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WHITE-LIGHT SOLAR CORONA AND ATMOSPHERIC CONDITIONS REGISTERED DURING TOTAL SOLAR ECLIPSES

Tsvetan Tsvetkov[1], Rositsa Miteva[2], Emil Ivanov[3], Velimir Popov[3], Yoana Nakeva[4], Ljube Bojevski[5], Tobias Damm[6], Nikola Petrov[1]

[1]Institute of Astronomy and National Astronomical Observatory – Bulgarian Academy of Sciences
[2]Space Research and Technology Institute – Bulgarian Academy of Sciences
[3]Konstantin Preslavsky University of Shumen
[4]King's College London
[5]Ss Cyril and Methodius University in Skopje
[6]Independent researcher
e-mail: tstsvetkov@astro.bas.bg

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Abstract: *We present an investigation on the structure and morphology of white-light solar corona using the data from 4 total solar eclipses. We pay attention to the variations of the temperature, speed and directions of the wind before, during and after the totality. A yet not fully studied atmospheric phenomenon observed immediately before and after the totality are the so called "shadow bands". During the solar eclipse of 2019 we provided a new experiment for registering the shadow bands and comparing their parameters with the wind characteristics.*

СЛЪНЧЕВАТА КОРОНА В БЯЛА СВЕТЛИНА И АТМОСФЕРНИТЕ УСЛОВИЯ ПО ВРЕМЕ НА ПЪЛНИ СЛЪНЧЕВИ ЗАТЪМНЕНИЯ

Цветан Цветков[1], Росица Митева[2], Емил Иванов[3], Велимир Попов[3], Йоана Накева[4], Любе Бойевски[5], Тобиас Дам[6], Никола Петров[1]

[1]Институт по астрономия с Национална астрономическа обсерватория – Българска академия на науките
[2]Институт за космически изследвания и технологии – Българска академия на науките
[3]Шуменски университет "Епископ Константин Преславски"
[4]Кралски колеж Лондон
[5]Университет „Св. св. Кирил и Методий“ Скопие
[6]Независим изследовател
e-mail: tstsvetkov@astro.bas.bg

Ключови думи: *Пълно слънчево затъмнение, слънчева корона, бягащи сенки*

Резюме: *Представяме изследване на структурата и морфологията на слънчевата корона в бяла светлина по данни от 4 пълни слънчеви затъмнения. Обръщаме внимание на изменението на температурата, скоростта и посоката на вятъра преди, по време и след пълната фаза. Едно ненапълно изучено все още атмосферно явление, което се наблюдава непосредствено преди и след тоталитета са т. нар. бягащи сенки. По време на слънчевото затъмнение от 2019 г. осъществихме нов експеримент по регистрация на бягащите сенки и сравняването на техните характеристики с тези на вятъра.*

Introduction

The Sun is a main source and "engine" of the cosmic climate determining its parameters in each and every moment of time depending on the magnitude and effects of the solar activity. The total solar eclipses (TSEs) provide the opportunity for qualitatively investigation of both the accompanying processes and solar corona. The photographies of the white-light corona are useful for studying the distribution of the coronal brightness, its shape, structure and flattening. But minutes before the corona is revealed, when the Sun becomes a tiny crescent a few interesting events could be observed. As a result of the rapid decrease of solar irradiance the atmospheric temperature usually drops [1] and conditions for turbulent mixing of small amounts of hot and cold air as well as for formation of air fronts are created. The temperature drop is larger in clear skies than cloudy skies [2]. There is also an associated eclipse-induced reduction of the wind speed. Wind properties (such as speed and direction) are connected with horizontal differences in atmospheric pressure, with the large-scale flow direction usually immediately apparent from pressure maps showing isobars. Flows near the surface encounter the additional effects of surface drag, modifying the wind speed and direction [3]. Since the solar crescent is as thin as a point source of light. All these and other factors support the formation of shadow bands immediately before and after the totality - diffraction effects caused by turbulence in our atmosphere, which can be observed as faint shadowy patterns on the ground [4, 5].

It is well known that the shape of the corona is subject to significant variations during the solar cycle [6]. The way of quantitatively describing the general coronal shape is the procedure first suggested by Ludendorff 90 years ago [7]. The flattening index ε can be determined by the equation:

(1) $$\varepsilon = \frac{E_0 + E_1 + E_2}{P_0 + P_1 + P_2} - 1,$$

where E_0 is the equatorial diameter of an isophote, E_1 and E_2 are the diameters measured at angles ±22.5° to the equatorial direction and P_i ($0 \le i \le 2$) is the analogous quantity for the polar direction. The value of ε is a function of the solar cycle phase Φ [7]:

(2) $$\Phi = \frac{T_{ecl} - T_{\min}}{\left|T_{\max} - T_{\min}\right|}.$$

Here T_{ecl} is the moment of the eclipse (in years), T_{max} and T_{min} are the times of closest to the eclipse solar cycle maximum and minimum, respectively. Φ changes in the range from –1 to 1.

The flattening index is also linked with the maximum monthly sunspot number W_{max} [8]:

(3) $$W_{\max} = -2.8 + 466.1\varepsilon.$$

This equation allows calculation of the maximum amplitude of the monthly sunspot numbers for the next solar cycle with uncertainty of ±65.

Members of our team participated in the successful observations of 4 solar eclipses – 1999 August 11 (from Bulgaria), 2006 March 29 (from Turkey), 2017 August 21 (from the USA) and 2019 July 2 (from Chile). Photographing the corona, shadow bands and registering eclipse meteorology was part of all these observations, despite the instrumentation and techniques varied from one eclipse to another.

