Prediction of solar activity: Role of long-term variations

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[1] From the near-zero values during the Maunder Minimum (1645–1715), the maxima *Rz*(max) of smoothed sunspot numbers reached values of ∼140 by cycle 0–1 (∼1750) and then had long-term fluctuations (high values for 3–5 cycles, followed by low values for 3–5 cycles, differing by as much as 50 units), on which random fluctuations were superposed. There is some indication of a ∼100-year oscillation that might have peaked near cycle 20 at *Rz*(max) values near ∼150. If this oscillation persists, the cycles in the next 50 years or so may have lower and lower *R*(max), perhaps dropping below 100, and recovering thereafter. The *aa*(min) values, and to a lesser degree, the *Rz*(min) values, are also expected to follow the same pattern. *INDEX TERMS:* 2162 Interplanetary Physics: Solar cycle variations (7536); 7536 Solar Physics, Astrophysics, and Astronomy: Solar activity cycle (2162); 7537 Solar Physics, Astrophysics, and Astronomy: Solar and stellar variability; *KEYWORDS:* solar activity, long-term variations, periodicities, predictions

1. Introduction

[2] For many purposes, it is important to know with some antecedence the maximum level of solar activity (sunspot numbers) that could be attained in a sunspot cycle. In the last two decades a wide variety of methods have been adopted to make such predictions. One of the precursor methods [*Ohl*, 1966; *Brown and Williams*, 1969] where the precursor is the geomagnetic activity in the declining phase of the previous cycle, made good predictions for solar cycles 20 (1964–1975), 21 (1976–1985), and 22 (1986–1995) [*Ohl*, 1966, 1976; *Ohl and Ohl*, 1979; *Sargent*, 1978; *Kane*, 1978, 1987; *Wilson*, 1988, 1990]. For the present solar cycle 23 (1996 onward), many predictions were made [e.g., *Obridko et al.*, 1994; *Joselyn et al.*, 1997]. The cycle 23 started in 1996 and seems to have already peaked in 2000, with a maximum smoothed sunspot number of ∼122. *Kane* [2001a] reviewed the performance of the various predictions and noted that out of 20 predictions, 8 were within 122 ± 20 (in the range 102–142, chosen arbitrarily), namely, those of *Schove* [1983], *Kontor et al.* [1983], *Schatten et al.* [1996], *Wilson et al.* [1998], *Rangarajan* [1998], *Ahluwalia* [1998], *Kane* [1999], and *Lantos* [2000]. Recently, *Ramesh* [2000] correlated the 13-month moving averages of maximum sunspot numbers with the preceding minimum sunspot numbers of solar cycles 0–22, obtained a mediocre correlation coefficient +0.57 and yet obtained by this simple method, a prediction 126 ± 26 for cycle 23, which turned out to be as good as the 8 predictions mentioned above. In this communication, the implication of this result is examined.

2. Plots

[3] Figure 1 shows the latest version of the Ohl's precursor method. The *Rz*(max) and *aa*(min) values are 12-month moving averages. For *aa*(min) the *aa* data used are from *Mayaud* [1973] (updated from Solar Geophysical Data Reports) for 1868 onward (cycle 12 onwards), but some indirect estimates of *aa* index were obtained from *Nevanlinna and Kataja* [1993] and their values for 1844–1880 could be used for cycles 9, 10, and 11 (annual values only). Using data for cycles 9–12, the correlation is excellent (+0.91) and the regression equation is *Rz*(max) = (8.29 ± 15.35) + (8.96 ± 1.17)*aa*(min). From these, using *aa*(min) = 15.7, which was centered on August 1997 (later than the sunspot minimum, which occurred in April 1996), the estimate for *Rz*(max) of cycle 23 is 149 ± 24. This is ∼27 units higher than the observed value ∼122.

[4] Figure 2 shows a plot of *Rz*(max) versus *Rz*(min) for solar cycles 1–22. The correlation is only +0.57, and the regression equation is *Rz*(max) = (76.3 ± 14.0) + (6.0 ± 2.0) *Rz*(min). Using the value *Rz*(min) = 8.1, which occurred centered on July 1996, *Ramesh* [2000] predicted a value of *Rz*(max) for cycle 23 as 126 ± 22, which turned out to be very near the observed value of ∼122. However, this should be considered as a chance coincidence, as the scatter of the other points does not warrant such accuracy. Incidentally, the standard error ±22 mentioned here is based on standard statistical methodology and is different from (smaller than) the error ±26 mentioned by *Ramesh* [2000, p. 421], which was estimated by him as "the average of the deviations from the observed to the fitted values."

