A 20 Year decline in solar magnetic fields and solar wind micro-turbulence levels:Are we heading towards a Maunder-like minimum?

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Abstract — Our study of solar high-latitude (≥45°) photospheric magnetic fields and interplanetary scintillation observations, at 327 MHz, of solar wind micro-turbulence levels showed a steady decline for the past 20 years. Also, the fact that cycle 24 has already past its peak, implies that high-latitude fields are likely to decline until ~2020. Based on a correlation between the solar high-latitude fields and the heliospheric magnetic fields (HMF), we estimated the HMF strength in 2020 and the floor value of the HMF, which were found to be 3.9 (±0.6) nT and 3.2 (±0.4) nT, respectively. Using estimated value of the HMF in 2020, the peak sunspot number for solar Cycle 25 was estimated to be 62 (±12). These results and the fact that solar magnetic fields continues to decline at present raise the question of a very low sunspot activity in near-future or another grand minimum similar to the Maunder minimum. So what is the possible impact of such a likely grand minimum on terrestrial ionospheric current systems? Our study night time F-region maximum electron density (a measure of terrestrial ionospheric currents) reveals that the impending minimum is not likely to have any adverse impact rather the period post cycle 25 will be useful for undertaking systematic ground based low-frequency radio astronomy as the night time ionospheric cutoff-frequency could be well below 10 MHz.

Keywords — solar magnetic fields; solar wind turbulence; heliospheric magnetic fields; solar-terrestrial relations

I. INTRODUCTION

From our studies of solar photospheric magnetic fields at helio-latitudes (≥45°), between 1975—2010 and interplanetary scintillation (IPS) observations, at 327 MHz, of solar wind turbulence levels in the inner heliosphere, between 1983—2009, we found a steady decline continuing for the past 18 years, that had begun in the mid-1990's [1, 2]. Also, from a study, covering solar cycle 23, of the solar wind density modulation index, $\epsilon_N \equiv \Delta N/N$, where, ΔN is the rms electron density fluctuations in the solar wind and N is the density, we reported a decline of around 8% in ϵ_N [3] attributing to the declining photospheric fields between mid-1990's and 2010.

The current solar cycle 24, with a peak smoothed sunspot number ~75 in November 2013, has been the weakest since cycle 14 in the early 1900's. Also, it was preceded by one of the deepest solar minima in the past 100 years, experienced at the end of cycle 23 with sunspot numbers remaining well below 25. In light of the very unusual nature of the minimum of solar cycle 23 and the current weak solar cycle 24, we re-examined in this paper, solar photospheric magnetic fields between 1975—2014 and the solar wind micro-turbulence levels between 1983—2013. Additionally, we estimated the peak sunspot number of solar cycle 25 and address whether we are heading towards a grand minimum. It is known that the changes in solar cycle magnetic activity modulate the heliospheric environment as well as the near-Earth space. The implication of such a likely grand minimum was also addressed by studying the night time F-region maximum electron density of the Earth's ionosphere.

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II. Decline in Solar Magnetic Fields and Solar Wind Micro-Turbulence Levels

For photospheric magnetic fields, we used mainly ground-based synoptic magnetograms from the National Solar Observatory (NSO), Kitt-Peak (NSO/KP), USA, covering Carrington Rotations (CR) CR1625—CR2151, for the period (February 1975) 1975.14—(July 2014) 2014.42. While for solar wind micro-turbulence levels, we used IPS observations of scintillation index (a measure of solar wind turbulence levels), at 327 MHz, from the four station IPS observatory of the Solar-Terrestrial Environment Laboratory (STEL), Nagoya University, Japan, covering the period from 1983—2013. Fig.1 (top) plots the temporal variations of the derived photospheric field strengths showing a steady decrease for past 20 years, from ~1995. It must be noted though that the high-latitude fields described here are the absolute value of the field in the latitude range 45° - 78° and not the signed value of the field which normally reverses their polarity.

