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White light corona during total solar eclipse on March 9, 2016

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Abstract. We observed the white-light corona during the total solar eclipse of 2016 March 9 from *Corong Beach*, East Borneo. The solar corona is nearly circular with exception on the southern part of the Sun. Coronal structures are clearly seen. Based on the data, we obtained the Ludendorff flattening index, Nikolsky geometric flattening index, and phases of solar activity (Φ and P) are 0.129, 1.32, -0.716, and 0.573 respectively. Relation between Ludendorff and Nikolsky index, sunspot number, and phases of solar activity were discussed. We also predicted the amplitude of solar cycle 25 to be 196 ± 52 (based on 13-month smoothed monthly data) and 130 ± 42 (based on monthly sunspot number data).

1. Introduction

The solar corona is the outermost layer of the Sun's atmosphere. The bright white corona is visible due to the scattered light of the photosphere by free electrons in the solar corona. Since the brightness is only one-millionth of the photosphere, white light corona (particularly the innermost part, up to about 1.5 solar radii) can only be observed during total solar eclipse or using K-coronagraph. Thus, the TSE has given an opportunity to investigate the corona.

It is widely accepted that the shape and structure of solar corona is changing by time, depends on solar activity or magnetic field variability. On the global scale, magnetic fields are shaping the corona to become asymmetric during minimum solar activity and nearly circular during maximum [1], while on the small scale they are generating basic structures (streamers, helmet streamers, plumes, etc.) and fine structures (voids, loops, radial threads, etc.) of the corona [2].

There is also a relation between shape and brightness of corona and sunspot number. The corona is bright and uniform when the sunspot number is maximum. It is getting dimmer and more elongated towards equator when the sunspot number is minimum [3].

One of the quantitative analyses of coronal shape and structure is proposed by Ludendorff. He was measuring ratio of isophotes diameter on equatorial and polar directions [4]. Another one is proposed by Nikolsky in 1956, he was measuring geometrical characteristics of polar rays and streamers [5].

In this paper we will discuss the structures of white light corona during total solar eclipse on the March 9, 2016 and show the measurement results of the Ludendorff and Nikolsky flattening indexes. We will also study the correlation between Ludendorff flattening index, Nikolsky geometric flattening index, sunspot number and phases of solar activity using the past 60 total solar eclipses in 1851-2010 from data compilation by Pishkalo [6, 7] and monthly sunspot number from World Data Center-SILSO (<http://www.sidc.be/SILSO/>) [8]. Lastly, we will predict the amplitude of solar cycle 25.

2. Observation and data reduction



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The observation of total solar eclipse was carried out on March 9, 2016 at *Corong Beach*, Penajam Paser Utara, East Borneo, Indonesia ($1^{\circ}24'12.4''$ S, $116^{\circ}39'14''$ E), 1.5 m above sea level. The totality was last for 1 minutes 51 seconds. The altitude of the Sun was 32.7° in the East. Nineteen images of white light corona were obtained using William Optic Zenithstar 66SD (66 mm, f/5.9) and Nikon D5100. Six best frames were chosen, combined, and processed using Adobe Photoshop CC 2015 and Adobe Lighthouse to bring out the details of coronal structures.

3. Results and discussions

3.1. Coronal structure

The composite image of white light corona shows an almost circular corona with an exception around south pole of the Sun. This suggests that the eclipse occurred more or less at the maximum of solar cycle. All structures of coronal formation are clearly seen (figure 1). At the north and south poles, polar plumes are well developed. The helmet streamers are visible on the high latitude of western side of the Sun, extended up to three solar radius. The helmet streamers are believed to be related to the chromospheric activity [9]. Small prominence and void are visible on the eastern side of the Sun.

3.2. Ludendorff flattening index (ε)

The Ludendorff flattening index ε is an ellipticity parameter of white light corona. To calculate the index, we produced isophotes of white light corona as displayed in figure 1. Since we did not take sky flat field image during the observation, the image is suffered from non-uniform sky background. We measured the index by,

$$\varepsilon = \frac{E_1 + E_2 + E_3}{P_1 + P_2 + P_3} - 1 \quad (1)$$

where E_1, E_2, E_3 and P_1, P_2, P_3 are defined as isophotes diameter on the equator and poles that separated at angles of 22.5° .

The rise of ε is properly approximated with a linear function,

$$\varepsilon = a + b(r_e - 1) \quad (2)$$

where r_e is the mean radius of the Sun. The value of ε equals to $a + b$ at $r_e = 2$. Therefore, we fitted the flattening index values based on the isophotes and obtained the value of ε is 0.129 at $r_e = 2$ (figure 1).

