An Examination of Sunspot Number Rates of Growth and Decay in Relation to the Sunspot Cycle

Robert M. Wilson and David H. Hathaway
Marshall Space Flight Center, Marshall Space Flight Center, Alabama

June 2006
Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the lead center for NASA’s scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA’s institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA’s counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.

- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and mission, often concerned with subjects having substantial public interest.

- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA’s mission.

Specialized services that complement the STI Program Office’s diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results…even providing videos.

For more information about the NASA STI Program Office, see the following:

- E-mail your question via the Internet to help@sti.nasa.gov
- Fax your question to the NASA Access Help Desk at 301–621–0134
- Telephone the NASA Access Help Desk at 301–621–0390
- Write to:
  NASA Access Help Desk  
  NASA Center for AeroSpace Information  
  7121 Standard Drive  
  Hanover, MD 21076–1320  
  301–621–0390
An Examination of Sunspot Number Rates of Growth and Decay in Relation to the Sunspot Cycle

Robert M. Wilson and David H. Hathaway
Marshall Space Flight Center, Marshall Space Flight Center, Alabama

June 2006
# TABLE OF CONTENTS

1. INTRODUCTION ...................................................................................................................... 1

2. RESULTS AND DISCUSSION .................................................................................................... 2

3. CONCLUSION ........................................................................................................................... 21

REFERENCES ............................................................................................................................ 22
LIST OF FIGURES

1. Cyclic variation of selected solar cycle parameters for cycles 12–23: (a) $SLOPE_{DES}$, (b) $SLOPE_{ASC}$, (c) $\Delta R_{GNV}$, (d) $\Delta R_{GPV}$, (e) $R_{max}$, and (f) $R_{min}$. The median value shown for each parameter is depicted as the thin horizontal line. Also identified are the mean and standard deviations (sd) for each parameter .......................................................... 3

2. Comparison of cycle 23 $R$-values against the mean sunspot number ($<R>$) for cycles 12–22, relative to the elapsed time ($t$) in years from the epoch of sunspot minimum ($E(R_{min})$). Also shown are the relative sizes and times of occurrences of $R_{max}$, the ascent duration ($ASC$), and the relative length of the cycle, period ($PER$). Cycle 23 is identified by the filled circles, and the mean by the line. On the basis of this figure, there appears a strong indication that $R_{min}$ occurrence for cycle 24, the next sunspot cycle, will be in year $t=10$, corresponding to the year 2006 ........................................................................................................... 4

3. Comparison of cycle 23 $R$-values against the mean sunspot number ($<R>$) for cycles 12–22, relative to the elapsed time ($T$) in years from the epoch of sunspot maximum ($E(R_{max})$). Also shown are the relative occurrences of the descent duration ($DES$). Cycle 23 is identified by the filled circles and the mean by the line. On the basis of this figure, there appears a strong indication that $R_{min}$ for cycle 24, the next sunspot cycle, will be in year $T=6$ or 7, corresponding to the years 2006 or 2007 ........................................................................................................... 5

4. A 3×3 contingency table comparing ascent durations ($ASC$) and periods ($PER$) for cycles 12–22. Individual cycle numbers are identified in each bin. The numbers in parentheses give the frequency of occurrence. A $\chi^2$ test yields $\chi^2=8.13$, which is a marginally significant result (at the 10-percent level of significance) .............................................................................................. 6

5. Comparison of cycle 23 $R$-values (filled circles) against the mean sunspot number ($<R>$) for cycles of $ASC=3$ yr (thick line), 4 yr (thin line), and 5 yr (dashed line) relative to the elapsed time ($t$) in years from the epoch of sunspot minimum ($E(R_{min})$) ................................................................. 7

6. Comparison of cycle 23 $R$-values (filled circles) against the mean sunspot number ($<R>$) for cycles of $PER=10$ yr (thick line), 11 yr (thin line), and 12 yr (dashed line) relative to the elapsed time ($t$) in years from the epoch of sunspot minimum ($E(R_{min})$) ................................................................. 8

7. Scatterplots of (a) $R_{max}$ versus $R_{min}$, (b) $R_{max}$ versus $\Delta R_{GPV}$, and (c) $R_{max}$ versus $R_{max}$ ($y_{x1x2}$) .......................................................................................................................................... 9

8. Scatterplot of $R_{max}$ versus $SLOPE_{ASC}$ ..................................................................................................................................... 10
LIST OF FIGURES (Continued)

9. Scatterplots of (a) $R_{max}$ versus $SLOPE_{ASC} (1)$, (b) $R_{max}$ versus $SLOPE_{ASC} (2)$, and (c) $R_{max}$ versus $SLOPE_{ASC}(3)$ ......................................................................................................................................................... 11

10. Scatterplots of (a) $\Delta R_{GNV}$ versus $\Delta R_{GPV}$ and (b) $\Delta R_{GNV}$ versus $R_{max}$ ......................................................................................................................... 12

11. Scatterplots of (a) $R_{min} (n+1)$ versus $R_{max} (n)$ and (b) $R_{min} (n+1)$ versus $\Delta R_{GNV} (n)$ .............................. 13

12. Scatterplots of (a) $SLOPE_{DES}$ versus $SLOPE_{ASC}$ and (b) $SLOPE_{DES}$ versus $R_{max}$ ...................................................................................................... 14

13. Scatterplot of $SLOPE_{DES}$ versus $SLOPE_{DES}(GNV)$ ................................................................................................................................. 15

14. Scatterplots of (a) $NSD$ versus $t$ and (b) $R$ versus $t$ ................................................................................................................................. 16

15. Cyclic variation of the number of spotless days ($NSD$) during the sunspot minimum year ($E(R_{min})$) for cycles 12–23 ................................................................................................................................. 17

