NASA/TP—2010–216433

Predicting the Size and Timing of Sunspot Maximum for Cycle 24

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LIST OF ACRONYMS AND ABBREVIATIONS

12-mma	12-month moving average
2-cma	2-cycle moving average
AA	12-mma value of the monthly aa-geomagnetic index
AAm	minimum value of 12-mma value of the monthly aa-geomagnetic index
ASC	ascent duration (from minimum sunspot amplitude to maximum sunspot amplitude)
E(AAm)	epoch of minimum value of 12-mma value of the monthly aa-geomagnetic index occurrence
E(Rm)	epoch of minimum sunspot amplitude occurrence
PER	period (from minimum sunspot amplitude of cycle *n* to minimum sunspot amplitude of cycle *n*+1, where *n* is the sunspot cycle number)
RM	maximum sunspot amplitude
Rm	minimum sunspot amplitude
TP	Technical Publication

NOMENCLATURE

cl	confidence level
f	fast rising cycle
n	sunspot cycle number
P	probability
r	coefficient of correlation
r^2	coefficient of determination
s	slow rising cycle
se	standard error of estimate
t	elapsed time in months from epoch of minimum sunspot amplitude occurrence
x	independent variable
y	dependent variable
σ	standard deviation

TECHNICAL PUBLICATION

PREDICTING THE SIZE AND TIMING OF SUNSPOT MAXIMUM FOR CYCLE 24

1. INTRODUCTION

Accurately predicting in advance the size and timing of sunspot maximum for an ongoing sunspot cycle continues to be one of the long-standing problems in solar physics, one that becomes quite relevant every 11 years or so, especially around the time of sunspot minimum (Rm).[1–9] Accurate prediction of the size and timing of sunspot cycles is important for a variety of reasons, in particular as related to climatic change and the effects of solar cycle-related phenomena, like earthward-directed coronal mass ejections and solar flares, on human space flight and on our modern technological systems (satellite orbital dynamics, electrical distribution, airline operations, etc.).[10–16]

Some 40 years ago, A.I. Ohl noted that the level of geomagnetic activity near Rm provides a reasonable estimate for the expected size of the ongoing sunspot cycle,[17] usually about 3 years in advance of maximum amplitude (RM) occurrence. Since Rm has now been ascertained for cycle 24, having occurred in December 2008 on the basis of the 12-month moving average (12-mma) of monthly mean sunspot number and since a minimum in geomagnetic activity in the vicinity of Rm (AAm) occurrence appears to have recently been seen in September 2009, a firm estimate of cycle 24's RM using the method of Ohl can now be made.

The purpose of this NASA Technical Publication (TP) is to give an estimate for the expected size and timing of the RM for cycle 24, one based on the updated inferred statistically significant relationship found between RM and AAm using 12-mma values (method of Ohl). Also, an alternate method for predicting cycle 24's RM using a variation of Ohl's method, one based on using 2-cycle moving averages (2-cmas) of RM and AAm, is given. Finally, the ascent duration (ASC), defined as the elapsed time between Rm and RM, is deduced for cycle 24 from the Waldmeier effect using the expected value of its RM.

2. RESULTS

Figure 1 displays an epoch analysis of the variation of the 12-mma values of the AA-geomagnetic index in the vicinity of sunspot minimum ($-18 \le t \le 18$, where t is the elapsed time in months relative to E(Rm), the epoch of Rm), with the solid line representing the mean values of the AA index for cycles 12–23 and the filled circles representing values for cycle 24 (determined by the British Geological Survey).[18] Across the top and to the right are denoted the occurrences (E(AAm)) and values (AAm) of the minimum AA-geomagnetic index for cycles 12–23. The minimum value of the mean occurs at about $t = 4$–6 months, having a value of 15.5 nT. Cycles 12, 13, 15, 17, 20, 21, and 22 had their AAm occurrences within the interval $t = 0$–9 months, while cycles 16, 18, 19, and 23 had their AAm occurrences during the interval $t = 12$–17 months. Only cycle 14 had its AAm occurrence prior to E(Rm). Also, cycles 17–19 and 21–23 had AAm values above the mean, while cycles 12–16 and 20 had AAm values below the mean.

Cycle 24's AAm appears to have minimized at $t = 9$ months (i.e., September 2009), having a value of about 8.4 nT. This value is well below the mean and, in fact, is now the smallest value on record, falling below that previously found for cycle 14 (8.9 nT), the smallest sunspot cycle of the modern record (64.2). (The reader should note that all AA values prior to 1957 have been increased by 3 nT to account for changes in the repositioning of the magnetometers used in the determination of the AA index.[19-20])

Figure 2(a) shows the variation of RM values for cycles 10–23, where the thin jagged line represents the actual cyclic values and the heavy smoother line represents the 2-cma values of RM (i.e., the trend line). In figure 2a, the filled circles represent longer duration cycles, those of minimum-to-minimum period (PER) 11 years or more in length, while the filled triangles represent shorter duration cycles, those of PER less than 11 years in length. The little *f*s and *s*s appearing beside each cyclic value denote the ascent duration class for each cycle, where fast-rising (*f*) cycles have $\text{ASC} < 48$ months and slow-rising (*s*) cycles have $\text{ASC} \ge 48$ months. Interestingly, all *f* cycles tend to lie above the 2-cma trend line except cycle 18, and all *s* cycles tend to fall below the 2-cma trend line except cycle 15. Also, all even-numbered cycles tend to lie below the 2-cma trend line except cycle 22, and all odd-numbered cycles tend to lie above the 2-cma trend line without exception. The implication is that cycle 24 probably will be a slow-rising cycle with RM below its 2-cma trend line value, once that value becomes known (unknown until cycle 25's RM is observed).

