Decline in solar polar magnetic fields and heliospheric micro-turbulence levels: Are we headed towards a Maunder minimum?

Susanta Kumar Bisoi[1], P. Janardhan[1] and S. Ananthakrishnan[2]

[1] *Physical Research Laboratory, Ahmedabad 380 009, India and susanta@prl.res.in, jerry@prl.res.in*
[2] *Department of Electronic Science, University of Pune, Pune 411 007, India and subra.anan@gmail.com.*

Abstract

Sunspots or dark regions of strong magnetic fields on the solar photosphere are generated via magnetohydrodynamic processes in the solar interior that involve the cyclic generation of toroidal fields (sunspot fields) from pre-existing poloidal fields and the eventual regeneration of the poloidal fields. This cyclic process, referred to as the solar dynamo, leads to the well known solar activity cycle of waxing and waning sunspot numbers with a period of 11 years. The sunspot minimum at the end of solar cycle 23, however, was one of the deepest recorded in the past 100 years, with cycle 24 starting about 16 months later than expected. A detailed study of solar high latitude ($\geq 45°$) or polar magnetic fields using ground based magnetograms has clearly shown a steady decline in polar field strength since mid-1990's [1, 2, 3] which has continued to the present, $i.e.$ until the end of February 2013. Since sunspot fields are generated from polar fields, this long term decline in polar field strength would eventually effect the sunspot field strength in the subsequent solar cycles. A continued decline in the polar fields in the manner indicated by our analysis would imply that the polar field strength will approach zero by $\sim$2031. In addition, a detailed analysis of solar wind micro-turbulence in the inner heliosphere has also shown a steady decline in sync with the declining solar photospheric magnetic fields. The fact that both solar polar fields and inner-heliospheric micro-turbulence levels show a similar decline raises the question as to whether we are headed towards an extended period of very little or no sunspot activity in a manner similar to what was seen in the Maunder minimum?

1. Introduction

We are currently in the declining phase of solar cycle 24 which has turned out to be a very weak cycle, with a peak sunspot number of around 70. Solar cycle 24 was also preceded by a very extended and deep solar minimum that caused it to start about 1.3 years later than expected, with sunspots of the new cycle 24 appearing only in March 2010 instead of December 2008. Since solar photospheric magnetic fields are an obvious indicator of solar activity, we have undertaken a detailed investigation of solar photospheric magnetic fields in the past three solar cycles, covering the period of 1975 – 2013. A striking feature of our analysis has been a steady and significant decline in photospheric magnetic fields, at latitudes $\geq 45°$ (referred to in the rest of the paper as polar fields) in both solar hemispheres, with the observed decline having begun in the mid-1990's [1]. Earlier, other authors have reported a steady decline in sunspot umbral field strengths since $\sim$1998 [4, 5] and proposed a very weak solar cycle 25.

In addition to the above study of solar polar fields, we have also examined solar wind micro-turbulence levels in the inner-heliosphere using interplanetary scintillation (IPS) observations at 327 MHz. Since photospheric fields are swept out into the heliosphere by the solar wind to form the interplanetary magnetic field (IMF), one would expect to see signatures of the declining photospheric fields in the solar wind. As stated earlier, our analysis of solar wind micro-turbulence in the inner heliosphere has also shown a steady decline which is in sync with the declining solar photospheric magnetic fields. In addition, the decline, which started in the mid-1990's has been continuing for the past 18 years which is almost a complete solar magnetic cycle of 22 years.

The current solar cycle has had a maximum sunspot number of around 70 and it is now in the declining phase so it is likely that the decline will continue through the minimum of solar cycle 24, expected around 2020. A peak sunspot number of around 70 in the current solar cycle makes this situation somewhat similar to the conditions that existed prior to the onset of the Maunder minimum between 1645 – 1715 when the solar photosphere was completely devoid of sunspots. Though the data in this period is sparse, it is known that the peak sunspot number prior to the onset of the Maunder minimum was around 50 [6].

2. Photospheric Magnetic Fields

Photospheric magnetic fields were obtained using synoptic maps from the National Solar Observatory (NSO) at Kitt-Peak (NSO/KP), USA. Synoptic maps are made from full disk magnetogram images of the Sun observed for a full Carrington Rotation (CR) period of 27.2753 days. Each CR map is available online as a standard FITS file array of 180 $\times$ 360 in sine of latitude and longitude format. The data used covers Carrington rotations from CR1625 to CR 2132 corresponding to the years 1975.14 to 2012.92. Photospheric magnetic fields were estimated using a longitudinal average of the whole 360° array of Carrington longitudes to produce 1°strip of data for each CR. Polar or high latitude fields in the desired latitude range 45° – 78° [1, 3] were then derived by appropriate averaging. Figure 1 shows the temporal variation of photospheric magnetic fields in the latitude range 45° – 78° computed from these synoptic magnetograms. The large open circles in Figure 1 are annual means of actual measurements of magnetic fields.

