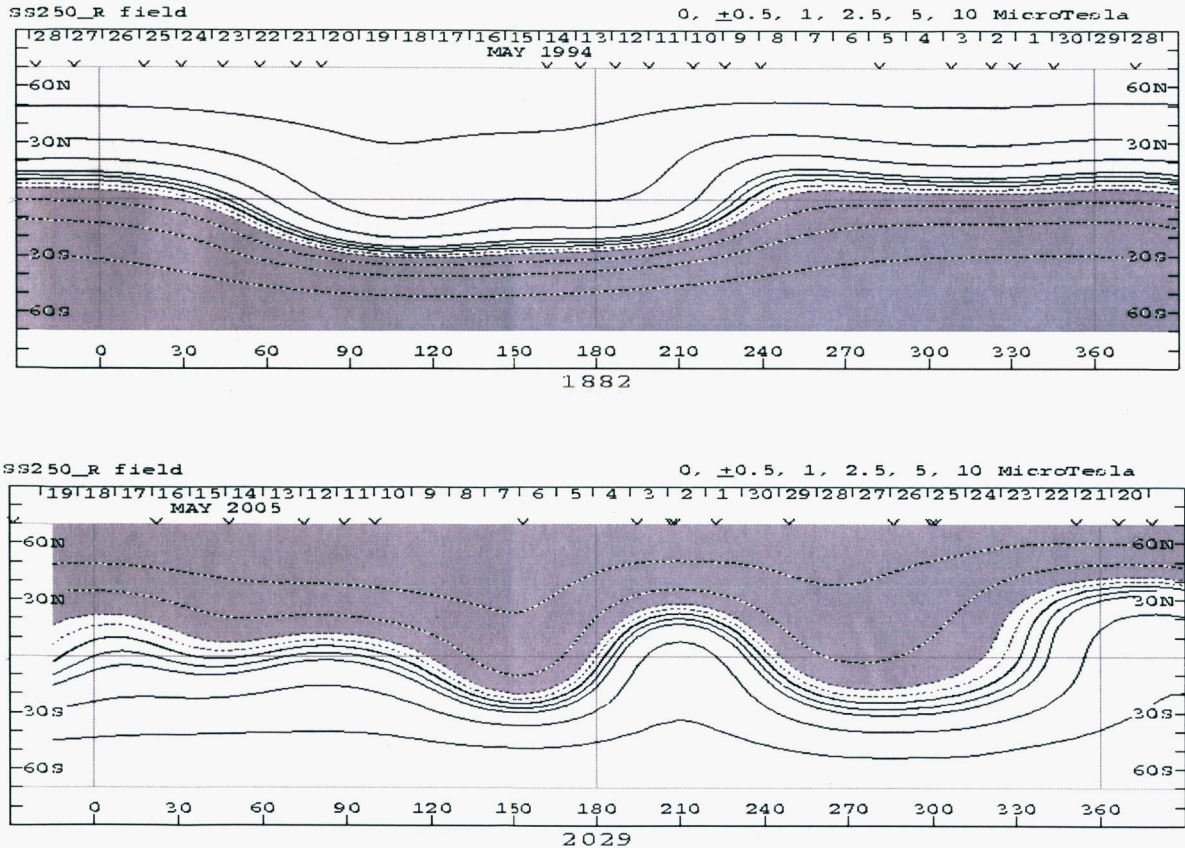

Figure 9. Calculated coronal magnetic field, based upon "source surface" calculations (ref. 13). Top shows the coronal field in May 1994, and Bottom, in May 2005. The flattening of the "heliospheric current sheet" (~ ±10 degrees) seen in the top figure supports a fully formed polar field which suppresses the undulations in the sheet. In the current situation, the undulations are ~ ±30 degrees, which suggests polar fields are insufficiently strong to suppress the current sheet curvatures.

IMPLICATIONS FOR NASA

The reduced levels of solar activity predicted for the next decade would have a number of large effects upon Earth's fragile thermosphere and exosphere, resulting in significant changes in the space environment of LEO spacecraft. The main direct effect for spacecraft flight dynamics would be reduced levels of density, and hence less atmospheric drag on satellites in orbit. Thus orbital prediction of satellites in LEO would need to be reexamined, based upon the altered thermospheric and exospheric densities. A decrease in solar activity would result in smaller satellite decay rates (and less variability). However, there are less obvious and less beneficial effects in the form of increased space debris and galactic cosmic radiation. Other potential effects which might be considered but are not discussed in this paper include changes in the chemical abundance of atmospheric constituents.

A large solar cycle has one benefit to satellites in orbit, namely that solar activity clears out some of the unwanted artificial space debris currently circling in low Earth orbit. The reverse is also true, that a small solar cycle could result in an increase in the amount of space debris. At the end of 2001, there were believed to be around 9000 objects larger than 10 cm orbiting the Earth. Of these, only 6 percent are operational satellites. The remainder represents old satellites, rocket bodies, and other fragments. They pose an impact hazard to the operational spacecraft and manned missions. Additionally, since 1957 (when Sputnik I was launched), space debris has increased to the point where there is now a real hazard to large operational structures such as the International Space Station. Dips in the amount of space debris occur during and after years of high solar activity. For example, during the years 1979-80, solar activity was large enough to cause the rapid re-entry of many objects in the 200-400 km altitude range. This was the first time that the attrition rate of space "junk" exceeded the generation rate from launch activity and fragmentation of existing objects in space. A similar and even more pronounced dip was produced at the maximum of solar cycle 22, around 1990.