16. Scatterplot of $R_{min}$ versus $NSD(E(R_{min}))$ ........................................................................................................................................... 18

LIST OF TABLES

1. Comparison of $R$ and $NSD$ values relative to $E(R_{min})$ ................................................................................................................................. 17

2. Selected solar cycle parametric values and times of occurrence based on annual averages of sunspot number ........................................................................................................................................... 19
ACRONYMS, SYMBOLS, AND ABBREVIATIONS

ASC  ascent duration in years

cl  confidence level

DES  descent duration in years

\( E(R_{min}) \)  epoch of sunspot minimum occurrence

\( E(R_{max}) \)  epoch of sunspot maximum occurrence

NSD  number of spotless days

\( NSD(E(R_{min})) \)  number of spotless days during sunspot minimum year

n  sunspot cycle number

P  probability of obtaining the observed contingency table or one more suggestive of a departure from independence, computed using Fisher’s exact test for 2×2 tables

PER  period or length of cycle in years

R  relative sunspot number

\(<R>\)  mean value of sunspot number

R_{max}  sunspot number maximum amplitude

R_{min}  sunspot number minimum amplitude

r  linear correlation coefficient

\( r^2 \)  coefficient of determination (a measure of the amount of variance explained by the inferred regression)

\( SLOPE_{ASC} \)  average rate of growth in sunspot number during the ascent

\( SLOPE_{DES} \)  average rate of decay in sunspot number during the descent
ACRONYMS, SYMBOLS, AND ABBREVIATIONS (Continued)

\[ SLOPE_{DES}(GNV) \] greatest yearly negative change in sunspot number during the evolving descent duration

sd standard deviation

se standard error of estimate

\[ T \] elapsed time in years from sunspot maximum

\[ T(E(SLOPE_{DES}(GNV))) \] elapsed time in years from sunspot maximum to the occurrence of the greatest negative value of the evolving \( SLOPE \) during the decline of the sunspot cycle

\[ t \] elapsed time in years from sunspot minimum

\[ t(E(\Delta R_{GNV})) \] statistic for independent samples

\[ t(E(\Delta R_{GPV})) \] elapsed time in years from sunspot minimum to the occurrence of the greatest negative value of the change in \( R \)

\[ t(E(\Delta R_{GPV})) \] elapsed time in years from sunspot minimum to the occurrence of the greatest positive value of the change in sunspot number \( (R) \)

\[ x \] independent variable

\[ x1, x2 \] variables

\[ Y.12 \] refers to the bivariate fit, where 1 means parameter \( x1 \) and 2 means parameter \( x2 \)

\[ y \] dependent variable

\[ y_L \] lower regression line

\[ y_U \] upper regression line

\[ y_{x1,x2} \] the bivariate fit

\[ \Delta R_{GNV} \] greatest negative value of the change in sunspot number

\[ \Delta R_{GPV} \] greatest positive value of the change in sunspot number

\[ \chi^2 \] a statistical test statistic
1. INTRODUCTION

Wolf’s relative sunspot number (R) is one of the oldest and most enduring of the sunspot records. Consequently, it is the one most often used to describe solar activity. Even so, recent studies have shown that its reliability is questionable for epochs earlier than the mid-1800s. In particular, Hoyt and Schatten’s group sunspot number has been shown to be virtually identical with Wolf’s relative sunspot number, but only since about 1882. Also, comparison of Wolf’s relative sunspot number against Greenwich sunspot areas shows fairly good consistency from about 1874. Hence, Wolf’s relative sunspot number is generally recognized to be most reliable from the onset of cycle 12 in 1878 to the present.

In this study, the rates of growth and decay in annual sunspot number averages are examined relative to minimum and maximum amplitudes to ascertain their predictive behavior in providing early estimates of minimum and maximum amplitudes and the timing of their occurrences.
2. RESULTS AND DISCUSSION

Figure 1 displays the cyclic behavior of several solar cycle parameters for cycles 12–23 including the following:

- Minimum sunspot number amplitude ($R_{\text{min}}$).
- Maximum sunspot number amplitude ($R_{\text{max}}$).
- Greatest positive value change in R from one year to the next ($\Delta R_{\text{GPV}}$).
- Greatest negative value change in R from one year to the next ($\Delta R_{\text{GNV}}$).
- Average sunspot number slope during ascent interval ($SLOPE_{\text{ASC}}$), computed as $R_{\text{max}} - R_{\text{min}} / \text{ASC}$, where ASC is ascent duration in years, or elapsed time between $R_{\text{min}}$ and $R_{\text{max}}$ occurrences; and average sunspot number slope during descent interval ($SLOPE_{\text{DES}}$), computed as $R_{\text{min}}(\text{cycle } n+1) - R_{\text{max}}(\text{cycle } n) / \text{DES}$, where DES is descent duration in years or elapsed time between $R_{\text{max}}$ occurrence cycle $n$ and $R_{\text{min}}$ occurrence cycle $n+1$.

The median, mean, and standard deviation (sd) for each parameter are shown.

Figure 1 reveals that cycles of late had values for these parameters that differ markedly from earlier cycles. Concerning $R_{\text{min}}$ for example, five of the last six cycles had an $R_{\text{min}}$ greater than both the median (6.1) and mean (7.0). Comparing $R_{\text{min}}$ for cycles 18–23 against $R_{\text{min}}$ for cycles 12–17, the difference in means is statistically important at the 2-percent level of significance. On the basis of hypothesis testing using the $t$-statistic for independent samples, note that a 5-percent level of significance means a confidence level (cl) of 95 percent, a level of significance of 1 percent means a cl of 99 percent, and so on. Similarly, the other parameters show statistically significant differences in the means for the two groupings as follows:

- $R_{\text{max}}$ at the 0.2-percent level of significance.
- $\Delta R_{\text{GPV}}$ at the 2-percent level of significance.
- $\Delta R_{\text{GNV}}$ at the 0.1-percent level of significance.
- $SLOPE_{\text{ASC}}$ at the 0.5-percent level of significance.
- $SLOPE_{\text{DES}}$ at the 2-percent level of significance.