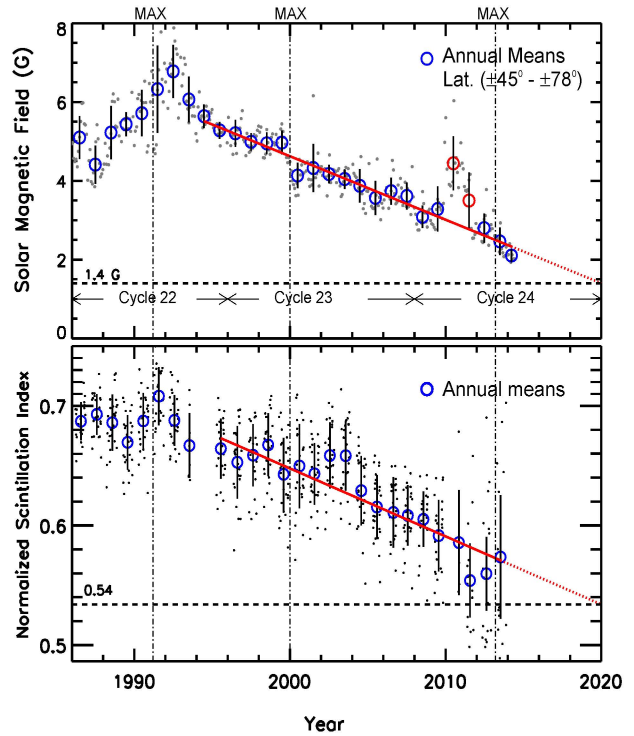

Fig.1 (Top) Temporal variations of solar high-latitude photospheric fields. The solid dots are the values for each Carrington rotation. The open circles in blue are annual means, while those in red are annual means for the year 2010 and 2011. The solid red line is a best fit to the annual means for the period 1995-2014, excluding those in red, while the dotted red line is an extrapolation of the best fit line up to 2020. (Bottom) Temporal variations of normalized scintillation index. The solid dots are daily measurements, while the open circles in blue are annual means. The solid red line is a best fit from 1995-2013, while dotted red line is an extrapolation of the best fit up to 2020.

The declining trend in the photospheric fields is apparent from Fig.1 except for a small increase during 2010-2011. A close inspection of the behaviour of the high-latitude fields shows that they normally decline after the solar maximum until the next solar minimum. Since the current solar cycle 24 is now past its maximum and the field strength is likely to continue to decline at least until 2020, the minimum of the current Cycle 24. The sunspot prediction by [4] showed that the coming solar minimum of cycle 24 is expected to occur in 2020. We, therefore, used 2020 to represent the expected year of minimum for cycle 24. The solid red line in Fig. 1 (top) is a best fit to the annual means, for the period 1995-2014, while the dotted red line is an extrapolation of the best fit line up to 2020. The fit is statistically significant (Pearson's correlation coefficient, r = -0.91, significance level = 99%) and the extrapolation implies the expected field strength is likely to drop to ~1.4 ± 0.08 G by 2020, by the expected minimum of cycle 24, indicated by a black horizontal dotted line.

Fig.1 (bottom) plots variation of normalized scintillation index obtained using IPS measurements. In a typical IPS phenomenon [5], the electromagnetic radiation from extragalactic radio sources suffers scattering when passes through the turbulent and refracting solar wind. This, in turn, produces random temporal variations of the signal intensity (scintillation) at the Earth, which is quantified by the scintillation index (m), given by m = ΔS/<S> where, ΔS is the scintillating flux and <S> is the mean flux of the observed source. The scintillation index drops off both with increasing heliocentric distance `r' and angular size of the radio source being observed where r is defined as the perpendicular distance from the Sun to the line-of-sight (LOS) of radio source observed. After making all the observations both distance and source size independent, we shortlisted 27 sources for further analysis, each of which had at least 400 observations distributed uniformly (with no significant data gaps) over the entire range of r spanning 0.2 to 0.8 AU. In Fig.1 (bottom), the fine black dots show the temporal variation of m for the 27 chosen sources with the large blue open circles representing annual means of m. It is evident that m continues to drop until the end of 2013.

