ESTIMATE OF SOLAR MAXIMUM USING THE 1–8 Å GEOSTATIONARY OPERATIONAL ENVIRONMENTAL SATELLITES X-RAY MEASUREMENTS

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ABSTRACT

We present an alternate method of determining the progression of the solar cycle through an analysis of the solar X-ray background. Our results are based on the NOAA Geostationary Operational Environmental Satellites (GOES) X-ray data in the 1–8 Å band from 1986 to the present, covering solar cycles 22, 23, and 24. The X-ray background level tracks the progression of the solar cycle through its maximum and minimum. Using the X-ray data, we can therefore make estimates of the solar cycle progression and the date of solar maximum. Based upon our analysis, we conclude that the Sun reached its hemisphere-averaged maximum in solar cycle 24 in late 2013. This is within six months of the NOAA prediction of a maximum in spring 2013.

Key words: Sun: activity – Sun: X-rays, gamma rays

Online-only material: color figures

1. INTRODUCTION

Predictions of the length of the solar cycle and the date of solar maximum are important for planning space missions and satellite orbits. Besides direct electromagnetic, particle, and mass effects, the Sun cyclically influences the terrestrial ionospheric structure and interplanetary structure. A number of empirical or semi-empirical methods for estimating solar cycle progression exist. The earliest method used relies upon the sunspot number, following the discovery by Wolf (1852) of the 11 yr periodicity in sunspot activity. The “geomagnetic precursor” methods, relying upon measurements of changes in the Earth’s magnetic field, determine correlations between sunspot number at solar maximum and the geomagnetic \(aa\) index at the preceding minimum (e.g., Ohl & Ohl 1979; Feynman 1982; Thompson 1993). Additionally, the solar radio emission at 10.7 cm (F10.7) is a consistent measurement that has been recorded daily since 1947 and is also found to follow the solar activity cycle (Feynman 1982).

Combinations of these techniques have been used to predict the intensity and date of the solar maximum of the current solar cycle. The solar cycle 24 prediction panel\(^3\) (Biesecker & Prediction Panel 2007), led by NOAA, examined several techniques and predicted a maximum in 2013 May that would be weak compared to recent solar cycles. Similarly, recent work presented in Pesnell (2014) predicts a solar cycle 24 maximum F10.7 of no stronger than average and likely weaker than recent solar cycles.

In this Letter, we present a novel approach for determining the solar cycle peak and duration. The solar X-ray background, like other tracers such as the sunspot number and solar radio emission, rises during active times and declines in quiet times. Through an analysis of the X-ray data from the past few solar cycles, we predict the maximum X-ray background level, date of solar maximum, and length of solar cycle 24. In Section 2, we describe our analysis. In Section 3, we compare the X-ray background results to the monthly sunspot number. Section 4 includes discussion of our results.

2. DETERMINATION OF THE SOLAR CYCLE MAXIMUM THROUGH THE X-RAY BACKGROUND

To make our solar cycle predictions, we analyzed Geostationary Operational Environmental Satellites (GOES) X-ray observations obtained from NOAA’s NGDC.\(^4\) We determined the 1–8 Å (corresponding to \(\sim 1.5–12.4\) keV) background levels using 1 minute data from 1986 through 2014 May 15. The data were obtained from GOES-6, -7, and -8 (solar cycle 22), GOES-8 and -10 (solar cycle 23), and GOES-14 and -15 (2009–present).

The X-ray background was computed as the smoothed minimum flux in a 24 hr time period preceding each 1 minute GOES observation. In detail, we use the technique of Hock et al. (2013), which includes the following steps: (1) compute the hourly median with a sliding 1 hr window, (2) determine the instantaneous background as the minimum of these hour medians in the previous 24 hr, and (3) smooth the instantaneous background by the previous 2 hr. The background was computed for both the 1–4 Å and 1–8 Å GOES observations. The harder X-ray emission shows no discernible solar cycle trends when compared with the soft X-ray emission, which is the focus of this Letter.

In order to determine the solar maximum and the length of the solar cycle for cycles 22–24, we fit a simple Gaussian to the X-ray background of each solar cycle. We chose a Gaussian for its simplicity in requiring only three free parameters and for its ability to reproduce the shape of the data over a solar cycle. To fit the data, we converted the date and time of the observation into decimal years from the start of the solar cycle (SCY). We identified solar cycle 22 as beginning in 1986 August and ending by 1996 May; solar cycle 23 as beginning in 1996 May and ending by 2008 December; and solar cycle 24 as beginning in 2008 December. We then fit a Gaussian of the form:

\[
F(\text{SCY}) = F_0 \exp((\text{SCY} - \text{Solar Max})^2/(2\sigma^2)),
\]

(1) to the X-ray background. In the equation, \(F\) is the logarithm of the X-ray background flux in \(\text{W m}^{-2}\), \(F_0\) is the logarithm of

\(^3\) The consensus statement of the solar cycle 24 prediction panel is available at http://www.swpc.noaa.gov/SolarCycle/SC24/.