There is a linear relation between Ludendorff flattening index and monthly sunspot number as shown by Pishkalo using data of 60 total solar eclipses on 1851 to 2012 [6]. We are re-calculated Ludendorff flattening index – daily (W_d) and monthly (W_m) sunspot number relation by adding the new value of ε (see figure 2a and 2b). Daily (W_d) and monthly (W_m) sunspot number datas were taken from WDC-SILSO. The results are quite similar, $a + b = 0.2357 - 0.0008 W_d$ for daily and $a + b = 0.2327 - 0.0007 W_m$ for monthly sunspot number.

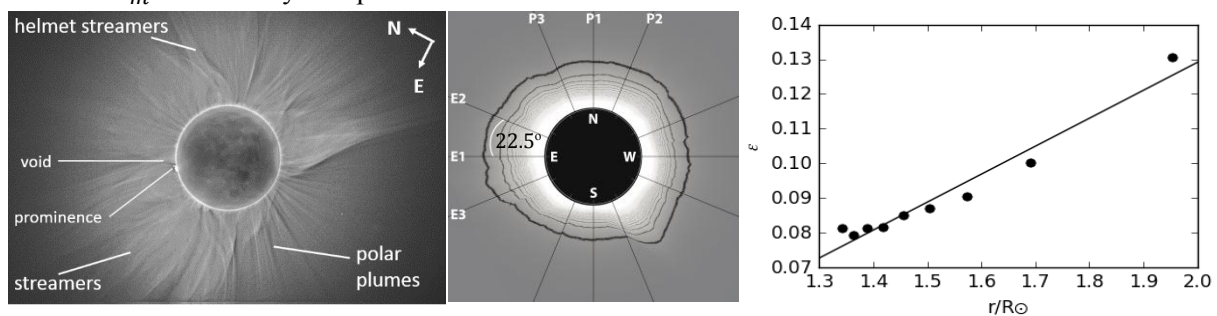


Figure 1. Left: Composite image of white light corona during total solar eclipse on March 9, 2016, with coronal structures marks. Center: Isophotes of the white light corona. Right: Plots of Ludendorff flattening index ε as a function of solar radius measured from isophotes.

We also study the relation of Ludendorff flattening index and solar cycle. Ludendorff introduced the phase of solar activity Φ and P as follows,

$$\Phi = \frac{T_{ecl} - T_{min}}{T_{max} - T_{min}} \quad (3)$$

$$P = \frac{T_{ecl} - T_{min1}}{T_{min2} - T_{min1}} \quad (4)$$

where T_{ecl} is the time of eclipse; T_{max} and T_{min} are the times of solar cycle maximum and minimum adjacent to the eclipse; and T_{min1} and T_{min2} are the time of solar cycle minimum at the beginning and the end of the cycle respectively [4,7]. We used data from WDC-SILSO to determine the time of solar cycle minimum and maximum, yielding $\Phi = -0.716$ and $P = 0.573$. These results suggest that the eclipse occurred after the maximum of solar cycle. Using the datas from Pishkalo and WDC-SILSO, we found the relation between Ludendorff flattening index and phases of solar activity. The results are shown in figure 2c and 2d, giving approximation of harmonic functions $a + b = 0.2385 - 0.0193\Phi - 0.1973\Phi^2$ and $a + b = 0.2681 - 0.6334P + 0.6707P^2$.

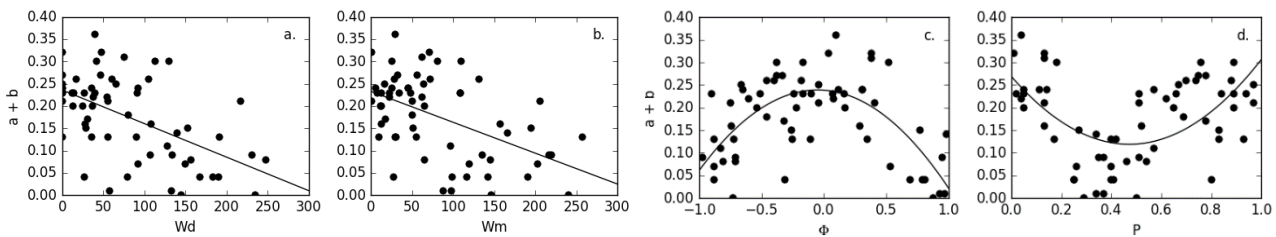


Figure 2. Relation between Ludendorff flattening index and daily sunspot number (2a), monthly sunspot number (2b), phases of solar cycle (2c and 2d).

