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A Prediction of Solar Cycle 24 Using a Modified Precursor Method

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Abstract Based on cycles 17 – 23, linear correlations are obtained between 12-month moving averages of the number of disturbed days when Ap is greater than or equal to 25, called the Disturbance Index (DI), at thirteen selected times (called variate blocks 1, 2, ..., each of six-month duration) during the declining portion of the ongoing sunspot cycle and the maximum amplitude of the following sunspot cycle. In particular, variate block 9, which occurs just prior to subsequent cycle minimum, gives the best correlation (0.94) with a minimum standard error of estimation of ± 13, and hindcasting shows agreement between predicted and observed maximum amplitudes to about 10%. As applied to cycle 24, the modified precursor technique yields maximum amplitude of about 124 ± 23 occurring about 45 ± 4 months after its minimum amplitude occurrence, probably in mid to late 2011.

1. Introduction

Many attempts to predict the future behavior of solar activity, using different methods, are well documented in the literature (Thompson, 1987, 1993, 1997; Li, 1997; Kane, 1997a, 1997b; Bounar, Cliver, and Boriakoff, 1997; Lantos and Richard, 1998; Shastri, 1998; Wilson, Hathaway, and Reichmann, 1998a, 1998b; Hanslmeier, Denkmayr, and Weiss, 1999; Lantos, 2000; Verdes *et al.*, 2000; Duhau, 2003). These techniques can be sorted into five main classes: curve fitting, precursor, spectral, neural network, and climatology. Of these, precursor class has found general favor with the scientific community. As an example, Ohl (1966) found a high correlation between the minimum of geomagnetic activity near sunspot minimum and the later occurring maximum sunspot amplitude. He also showed that the level of geomagnetic activity during the last years of a sunspot cycle is well correlated with the maximum sunspot amplitude of the following cycle (Ohl, 1971; Svalgaard, 1977; Legrand and Simon, 1981), giving rise to the notion of the "extended cycle" (Wilson, 1994),

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in which the new sunspot cycle actually begins several years before the end of the old cycle.

Various researchers (Ohl and Ohl, 1979; Feynman, 1982; Thompson, 1987, 1993; Li, 1997; Shastri, 1998; Hathaway and Wilson, 2006; Kane, 2007a; and references contained therein) have established strong links between geomagnetic activity and the solar cycle, in particular, for the prediction of the strength of the following sunspot cycle. In this paper, a modified geomagnetic precursor technique, based on 12-month moving averages of the number of disturbed days (Ap greater than or equal to 25) during the declining portion of the sunspot cycle at 13 six-month variate blocks are used to predict the size and timing of the maximum sunspot amplitude for cycle 24, the next sunspot cycle.