3. Hypothesis of Random Nature

[5] What is the implication of these results? Do they imply that no relationship with any other parameter besides the sunspot number itself is relevant? Since even a low correlation (+0.57) gave good prediction, one could speculate that no relationship of any kind is necessary, and the *Rz*(max) occurs randomly. In that case, the 22 values for cycles 1–22 would have a Gaussian distribution with a mean value 114 and a standard deviation σ = ±41. Thus the

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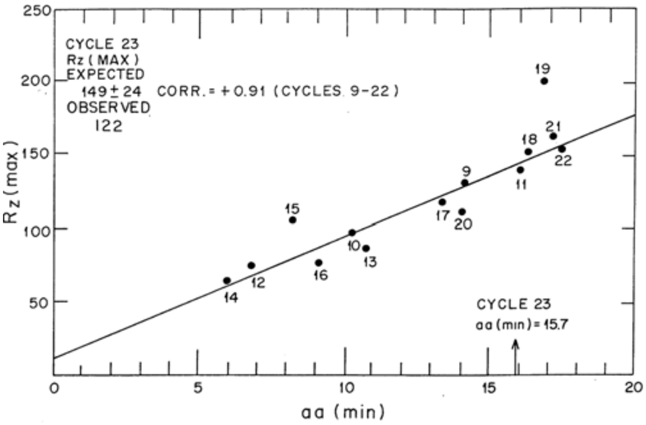

Figure 1. Plot of 12-monthly moving averages of *aa*(min) versus sunspot number maximum *Rz*(max), for sunspot cycles 9–22.

range 73–155 would be in a 66% confidence level, while 32–196 would be in the 95% confidence level. However, these are very wide ranges, engulfing very low to very high activity levels. The plots in Figures 1 and 2 certainly give more sensible predictions, as compared to that of a random hypothesis. Thus some regularity is involved, and the hypothesis of pure randomness is ruled out. However, there is another possibility, namely, there might be long-term, oscillatory changes, over which randomness is superposed.

4. Long-Term Variability

[6] The smoothed sunspot maxima *Rz*(max) increased considerably from cycle 14(64) to cycle 19(201) [*McKinnon*, 1987]. As shown in the detailed plots in the work of *Kane* [2001b], the *aa*(min) has also shown a similar increase (see also *Wang and Sheeley* [1995] and *Lockwood et al.* [1999]). Figure 3 shows plots for *Rz*(max) and *Rz*(min) not only for cycles 1–22 but extended backward to cycle −9, using the data of smoothed sunspot number values from *McKinnon* [1987] for 1749 onward. Recently, *Hoyt and Schatten* [1998a, 1998b] examined all the Wolf sunspot numbers *Rz* since 1700, found that *Rz* had many inhomogeneities, and constructed a new time series, namely Group Sunspot Numbers RG. For 1700–1750, use is made of the *Rz* values given by *Hoyt and Schatten* [1998a, 1998b], and their RG values are also used for comparison.

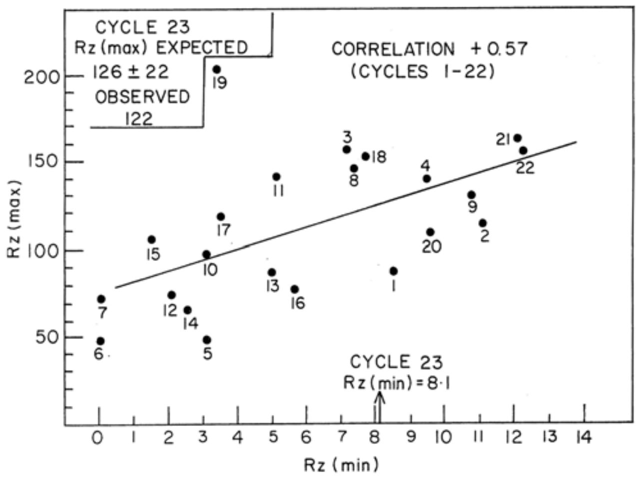

Figure 2. Plots of 12-month moving averages of sunspot number minimum *Rz*(min) versus sunspot number maximum *Rz*(max), for sunspot cycles 1–22 [*Ramesh*, 2000].