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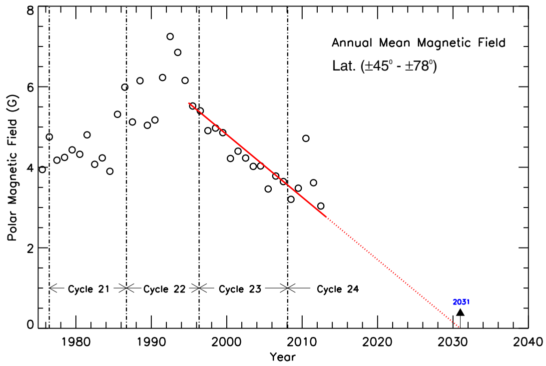

Figure 1: Shows photospheric magnetic fields in the latitude range $45° – 78°$, for the period of 1975 – 2013. The open circles are annual means of actual measurements while the solid red line is a fit to the declining trend that has been extrapolated to a hypothetical magnetic field strength of zero which, if the trend continues, would occur in $\sim$2031.

In Figure 1, an increase in the strength of polar magnetic fields for the period of 2009 – 2011 is clearly noticeable. However, the field strength again reduced and the declining trend continued from 2012 to the present. Thus, a steady decline in polar magnetic fields has been observed for $\sim$18 years. A study of the sunspot umbral field strengths has reported [4] a steady decrease $\sim$50 Gauss (G) per year. It is known that for field strengths below about $\sim$1500 G, there is no contrast between the photosphere and sunspot regions. Thus, sunspots will not be visible when umbral fields drop to this value. In addition, Livingstone, Penn and Svalgard, derived a parameter, using the 10.7 cm radio flux from the Sun, to estimate sunspot formation fraction and showed that this quantity began to steadily drop from around 1995 [5]. It must be noted that our observations also show a decline in polar photospheric fields starting from $\sim$1995.

Our observations have show that the polar field strength of cycle 23 was comparatively weaker than the previous cycles 21 and 22 [1] and the current cycle 24 was the weakest of the three earlier cycles. Assuming that the declining trend in the polar fields continues at the present rate, a simple extrapolation of the data will show that the field strength is expected to drop to zero by 2031. The solid red line in Figure 1 is a fitted curve to the annual means of the actual measurements for the period 1995 – 2013.

3. Solar Wind Micro-turbulence

Photospheric fields are swept out continuously by solar wind flows into the interplanetary medium and form the interplanetary magnetic field (IMF) and solar wind turbulence levels are related to the rms electron density fluctuations and large-scale magnetic field fluctuations in the fast solar wind streams [7]. So signatures of any long-term and global variation in solar photospheric fields are expected to be reflected as a change in the solar wind micro-turbulence levels. Such changes, if any, can be effectively measured via the ground-based technique of interplanetary scintillation (IPS) at meter wavelengths. IPS is a diffraction phenomenon in which coherent electromagnetic radiation from a distant radio source passes through the turbulent and refracting solar wind and suffers scattering. This results in random temporal variations of the signal intensity (scintillation) at Earth [8]. Using IPS measurements on a number of compact extra-galactic radio sources covering the period of 1983 – 2008, it was found that solar wind micro-turbulence levels have also been declining steadily since the mid-1990's [2]. These results were derived from measurements of scintillation index (m) at 327 MHz from the four station IPS observatory of the Solar Terrestrial Environment Laboratory (STEL), Nagoya University, Japan.

It may be re-emphasized here that between 2009 – 2011 photospheric magnetic fields seemed to be again increasing as can be seen in Figure 1. However, by early 2012, the fields had declined again and the declining trend has continued to the present. In general, the degree to which a compact radio source scintillates depends on both its intrinsic angular diameter or source size and the distance of the line-of-sight (LOS) to the source from the sun. Larger angular diameter sources yield a lower level of scintillation, m, at a given distance from the sun and in addition, m also declines with increasing radial distance. In a typical IPS observation at 327 MHz, the distance of the LOS from the sun lies in the range 0.2 –0.8 AU and the source sizes range from 10 milli arc second (mas) for the most compact radio sources to about 250 mas. We have therefore re-examined the IPS data for the period 1983 – 2012 in a much more rigourous manner after removing both the source size and distance dependence of m.

The scintillation index (m) is given by $\mathrm{m} = \frac{\Delta S}{<S>}$, where ΔS is the scintillating flux and <S> is the mean flux of the observed radio source. For an ideal point-like radio source and at an observing wavelength λ, m steadily increases with decreasing distance 'r' from the Sun until it reaches a value of unity at some distance from the Sun. As r continues to decrease beyond this point, m will again drop off to values below unity. The region beyond the turn over is referred to as the weak scattering regime where the total rms phase deviation imposed by the solar wind on a plane wave front from the radio source is $<<$ 1 radian.