3.3. Nikolsky geometric flattening index (H)

The Nikolsky geometric flattening index is calculated based on the extent and position of streamer and polar rays. It is expressed as

$$H = \frac{\Pi_N + \Pi_S}{2\pi} + \frac{\pi}{\frac{1}{n} \sum (\varphi_n + \beta_n) + \frac{\pi}{2}} \quad (5)$$

where Π_N and Π_S are the extents of the northern and southern polar ray systems (plumes) along the limb, n is the number of streamers, φ is the heliographic latitude of the bases of streamers; β is the angle of streamers to the equator. From the composite image on figure 1, we obtained H is equal to 1.32.

We used the above value along with 77 data of TSEs in 1860-2010 [7] and sunspot number data from WDC-SILSO to find the relation in figure 3a and 3b. In general, the maximum value of H is expected during minimum sunspot number according to the relation $H = 1.6095 - 0.0013 W_d$ for daily sunspot number and $H = 1.6514 - 0.0018 W_m$ for monthly sunspot number. We calculated phases of solar activity Φ and P using equation (3) and (4), yielding best fit of harmonic function $H = 1.6219 - 0.1794\Phi - 0.4192\Phi^2$ and $H = 2.0138 - 3.3562P + 3.46893P^2$ as shown in figure 3c and 3d.

3.4. Relation between ε and H

As it is done by Pishkalo [7], we investigated the relation between Ludendorff and Nikolsky flattening index. As shown in figure 3e, a linear relation is, $H = 0.6661 \varepsilon + 1.3853$. This figure is useful to calculate Ludendorff flattening index in case the white light corona image is heavily suffered from non-uniform background or foreground (e.g. partially cloudy weather during total solar eclipse).

3.5. Prediction of solar cycle 25

The relation between Ludendorff flattening index, sunspot number and phases of solar activity as shown before, suggest that the flattening index can be used to forecast the amplitude of the next solar cycle. To do this, we plotted Ludendorff flattening index from 10 total solar eclipses which occurred near the maximum solar cycle during 1851-2012. Then used two datas of sunspot number from WDC-SILSO, i.e. monthly and 13-month smoothed monthly sunspot number to construct figure 3f and 3g. The best approximation of maximum sunspot number based on monthly and 13-month smoothed monthly sunspot number data are $W_{max} = 159.22(a + b) + 109.43$ and $W_{max} = 264.1(a + b) + 162.61$ respectively. The results are 196 ± 52 for 13-month smoothed monthly data and 130 ± 42 for monthly sunspot number. In general, these values are higher compared to the published prediction of other authors [10, 11, 12, 13].

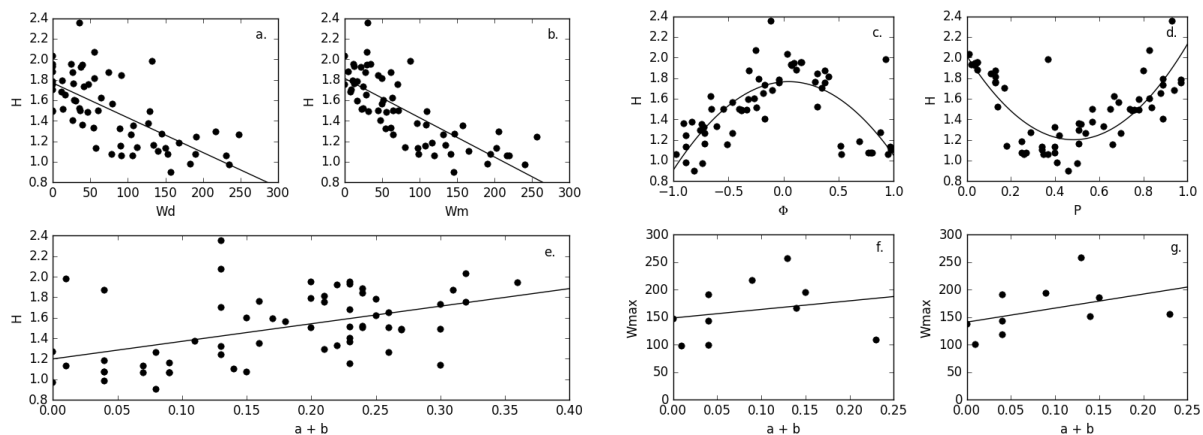


Figure 3. Relation between Nikolsky flattening index and daily sunspot number (3a), monthly sunspot number (3b), phases of solar cycle (3c and 3d), relation between Ludendorff and Nikolsky flattening index (3e), plots of Ludendorff flattening index and maximum 13-month smoothed monthly sunspot number (3f), and plots of Ludendorff flattening index and maximum monthly sunspot number (3g).

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