2. Modified Precursor Technique and Results

The precursor methods utilize the concept that the imminent solar cycle actually starts in the declining phase of the previous cycle, where it manifests in the form of occurrence of coronal holes and the strength of the solar polar magnetic field. High-speed solar wind streams from low-latitude coronal holes give rise to recurrent geomagnetic disturbances that are used as the predictor of the strength of the next cycle (Thompson, 1993, 1997). The present study uses the frequencies of geomagnetic disturbances (as precursors), evaluated at specific time intervals during the declining period (cycle maximum to minimum), to predict the maximum amplitude of the forthcoming solar cycle 24. Magnetic disturbances considered here are the number of geomagnetic disturbed days, in a month, when Ap is greater than or equal to 25 (Thompson, 1987), and the data used are for the period corresponding to the past seven solar cycles (17 – 23). Daily Ap indices and 12-month smoothed sunspot R12, for this period, are obtained from the National Geophysical Data Center (NGDC) NOAA ftp site. Similar to R12, the Disturbance Index (DI) is determined by using 12-month moving averages of the monthly geomagnetic disturbed days. Figure 1 shows the temporal behaviors of 12-month smoothed sunspot numbers R12 and the disturbance index DI for sunspot cycles 17 – 23. As seen from the figure the values of DI vary from about 1 to 12. For cycles 17 – 22, the descent durations span 79 – 91 months, whereas for cycle 23, its descent duration already exceeds 83 months and likely will be longer than 90 months. To better describe the behavior of DI during the declining part of each solar cycle, the common descent duration (78 months) is divided into 13 equally spaced blocks (every six months), starting after each cycle's R12 peak (RM), which are thereafter referred to as variate blocks 1, 2, and so on. Each variate block in this way contains six DI values, indicated by DI-1, DI-2, etc. In addition, the minimum (DI-MIN), maximum (DI-MAX), and average (DI-AVG) of each of the six DI values are also determined for each of the variate blocks. A linear regression analysis is carried out between each of these DI values in the falling part of a cycle and the next sunspot maximum (RM) to find the best correlation between them. Table 1 shows first-degree regression results of the coefficient of determination (R^2) between the observed RM and the different DI values for each variate block. It is interesting to note that all DI values show negative correlation with RM until the 6th variate block but have statistically important positive values in the 8th and 9th variate blocks with R^2 values reaching as high as 0.87, decreasing thereafter. As seen from Table 1, the DI-1 and DI-2 values in the 9th variate block, corresponding to the 49th and 50th months after RM maximum (see Table 2) of each cycle, give the best correlations, having correlation coefficients (CC) equal to 0.92 and 0.94 and least standard error of estimations equal to $\pm$ 14 and $\pm$ 13, respectively. The straight-line fit between DI-2 and RM for cycles 17 to 22 is shown in Figure 2, along with its coefficient of determination

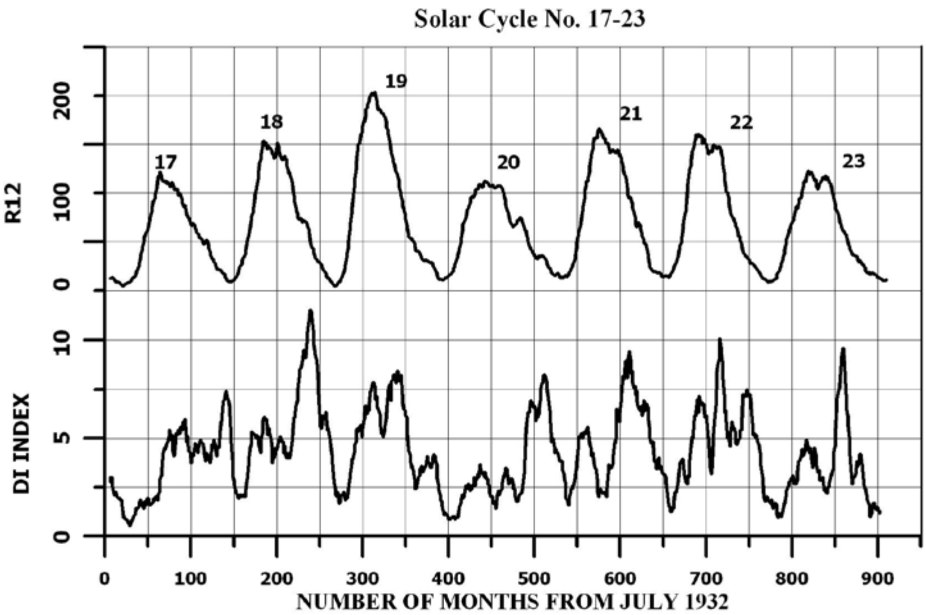

Figure 1 Variations of R12 and DI for solar cycle numbers 17 – 23.

Table 1 Results of the linear correlation analysis between running average of observed RM and different monthly DI at each variate block.

