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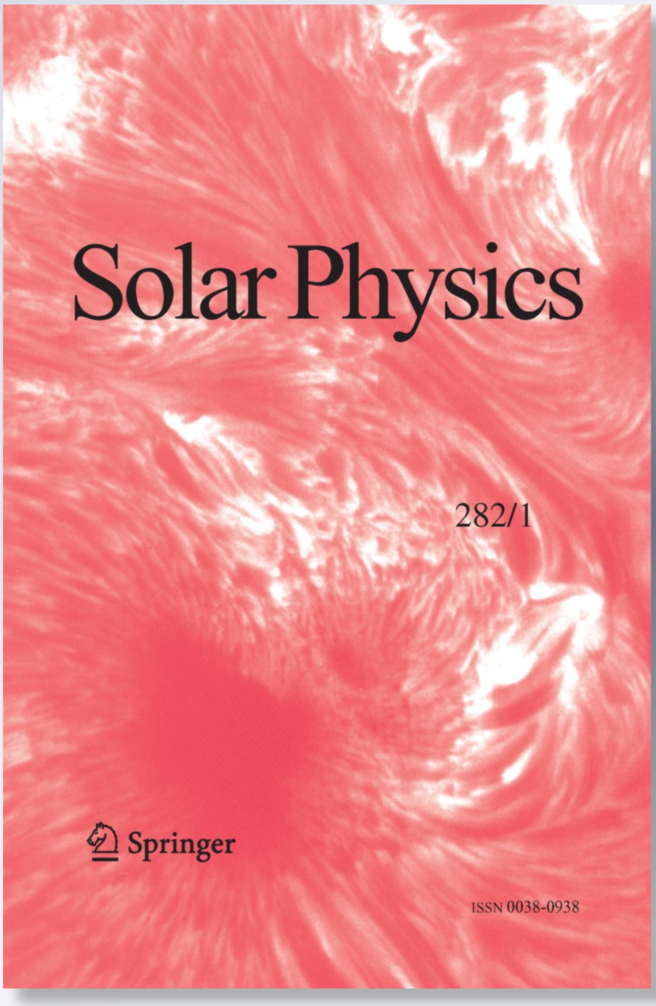

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Abstract For the sunspot cycles in the modern era (cycle 10 to the present), the ratio of $R_\mathrm{Z}(\max)/R_\mathrm{Z}(36\text{th month})$ equals 1.26 ± 0.22, where $R_\mathrm{Z}(\max)$ is the maximum amplitude of the sunspot cycle using smoothed monthly mean sunspot number and $R_\mathrm{Z}(36\text{th month})$ is the smoothed monthly mean sunspot number 36 months after cycle minimum. For the current sunspot cycle 24, the 36th month following the cycle minimum occurred in November 2011, measuring 61.1. Hence, cycle 24 likely will have a maximum amplitude of about 77.0 ± 13.4 (the one-sigma prediction interval), a value well below the average $R_\mathrm{Z}(\max)$ for the modern era sunspot cycles (about 119.7 ± 39.5).

Keywords Prediction · Sunspot cycle

1. Introduction

Sunspots vary in number over an approximately 11-year cycle, where each cycle is determined on the basis of using 12-month moving averages of monthly mean sunspot number, the so-called smoothed monthly mean sunspot number. Conventionally, a sunspot cycle begins at the time of a minimum amplitude ($R_\mathrm{Z}(\min)$) of the 12-month moving average value, rises to a maximum amplitude ($R_\mathrm{Z}(\max)$) and ends at a subsequent minimum amplitude that marks the conventional start of the next sunspot cycle. Each sunspot cycle is numbered, with the present sunspot cycle being 24, and cycle 10 and onwards are here collectively called the modern era sunspot cycles. Prediction of the maximum amplitude and timing of a sunspot cycle is of vital importance, especially as related to the potential for damage to electronic components aboard earth-orbiting satellites (Dyer *et al.*, 2003) and to the possible health hazards for astronauts (Lockwood and Hapgood, 2007).