\(^4\) The GOES Space Environment Monitor data are available at http://www.ngdc.noaa.gov/stp/satellite/goes/dataaccess.html.
the X-ray background flux at solar maximum in \( W \text{ m}^{-2} \), \( SCY \) is the solar cycle year in years, \( Solar \ Max \) is the fitted solar maximum value in years from the start of the solar cycle, and \( \sigma \) is the half-width of the solar cycle. In the fitting process, we filtered out any data points with background levels below \( 10^{-9} \text{ W m}^{-2} \). Such measurements are below the \( GOES \) 1–8 Å threshold of \( 3.7 \times 10^{-9} \text{ W m}^{-2} \). The Levenberg–Marquardt algorithm (Levenberg 1944; Marquardt 1963) was used to find the best-fit parameters \( F_0 \), \( Solar \ Max \), and \( \sigma \) with the SciPy optimization library in Python.

We determined the effect of the choice of bin size on the solar cycle parameters by computing best-fit values and \( \chi^2 \) statistics for bin sizes of one month, two weeks, one week, 0.5 weeks, and one day. The best-fit parameters for each solar cycle examined and for each binning level are listed in Table 1. We find that the peak background flux is the most stable parameter, with very little variation in this parameter regardless of bin size. For solar cycles 22 and 23, the solar maximum calculation is also stable, but the duration of the cycle varies by two months for cycle 22 and six months for cycle 23. We tested goodness of fit with the \( \chi^2 \) statistic, defined as \( \chi^2 = \Sigma(\text{observed} - \text{model})^2/\text{std}^2 \), where std is the standard deviation of the measurements. The ideal case is where the reduced \( \chi^2 \) statistic, \( \chi^2_\text{red} \) divided by the degrees of freedom (the number of data points fitted minus the number of free parameters fit by the model), is closest to one. For the smaller bin sizes, cases where the reduced \( \chi^2 \) value is much greater than one are labeled as oversampled. For the largest bin sizes, the standard deviation is large, causing reduced \( \chi^2 \ll 1 \). The optimized reduced \( \chi^2 \) values in Table 1 correspond to the one-week binning. The best-fit parameters from the one-week bin size are shown in Table 2. The median one-week background and best-fit Gaussians are shown for solar cycles 22–24 in Figure 1.

Traditional measures of the solar cycle such as sunspot numbers show a double peak due to the solar activity in the northern and southern hemispheres (e.g., Roy 1977). Similarly, the X-ray observations also show the double-peak profile. However, our choice of binning size affects whether the double-peak structure is blurred or distinct. For this reason, we chose to fit only a single Gaussian to derive the solar maximum and duration, but determined the peaks from examination of the one-week binned data. In Table 2, peak 1 corresponds to the peak in the X-ray background occurring before the fitted solar maximum and peak 2 is the peak following the solar maximum.

Since the current solar cycle 24 is incomplete, the resulting fewer measurements lead to more variability in the fitted solar maximum and duration parameters depending on the chosen bin size. In all cases (Table 2), however, we find that we have reached or passed the solar maximum. Solar cycle 24 is likely to end around 2020, with a maximum uncertainty of 2 yr.

### Table 1

| Solar Cycle | \( F_0 \) (log W m\(^{-2}\)) | Solar Max (SCY) | \( \sigma \) (yr) | End Cycle | \( \chi^2 \) |
|-------------|-------------------------------|-----------------|-----------------|------------|-------------|
| One month   |                               |                 |                 |            |             |
| 22          | −5.95                         | 1990 Dec (4.27) | 6.35            | 1997 Apr   | 22.2/94    |
| 23          | −6.16                         | 2001 Sep (5.38) | 7.69            | 2009 Jun   | 24.4/118   |
| 24          | −6.28                         | 2014 Jun (5.53) | 7.75            | 2022 Mar   | 7.4/35     |
| Two weeks   |                               |                 |                 |            |             |
| 22          | −5.96                         | 1990 Dec (4.27) | 6.39            | 1997 Apr   | 82.7/189   |
| 23          | −6.19                         | 2001 Sep (5.36) | 8.05            | 2009 Oct   | 99.2/239   |
| 24          | −6.29                         | 2014 Jan (5.11) | 6.94            | 2020 Dec   | 24.0/72    |
| One week    |                               |                 |                 |            |             |
| 22          | −5.97                         | 1990 Dec 12 (4.28) | 6.40         | 1997 May   | 326.5/387  |
| 23          | −6.21                         | 2001 Sep 16 (5.38) | 8.18         | 2009 Nov   | 386/478    |
| 24          | −6.31                         | 2013 Nov (5.00) | 6.76            | 2020 Sep   | 107/0/153  |
| 0.5 weeks   |                               |                 |                 |            |             |
| 22          | −5.98                         | 1990 Dec 17 (4.29) | 6.46         | 1997 Jun   | 1251.2/774 |
| 23          | −6.21                         | 2001 Sep 13 (5.37) | 8.24         | 2009 Dec   | 1499.3/956 |
| 24          | −6.32                         | 2013 Oct (4.82) | 6.25            | 2020 Jan   | Oversampled |
| One day     |                               |                 |                 |            |             |
| 22          | −5.97                         | 1990 Dec 17 (4.29) | 6.46         | 1997 Jul   | Oversampled |
| 23          | −6.21                         | 2001 Sep 2 (5.34) | 8.29         | 2009 Dec   | Oversampled |
| 24          | −6.30                         | 2013 Jun (4.51) | 5.17            | 2018 Aug   | Oversampled |