Variate block number	Coefficient of determination (R^2)								
	Fixed DI-1	Fixed DI-2	Fixed DI-3	Fixed DI-4	Fixed DI-5	Fixed DI-6	Maximum DI-MAX	Minimum DI-MIN	Average DI-AVG
1	0.14*	0.14*	0.15*	0.23*	0.25*	0.19*	0.19*	0.20*	0.21*
2	0.15*	0.16*	0.24*	0.35*	0.34*	0.39*	0.18*	0.32*	0.36*
3	0.28*	0.28*	0.26*	0.20*	0.12*	0.13*	0.32*	0.11*	0.11*
4	0.16*	0.17*	0.43*	0.56*	0.69*	0.65*	0.58*	0.32*	0.63*
5	0.66*	0.65*	0.54*	0.56*	0.51*	0.48*	0.54*	0.62*	0.47*
6	0.44*	0.43*	0.12*	0.05	0.00	0.00	0.18*	0.11*	0.00
7	0.00	0.00	0.08	0.14	0.15	0.23	0.06	0.13	0.16
8	0.28	0.31	0.43	0.58	**0.71**	**0.83**	**0.72**	0.45	**0.81**
9	**0.85**	**0.87**	**0.80**	**0.78**	0.68	0.60	0.63	**0.74**	0.62
10	0.61	0.56	0.52	0.47	0.37	0.39	0.52	0.41	0.38
11	0.39	0.35	0.37	0.28	0.26	0.17	0.39	0.20	0.16
12	0.13	0.17	0.23	0.18	0.26	0.32	0.34	0.34	0.31
13	0.30	0.24	0.11	0.32	0.30	0.26	0.33	0.34	0.23

*Negative correlation

Table 2 The occurrence dates and values of DI-1 and DI-2 in variate block 9 giving maximum correlation with RM during the declining phase of sunspot cycles 17 – 23.

Solar cycle			Variate 9		Variate 9	
No	RM	Date mm-yy	DI-1	Date mm-yy	DI-2	Date mm-yy
17	121	4-1937	4.8	5-1941	4.8	6-1941
18	152	5-1947	9.3	6-1951	9.8	7-1951
19	201	2-1958	2.5	3-1962	2.8	4-1962
20	111	10-1968	5.6	11-1972	6.1	12-1972
21	165	12-1979	6.7	1-1984	6.2	2-1984
22	159	5-1989	4.9	6-1993	5.0	7-1993
23	122	3-2000	4.1	4-2004	3.3	5-2004

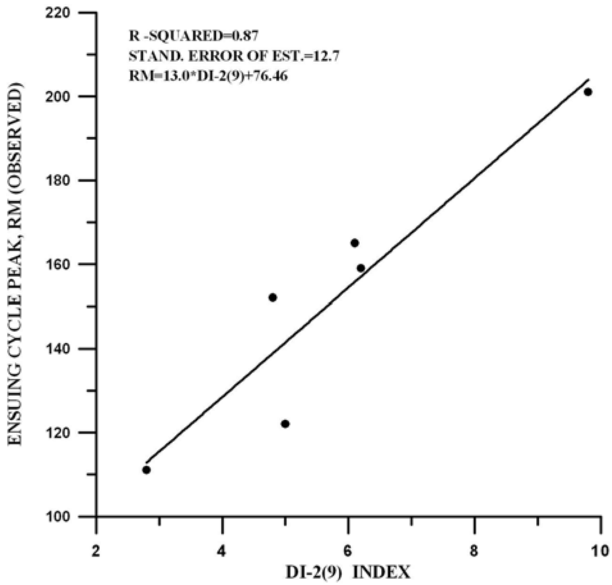

Figure 2 The first-degree correlation of DI-2 of variate block 9 having correlation coefficient = 0.94 in each cycle with maximum RM of ensuing cycle. Both R^2 and standard error of estimation are shown in the figure.

(R^2) and first-degree polynomial coefficients. Also seen from Table 2 and Figure 2 are the coefficient of determination ($R^2 = 0.87$), its standard error of estimation (12.9), and the inferred regression relation. The two best regressions against RM are, respectively given as

$$\text{RM} = 77.57 + 13.15 \times \text{DI-1}(9), \tag{1a}$$

$$\text{RM} = 76.46 + 13.0 \times \text{DI-2}(9). \tag{1b}$$

A bivariate fit was also tried by using RM for cycles 17 – 23 against the combination of these two indices. However, the results did not statistically improve the predictive ability of the modified precursor technique, as given in Equations (1a) and (1b).