Figure 2(b) shows the corresponding cyclic AAm and 2-cma values of AAm, where the filled square represents the provisional minimum value of AAm for cycle 24. Comparison of the two curves reveals an unmistakable coupled behavior, especially as described using the 2-cma values. Increasing/decreasing values of AAm are strongly associated with increasing/decreasing values of RM. The suggestion then is that, because AAm for cycle 24 has decreased in value relative to cycle 23's AAm, RM for cycle 24, likewise, will decrease in value relative to cycle 23's RM (120.8).

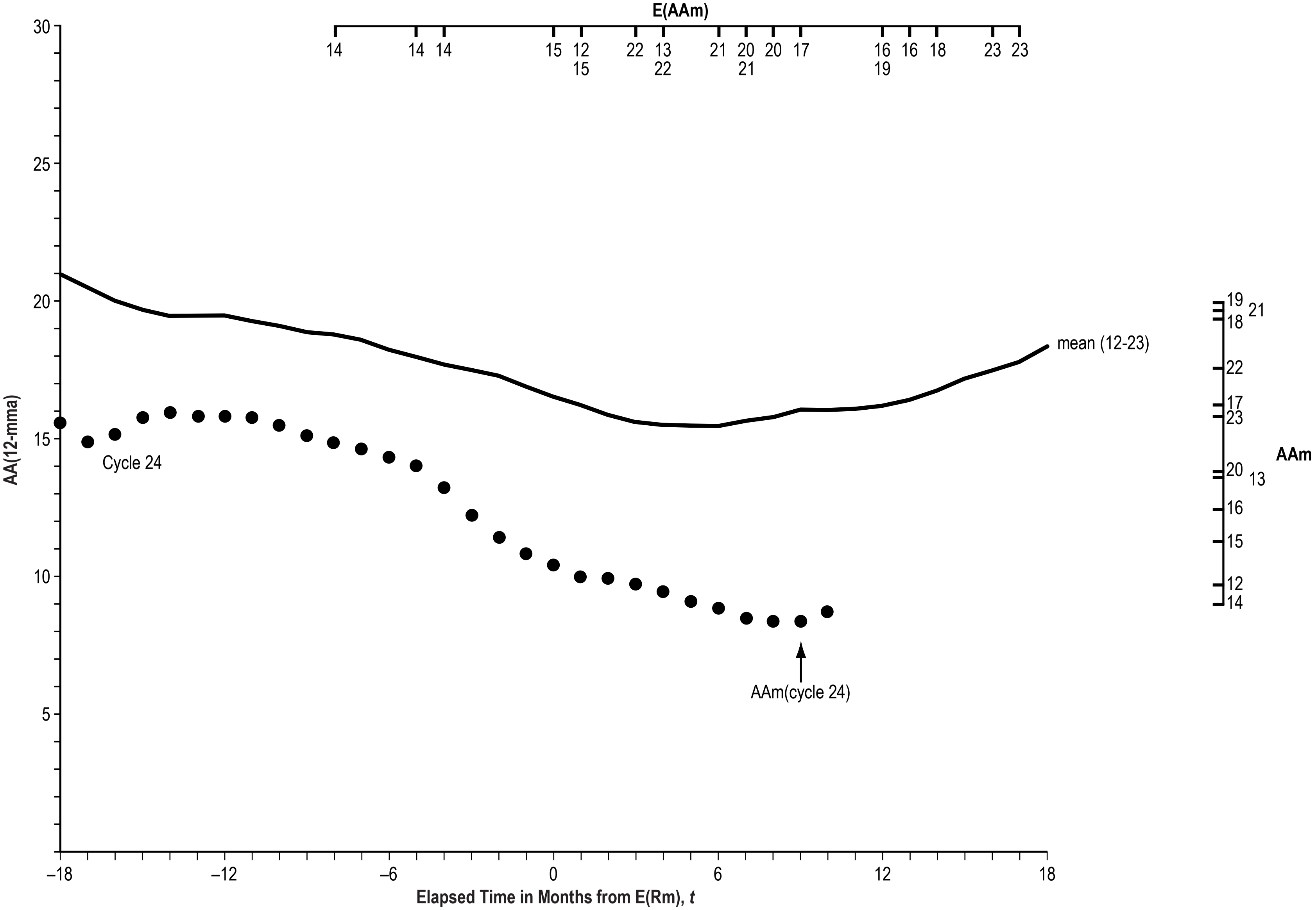

Figure 1. Comparison of cycle 24’s AA values and mean AA values for cycles 12–23 for elapsed time in months relative to E(Rm), $-18 \leq t \leq 18$.