For the current sunspot cycle 24, a number of predictions previously have been made for its size, with the predictions spanning a large range of values from < 70 to > 170 (Kane, 2007a; Pesnell, 2008). Using $\mathrm{aa}(\min) = 8.7$ of geomagnetic aa index in conjunction with

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the Ohl precursor method (Ohl, 1966, 1976), Kane (2010) previously predicted $R_Z(\max) = 58.0 \pm 25.0$ for cycle 24, a value considerably below the mean for the modern era sunspot cycles (about 120). If this predicted value proves to be correct, then the predictions calling for cycle 24 to be a large maximum amplitude cycle (*e.g.*, Dikpati, de Toma, and Gilman, 2006) will prove to be utterly erroneous. Other predictions of below average $R_Z(\max)$ for cycle 24 include those of Clilverd *et al.* (2006) and Badalyan, Obridko, and Sykora (2001).

In addition to the prediction by Kane (2010), Kane (2007b, 2007c, 2008a, 2008b) made several earlier predictions regarding $R_Z(\max)$ for cycle 24. Kane (2007b) predicted cycle 24 to have $R_Z(\max) = 130$, based on solar activity at different solar latitudes; Kane (2007c) predicted $R_Z(\max) = 92$, based on the extrapolation of spectral components; Kane (2008a) predicted $R_Z(\max) = 94$, based on cycle lengths; and Kane (2008b) predicted $R_Z(\max) = 106$, based on the Gnevyshev–Ohl–Kopecky rule (Gnevyshev and Ohl, 1948; Kopecky, 1950) and the three-cycle periodicity scheme. More recently, based on the long-term changes in solar activity and the unusual quietness associated with the early rising portion of cycle 24, Lockwood *et al.* (2012) estimated that cycle 24 would have maximum amplitude near 60, probably in mid 2012.

In this study, the ratio of $R_Z(\max)/R_Z(\text{36th month})$ is investigated to determine its predictive power for estimating $R_Z(\max)$, where $R_Z(\text{36th month})$ is the smoothed monthly mean sunspot number 36 months after cycle minimum. Indeed, the ratio strongly suggests that $R_Z(\max)$ for cycle 24 will be well below average in size.

2. Data

The data employed in this study are the 12-month moving averages of monthly mean sunspot number, the so-called smoothed monthly mean sunspot numbers, given at ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SUNSPOT_NUMBERS/INTERNATIONAL/smoothed/. The 36th month following minimum amplitude occurrence (November 2008) corresponds to November 2011 and measures 61.1.

3. Results

Table 1 gives the data for the modern era sunspot cycles that are considered pertinent for this study. Columns from left to right give the cycle number, the year and month of minimum, the value of $R_Z(\min)$, the timing of 36 months past minimum, the value of R_Z at 36 months past minimum, the year and month of maximum, the value of $R_Z(\max)$, the elapsed time from $R_Z(\min)$ to $R_Z(\max)$ in months, and the ratio $R_Z(\max)/R_Z(36)$. Also included in Table 1 are the observed values of $R_Z(\min)$, $R_Z(36)$, and the dates of their occurrence for cycle 24, as well as its estimated $R_Z(\max)$ based on the mean ratio for the modern era cycles (*i.e.*, 1.26 ± 0.22) by applying the observed $R_Z(36)$ for cycle 24 ($= 61.1$). Clearly, the one-sigma prediction interval for cycle 24 $R_Z(\max)$ is equal to 77.0 ± 13.4, which suggests that it will be considerably below the mean $R_Z(\max)$ for the modern era sunspot cycles ($= 119.7 \pm 39.5$).

4. Conclusion and Discussion

In this brief study, the ratio of $R_Z(\max)/R_Z(36)$ has been used to estimate the size of the ongoing sunspot cycle 24. Using the observed value of $R_Z(36) = 61.1$ and the mean ratio

Table 1 Details of sunspot number R_Z (12-month moving averages), their ratios, and their occurrence dates for individual sunspot cycles 10 – 23.