The regressions of Equations (1a) and (1b) obtained between DI and RM maximum of the ensuing solar cycle are used to hindcast the observed RM peak values for cycles 17 – 23.

Table 3 Hindcast results using correlation analysis as given in Table 2 represented by a linear regression of the two best correlated indexes DI-1 and DI-2 of variate block 9 and multiregression analysis of these two as given by Equations (1a) and (1b) respectively.

Cycle	Observed peak	Predicted using Equation (1a) (DI-1)	ΔRM (observed –predicted)	Predicted using Equation (1b) (DI-2)	ΔRM (observed –predicted)
18	152	141	11	139	13
19	201	200	1	204	−3
20	111	110	1	112	−1
21	165	151	14	156	9
22	159	166	−7	157	2
23	122	142	−20	141	−19
24	Predicted	131 ± 14	?	119 ± 13	?

Table 3 gives the observed and predicted RM in each of these cases and the difference between prediction and observation (ΔRM) for cycles 17 to 23. The results show that in most of the cases the predicted values are very close to the observed ones and the overall predicted values are found to agree approximately to within $\pm 10\%$. Also, as seen from Table 3, the relations represented by Equations (1a) and (1b) predicted the maximum amplitude (RM) for the forthcoming solar cycle number 24 to be about 119 ± 13 and 131 ± 14, respectively. Usually, predictions are given as 90% prediction intervals (based on the number of degrees of freedom and the sample size). In the present case a sample size of six cycles has four degrees of freedom and hence each standard error of estimation should be multiplied by 2.132 to get the 90% prediction interval. Hence, the prediction value of maximum amplitude for cycle 24 based on DI-1(9) should be 131 ± 30 and the prediction based on DI-2(9) should be 119 ± 28, yielding an overlap of the two predictions of about 124 ± 23, which is adopted hereafter as the final prediction for the RM of cycle 24.

3. Estimation of Shape and Length of Solar Cycle 24

From examination of the rise time, which varies from 34 to 60 months for cycles 10 – 23 in terms of 12-month moving averages of monthly mean sunspot number (R12), it is noted that the higher the RM the lesser is the rise time (*i.e.,* the number of months taken from solar minimum to maximum). Roughly, it is also noted that the faster is the rise time the slower is the falling portion, so that the average length of a solar cycle is approximately 11 years. Actually, based on the use of smoothed monthly mean sunspot numbers, the lengths of sunspot cycles were examined by Wilson (1987) and, arguably, were found to be distributed bimodally, with a long-period cycle grouping (cycles having periods longer than 134 months) and a short-period cycle grouping (cycles having periods shorter than 127 months). Because solar cycle 23 has now persisted, at least, 133 months (with smoothed monthly mean sunspot numbers known through June 2007) and the minimum number for cycle 24 has not yet occurred, plainly, it is a cycle of longer than average period. For the modern era, long-period cycles have an observed range of periods measuring 135 – 142 months; hence, cycle 24 probably will have its minimum amplitude anytime after August 2007. (The Royal Observatory of Belgium has reported a high-latitude new cycle sunspot in January 2008.)