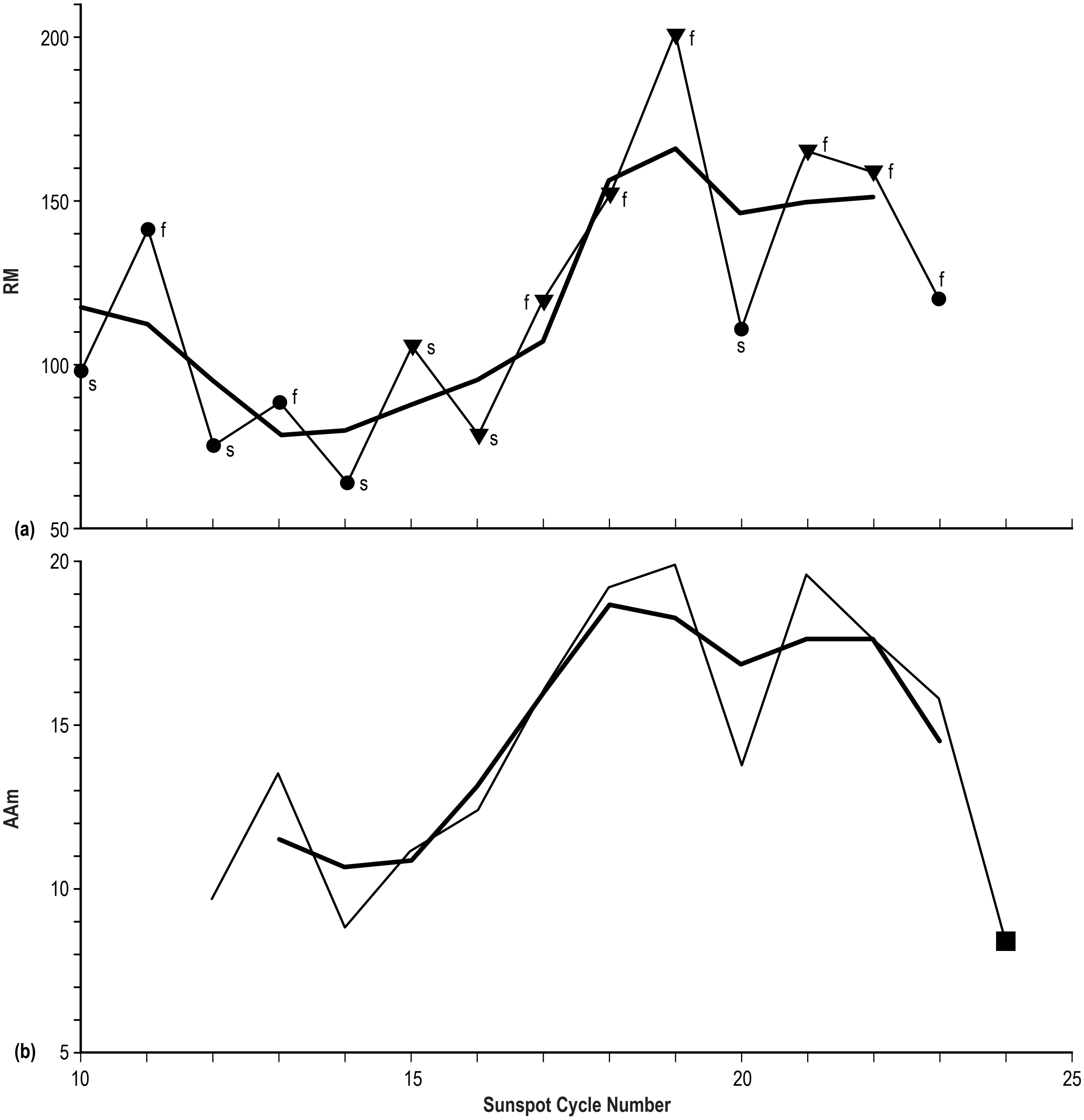

Figure 2. Cyclic variation of (a) RM and (b) AAm for cycles 12–24.

Figure 3(a) displays the scatter plot of RM versus AAm for cycles 12–23 (the method of Ohl). The thin horizontal and vertical lines are the medians for RM and AAm, respectively. The results of statistical testing using Fisher's exact test for 2×2 contingency tables is shown in the lower-right portion of figure 3(a).[21] The probability (*P*) of obtaining the observed distribution or one more suggestive of a departure from independence (chance) is computed to be $P = 0.1\%$, based on the sample size of 12 sunspot/geomagnetic cycles, suggesting a very strong association between the two parameters. The diagonal line running from the lower left to the upper right is the inferred regression