Measurements of m are basically a measure of the rms electron density fluctuations (ΔN) in the solar wind and it has been shown [6] that solar wind micro-turbulence levels are related to both ΔN and large-scale magnetic field fluctuations in fast solar wind streams. It is known that the high-latitude fields during solar minimum conditions generally provide most of the heliospheric open flux [7], and they extend down to low latitudes into the corona and are then carried by the continuous solar wind flow to the interplanetary space to form the interplanetary magnetic field (IMF) [8]. The causal relationship between the photospheric magnetic fields and solar wind micro-turbulence levels implies that a decrease in photospheric high-latitude fields will lead to a decrease in micro-turbulence levels in the solar wind [2]. Therefore, assuming that the declining trend continues, we extrapolated

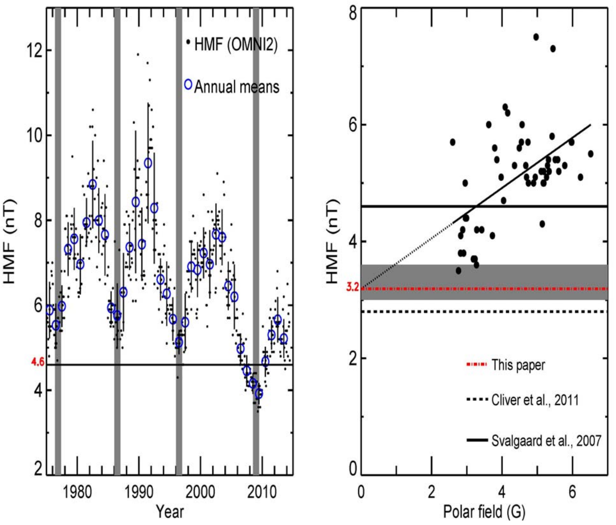

Fig.2 (Left) Variations of the heliospheric magnetic field from the OMNI2 data base at 1 AU between 1975 and 2014. The solid black dots are 27-day values of HMF, while open blue circles are their annual means with one sigma error bars. The horizontal line is marked 4.6 nT. The vertical grey bands demarcate 1 year intervals around the minima of solar cycles 20, 21, 22 and 23. (Right) A correlation plot of polar field (B_p) as a function of the HMF for values during 1 year intervals around the minima of Cycles 20, 21, 22 and 23. The solid black and dashed black horizontal lines indicate the floor levels of the HMF, derived by other researchers, of 4.6 nT, and 2.8 nT respectively, while the dotted red line is marked at 3.2 nT derived, the HMF floor level derived from the present work. The grey band shows the range for our derived floor value of 3.2 nT.

the value of m until 2020, as indicated by a dotted red line in Fig.1 (bottom), while the solid red line is a best fit to the measurements of m for the period 1995-2013. The horizontal line indicates a value of 0.54 at 2020 which implies a reduction of approximately 30% in the solar wind micro-turbulence levels.

III. HELIOSPHERIC MAGNETIC FIELDS

Based on studies of a correlation between polar flux and HMF at solar minimum [9, 10], and the fact that the surviving polar fields actually determine the floor level of the HMF [11], we examined its correlation with the unsigned high-latitude photospheric fields. Fig.2 (left) shows (filled black circles) measurements of the 27-day averaged values of HMF and (open blue circles) annual means of HMF with 1 σ error bars between 1975-2014, obtained using data, at 1 AU, from the OMNI2 database. The horizontal dotted line is marked at the proposed floor value of the HMF of 4.6 nT [12], while the vertical grey bands demarcate 1 year intervals around the minima of solar cycles 20, 21, 22 and 23 corresponding to CR1642-1654, CR1771-1783, CR1905-1917, and CR2072-2084, respectively. Average values of the high latitude (45°-78°) fields were computed in these 1 year intervals for the period 1975-2014 using NSO/KP synoptic magnetograms. Fig.2. (right) shows the correlation between the high latitude or polar field (B_p) and the HMF (B_r) obtained using values for both B_p and B_r for 1 year intervals around the minima of cycles 20, 21, 22 and 23, demarcated in Figure 4 (upper panel) by grey vertical bands. A linear least square fit to the data, with a Pearson's correlation coefficient of r=0.54 at a significance level of 99%, gave a value of the HMF of B_r = 3.2±0.4 nT, when B_p = 0 as shown in equation 1.