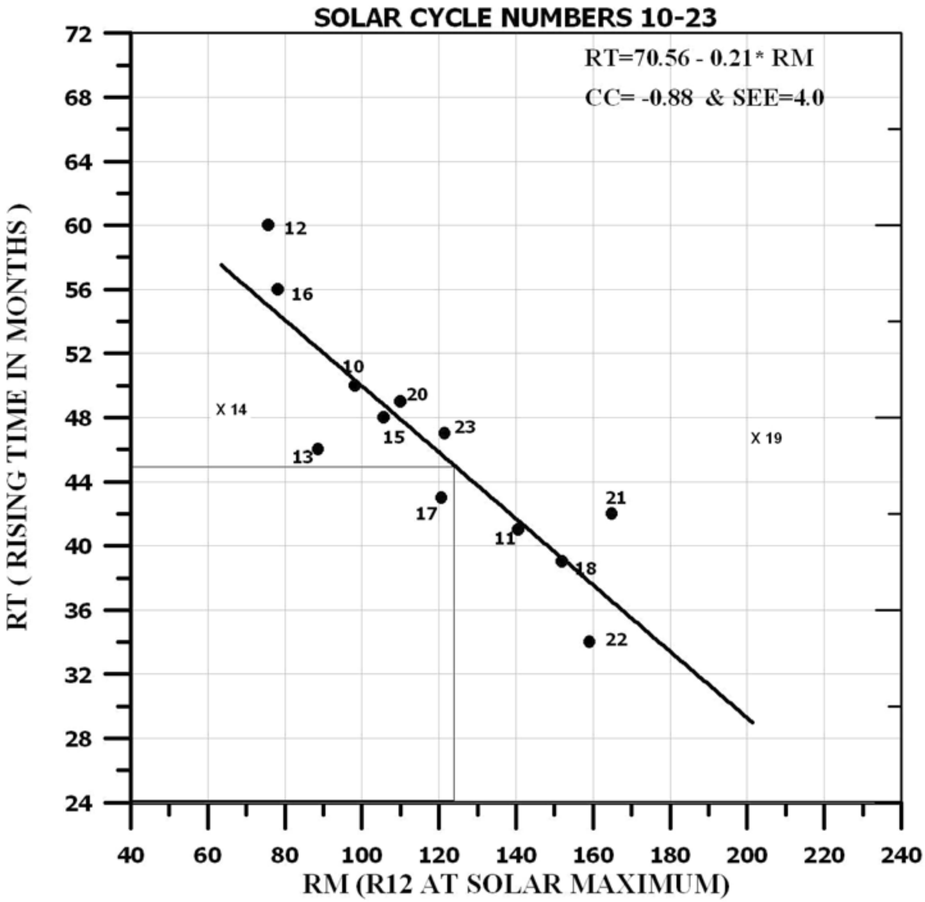

Figure 3 The relationship between rise time (in months) of a solar cycle from its minimum to maximum and its peak amplitude (RM) for cycle numbers 10 – 23. The straight line fit is obtained by ignoring two extreme data points (shown by crosses) of cycles 14 and 19. There exists a negative correlation between the two. With the predicted peak RM = 124 for solar cycle 24, this relation roughly estimates a rise time equal to 45 ± 4 months, by using a first-degree fit after the start of cycle 24.

Figure 3 shows the plot between RM and the rise time (in months) for cycles 10 – 23, indicating a statistically important negative correlation (CC = −0.88) between the two. In the figure, the straight-line fit is obtained by ignoring two extreme data points (shown by crosses) of cycles 14 and 19. Note that rise time (RT) seems to decrease linearly with RM and is represented by a straight-line fit of the form

$$\mathrm{RT} = 70.56 - 0.21 \times \mathrm{RM}. \quad (2)$$

By using the predicted maximum, RM = 124 for cycle 24 in the first-degree relation of Figure 3, the rise time for cycle 24 is estimated to be about 45 ± 4 months. Having the predicted maximum amplitude and rise time for the forthcoming cycle 24, one can predict the shape of the cycle following the method given by Hathaway, Wilson, and Reichmann (1994), given as