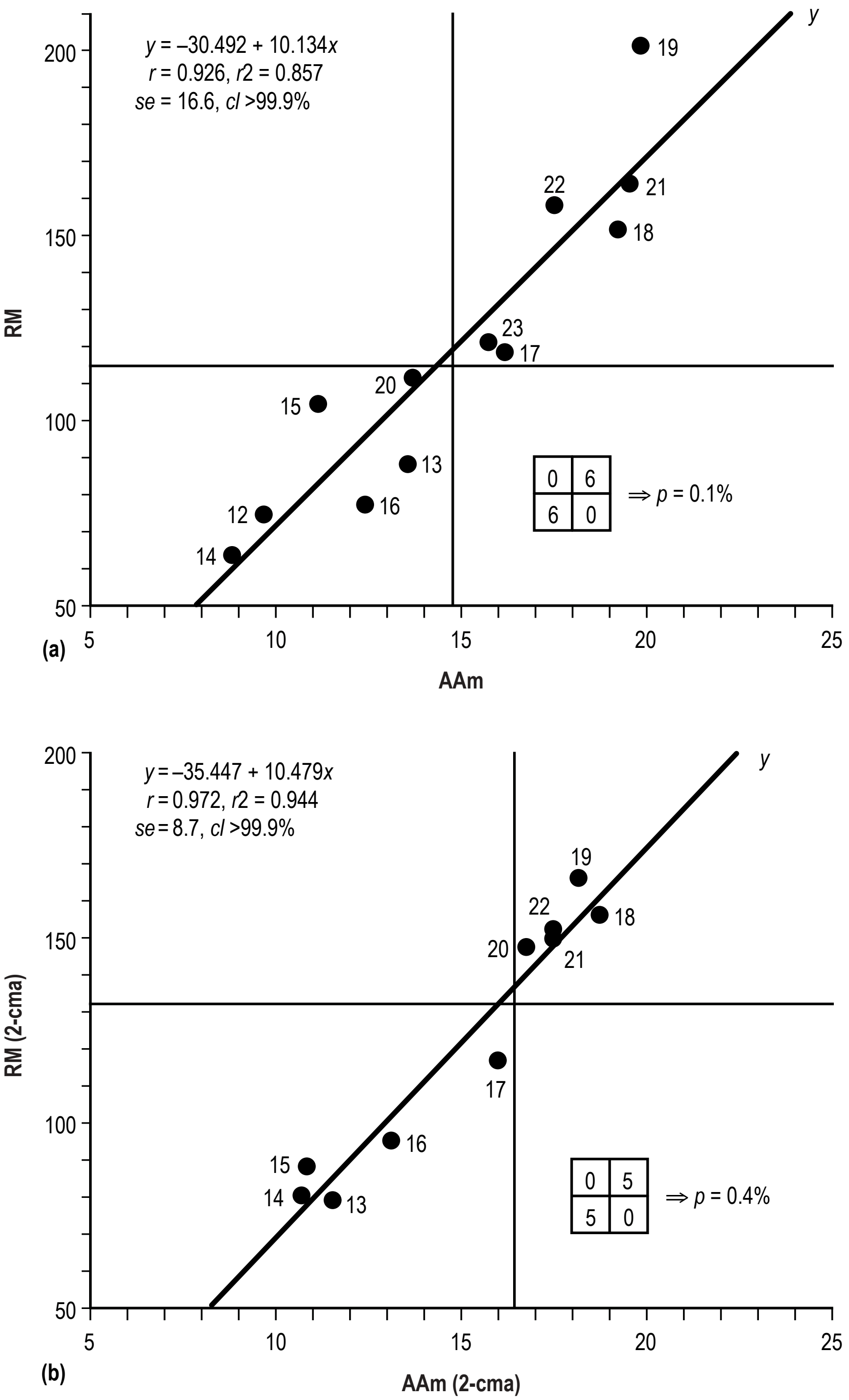

Figure 3. Scatter plots of (a) RM versus AAm based on single-cycle values (the method of Ohl) and (b) RM versus AAm based on 2-cma values.

based on linear regression analysis with the line given as $y = -30.492 + 10.134x$, where y represents the predicted value of RM and x represents the observed value of AAm. The inferred correlation has a coefficient of correlation (r) equal to 0.926 and a coefficient of determination (r^2) equal to 0.857, suggesting that about 86% of the variance in RM can be explained simply by the variation of AAm alone. The standard error of estimate (*se*) is estimated to be about 16.6 units of smoothed monthly mean sunspot number and the inferred linear correlation is found to have a confidence level (cl) > 99.9%, meaning that the inferred correlation is considered statistically very important.

Figure 3(b) is similar to figure 3(a), except now it is based on using the 2-cma values of RM and AAm (a variation of the method of Ohl). Although it is based on two fewer cycles, the inferred regression (based on linear regression analysis) is inferred to be slightly stronger, having $r = 0.972$, $r^2 = 0.944$, and $se = 8.7$ units of smoothed monthly mean sunspot number. The inferred regression is $y = -35.447 + 10.479x$.

Using AAm = 8.4 nT for cycle 24, RM for cycle 24 is expected to lie within the lower-left quadrant of figure 3(a). The inferred regression equation yields RM = 54.6 ± 16.6 (i.e., the $\pm 1 - \sigma$ prediction interval). Hence, there is a 75% chance that cycle 24's RM will measure ≤66.2, a 95% chance that it will measure ≤84.7, and only a 1% chance that it will measure ≥100.5.

On the basis of the observed 2-cma of AAm for cycle 23, equal to (17.5 + 2(15.8) + 8.4)/4 = 14.4 nT, one expects the 2-cma of RM for cycle 23 to lie in the lower-left quadrant of figure 3(b). The inferred regression equation yields the 2-cma of RM for cycle 23 to be about 115.5 ± 8.7 (the $\pm 1 - \sigma$ prediction interval). Hence, RM for cycle 24 can be crudely estimated to be RM = 4(115.5 ± 8.7) − 2(120.8) − 158.5 = 61.9 ± 34.8. Because the average deviation between predicted and observed 2-cma values of RM is about 6.5, cycle 24's RM, based on the 2-cma correlation, is estimated to be about 62 ± 26.