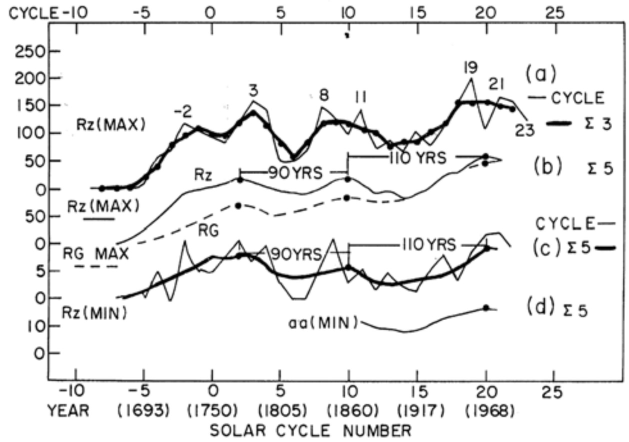

Figure 3. Plots of (a) sunspot maxima *Rz*(max) for cycles (−9 to +22) (thin line) and their three-cycle moving averages (thick line), (b) five-cycle moving averages of *Rz*(max) (solid line) and RG(max) [*Hoyt and Schatten*, 1998a, 1998b] (dashed line), (c) sunspot minima *Rz*(min) for cycles (−9 to +22) (thin line) and their five-cycle moving averages (thick line), and (d) five-cycle moving averages of geomagnetic index *aa*(min).

[7] Figure 3a shows the *Rz*(max) values for individual cycles (thin line) and moving averages over three consecutive cycles (superposed thick line). Starting with near zero values in the Maunder Minimum (1645–1715), the *Rz*(max) values (three-cycle moving averages) increased rapidly to ∼100 near cycle 0, rose further to ∼140 by cycle 3, dropped down to ∼50 by cycle 6, rose to ∼120 for cycles 8–11, dropped down to 80–110 for cycles 12–16, rose to ∼140 by cycle 18, and remained there till cycle 22. These are large, long-term changes, with mean values changing by 50 units or more from one level to the next, and individual cycles are within ∼30 units (sunspot numbers) of these levels. In the five-cycle moving averages shown in Figure 3b, after the rise from Maunder Minimum to cycle 0, the *Rz*(max) values (solid line) seem to oscillate, with a spacing of ∼90 years between cycles 2–10, and ∼110 years between cycles 10–20, reminiscent of the *Gleissberg* [1965] cycle of ∼80 years, but not quite. The RG(max) values (dashed line) are considerably smaller than the *Rz*(max) values up to cycle 13, but the oscillatory pattern is similar to that of *Rz*(max). Figure 3c shows the plot for *Rz*(min) values for each cycle (thin line) and for five-cycle moving averages (thick line). The thick line pattern is almost similar to that for *Rz*(max), indicating that the correlation between *Rz*(max) and *Rz*(min) seen in Figure 2 is mostly due to their similar long-term variation, but the correlation is low (only +0.57) because of large random fluctuations (thin line). Finally, Figure 3d shows the plot for five-cycle moving averages of *aa*(min) for the limited common period from cycle 10 onward, and the variations

are similar to those of *Rz*(max). Thus large long-term fluctuations dominate the variability.

[8] Cyclic oscillations are notoriously unstable, and even if these have a physical basis, there is no guarantee as such that oscillations seen in the past will continue to occur in future with the same magnitude. However, there is some indication that a ~110 year oscillation had peaked near cycle 20 and a downtrend might have started thereafter. If true, the *Rz*(max) for cycles in the next 50 years or so may be smaller and smaller, perhaps dropping down below 100, and may recover in the next 50 years or so thereafter. This is, of course, pure speculation, but may turn out to be an intelligent guess! For individual cycles during the Cyclic oscillation intervals, the *aa*(min) values, which have very good correlations with *Rz*(max) values, may yield good predictions within ±25 units (Figure 1), but the *R*(min) values have low correlations and the predictions may deviate more than 25 units. Also, idiosyncrasies like those of cycle 19 (considerable deviation of *Rz*(max) from the general pattern, in both Figures 1 and 2) may still occur.

5. Conclusions

[9] The maxima *Rz*(max) of sunspot numbers in successive sunspot cycles fluctuate considerably. A part of this is random, but there have been long-term fluctuations (high values for several cycles, followed by low values for several cycles, differing by as much as 50 units), on which the random fluctuations are superposed. There is some indication of a ~100-year oscillation that might have peaked near cycle 20 at *Rz*(max) values near ~150. If this oscillation continues, the cycles in the next 50 years or so may have lower and lower *Rz*(max), perhaps dropping below 100, and recovering thereafter. The *aa*(min) values, and to a lesser degree, the *Rz*(min) values, are also expected to follow the same pattern.

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