Thus, cycles 18–23 appear to be inherently more robust than cycles 12–17.
Figure 1. Cyclic variation of selected solar cycle parameters for cycles 12–23: (a) $SLOPE_{DES}$, (b) $SLOPE_{ASC}$, (c) $\Delta R_{GNV}$, (d) $\Delta R_{GPV}$, (e) $R_{max}$, and (f) $R_{min}$. The median value shown for each parameter is depicted as the thin horizontal line. Also identified are the mean and sd for each parameter.
Figure 2 compares yearly sunspot number averages for cycle 23 (filled circles) against the mean yearly averages ($<R>$) for cycles 12–22, relative to the epoch of $R_{\text{min}}$ occurrence ($E(R_{\text{min}})$). It also shows the relative sizes and times of $R_{\text{max}}$ occurrences, the ascent duration ($ASC$), and the relative length of the cycles ($PER$). On the basis of figure 2, it appears that cycle 23 is nearly to its end, with $R_{\text{min}}$ for cycle 24 expected either in 2006 or 2007, which corresponds respectively to year 10 or 11 of the sunspot cycle. For cycles 12–23, cycle 23 ranks fifth in relative size, having a maximum amplitude of 119.5 that occurred in year 4 of the sunspot cycle (counting the minimum year as year 0).

Figure 2. Comparison of cycle 23 $R$-values against the mean sunspot number ($<R>$) for cycles 12–22, relative to the elapsed time ($t$) in years from the epoch of sunspot minimum ($E(R_{\text{min}})$). Also shown are the relative sizes and times of occurrences of $R_{\text{max}}$, the ascent duration ($ASC$), and the relative length of the cycle, period ($PER$). Cycle 23 is identified by the filled circles and the mean by the line. On the basis of this figure, there appears a strong indication that $R_{\text{min}}$ occurrence for cycle 24, the next sunspot cycle, will be in year $t=10$, corresponding to the year 2006.
Figure 3 compares yearly sunspot number averages for cycle 23 (filled circles) against the mean yearly averages ($<R>$) for cycles 12–22, relative to the elapsed time ($T$) in years from the epoch of sunspot maximum ($E(R_{max})$). It also shows the relative times of occurrences for the succeeding cycle $R_{min}$ descent duration ($DES$), thereby marking the conventional onset of the following cycle. On the basis of figure 3, it is suggested that cycle 23 will probably end in year seven from $E(R_{max})$, corresponding to 2007, inferring an 11-yr period for cycle 23 ($ASC+DES=PER$, or $4+7\text{ yr}=11\text{ yr}$). It should be noted, however, that minimum could come earlier in 2006, especially if cycle 24 proves to be above average in size, since robust cycles tend to start early, be fast risers, and often are of a shorter period.

![Figure 3](image.png)

**Figure 3.** Comparison of cycle 23 $R$-values against the mean sunspot number ($<R>$) for cycles 12–22, relative to the elapsed time ($T$) in years from the epoch of sunspot maximum ($E(R_{max})$). Also shown are the relative occurrences of the descent duration ($DES$). Cycle 23 is identified by the filled circles and the mean by the line. On the basis of this figure, there appears a strong indication that $R_{min}$ for cycle 24, the next sunspot cycle, will be in year $T=6$ or 7, corresponding to the years 2006 or 2007.
Figure 4 shows the distribution of cycles based on cycle length (PER) and ASC for cycles 12–22. All cycles have ASC of 3, 4, or 5 yr and PER of 10, 11, or 12 yr. A $\chi^2$ test of the observed 3×3 distribution yields $\chi^2=8.13$, suggesting that ASC and PER might be weakly associated at the 10-percent level of significance. At the 5-percent level of significance, the two parameters must be viewed as being independent of each other.

<table>
<thead>
<tr>
<th>ASC</th>
<th>PER 10</th>
<th>PER 11</th>
<th>PER 12</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>18, 19, 21, 22 (4)</td>
<td>(0)</td>
<td>(0)</td>
</tr>
<tr>
<td>4</td>
<td>15 (1)</td>
<td>17</td>
<td>13, 14, 20 (3)</td>
</tr>
<tr>
<td>5</td>
<td>16 (1)</td>
<td>12 (1)</td>
<td>(0)</td>
</tr>
</tbody>
</table>

$\chi^2=8.13$

Figure 5 compares yearly sunspot number averages for cycle 23 (filled circles) against the mean yearly averages ($<R>$) for cycles of ASC=3 yr (thick line), 4 yr (thin line), and 5 yr (dashed line). Throughout its rise, cycle 23 yearly sunspot numbers fell below the mean for ASC=3 yr and above the mean for ASC=4 yr, making it difficult to accurately determine whether it would have a 3 yr or 4 yr rise. The cycle 23 decline appears to be more like the decline found for ASC=3 yr rather than ASC=4 yr, except for the last year or two. The cycle 23 $R$ value at $t=9$ yr (2005) equals 29.9, which is slightly smaller than was seen for the same $t$ in cycles 17 (30.6) and 20 (38.2) and slightly larger than was seen for the same $t$ in cycle 19 (27.9). The suggestion from figure 5 is that minimum for cycle 24, the next sunspot cycle, will probably occur either at $t=10$ yr (2006) or $t=11$ yr (2007).