Together, the two predictions strongly indicate that the RM for cycle 24 will be considerably smaller than was observed for cycle 23 (120.8), measuring probably about 55–62 in terms of smoothed monthly mean sunspot number. Using these values, one can easily estimate the timing of RM occurrence relative to E(Rm) for cycle 24 using the Waldmeier effect, a loose but statistically significant relationship between RM and ASC.[22]

Figure 4 depicts the Waldmeier effect, plotting ASC versus RM, where the number appearing beside each plotted point is the sunspot cycle number. Statistical testing, using Fisher's exact test for 2×2 contingency tables, reveals a strong association between the two parameters, having $P = 0.2\%$, meaning that the P of obtaining the observed table or one more suggestive of independence is only 0.2%. Thus, smaller RM cycles tend to have ASC ≥ 48 months (relative to E(Rm)), while larger RM cycles tend to have ASC < 48 months. Of the smaller RM cycles, all have had ASC ≥ 48 months, except cycle 13, with all smaller RM cycles having ASC ≥ 47 months. Furthermore, 5 of 7 smaller RM cycles have also been cycles of longer duration (PER > 11 years), the only exceptions being cycles 15 and 16. Because cycle 24 is predicted to be a smaller RM cycle, one infers that it too likely will be a slow riser (ASC ≥ 48 months) and quite possibly be a cycle of longer duration. This suggests that RM occurrence for cycle 24 very likely will occur after December 2012, since E(Rm) for cycle 24 occurred in December 2008, and that cycle 24 very likely will end sometime in 2020 or later.

Also shown in figure 4 is the inferred regression, ignoring cycles 14 and 19, the extremes in RM and considered here as statistical outliers with respect to the Waldmeier effect. Presuming RM = 55–62 for cycle 24, the ASC for cycle 24 is estimated to be about 58–59 ± 4 months (the $\pm 1-\sigma$ prediction interval). Thus, RM for cycle 24 is, indeed, expected to occur sometime in 2013–14 unless, of course, cycle 24 turns out to be a statistical outlier. Interestingly, cycles 14 and 19, the cycles of extremes in terms of RM, are 5 cycles apart, and cycle 24 follows cycle 19 by exactly 5 cycles. Will cycle 24 also be a statistical outlier with respect to the Waldmeier effect? (The reader should note that cycle 9, which precedes cycle 14 by 5 cycles, also appears to be a statistical outlier with respect to the Waldmeier effect, having RM = 131.6 and ASC = 55 months.)

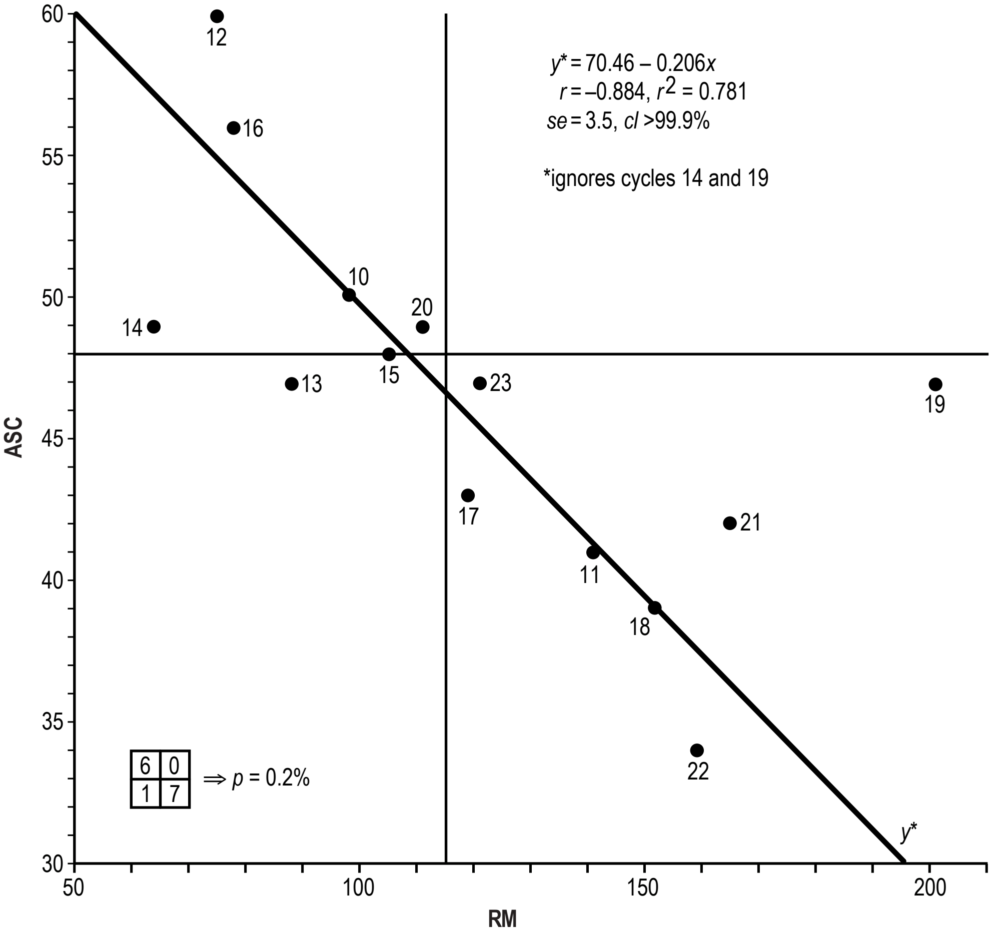

Figure 4. Scatter plot of ASC versus RM (the Waldmeier effect).

For convenience, table 1 is included to provide the reader with the exact values and dates for the selected cyclic parameters associated with the modern era sunspot cycles used in plotting figures 1–4.

Table 1. Selected solar cycle parametric values for cycles 10–24.