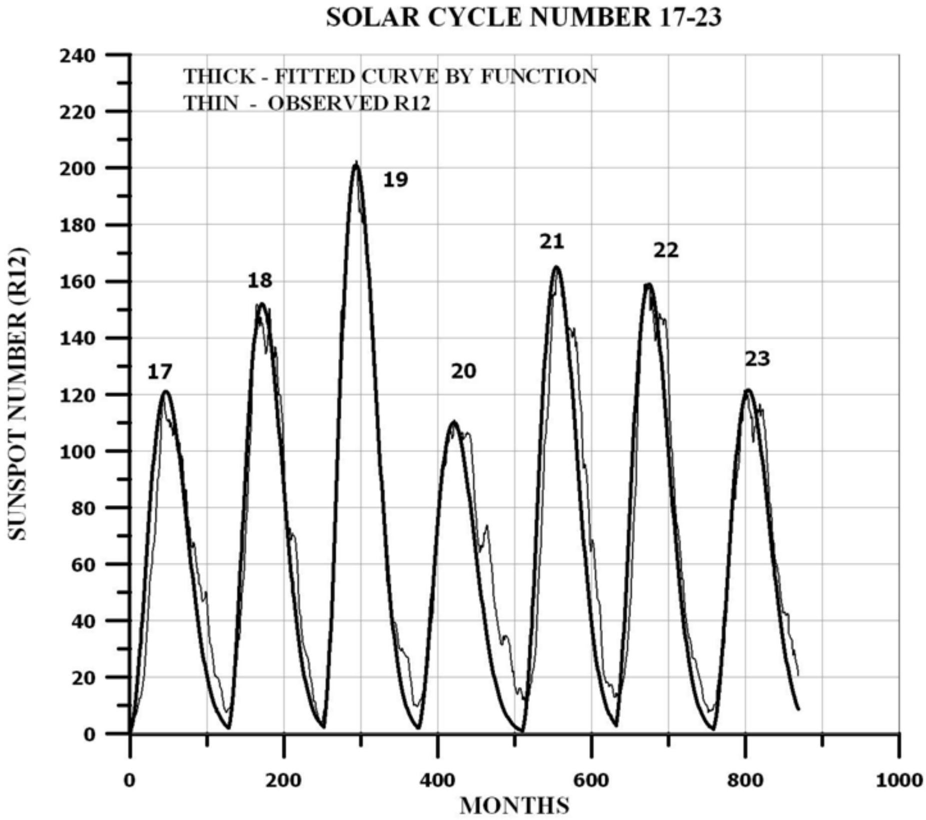

Figure 4 Monthly mean observed sunspot numbers (thin line) and fitted curve (thick line) by function estimated by using RM only, showing a good agreement in terms of amplitude and its occurrence time for cycle numbers 17 – 23.

$$\mathrm{R12}(t) = a(t - t_0)^3 / \{\exp[(t - t_0)^2 / b^2] - c\}, \tag{3}$$

where R12(t) is the monthly mean sunspot number in a given cycle at time t, t_0 is the time of the start of each cycle, and a, b, and c are fitting parameters. Hathaway, Wilson, and Reichmann (1994) determined each of the fitting parameters separately by a nonlinear least-square method. They also noted that a single value ($c = 0.71$) was adequate for most of the cycles. In this analysis, parameters a and b can easily be estimated for each of the past cycles, by using sunspot maximum values RM and their rise time in months. In a similar way we determined parameters a and b separately for each cycle from 17 to 23. By using the values of these parameters in Equation (3) for each cycle, corresponding values of the function R12(t) are obtained. The fitted results, for each of the last seven cycles (17 – 23) along with the observed 12-month smoothed sunspot numbers (R12) are shown in Figure 4. It is noted that for most of these cycles, the function R12(t), given by Equation (3), follows the observations very closely, matching both in peak values of RM as well as times of maximum. Hence, by using the analysis of Hathaway, Wilson, and Reichmann (1994), it appears that one can also predict confidently the shape and size of the forthcoming cycle 24 by using the predicted RM $= 124 \pm 23$.

Here, unlike past cycles, only the predicted peak amplitude (RM) is known for cycle 24; we do not know its rise time, which is required to get parameters *a* and *b* and hence the shape of the cycle [from Equation (3)]. One method is to use the results of Figure 3, which give estimated values of rise time equal to 49.4, 44.5, and 39.7 months [obtained from Equation (2)], corresponding to the predicted values of RM (= 124 ± 23), or to 101, 124, and 147, respectively for sunspot cycle 24. Using these values of rise time and RM in Equations (2) and (3) of Hathaway, Wilson, and Reichmann (1994), we determine the parameter $a = (3.69 \pm 1.3) \times 10^{-3}$ and $b = 40.6 \pm 2.5$, which can be used in Equation (3) to get the length and shape of solar cycle 24 (shown in Figure 5).