**Notes.** The solar cycle, peak flux, solar maximum date, and the corresponding decimal years since the beginning of the solar cycle (SCY), half-width (\( \sigma \)) of the solar cycle, date of the end of the cycle, and \( \chi^2 \) from the model fit are given. Cases where reduced \( \chi^2 \gg 1 \) are indicated as “oversampled.”

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5 The monthly sunspot number was obtained from NASA Marshall Space Flight Center’s compilation available here: http://solarscience.msfc.nasa.gov/greenwch/spot_num.txt.
Figure 1. Results of a Gaussian fit (lines) to the one-week averaged 1–8 Å X-ray background (points; in units of log of W m$^{-2}$) for solar cycles 22–24. The X-ray background flux varies within the solar cycle, with higher values by a factor of 100 from solar minimum to solar maximum. (A color version of this figure is available in the online journal.)

Table 2

| Solar Cycle | $F_0$ (log W m$^{-2}$) | Solar Max (SCY) | Peak 1 (log W m$^{-2}$) | Peak 1 Date | Peak 2 (log W m$^{-2}$) | Peak 2 Date |
|-------------|------------------------|----------------|------------------------|-------------|------------------------|-------------|
| 22          | $-5.97$                | 1990 Dec (4.28) | $-5.59$                | 1989 Jun    | $-5.70$                | 1991 Apr    |
| 23          | $-6.21$                | 2001 Sep (5.38) | $-5.72$                | 2000 Jul    | $-5.87$                | 2002 Jan    |
| 24          | $-6.31$                | 2013 Nov (5.00) | $-5.82$                | 2012 Jul    | $-5.92$                | 2014 Feb    |

Note. The solar cycle, hemisphere-averaged solar maximum flux, hemisphere-averaged solar maximum date, and corresponding value in solar cycle years (SCY) or decimal years since the beginning of the solar cycle, and the flux and date of each of the two peaks in each cycle are given.

Table 3

| Solar Cycle | SS Max No. | SS Max Date | Peak 1 No. | Peak 1 Date | Peak 2 No. | Peak 2 Date |
|-------------|------------|-------------|------------|-------------|------------|-------------|
| 22          | 162        | 1990 Jul    | 196        | 1989 Jun    | 173        | 1991 Jul    |
| 23          | 120        | 2001 Mar    | 170        | 2000 Jul    | 150        | 2001 Sep    |
| 24          | 75         | 2013 Nov    | 96         | 2011 Nov    | 102        | 2014 Feb    |

Notes. The hemisphere-averaged sunspot (SS) Max values correspond to best-fit median date from a Gaussian fit and the sunspot number at that date. Peak 1 corresponds to the peak occurring before the fitted median and Peak 2 corresponds to the peak level after the fitted median (SS Max).

4. DISCUSSION

The solar soft X-ray emission is an important indicator of the state of the corona. While the mechanisms of coronal heating are poorly understood, the process is connected with solar magnetic activity (e.g., Vaiana & Rosner 1978). Previous soft X-ray studies have shown that variations exist in the derived luminosity from minimum to maximum, by a ratio of five to six times (Judge et al. 2003). With uniform observations over the past nearly three solar cycles, the GOES soft X-ray measurements provide a powerful database for characterizing the coronal variability and a tool for not only monitoring of flare activity but also for space weather forecasting.

Based on our analysis of the GOES 1–8 Å ($\sim$1.5–12 keV) observations from 1986 to the present, we have confirmed that the X-ray emission varies with solar cycle. We determined a soft X-ray background as the minimum flux in a 24 hr time analysis), which was the maximum in sunspot number to date, although there is a large difference in the peak 1 dates of eight months.

The peaks in the sunspot number and X-ray background are both higher preceding the solar max for cycles 22 and 23. The sunspot peak numbers in cycle 22, 192 for peak 1, and 173 for peak 2, were higher than in subsequent cycles. The overall highest peaks in sunspot number from cycles 23 and 24 are 13% and 48% lower than the peak in cycle 22, respectively.
Figure 2. Comparison of the one-month averaged 1–8 Å X-ray background (colored lines; in units of log of W m$^{-2}$) to the monthly sunspot number (gray line) for solar cycles 22–23. The dashed lines show the Gaussian fit to the sunspot number. Note that color notations are the same as in Figure 1.

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