Cycle	RM	Rm	E(Rm)	ASC	PER	AA(Rm)	AAm*	RM(2-cma)	AAm*(2-cma)
10	97.9	3.2	12-1855	50	135	–	–	117.0	–
11	140.5	5.2	03-1867	41	141	–	–	113.4	–
12	74.6	2.2	12-1878	60	135	9.8	9.7	94.4	–
13	87.9	5.0	03-1890	46	142	14.2	13.6	78.7	11.5
14	64.2	2.6	01-1902	49	139	9.1	8.9	80.4	10.7
15	105.4	1.5	08-1913	48	120	11.2	11.2	88.3	10.9
16	78.1	5.6	08-1923	56	121	13.4	12.4	95.2	13.1
17	119.2	3.4	09-1933	43	125	18.6	16.2	117.1	16.0
18	151.8	7.7	02-1944	39	122	26.2	19.3	156.0	18.7
19	201.3	3.4	04-1954	47	126	20.9	19.9	166.3	18.2
20	110.6	9.6	10-1964	49	140	15.2	13.8	146.8	16.8
21	164.5	12.2	06-1976	42	123	22.3	19.6	149.5	17.6
22	158.5	12.3	09-1986	34	116	18.3	17.5	150.6	17.6
23	120.8	8.0	05-1996	47	151	18.8	15.8	–	14.4
24	–	1.7	12-2008	–	–	10.4	8.4	–	–

*means in the vicinity of E(Rm). For cycle 21, its true AAm occurred about 46 months after E(Rm), measuring 17.2.

3. DISCUSSION AND SUMMARY

Several years ago during the declining portion of cycle 23, efforts were made to reach a consensus prediction for the size and timing of sunspot cycle 24. The outcome was a split prediction, some favoring a large RM and quick rise and others favoring a more subdued RM and slower rise. Pesnell provides a summary of some of these early attempts at predicting the size and timing of cycle 24,[8] as do Obridko and Shelting.[7] Additionally, a useful Web site for comparing the many predictions that have been made for cycle 24 is readily available for access.[9]

While many methods for predicting the latter-occurring RM of a sunspot cycle have been proffered, the method of Ohl seems to be one of the most reliable, having a $\pm 1-\sigma$ uncertainty of about 17 units of smoothed monthly mean sunspot number. The difficulty associated with obtaining a singular consensus prediction of RM for cycle 24 was largely caused by its delayed minimum. Early on, because cycle 23 had an RM larger than the mean amplitude, statistically speaking, it could be argued that it was destined to be a cycle of shorter duration. If true, its end (and consequently the conventional onset of cycle 24) was anticipated to occur prior to May 2007.[23–26]

Because the minimum for cycle 24 appeared most imminent in 2006, because a maximum in geomagnetic activity had occurred in August 2003 (the highest ever recorded for the 12-mma of AA), and because there exists a statistically significant relationship between the maximum of geomagnetic activity during the declining portion of an ongoing sunspot cycle and the size of the following cycle, these observations became the basis for the prediction of a large RM for cycle 24, which was also supportive of a particular flux-transport dynamo model prediction and of evidence for the deep meridional flow setting the sunspot cycle period.[20, 27–32] It has since become apparent that E(Rm) for cycle 24 would occur later than 2006–2007, inferring that the initial prediction for cycle 24's RM was premature.[33–39]

In this NASA TP, it has been shown that AAm for cycle 24 appears likely to have occurred in September 2009, some 9 months past cycle 24's E(Rm), measuring about 8.4 nT, a value smaller than the smallest previous value on record (8.9 nT for cycle 14, also the smallest sunspot cycle on record). The consequence of this is that, unless cycle 24 proves to be a statistical outlier, its RM is now anticipated to be much smaller in size than previously forecast, possibly becoming the smallest of the modern era.[40, 41] The method of Ohl predicts $\mathrm{RM} = 54.6 \pm 16.6$ (the $\pm 1-\sigma$ prediction interval), while using a variation of the Ohl method (2-cma values), RM for cycle 24 is predicted to be about 62 ± 26. A value of RM equal to 55–62 suggests from the Waldmeier effect that cycle 24 will be a slow-rising cycle, peaking probably about $58\text{–}59 \pm 4$ months (the $\pm 1-\sigma$ prediction interval) after E(Rm) or sometime in 2013–14. Likewise, because cycle 24 is anticipated to be a slow-rising, small-amplitude sunspot cycle, statistically speaking, it should also be a cycle of longer duration, inferring that the onset of cycle 25 should not be expected until sometime in 2020 or later. Predicting the overall shape of cycle 24, however, will not be particularly reliable for at least another 2–3 years,[42–44] as will be predicting its effects on the space weather environment.[45–47]

REFERENCES

1. Kiepenheuer, K.O.: “Solar Activity,” in *The Sun*, Vol. I., *The Solar System*, G.P. Kuiper (ed.), The University of Chicago Press, Chicago, IL, p. 322, 1953.

2. McIntosh, P.S.; and Dryer, M. (eds.): *Solar Activity Observations and Predictions*, *Progress in Astronautics and Aeronautics*, MIT, Alpine Press, Inc., Colonial Press, Inc., Boulder, CO, Vol. 30, 1972.

3. Donnelly, R.F. (ed.): *Solar-Terrestrial Predictions Proceedings*, Working Group Reports and Reviews, National Oceanic and Atmospheric Administration, Environmental Research Laboratories, Boulder, CO, Vol. 2, 1979.

4. Schove, D.J. (ed.): *Sunspot Cycles*, *Benchmark Papers in Geology*, Hutchinson Ross Publ. Co., Stroudsburg, PA, Vol. 68, 1983.