The second approach is one used by Li (1997), where only the predicted value of RM is used to solve Equations (3) and (4) of Hathaway, Wilson, and Reichmann (1994) in the determination of parameters *a* and *b* and the rise time. In a similar way, using the predicted value of RM = 124 ± 23, we also solved those equations using an iteration method and determined $a = (2.28 \pm 0.6) \times 10^{-3}$, $b = 47.6 \pm 1.6$, and rise time of 51.5 ± 1.5 months for cycle 24. This rise time of 52 months (average) seems to be somewhat higher than that of 44.5 months, estimated by using the results of Figure 3. Since the value of RM (=124) predicted for cycle 24 suggests that it will be slightly above average size, its rise time should also be slightly below average in length (because of the inferred inverse relationship between RM and rise time); hence the 52-month rise time seems to be too long. Therefore, we prefer to employ the 45-month rise time, obtained by using the results of Figure 3, for estimating the shape and length of cycle 24. The actual shape for cycle 24 will remain indeterminate until about 1 – 2 years following its cycle minimum occurrence. It should be noted that the Royal Observatory of Belgium (http://sidc.oma.be/news/101/welcome.html), on 4 January 2008, reported the first observation of a high-latitude new cycle spot, thus indicating the nearness of cycle 24's minimum, and R12 measured 7.7 in June 2007, a value well within the range of sunspot minimum values. Presuming a cycle start for cycle 24 in early 2008, we predict a maximum amplitude occurrence in mid to late 2011 (see Figure 5).

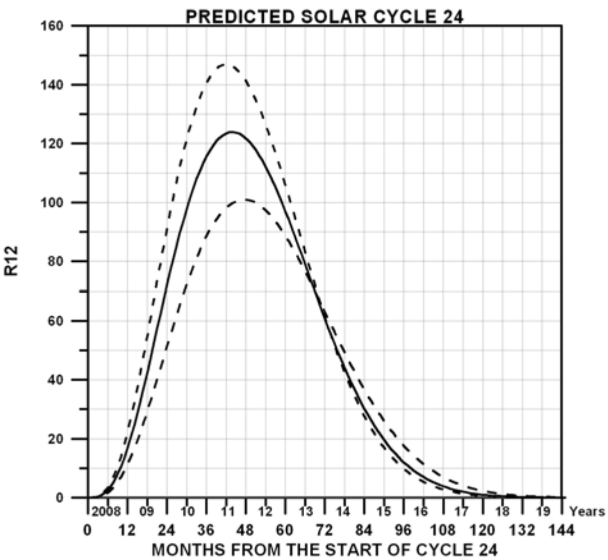

Figure 5 Shape and length of predicted solar cycle number 24 having peak amplitude of RM = 124 ± 23 occurring about 45 ± 4 months from the minimum of solar cycle number 24 (*i.e.*, sometime about mid to late 2011).