Figure 6 compares yearly sunspot number averages for cycle 23 (filled circles) against the mean yearly averages ($<R>$) for cycles of PER=10 yr (thick line), 11 yr (thin line), and 12 yr (dashed line). Throughout its rise and fall, cycle 23’s behavior has closely mimicked the mean behavior of cycles having 10-yr lengths. Hence, it may be that cycle 23 is also a cycle of PER=10 yr. If true, then 2006 should mark the onset year for cycle 24, on the basis of annual averages.
Figure 5. Comparison of cycle 23 $R$-values (filled circles) against the mean sunspot number ($<R>$) for cycles of $ASC=3$ yr (thick line), 4 yr (thin line), and 5 yr (dashed line) relative to the elapsed time ($t$) in years from the epoch of sunspot minimum ($E(R_{min})$).
Figure 6. Comparison of cycle 23 $R$-values (filled circles) against the mean sunspot number ($\langle R \rangle$) for cycles of $PER=10$ yr (thick line), 11 yr (thin line), and 12 yr (dashed line) relative to the elapsed time ($t$) in years from the epoch of sunspot minimum ($E(R_{\text{min}})$).

Once it is clear that sunspot minimum has occurred, one can readily employ observed sunspot number values to predict $R_{\text{max}}$. Figure 7 displays scatterplots of $R_{\text{max}}$ versus $R_{\text{min}}$, left panel; $R_{\text{max}}$ versus $\Delta R_{\text{GPV}}$, center panel; and $R_{\text{max}}$ versus $R_{\text{max}}$, (y, x1, x2), right panel, where $R_{\text{max}}(y,x_{1,2})$ is a bivariate fit of $R_{\text{max}}$ against both $R_{\text{min}}$ (x1) and $\Delta R_{\text{GPV}}$ (x2). Plainly, $R_{\text{min}}$ provides a crude first-order prediction some 2–4 yr in advance for the later occurring $R_{\text{max}}$. A much better prediction can be made following the occurrence of $\Delta R_{\text{GPV}}$, which usually precedes $R_{\text{max}}$ occurrence by 1–2 yr (usually occurring in years 2 or 3 following $R_{\text{min}}$ occurrence). $\Delta R_{\text{GPV}}$ represents the inflection point during the rising portion of the ongoing sunspot cycle. The bivariate fit is found to further improve upon the prediction for $R_{\text{max}}$ of the growing sunspot cycle.24
Figure 7. Scatterplots of (a) $R_{\text{max}}$ versus $R_{\text{min}}$, (b) $R_{\text{max}}$ versus $\Delta R_{GPV}$, and (c) $R_{\text{max}}$ versus $R_{\text{max}}$ ($y_{X1X2}$).
Figure 8 depicts the scatterplot of $R_{max}$ versus $SLOPE_{ASC}$, where $SLOPE_{ASC}$ is the average rate of growth during the rising portion of the cycle. As noted before, it is computed as $(R_{max}-R_{min})/ASC$. Unfortunately, one cannot compute $SLOPE_{ASC}$ until $R_{max}$ has been observed. While strictly true, one can examine the evolving average rate of growth as the cycle progresses from $R_{min}$ occurrence to estimate the later occurring $R_{max}$.

![Figure 8. Scatterplot of $R_{max}$ versus $SLOPE_{ASC}$](image)

As an example, cycle 23 had—

- $R=8.6$ in year 0, 1996, the sunspot minimum year.
- $R=21.5$ in year 1, 1997.
- $R=64.2$ in year 2, 1998.
- $R=93.2$ in year 3, 1999.

Hence, for cycle 23 $SLOPE_{ASC}(1)=12.9$, $SLOPE_{ASC}(2)=27.8$, and $SLOPE_{ASC}(3)=28.2$. 

Figure 9 shows $R_{max}$ versus $SLOPE_{ASC}(1)$, left panel; $R_{max}$ versus $SLOPE_{ASC}(2)$, center panel; and $R_{max}$ versus $SLOPE_{ASC}(3)$, right panel, where

- $SLOPE_{ASC}(1)$ is the difference in $R$ between year 0 (sunspot minimum year) and year 1 (year after sunspot minimum year).
- $SLOPE_{ASC}(2)$ is the difference in $R$ between year 0 and year 2 divided by 2.
- $SLOPE_{ASC}(3)$ is the difference in $R$ between year 0 and year 3 divided by 3.
y = 53.682 + 2.208x, r = 0.931, r² = 0.866, se = 15.68, cl > 99.9%

y = 42.679 + 2.200x, r = 0.894, r² = 0.799, se = 18.24, cl > 99.9%

y = 76.101 + 3.558x, r = 0.861, r² = 0.742, se = 21.66, cl > 99.9%

Figure 9. Scatterplots of (a) Rmax versus SLOPE_asc (1), (b) Rmax versus SLOPE_asc (2), and (c) Rmax versus SLOPE_asc (3).

Plainly, beginning at one year past Rmin occurrence, one can estimate Rmax considerably better (standard error (se) of 21.7 units of sunspot number) than at Rmin (se = 36.3 units of sunspot number), and better yet at two years past Rmin occurrence (se = 15.7 units of sunspot number).

Another parameter of interest is ΔR_{GNV}, the inflection point during the cycle decline from Rmax occurrence of the ongoing cycle to the Rmin occurrence of the following cycle. ΔR_{GNV} usually precedes Rmin occurrence of the succeeding cycle by about three to four years, usually occurring in year seven following Rmin occurrence of the ongoing cycle. Figure 10 displays scatterplots of ΔR_{GNV} versus ΔR_{GPV} (left panel) and ΔR_{GNV} versus Rmax (right panel). Both the inflection amplitude during the rise and the actual maximum sunspot number amplitude provide a reliable prediction for the inflection amplitude during the fall of the ongoing sunspot cycle. A bivariate fit employing both ΔR_{GPV} and Rmax does not significantly improve the estimate for ΔR_{GNV}.