The magnetic field of the sun is interwoven within the solar wind. The solar wind is made from a continuous stream of plasma, mainly protons and electrons. The solar wind expands throughout the solar system, until about 200 AU, in a region called the Heliosphere. The magnetic structure of the Heliosphere functions as a shield, allowing only some of the galactic cosmic ray particles (GCR) to penetrate to the inner part of the solar system. If solar activity were constant, the GCR flux at Earth would be constant. When the sun is active, the magnetic field and resulting shield are stronger and fewer GCR arrive in the vicinity of Earth. When solar activity is low, the shield is weaker, and more GCR arrive. The GCR is thus inversely correlated with solar activity. The increase in GCR compared with recent average GCR might spell trouble for astronauts on long space voyages (e.g., to the Moon or Mars) and these effects will need to be considered. Note, there are solar cosmic rays that vary proportionally to solar activity but they are of lower energy.

SUMMARY AND CONCLUSIONS

This paper outlines the solar dynamo method for solar activity prediction. Additionally, past predictions are updated, with the most recent solar data. This suggests a peak (smoothed) activity level for solar cycle #24 of about 124 ± 30 for F10.7 Radio Flux. It is important to remember that the uncertainties do not reflect the daily, monthly, and yearly variations associated with the stochastic component of solar activity, but only the uncertainty in the smoothed activity level. The reduced levels of activity are predicted using outgrowths of the solar "precursor" or dynamo methods, currently using the Solar Dynamo Amplitude (SODA) index. This reduction may be a result of low latitude coronal holes which caused the typical reversal of the Sun's polar field to shut down. Support for reduced activity is found from a number of other polar field proxies. Independent of the cause, a significant reduction in solar activity would result in significant impacts to LEO spacecraft. These impacts include reductions in atmospheric drag leading to lower orbit decay rates of LEO spacecraft and, as a further result, increases in the amounts of space debris. Additional impacts include increased GCR activity within the space environment.

REFERENCES

1. Schatten, K. H., "Long-Range Solar Activity Predictions: A Reprieve From Cycle #24's Activity", NASA-GSFC, Flight Mech. Symposium, Editor, John Lynch, 2003.

2. Schatten, K. H., Scherrer, P. H., Svalgaard L., and Wilcox, J. M., "Using Dynamo Theory to Predict the Sunspot Number During Solar Cycle 21", *Geophys. Res. Lett., 5*, 411, 1978.

3. Schatten, K. H., and Sofia, S., "Forecast of an Exceptionally Large Even Numbered Solar Cycle," Geophys. Res. Lett., 14, 632, 1987.

4. Schatten, K. H., Myers, D. J., and Sofia, S., "Solar Activity Forecast for Solar Cycle 23", *Geophys. Res. Lett., 6*, 605-608, 1996.

5. Joselyn, J.A., J.B. Anderson, H. Coffey, K. Harvey, D. Hathaway, G. Heckman, E. Hildner, W. Mende, K. Schatten, R. Thompson, A.W.P. Thomson, and O.R. White, "Panel achieves consensus prediction of Solar Cycle 23", *EOS, Trans. Amer. Geophys. Union, 78*, pp. 205, 211-212, 1997.

6. Feynman, J., and X.Y. Gu, "Prediction of geomagnetic activity on time scales of one to ten years", *Rev. Geophys., 24*, 650, 1986.

7. Ohl, A. I. *Soln. Dann.* No. 12, 84, 1966.

8. Ohl, A. I. and Ohl, G. I. in R. Donnelly, "A New Method of Very Long-Term Prediction of Solar Activity", ed. *Solar-Terrestrial Predictions Proceedings*. Boulder, CO, USA. Vol 2, 258-263, 1979.

9. Babcock, H.W.,"The topology of the Sun's magnetic field and the 22-year cycle," Ap. J. 133, 572-587, 1961.

10. Leighton, R. B., "A magneto-kinematic model of the solar cycle," Ap. J, 156, 1-26, 1969.

11. Dikpati, M., and Charbonneau, P., "A Babcock-Leighton Flux Transport Dynamo with Solar-like Differential Rotation", Ap. J., 518, 508, 1999.

12. Schatten, K.H., and Pesnell, W.D., "An early solar dynamo prediction: Cycle 23 ~ Cycle 22," *Geophys. Res. Lett, 20*, 2275-2278, 1993.

13. Hoeksema, T., Scherrer, P. et al., "Wilcox Solar Observatory Polar Field strengths, 3' aperture, 20 nhz low pass (~500 day) filter" and "computed coronal field for 2.5 solar radii (Source Surface)", 1977-2005,

14. Boyden, J. and Ulrich, R., Mount Wilson Observatory (MWO), private comm., 2005.

15. Svalgaard, L., E. Cliver, and Y. Kamide, "Sunspot cycle 24: Smallest cycle in 100 years?", Geophys. Res.Lett., VOL. 32, L01104, 2005.

16. Sheeley, Jr.,N., "Polar faculae - 1906-1990",Astrophysical Journal, Part 1 (ISSN 0004-637X), vol. 374, p. 386-389, 1991 and private communications, 2005.

17. Dubois, F., Janssens, J. et al. "world net of polar facular observers", data located at http://www.digilife.be/club/Franky.Dubois/polar.htm, 2005.

18. Kahler, S. W.; Davis, J. M.; Harvey, J. W. "Comparison of coronal holes observed in soft X-ray and HE I 10830 A spectroheliograms",Solar Physics, vol. 87, p. 47-56, 1983.

19. Bumba, V., and Howard, R., "Large Scale Distribution of Solar Magnetic Fields", Ap. J., 141, 1502, 1965.