4. Comparison of Results with Other Predictions

The results of the preceding analysis (RM = 124 ± 23 for solar cycle 24 and likely occurrence probably in mid to late 2011) can now be compared with those that have been predicted by others, basically using different precursor methods. First, Kane (2007a) has given a preliminary prediction of RM = 142 ± 24 and a revised estimate of RM = 124 ± 26 for cycle 24, occurring in 2011 – 2012. Further, based on extrapolation of spectral components, he has given an updated estimate of RM = 119 ± 8 (Kane, 2007b). The NOAA Solar Cycle 24 Prediction Panel, presided by Douglas Biesecker (http://www.sec.noaa.gov/SolarCycle/SC24/index.html), also has issued an opinion suggesting that although cycle 24 might commence about March 2008 (± 6 months) no single consensus could be reached regarding cycle 24's RM; in particular, the panel has given two opinions regarding cycle 24's RM: 140 ± 20 in October 2011 or 90 ± 10 in August 2012. Also, Hathaway and Wilson (2004) have predicted RM = 145 ± 30 by assuming that a fast solar meridional circulation speed during solar cycle 22 would lead to a strong solar cycle 24, and Jain (2006), using a modified version of the precursor method, has predicted a value of 144 ±18 for cycle 24. Lastly, the IPS Radio and Space Services (Australian Government, http://www.ips.gov.au/mailman/listinfo/) has predicted RM = 134 ± 50 for cycle 24 based on the average of the past nine solar cycles (cycles 15 – 23).

5. Discussion

Statistically, it is now well established that there is a correlation between geomagnetic indices (in the declining phase prior to the minimum of the sunspot cycle) and the maximum amplitude of the ensuing cycle. To understand the physical relationship or linkage between solar and geomagnetic activities, considerable efforts have been made by several groups during the past two decades. Geomagnetic activity is related to solar activity through the solar wind but the 11-year solar cycle, expressed as sunspot numbers, is different from the one expressed by solar wind and geomagnetics (Feynman, 1982). Sunspot numbers rise steadily to maximum and then fall steadily to a low level during each sunspot cycle, whereas geomagnetic indices (Ap or aa) show two or more maxima per cycle, one near or before the sunspot maximum and others in the declining phase, and the gap between the two primary maxima (the Gnevyshev gap) results in the quasi-biennial and quasi-triennial periodicities observed in the geomagnetic indices (Kane, 1997a). Legrand and Simon (1991) have explained the linkage in terms of relationships occurring between the solar dipole and the latitudinal distribution of the solar wind velocity and also discussed the mechanisms for the origin of the solar cycle (Simon and Legrand, 1992). Kane (1997b) has examined the relationship between the aa index and solar wind velocity and found good correlation in some cycles, but not all, indicating the influence of some other factors. Based on the solar dynamo theory, Schatten *et al.* (1978) offered a plausible explanation for the Ohl (1966) hypothesis, wherein the solar polar field serves as a seed for future solar activity. According to solar dynamo theory, solar magnetism oscillates between poloidal and toroidal components and there is a degree of "magnetic persistence" in dynamos (Schatten, Myers, and Sofia, 1996). The correlation arises because geomagnetic indices reflect the magnitude of the poloidal field and, as sunspot minimum is reached, it becomes the dominant component of solar magnetism. Thus, the solar cycle really starts many years before sunspot minimum and it becomes necessary to use geomagnetic indices at different phases (*e.g.*, variate blocks 9-1 and 9-2 used in the present analysis, which show excellent correlations, as shown in Table 1) in the decaying part of a cycle to predict the size of the forthcoming cycle.

6. Conclusion

In the present study, by using a modified precursor method based on 12-month running averages of sunspot number and Disturbances Index, maximum amplitude for cycle 24 is found to be RM = 124 ± 23. The DI a few years before cycle minimum (*e.g.*, variate blocks 9-1 and 9-2 as shown in Table 1) can be used as a precursor to estimate the size of the following cycle. For cycles 17 – 23, the method shows good correlation, having a correlation coefficient as high as 0.94 and predicted sizes lying within ±10% of the observed one (see Table 3), in line with those reported by Ohl (1968, 1971, 1976) and Ohl and Ohl (1986). This method has the further advantage of predicting the maximum amplitude of the next cycle about 1 – 2 years before its official start. For estimating the shape and length of the forthcoming cycle, the predicted value of RM = 124 ± 23 was used in the analysis of Figure 3, and following a method described by Hathaway, Wilson, and Reichmann (1994) we estimate the rise time for cycle 24 to be about 45 ± 4 months; presuming an official start of cycle 24 in early 2008, we estimate cycle 24's maximum amplitude to occur in mid to late 2011.

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