Figure 11 depicts scatterplots of Rmin for cycle n+1 versus Rmax for cycle n (left panel), and Rmin for cycle n+1 versus ΔR_{GNV} for cycle n. Of the two, only the first is marginally statistically significant. Because Rmax for cycle 23 (119.5 denoted by the small downward pointing arrow along the x-axis) was above the median for cycles 12–22 (thin vertical line), the indication is that Rmin for cycle 24 will lie above the median for Rmin (thin horizontal line) in the upper right quadrant. On the basis of the inferred regression, cycle 24 Rmin will probably measure about 7.6±3.4. Similarly, on the basis of cycle 23 ΔR_{GNV} (−40.5 denoted by the small downward pointing arrow along the x-axis), cycle 24 Rmin is expected to lie within the upper left quadrant, having a value of about 7.9±3.5. A bivariate fit employing both parameters does not significantly improve the estimate of Rmin for cycle n+1.
\[
\{ 
\begin{align*}
    y &= -13.312 - 0.477 x \\
    r &= -0.839, r^2 = 0.703 \\
    se &= 7.67, cl > 99.9%
\end{align*}
\]

\[
\{ 
\begin{align*}
    y &= -3.321 - 0.288 x \\
    r &= -0.883, r^2 = 0.779 \\
    se &= 6.74, cl > 99.9%
\end{align*}
\]

Figure 10. Scatterplots of (a) \(\Delta R_{GNV}\) versus \(\Delta R_{GPV}\) and (b) \(\Delta R_{GNV}\) versus \(R_{max}\).
\[ y = 1.422 + 0.051x \]
\[ r = 0.563, r^2 = 0.317 \]
\[ se = 3.43, cl > 90\% \]

Figure 11. Scatterplots of (a) \( R_{\text{min}}(n+1) \) versus \( R_{\text{max}}(n) \) and (b) \( R_{\text{min}}(n+1) \) versus \( \Delta R_{\text{GNV}}(n) \).

Figure 12 shows scatterplots of \( SLOPE_{\text{DES}} \) versus \( SLOPE_{\text{ASC}} \) (left panel) and \( SLOPE_{\text{DES}} \) versus \( R_{\text{max}} \) (right panel). Both plots reveal strong linear negative correlation between the parameters. \( SLOPE_{\text{DES}} \) provides a simple way to estimate the \( R_{\text{min}} \) year of occurrence for the following cycle. For example, cycle 23 had \( SLOPE_{\text{ASC}} = (119.5 – 8.6)/4 = 27.73 \), as denoted by the small downward pointing arrow along the x-axis. Using this value, one estimates cycle 23 \( SLOPE_{\text{DES}} \) to be about \(-14.67 \pm 1.97\). Also, using cycle 23 \( R_{\text{max}} \), 119.5 (denoted by the small downward pointing arrow along the x-axis), one estimates \( SLOPE_{\text{DES}} \) to be about \(-16.27 \pm 1.92\). Presuming cycle 24 \( R_{\text{min}} \) will measure about 9.8\( \pm \)3.2, the average for cycles 18–23, one finds that cycle 24 \( R_{\text{min}} \) should follow cycle 23 \( R_{\text{max}} \) occurrence by about 7 yr, indicating cycle minimum in the year 2007. For cycle 24 minimum to occur in 2006, cycle 23 \( SLOPE_{\text{DES}} \) must measure at least \(-17 \) (or more negative) in value.

Strictly speaking, one cannot measure \( SLOPE_{\text{DES}} \) until after the minimum for the following cycle has occurred. However, in addition to using \( SLOPE_{\text{ASC}} \) and \( R_{\text{max}} \) to estimate the value of \( SLOPE_{\text{DES}} \), another simple way for estimating \( SLOPE_{\text{DES}} \) is based on the evolving values during the decline of the cycle.
Figure 12. Scatterplots of (a) $SLOPE_{DES}$ versus $SLOPE_{ASC}$ and (b) $SLOPE_{DES}$ versus $R_{max}$.

Figure 13 displays the scatterplot of $SLOPE_{DES}$ versus $SLOPE_{DES}(GNV)$, where $SLOPE_{DES}(GNV)$ is the greatest negative value of the evolving slope during the sunspot cycle decline. As an example, cycle 23 $R_{max}$ measured 119.5 in the year 2000. For 2001–2005, $R$ measured 110.9, 104.1, 63.6, 40.4, and 29.9, respectively. The evolving $SLOPE_{DES}$ has values of $-8.60$ (the difference of 119.5–110.9), $-7.70$ (the difference of (119.5–104.1)/2), $-18.63$ (the difference of (119.5–63.6)/3), $-19.78$ (the difference of (119.5–40.4)/4), and $-17.92$ (the difference of (119.5–29.9)/5. The greatest negative value of the evolving $SLOPE_{DES}$ is $-19.78$, shown in the plot as the small downward pointing arrow along the x-axis.

While for the general scatterplot, one infers a strong linear positive correlation between the parameters at <0.1-percent level of significance, having the form $y=-0.393+0.773x$, a correlation coefficient of $r=0.959$ and an se of 1.76, a more interesting result is that the cycles appear to be distributed along two different regression lines—cycles 12–16 along $y_U$ and cycles 17–22 along $y_L$. As stated earlier, cycle 23 $SLOPE_{DES}(GNV)$ equals $-19.78$, hence, cycle 23 $SLOPE_{DES}$ will either be equal to $-13.87\pm0.4$, based on the $y_U$ fit, or $-17.36\pm1.03$, based on the $y_L$ fit. Ignoring the cyclic split and using the general regression, cycle 23 $SLOPE_{DES}$ equals $-15.68\pm1.76$. If cycle 23 continues the trend characterized by $y_L$ for cycles 17–22, then cycle 24 $R_{min}$ occurrence will be in 2006; however, if cycle 23 reverts to the cycle 12–16 trend, then cycle 24 $R_{min}$ occurrence will be delayed until 2007.