The expected values of m for radio sources of a given source size as a function of r can be computed by obtaining the theoretical temporal power spectra using the well known Marians model assuming weak scattering and a power law

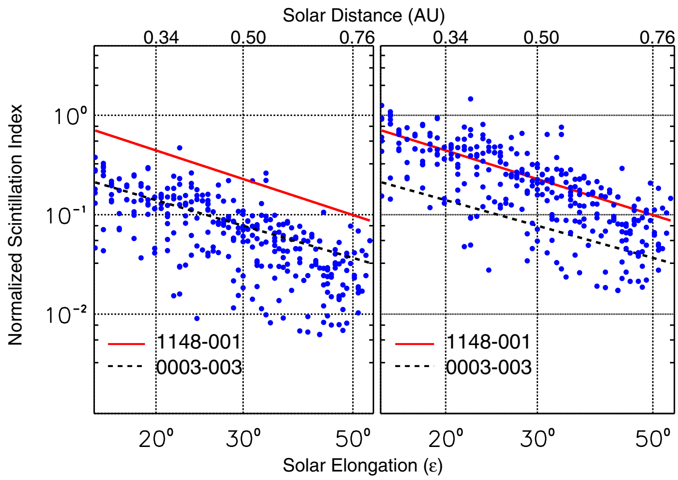

Figure 2: The left hand panel shows curves of theoretical m computed using Marians model for the sources, 1148-001 (solid red line) and 0003-003 (dashed black line). The filled blue dots are the actual measurements of normalized scintillation indices for the source 0003-003. The right hand panel shows the data for the source 0003-003 after are it has been multiplied by a factor given by the ratio of theoretical curves of 1148-001 (solid red line) and 0003-003 (dashed black line) at each ϵ.

distribution of density irregularities in the IP medium [9]. It is known from VLBI observations that the radio source 1148-001 is a good approximation to an ideal point source, being about 10 mas in angular size [10]. Thus, m can be made independent of source size by multiplying the observed scintillation index values of all other sources by a factor equal to the difference between the best fit Marians curve for the given source and the best fit Marians curve for 1148-001, at the corresponding solar elongation (ϵ) where ϵ is the angle between the sun-earth line and the LOS to the radio source, with the distance r of the LOS being r = sin(ϵ) AU.

The left hand panel of Figure 2 shows, by filled blue dots, the actual observations of m as a function of heliocentric distance, r, for the source 0003-003. The dashed red line is the Marians curve corresponding to a source size of 10 mas, while the dashed black line is the Marians curve which best fits the the data for the source 0003-003. The right hand panel of Figure 2 shows the same data after it has been normalized, as described above to remove the effect of the finite source size. After normalizing all the observations in the above manner, we chose only 27 sources for further analysis, which had at least 400 observations distributed uniformly over the entire range of heliocentric distances without any significant data gaps. The normalized, source size independent data for all 27 sources can thus be obtained by adopting the above procedure. The distance dependence of m can now be removed [2] by normalizing every individual observations by the theoretical value of m at the corresponding ϵ, obtained from the best fit Marians curve for 1148-001.

Figure 3 shows variation of m as function of time in years for all observations of m for the 27 sources after making them both source size and distance independent. The large open circles are annual means of m. The declining trend in the data from ∼1995 is clearly evident. The solid red line is the best fit curve to the measurements of m for the period 1992 – 2012. The dashed red line is an extrapolation of this curve, assuming that the declining trend continues, to the same point in time when the extrapolated magnetic fields reach a value of zero.

4. Discussion and Conclusion

From the present analysis of both polar fields and solar wind turbulence levels, it is seen that the declining behavior of solar activity has been continuing and currently for the past 18 years. According to the current understanding of the solar dynamo, the poloidal fields are generated through the Babcock–Leighton mechanism by the decay of tilted bipolar sunspots. The generation of the polar fields by this mechanism cause the polar field to be randomly weaker or stronger than in the previous cycle [11, 12]. Our analysis has shown a decline in the polar fields for the past ≈18 years implying weak polar fields being generated in the past three successive solar cycles *viz.* Cycles 22, 23, and 24. A continuation of this declining trend beyond 22 years would have serious implications on our present understanding of the solar dynamo. Since we are already in the declining phase of solar cycle 24, the declining trend is likely to continue at least until the minimum of the current cycle 24. Given the fact that there would be no contrast between the photosphere and sunspot umbra when umbral fields decline to about 1500 G [4], it appears that we are headed to an extended period of little or no sunspot activity, thereby raising the all important question of whether we are heading towards another Maunder minimum? The data seems to indicate that we are.

5. Acknowledgments

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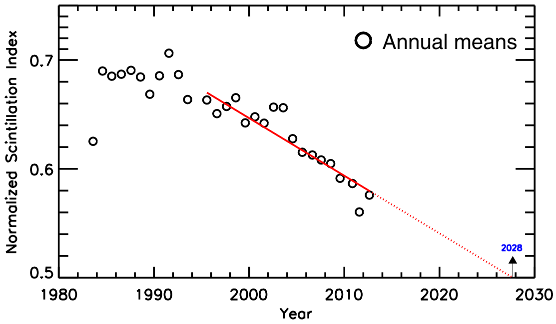

Figure 3: Shows m as function of time in years for 27 sources after making the data of each source independent of source size and radial distance. The large open circles are annual means of the actual measurements of the normalized m. The solid red line is a fit to the declining trend with the dashed red part being an extrapolation to the time when the magnetic fields would, if the decline continued, be equal to zero.

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