5. Simon, P.A.; Heckman, G.; and Shea, M.A. (eds.): *Solar-Terrestrial Predictions: Proceedings of a Workshop at Meudon, France, June 18–22, 1984*, National Oceanic and Atmospheric Administration, Environmental Research Laboratories, Boulder, CO, 1986.

6. Joselyn, J.A.; et al.: “Panel Achieves Consensus Prediction of Solar Cycle 23,” *Eos Trans. AGU*, Vol. 78, p. 205, 1997.

7. Obridko, V.N.; and Shelting, B.D.: “On Prediction of the Strength of the 11-Year Solar Cycle No. 24,” *Solar Phys.*, Vol. 248, p. 191, 2008.

8. Pesnell, W.D.: “Predictions of Solar Cycle 24,” *Solar Phys.*, Vol. 252, p. 209, 2008.

9. “Predictions for Solar Cycle 24,” <http://users.telenet.be/j.janssens/SC24.html>, (Accessed November 2009).

10. Butler, C.J.: “Maximum and Minimum Temperatures at Armagh Observatory, 1844–1992, and the Length of the Sunspot Cycle,” *Solar Phys.*, Vol. 152, p. 35, 1994.

11. Hoyt, D.V.; and Schatten, K.H.: *The Role of the Sun in Climate Change*, Oxford University Press, New York, NY, 1997.

12. Wilson, R.M.: “Evidence for Solar-Cycle Forcing and Secular Variation in the Armagh Observatory Temperature Record (1844–1992),” *J. Geophys. Res.*, Vol. 103, p. 11,159, 1998.

13. Baker, D.N.: "Effects of the Sun on the Earth's Environment," *J. Atmos. Solar-Terr. Phys.*, Vol. 62, p. 1669, 2000.

14. Soon, W.W.-H.; and Yaskell, S.H.: *The Maunder Minimum and the Variable Sun-Earth Connection*, World Scientific Publishing Co., Singapore, China, 2003.

15. Qian, L.S.; et. al.: "Thermospheric Neutral Density Response to Solar Forcing," *Adv. Space Res.*, Vol. 42, p. 926, 2008.

16. Ram, M.; Stolz, M.R.; and Tinsley. B.A.: "The Terrestrial Cosmic Ray Flux: Its Importance for Climate," *Eos Trans. AGU*, Vol. 90, p. 397, 2009.

17. Ohl, A.I.: "Forecast of Sunspot Maximum Number of Cycle 20," *Solice Danie*, Vol. 9, p. 84, 1966.

18. British Geological Survey, <http://www.geomag.bgs.ac.uk./gifs/aaindex.html>, (Accessed November 2009).

19. Svalgaard, L.; Cliver, E.W.; and Le Sager, P.: "IHV: A New Long-Term Geomagnetic Index," *Adv. Space Res.*, Vol. 34, p. 436, 2004.

20. Wilson, R.M.; and Hathaway, D.H.: "An Examination of Selected Geomagnetic Indices in Relation to the Sunspot Cycle," NASA/TP—2006–214711, Marshall Space Flight Center, AL, December 2006.

21. Everitt, B.S.: *The Analysis of Contingency Tables*, John Wiley and Sons, New York, NY, p. 15, 1977.

22. Hathaway, D.H.; Wilson, R.M.; and Reichmann, E.J.: "Group Sunspot Numbers: Sunspot Cycle Characteristics," *Solar Phys.*, Vol. 211, p. 357, 2002.

23. Wilson, R.M.; Hathaway, D.H.; and Reichmann, E.J: "On Determining the Rise, Size, and Duration Classes of a Sunspot Cycle," NASA-TP-3652, Marshall Space Flight Center, AL, September 1996.

24. Wilson, R.M.; and Hathaway, D.H.: "Application of the Maximum Amplitude-Early Rise Correlation to Cycle 23," NASA/TP—2004–213281, Marshall Space Flight Center, AL, June 2004.

25. Wilson, R.M.; and Hathaway, D.H.: "On the Relation Between Spotless Days and the Sunspot Cycle," NASA/TP—2005–213608, Marshall Space Flight Center, AL, January 2005.

26. Wilson, R.M.; and Hathaway, D.H.: "An Examination of Sunspot Number Rates of Growth and Decay in Relation to the Sunspot Cycle," NASA/TP—2006–214433, Marshall Space Flight Center, AL, June 2006.

27. Hathaway, D.H.; Wilson, R.M.; and Reichmann, E.J.: "A Survey and Synthesis of Solar Cycle Prediction Techniques," *J. Geophys. Res.*, Vol. 104, p. 22,375, 1999.

28. Hathaway, D.H.; Nandy, D.; Wilson, R.M.; and Reichmann, E.J.: "Evidence That a Deep Meridional Flow Sets the Sunspot Cycle Period," *Astrophys. J.*, Vol. 589, p. 665, 2003.

29. Hathaway, D.H.; Nandy, D.; Wilson, R.M.; and Reichmann, E.J.: "Erratum: 'Evidence that a Deep Meridional Flow Sets the Sunspot Cycle Period' (*Ap. J.*, Vol. 589, p. 665 (2003))," *Astrophys. J.*, Vol. 602, p. 543, 2004.

30. Dikpati, M.; de Toma, G.; and Gilman, P.A.: "Predicting the Strength of Solar Cycle 24 Using a Flux-Transport Dynamo-Based Tool," *Geophys. Res. Lett.*, Vol. 33, p. L05102, doi:10.1029/2005GL025221, 2006.