Column								
1	2	3	4	5	6	7	8	9
Cycle No.	Month of R_Z(min)	R_Z(min)	36th month	R_Z at 36th month	Month of R_Z(max)	R_Z(max)	Months, R_Z(min) to R_Z(max)	Ratio, R_Z(max)/ R_Z(36 mon)
10	1855(12)	3.2	1858(12)	75.5	1860(02)	98.0	50	1.30
11	1867(03)	5.2	1870(03)	121.5	1870(08)	140.3	41	1.15
12	1878(12)	2.2	1881(12)	62.4	1883(12)	74.6	60	1.20
13	1890(02)	5.0	1893(02)	79.8	1894(01)	87.9	47	1.08
14	1901(05)	2.8	1904(05)	41.5	1906(02)	64.2	57	1.55
15	1913(06)	1.5	1916(06)	56.3	1917(08)	105.4	50	1.87
16	1923(02)	5.9	1926(02)	64.1	1928(04)	78.1	62	1.22
17	1933(09)	3.5	1936(09)	90.3	1937(04)	119.2	43	1.32
18	1944(02)	7.7	1947(02)	136.8	1947(05)	151.8	39	1.11
19	1954(04)	3.4	1957(04)	181.0	1958(03)	201.3	47	1.11
20	1964(10)	9.6	1967(10)	95.0	1968(11)	110.6	49	1.16
21	1976(06)	12.2	1979(06)	153.0	1979(12)	164.5	42	1.21
22	1986(09)	12.3	1989(09)	156.6	1989(07)	158.5	34	1.01
23	1996(05)	8.0	1999(05)	90.5	2000(04)	120.8	47	1.33
24	2008(11)	1.7	2011(11)	Obs.61.1	Estimated	77.0		1.26
					std. deviation	±13.4		±0.22

$R_Z(\max)/R_Z(36) = 1.26 \pm 0.22$ found for the modern era sunspot cycles, one can estimate $R_Z(\max) = 77.0 \pm 13.4$ for cycle 24 (with the one-sigma prediction interval). Hence, it appears highly likely that $R_Z(\max)$ for cycle 24 will be below the mean $R_Z(\max)$ value found for the modern era sunspot cycles, with only a 5 % chance of it being about 106 or more, thus negating the predictions of Dikpati, de Toma, and Gilman (2006; $R_Z(\max) = 180$) and Tsirulnik, Kuznetsova, and Oraevsky (1997; $R_Z(\max) = 185$). The finding reported here is in agreement with that of Lockwood *et al.* (2012), who indicated that long-term solar changes appear to be happening and suggested the likely occurrence of another Maunder-like minimum in solar activity later this century. They further stated that the unusual quietness of sunspot cycle 24 suggests that it will have $R_Z(\max)$ near 60 in mid 2012. The finding reported here also is in agreement with that of Duhau and de Jager (2010), who argue that the solar variability is presently entering into a long grand minimum, longer than a century, with cycle 24 having $R_Z(\max)$ near 55.

Additionally, the finding reported here agrees with that of Wilson (2011), who using the Hathaway–Wilson–Reichmann shape-fitting function (Hathaway, Wilson, and Reichmann, 1994), found that the early rise of cycle 24 (the first 18 months) was consistent with it having $R_Z(\max) = 70$, peaking about 56 months after the minimum (about mid 2013). He also noted that the expected $R_Z(\max)$ for cycle 24 deduced using the minimum value of geomagnetic aa index gave only a 1 % chance of $R_Z(\max)$ exceeding 100.5. Wilson (2011) also included in his study a formulation for predicting $R_Z(\max)$ on the basis of the maximum month-to-month rate of growth in smoothed monthly mean sunspot number, which was unknown at the time of his publication but now appears to be known (5.8), a value suggesting $R_Z(\max) = 103.4 \pm 21.3$ as applied to cycle 24.

In conclusion, although the present technique appears to have limited use for predicting the size of the sunspot cycle well in advance, it obviously can be used to confirm earlier predictions and differentiate between those that appear to be reasonable and those that appear to be unreasonable.

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