It should be noted that the sunspot minimum year is closely related to the peak in the number of reported spotless days during that year. Figure 14 shows the envelope (lines 1 and 4) and means of cycles 12–16 (line 2) and 17–23 (line 3) of the number of spotless days (top panel) and sunspot number (bottom panel) relative to $R_{min}$ occurrence. Plainly, as one approaches sunspot minimum, the sunspot number decreases and the number of spotless days (NSD) increase. Table 1 gives the NSD and $R$ relative to $E(R_{min})$ for the elapsed time of 3 yr before cycle minimum to 2 yr after sunspot minimum.
Cycle 23 experienced its first spotless days during its decline in the year 2004. The total number of spotless days in 2004 numbered three and $R$ measured 40.4. For 2005, the number of spotless days numbered 13 and $R$ measured 29.9. Now, in 2006 (through February) there have been 17 spotless days and $R$ has averaged only 10.5. Such values are suggestive that, for cycle 24, the sunspot minimum year will be either 2006, especially if cycle 24 has an unusually high $R_{min}$ value and is a robust cycle, or 2007.

Figure 15 displays the cyclic variation of the number of spotless days during the sunspot minimum year for cycles 12–23. A strong downward decrease is noticeable in the number of spotless days, which is statistically significant at the 0.5-percent level of significance. Presuming the validity of the inferred regression and extrapolating it to cycle 24 suggests that cycle 24 will have $107\pm48$ spotless days in the sunspot minimum year. Cycles 18–23 have averaged $152\pm50$ spotless days, significantly less than the $255\pm44$ average of cycles 12–17.
Figure 14. Scatterplots of (a) \( NSD \) versus \( t \) and (b) \( R \) versus \( t \).
Table 1. Comparison of $R$ and $NSD$ values relative to $E(R_{min})$.

<table>
<thead>
<tr>
<th>Cycle</th>
<th>$R_{-3}$</th>
<th>$NSD_{-3}$</th>
<th>$R_{-2}$</th>
<th>$NSD_{-2}$</th>
<th>$R_{-1}$</th>
<th>$NSD_{-1}$</th>
<th>$R_0$</th>
<th>$NSD_0$</th>
<th>$R_{+1}$</th>
<th>$NSD_{+1}$</th>
<th>$R_{+2}$</th>
<th>$NSD_{+2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>17.0</td>
<td>130</td>
<td>11.3</td>
<td>190</td>
<td>12.4</td>
<td>139</td>
<td>3.4</td>
<td>280</td>
<td>6.0</td>
<td>217</td>
<td>32.2</td>
<td>32</td>
</tr>
<tr>
<td>13</td>
<td>25.4</td>
<td>62</td>
<td>13.1</td>
<td>104</td>
<td>6.8</td>
<td>150</td>
<td>6.3</td>
<td>212</td>
<td>7.1</td>
<td>171</td>
<td>35.6</td>
<td>24</td>
</tr>
<tr>
<td>14</td>
<td>26.7</td>
<td>39</td>
<td>12.1</td>
<td>104</td>
<td>9.5</td>
<td>158</td>
<td>2.7</td>
<td>287</td>
<td>5.1</td>
<td>257</td>
<td>24.4</td>
<td>45</td>
</tr>
<tr>
<td>15</td>
<td>18.6</td>
<td>75</td>
<td>5.7</td>
<td>200</td>
<td>3.6</td>
<td>254</td>
<td>1.4</td>
<td>311</td>
<td>9.6</td>
<td>153</td>
<td>47.4</td>
<td>12</td>
</tr>
<tr>
<td>16</td>
<td>37.6</td>
<td>7</td>
<td>26.1</td>
<td>46</td>
<td>14.2</td>
<td>134</td>
<td>5.8</td>
<td>200</td>
<td>16.7</td>
<td>116</td>
<td>44.3</td>
<td>27</td>
</tr>
<tr>
<td>17</td>
<td>35.7</td>
<td>3</td>
<td>21.2</td>
<td>42</td>
<td>11.1</td>
<td>108</td>
<td>5.7</td>
<td>240</td>
<td>8.7</td>
<td>154</td>
<td>36.0</td>
<td>19</td>
</tr>
<tr>
<td>18</td>
<td>47.5</td>
<td>5</td>
<td>30.6</td>
<td>24</td>
<td>16.3</td>
<td>64</td>
<td>9.6</td>
<td>159</td>
<td>33.1</td>
<td>16</td>
<td>92.5</td>
<td>0</td>
</tr>
<tr>
<td>19</td>
<td>69.4</td>
<td>0</td>
<td>31.4</td>
<td>23</td>
<td>13.9</td>
<td>131</td>
<td>4.4</td>
<td>241</td>
<td>38.0</td>
<td>48</td>
<td>141.7</td>
<td>0</td>
</tr>
<tr>
<td>20</td>
<td>53.9</td>
<td>6</td>
<td>37.6</td>
<td>9</td>
<td>27.9</td>
<td>21</td>
<td>10.2</td>
<td>111</td>
<td>15.1</td>
<td>67</td>
<td>46.9</td>
<td>8</td>
</tr>
<tr>
<td>21</td>
<td>38.2</td>
<td>27</td>
<td>34.4</td>
<td>20</td>
<td>15.5</td>
<td>95</td>
<td>12.6</td>
<td>105</td>
<td>27.5</td>
<td>25</td>
<td>92.7</td>
<td>0</td>
</tr>
<tr>
<td>22</td>
<td>66.6</td>
<td>4</td>
<td>45.9</td>
<td>13</td>
<td>17.9</td>
<td>82</td>
<td>13.4</td>
<td>129</td>
<td>29.2</td>
<td>44</td>
<td>100.0</td>
<td>0</td>
</tr>
<tr>
<td>23</td>
<td>54.7</td>
<td>0</td>
<td>29.4</td>
<td>19</td>
<td>17.5</td>
<td>59</td>
<td>8.6</td>
<td>165</td>
<td>21.5</td>
<td>60</td>
<td>64.2</td>
<td>3</td>
</tr>
</tbody>
</table>