31. Hathaway, D.H.; and Wilson, R.M.: "Geomagnetic Activity Indicates Large Amplitude for Sunspot Cycle 24," *Geophys Res. Lett*., Vol. 33, p. L18101, doi:10.1029/2006GL027053, 2006.

32. Wilson, R.M.; and Hathaway, D.H.: "Anticipating Cycle 24 Minimum and Its Consequences," NASA/TP—2007–215134, Marshall Space Flight Center, AL, November 2007.

33. Wilson, R.M.; and Hathaway, D.H.: "Using the Modified Precursor Method to Estimate the Size of Cycle 24," NASA/TP—2008–215467, Marshall Space Flight Center, AL, July 2008.

34. Wilson, R.M.; and Hathaway, D.H.: "Using the Inflection Points and Rates of Growth and Decay to Predict Levels of Solar Activity," NASA/TP—2008–215473, Marshall Space Flight Center, AL, September 2008.

35. Wilson, R.M.; and Hathaway, D.H.: "Anticipating Cycle 24 Minimum and Its Consequences: An Update," NASA/TP—2008–215576, Marshall Space Flight Center, AL, October 2008.

36. Wilson, R.M.; and Hathaway, D.H.: "On the Period-Amplitude and Amplitude-Period Relationships," NASA/TP—2008–215580, Marshall Space Flight Center, AL, November 2008.

37. Wilson, R.M.; and Hathaway, D.H.: "Predicting the Size of Sunspot Cycle 24 on the Basis of Single- and Bi-Variate Geomagnetic Precursor Methods," NASA/TP—2009–215687, Marshall Space Flight Center, AL, February 2009.

38. Wilson, R.M.; and Hathaway, D.H.: "Sunspot Activity Near Cycle Minimum and What It Might Suggest for Cycle 24, the Next Sunspot Cycle," NASA/TP—2009–216061, Marshall Space Flight Center, AL, September 2009.

39. Hathaway, D.H.; and Wilson, R.M.: "Recent Geomagnetic Activity Indicates Small Amplitude for Sunspot Cycle 24," (in preparation), 2010.

40. Svalgaard, L.; Cliver, E.W.; and Kamide, Y.: "Sunspot Cycle 24: Smallest Cycle in 100 Years?" *Geophys. Res. Lett.*, Vol. 32, p. L01104, 2005.

41. Choudhuri, A.R.; Chatterjee, P.; and Jiang, J.: "Predicting Solar Cycle 24 With a Dynamo Model," *Phys. Rev. Lett.*, Vol. 98, p. 131,103, 2007.

42. Hathaway, D.H.; Wilson, R.M.; and Reichmann, E.J.: "The Shape of the Sunspot Cycle," *Solar Phys.*, Vol. 151, p. 177, 1994.

43. Wilson, R.M.; Hathaway, D.H.; Reichmann, E.J.: "On the Correlation Between Maximum Amplitude and Smoothed Monthly Mean Sunspot Number During the Rise of the Cycle (From $t=0$–48 Months Past Sunspot Minimum)," NASA/TP—1998–208591, Marshall Space Flight Center, AL, August 1998.

44. Wilson, R.M. and Hathaway, D.H.: "Application of the Maximum Amplitude-Early Rise Correlation to Cycle 23," NASA/TP—2004–213281, Marshall Space Flight Center, AL, June 2004.

45. Wilson, R.M.: "On the Relationship Between Transient Velocity of Interplanetary Shocks and Solar Active Processes," *Planet. Space Sci.*, Vol. 44, p. 441, 1996.

46. Hathaway, D.H.; and Wilson, R.M.: "What the Sunspot Record Tells Us About Space Climate," *Solar Phys.*, Vol. 224, p. 5, 2004.

47. Wilson, R.M.; and Hathaway, D.H.: "On the Relationship Between Solar Wind Speed, Earthward-Directed Coronal Mass Ejections, Geomagnetic Activity, and the Sunspot Cycle Using 12-Month Moving Averages," NASA/TP—2008–215413, Marshall Space Flight Center, AL, June 2008.

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14. ABSTRACT

For cycle 24, the minimum value of the 12-month moving average (12-mma) of the AA-geomagnetic index in the vicinity of sunspot minimum (AAm) appears to have occurred in September 2009, measuring about 8.4 nT and following sunspot minimum by 9 months. This is the lowest value of AAm ever recorded, falling below that of 8.9 nT, previously attributed to cycle 14, which also is the smallest maximum amplitude (RM) cycle of the modern era (RM = 64.2). Based on the method of Ohl (the preferential association between RM and AAm for an ongoing cycle), one expects cycle 24 to have RM = 55 ± 17 (the $\pm 1-\sigma$ prediction interval). Instead, using a variation of Ohl's method, one based on using 2-cycle moving averages (2-cma), one expects cycle 23's 2-cma of RM to be about 115.5 ± 8.7 (the $\pm 1-\sigma$ prediction interval), inferring an RM of about 62 ± 35 for cycle 24. Hence, it seems clear that cycle 24 will be smaller in size than was seen in cycle 23 (RM = 120.8) and, likely, will be comparable in size to that of cycle 14. From the Waldmeier effect (the preferential association between the ascent duration (ASC) and RM for an ongoing cycle), one expects cycle 24 to be a slow-rising cycle ($\text{ASC} \geq 48$ months), having RM occurrence after December 2012, unless it turns out to be a statistical outlier.

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