$$B_r = (3.2 \pm 0.4) + (0.43 \pm 0.09) \times B_p \quad (1)$$

From Fig. 1 (top) it can be seen that the high latitude field drops to be 1.4 ± 0.08 G in 2020, the expected minimum of Cycle 24. The linear relation obtained between the polar field and the HMF (equation 1) implies that the HMF will drop to be 3.9 ± 0.6 nT by ~2020. A strong correlation (Fig. 2 in [9]) between the peak values of sunspot numbers smoothed over 13-month period (SSN_{max}) and the HMF at solar cycle minimum reported by [9] is given by equation 2.

$$SSN_{max} = 63.4 \times B_r - 184.7 \quad (2)$$

Using our estimates of 3.9 nT for the HMF (B_r) at 2020, the expected minimum of Cycle 24, in the above linear relationship of SSN_{max} and B_r, the SSN_{max} in Cycle 25 can be estimated and is likely to be 62 ± 12.

IV. IONOSPHERIC MAXIMUM ELECTRON DENSITY

The critical frequency, in MHz, of the F-region (foF2), is an important parameter for ionospheric studies. foF2 is proportional to the square root of the electron number density at the height corresponding to that of maximum electron density [13]. Using data from a digital ionosonde at an equatorial station, Trivandurm (8.5° N, 77° E, 0.5° N dip lat), we studied the temporal variations in foF2 using continuous data in the period 1994-2014.

Fig.3 depicts the relation between the measured $(foF2)^2$ and sunspot number. It is apparent from Fig.3 the existence of a well known correlation between the two. Shown in the inset is their correlation with a correlation coefficient of R = 0.96. Such a high degree of correlation shows that the F-region densities are very closely tied up to the solar activity represented by the sunspot number and indicates the absence of any long term declining trend as seen in the solar and interplanetary parameters.

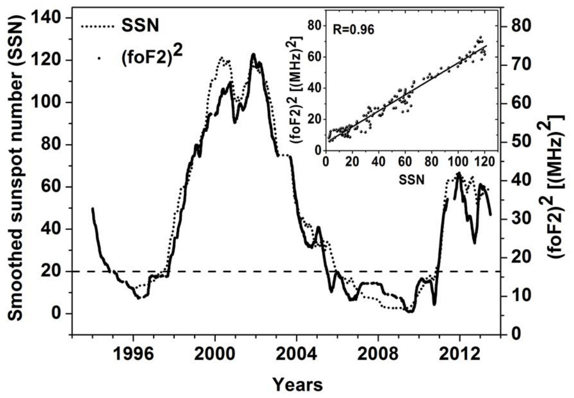

Fig.3 The correlation between the measured (foF2)^2 with that of the sunspot number. A linear correlation plot between the two parameters, with a correlation coefficient of R=0.96 is shown in the inset. The horizontal dashed line is drawn at a sunspot number of 25.

V. SUMMARY AND CONCLUSION

Based on our present study of solar and interplanetary observations, covering solar cycles 21-24, we found that

1. Both solar photospheric fields and solar wind micro-turbulence showed a steady decline from mid-1990's and the declining trend is likely to continue at least until 2020.
2. The HMF is expected to decline to a value of ~3.9 (±0.6) nT by 2020.
3. The peak 13 month smoothed sunspot number of Cycle 25 is likely to be ~62 ± 12, thereby making Cycle 25 a slightly weaker cycle than Cycle 24, and only a little stronger than the cycle preceding the Maunder Minimum.