Figure 15. Cyclic variation of the number of spotless days ($NSD$) during the sunspot minimum year ($E(R_{min})$) for cycles 12–23.

\[ y = 463.019 - 14.839x \]
\[ r = -0.76, r^2 = 0.578 \]
\[ se = 47.94, cl >99.5\% \]

\[ \Rightarrow NSD \text{ Cycle 24} = 107 \pm 48 \]
Figure 16 depicts the scatterplot of $R_{\text{min}}$ versus $\text{NSD}(E(R_{\text{min}}))$, the latter term meaning the number of spotless days during the sunspot minimum year. The inferred regression is statistically significant at the 0.1-percent level of significance. If cycle 24 has $\text{NSD}((E(R_{\text{min}}))=107\pm48$, then cycle 24 $R_{\text{min}}$ would be expected to be about $12.1\pm2.5$. Such a value, when applied using the $y_L$ regression (fig.13) suggests an expected $\text{SLOPE}_{DES}$ for cycle 23 that implies cycle 24 sunspot minimum year to be 2006.

![Figure 16. Scatterplot of $R_{\text{min}}$ versus $\text{NSD}(E(R_{\text{min}}))$.](image)

Table 2 provides a summary of the values and times of occurrences for the various parameters discussed in this section. Temporal parameters ($ASC$ and $PER$) are expressed in years, and $t$ and $T$ refer, respectively, to the elapsed time in years from the epochs of sunspot minimum ($E(R_{\text{min}})$) and sunspot maximum ($E(R_{\text{max}})$).
Table 2. Selected solar cycle parametric values and times of occurrence based on annual averages of sunspot number.

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Rmin</th>
<th>E(Rmin)</th>
<th>Rmax</th>
<th>ASC</th>
<th>PER</th>
<th>$\Delta R_{GPV}$</th>
<th>$t/E(\Delta R_{GPV})$</th>
<th>$\Delta R_{GNV}$</th>
<th>$t/E(\Delta R_{GNV})$</th>
<th>SLOPE ASC</th>
<th>SLOPE DES</th>
<th>T</th>
<th>NSD (E(Rmin))</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>3.4</td>
<td>1578</td>
<td>63.6</td>
<td>5</td>
<td>11</td>
<td>22.1</td>
<td>3</td>
<td>-26.6</td>
<td>8</td>
<td>12.04</td>
<td>-9.55</td>
<td>-12.73</td>
<td>3</td>
</tr>
<tr>
<td>13</td>
<td>6.3</td>
<td>1889</td>
<td>85.1</td>
<td>4</td>
<td>12</td>
<td>37.3</td>
<td>3</td>
<td>-22.2</td>
<td>7</td>
<td>19.70</td>
<td>-10.30</td>
<td>-14.73</td>
<td>4</td>
</tr>
<tr>
<td>14</td>
<td>2.7</td>
<td>1901</td>
<td>63.5</td>
<td>4</td>
<td>11</td>
<td>21.5</td>
<td>4</td>
<td>-25.3</td>
<td>9</td>
<td>15.20</td>
<td>-7.76</td>
<td>-9.63</td>
<td>6</td>
</tr>
<tr>
<td>15</td>
<td>1.4</td>
<td>1913</td>
<td>103.9</td>
<td>4</td>
<td>10</td>
<td>46.8</td>
<td>4</td>
<td>-26.0</td>
<td>7</td>
<td>25.63</td>
<td>-16.35</td>
<td>-23.30</td>
<td>1</td>
</tr>
<tr>
<td>16</td>
<td>5.8</td>
<td>1923</td>
<td>77.8</td>
<td>5</td>
<td>10</td>
<td>27.6</td>
<td>2</td>
<td>-29.2</td>
<td>7</td>
<td>14.40</td>
<td>-14.42</td>
<td>-21.05</td>
<td>2</td>
</tr>
<tr>
<td>17</td>
<td>5.7</td>
<td>1933</td>
<td>114.4</td>
<td>4</td>
<td>11</td>
<td>43.7</td>
<td>3</td>
<td>-21.0</td>
<td>7</td>
<td>27.18</td>
<td>-14.97</td>
<td>-16.76</td>
<td>5</td>
</tr>
<tr>
<td>18</td>
<td>9.6</td>
<td>1944</td>
<td>151.5</td>
<td>3</td>
<td>10</td>
<td>59.4</td>
<td>2</td>
<td>-51.2</td>
<td>6</td>
<td>47.30</td>
<td>-21.01</td>
<td>-24.02</td>
<td>5</td>
</tr>
<tr>
<td>19</td>
<td>4.4</td>
<td>1954</td>
<td>189.9</td>
<td>3</td>
<td>10</td>
<td>103.7</td>
<td>2</td>
<td>-58.4</td>
<td>7</td>
<td>61.83</td>
<td>-25.67</td>
<td>-34.00</td>
<td>4</td>
</tr>
<tr>
<td>20</td>
<td>10.2</td>
<td>1964</td>
<td>105.9</td>
<td>4</td>
<td>12</td>
<td>46.8</td>
<td>3</td>
<td>-38.9</td>
<td>7</td>
<td>23.93</td>
<td>-11.66</td>
<td>-13.54</td>
<td>5</td>
</tr>
<tr>
<td>21</td>
<td>12.6</td>
<td>1976</td>
<td>155.3</td>
<td>3</td>
<td>10</td>
<td>65.2</td>
<td>2</td>
<td>-49.7</td>
<td>7</td>
<td>47.57</td>
<td>-20.27</td>
<td>-22.90</td>
<td>6</td>
</tr>
<tr>
<td>22</td>
<td>13.4</td>
<td>1986</td>
<td>157.8</td>
<td>3</td>
<td>10</td>
<td>70.8</td>
<td>2</td>
<td>-51.3</td>
<td>6</td>
<td>48.13</td>
<td>-21.31</td>
<td>-25.78</td>
<td>4</td>
</tr>
<tr>
<td>23</td>
<td>8.6</td>
<td>1996</td>
<td>119.5</td>
<td>4</td>
<td>-</td>
<td>42.7</td>
<td>2</td>
<td>-40.5</td>
<td>7</td>
<td>27.73</td>
<td>-19.78</td>
<td>-165</td>
<td>4</td>
</tr>
</tbody>
</table>
3. CONCLUSION

The preceding sections have shown that cycles of late have been rather robust in comparison to earlier cycles in the span of cycles 12 through present, the most reliably known sunspot cycles (corresponding to the interval 1878 to present). In particular, five of the past six cycles have had minimum ($R_{min}$) and maximum ($R_{max}$) amplitudes that are above both the yearly median (6.1 and 110.2, respectively) and mean (7.0 and 115.7) values. Cycle 23, the current ongoing sunspot cycle, ranks fifth in size in terms of its observed $R_{min}$ and $R_{max}$. Comparison of its yearly sunspot number averages against the mean of cycles 12–22 strongly suggests that onset for cycle 24 will likely occur in year 10 of the sunspot cycle from sunspot minimum occurrence, corresponding to the year 2006. However, using $R_{max}$ occurrence as the epoch of comparison, it is difficult to strictly determine the onset year for cycle 24, being either year six (2006) or year seven (2007), following sunspot maximum amplitude. For nearly its entire life, cycle 23 behavior, in terms of yearly averages of sunspot number, seems to be more like the mean of 10-yr length sunspot cycles, which, if true, indicates that onset for cycle 24 will be 2006.

Various techniques were examined to determine the predictive capabilities regarding $R_{max}$, $\Delta R_{GNV}$, SLOPE$_{DES}$, $R_{min}$, and NSD. Very strong positive correlations are found to exist between $R_{max}$ and $\Delta R_{GPV}$ and $R_{max}$ and both $\Delta R_{GPV}$ and $R_{min}$ (a bivariate fit). Likewise, very strong positive correlations are found between $R_{max}$ and SLOPE$_{ASC}$ and inferred growth rates after one, two, and three years. $\Delta R_{GNV}$ is found to strongly and negatively correlate against $\Delta R_{GPV}$ and against $R_{max}$. Also, SLOPE$_{DES}$ is found to strongly and negatively correlate against SLOPE$_{ASC}$ and $R_{max}$. A rather interesting finding seems to exist for SLOPE$_{DES}$ when compared against SLOPE$_{DES}(GNV)$, which is the greatest negative value of the evolving slope during the declining phase of the sunspot cycle. Namely, cycles 12–16 appear to prefer a regression line that differs from the preferred regression line for cycles 17–22. If cycle 23 SLOPE$_{DES}$ is similar to those of recent cycles 17–22, then onset for cycle 24 will occur in 2006; on the other hand, if cycle 23 SLOPE$_{DES}$ is similar to those of earlier cycles 12–16, then onset for cycle 24 will be delayed until 2007. It should be noted that the general distribution of SLOPE$_{DES}$ versus SLOPE$_{DES}(GNV)$, ignoring the apparent division of cycles into two distinct groupings, has a strong positive correlation at the 0.1-percent level of significance. Finally, the number of spotless days has been increasing since 2004, this being a sign of the approach of onset for cycle 24. The number of spotless days is at maximum during the sunspot minimum year. Because five of the past six cycles have had NSD <206 days (the median) and because there appears to exist a strong negative correlation (at the 0.5-percent level of significance) between NSD at $E(R_{min})$ against sunspot cycle number, one predicts cycle 24 to have 107±48 days (the mean and standard deviation of NSD for cycles 18–22 is 152±50). This suggests that NSD at $E(R_{min})$ for cycle 24 will be <206 days and that $R_{min}$ will be >6.1, indicating further that cycle 24 should be expected to be another robust cycle, probably of larger than average maximum amplitude ($R_{max}$), shorter than average ascent duration (ASC) and shorter than average length (PER)$^{25–27}$. 


An Examination of Sunspot Number Rates of Growth and Decay in Relation to the Sunspot Cycle

Robert M. Wilson and David H. Hathaway

George C. Marshall Space Flight Center
Marshall Space Flight Center, AL 35812

National Aeronautics and Space Administration
Washington, DC 20546–0001

Prepared by the Science and Exploration Research Office, Science and Mission Systems Office

On the basis of annual sunspot number averages, sunspot number rates of growth and decay are examined relative to both minimum and maximum amplitudes and the time of their occurrences using cycles 12 through present, the most reliably determined sunspot cycles. Indeed, strong correlations are found for predicting the minimum and maximum amplitudes and the time of their occurrences years in advance. As applied to predicting sunspot minimum for cycle 24, the next cycle, its minimum appears likely to occur in 2006, especially if it is a robust cycle similar in nature to cycles 17–23.