The declining trend for the past 20 years and prediction for a weak cycle 25, thus, beg the question as to whether we are approaching a very low sunspot activity similar to Maunder minimum beyond Cycle 25? Our results indicate we may head towards a Maunder-like minimum. What is the likely impact on the near-Earth space then?

Our study of ionospheric electron density suggests an impending grand minimum is not likely to have any adverse impact at least on the Earth's ionosphere. This is inferred from ionospheric study which showed that the average (foF2)^2 for 2008-2009 was around 10 (MHz)^2, implying an ionospheric reflection cutoff of <3.5 MHz, even during sunspotless period of 2008-2009. Thus even in the complete absence of sunspots there is always a floor level of solar EUV flux which would produce a background ionospheric electron density.

It is for the first time such an assessment has become possible using ionospheric data as the existence of the ionosphere itself was not known during the previous grand solar minimum. Our results establish that such prolonged low levels of night time F-region electron densities (<5 MHz) will be a boon to low frequency radio astronomy for ground based studies at frequency well below 10 MHz.

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References

[1] S. K. Bisoi, P. Janardhan, D. Chakrabarty, S. Ananthakrishnan, and A. Divekar,"Changes in quasi-periodic variations of solar photospheric fields: Precursor to the deep solar minimum in cycle 23?", Sol. Phys., vol. 289, pp. 41–61, 2014.

[2] P. Janardhan, S.K. Bisoi, S. Ananthakrishnan, M. Tokumaru, and K. Fujiki, "The prelude to the deep minimum between solar cycles 23 and 24:Interplanetary scintillation signatures in the inner heliosphere", Geophys. Res. Lett., vol. 382, pp. 20108, 2011.

[3] S. K. Bisoi, P. Janardhan, M. Ingale, P. Subramanian, S. Ananthakrishnan, M. Tokumaru, and K. Fujiki, "A study of density modulation index in the inner heliospheric solar wind during solar cycle 23", Astrophys. J., vol. 795, pp. 69, 2014.

[4] M. L. Goelzer, C. W. Smith, and N. A. Schwadron, "An analysis of heliospheric magnetic fieldflux based on sunspot number from 1749 to today and predictionfor the coming solar minimum", J. Geophys. Res., vol. 118, pp. 7525–7531, 2013.

[5] A. Hewish, P.F. Scott, and D. Wills, "Interplanetary scintillation of small diameter radio sources,"Nature, vol. 203, pp. 1214, 1964.

[6] S. Ananthakrishnan, W.A. Coles, and J.J. Kaufman, "Microturbulence in solar wind streams," J. Geophys. Res., vol. 85, pp. 6025, 1980

[7] S.K. Solanki, S. K., M. Schussler, and M. Fligge, "Evolution of the Sun's large-scale magnetic field since the Maunder minimum", Nature, vol. 408, pp. 445, 2000.

[8] K.H. Schatten, and W.D. Pesnell, "An early solar dynamo prediction: Cycle 23 is approximately cycle 22", Geophys. Res. Lett., vol. 20, pp. 2275, 1993.

[9] E.W. Cliver, and A.G. Ling, "The floor in the solar wind magnetic field revisited", Sol. Phys., vol. 274, pp. 285–301, 2011.

[10] A. Munoz-Jaramillo, N.R. Sheeley, J. Zhang, and E.E. DeLuca, "Calibrating 100 years of polar faculae measurements: Implications for the evolution of the heliospheric magnetic field", Astrophys. J., vol. 753, pp. 146, 2012.

[11] Y.-M Wang, and Jr.N.R. Sheeley, "The solar wind and interplanetary field during very low amplitude sunspot cycles", Astrophys. J., vol. 764, pp. 90, 2013.

[12] L. Svalgaard, and E.W. Cliver, "A floor in the solar wind magnetic field", Astrophys. J., vol. 661, pp. L203–L206, 2007.

[13] R. Lukianova, and K. Mursula, "Changed relation betweensunspot numbers, solar UV/EUV radiation and TSIduring the declining phase of solar cycle 23", J. Atmospheric Sol. Terrestrial Phys., vol. 73, pp. 235, 2011.