Observations

We used the data from the eclipses in 1999, 2006, 2017 and 2019 to estimate the value of the flattening index ε according to our observations (Fig. 1.).

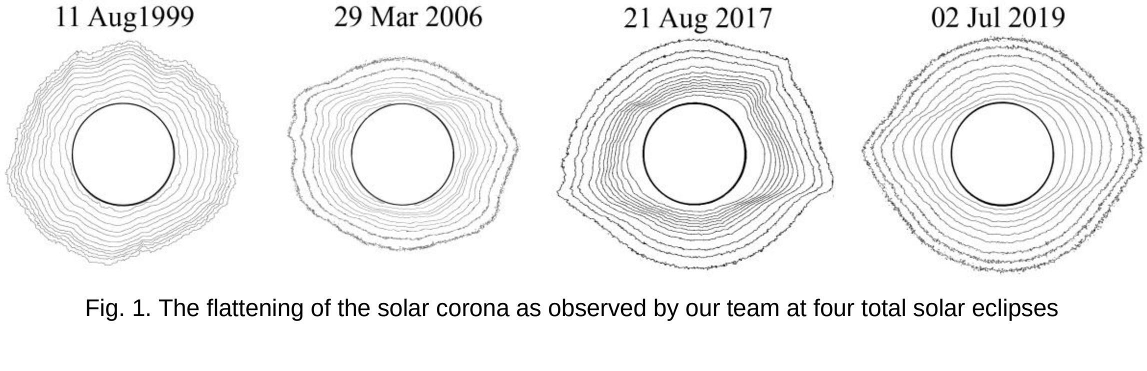

Fig. 1. The flattening of the solar corona as observed by our team at four total solar eclipses

The results for ε are given in Table 1. Since the four TSEs happened in different periods, we also evaluated the parameter Φ – the phase of the solar cycle. For the last two eclipses (2017 and 2019) we used the prediction of NOAA SWPC for the minimum of monthly sunspot number to be reached in 2019 December.

Table 1. The values of the phase of the solar cycle Φ and the flattening index ε estimated by our observations of 4 total solar eclipses

No.	Eclipse	Φ	$\varepsilon \pm \Delta\varepsilon$
1	1999 August 11	0.689	0.053±0.0024
2	2006 March 29	-0.346	0.138±0.0014
3	2017 August 21	-0.411	0.220±0.0023
4	2019 July 02	-0.079	0.126±0.0011

The dependence of the flattening index on the sunspot numbers is shown in Fig. 2. The index value increases with the decrease of the sunspot numbers [8]. The distribution of monthly average sunspot number since 1995 January (as estimated by the Royal Observatory of Belgium) is given on the right plot and on the left is presented the dependence of the index on the solar cycle phase. Values obtained by our observational material are marked with larger dots and numbered as in Table 1. Other values are taken by study from Pishkalo [8], who collected the values estimated by different authors from TSEs in the period 1851–2009.

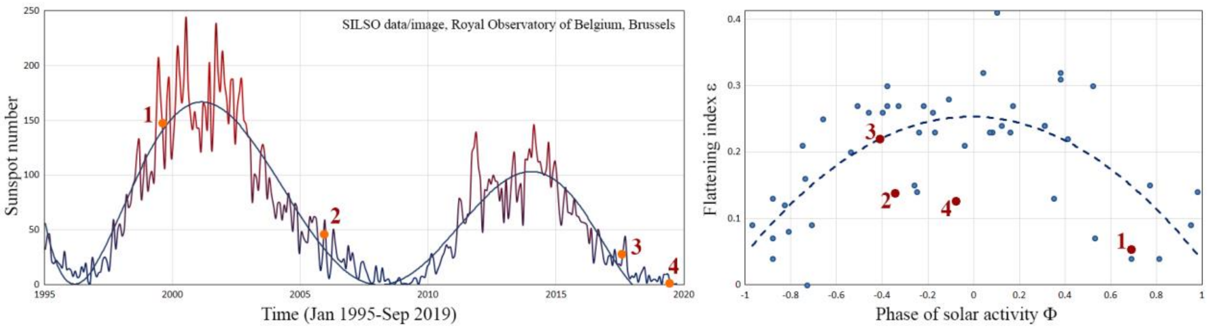

Fig. 2. Left panel: Smoothed monthly sunspot number since 1995 January. Right panel: Dependence of the flattening index ε on the phase of solar cycle Φ shown separately for ascending (Φ > 0) and descending (Φ < 0) parts of the cycle. The values for the flattening index ε estimated using our observations are given with larger circles numbered 1–4 as in Table 1.

Furthermore, the flattening index ε of the corona from the 2019 July 2 TSE allows prediction for maximum amplitude of the sunspot numbers for the 25th solar cycle. Using Equation 3, we estimated W_{max}= 56±65. Our result means that the 25th solar cycle is expected to be lower than the current, which had W_{max}=146 peaked in February 2014. Predications obtained by other authors show similar results. By exploring the flattening index of the corona during 2016 TSE another team predicts W_{max}= 70±65 [9]. Li et al. [10] expect the next maximum in 2023 October with W_{max}=109, Javaraiah [11] forecasts maximum amplitude as low as 50±10 and Rigozo et al. [12] give higher prediction with 132 maximum value of the sunspot number.

Another aspect of our observations during various TSEs (1999, 2006 and 2019) was exploring the pre- and post-totality shadow bands (Table 2). During the 2017 TSE our team also performed a videotaping of the bands, but the quality of the data does not allow accurate measurements. The data from 2019 TSE consists of our preliminary results.

Table 2. Properties of the registered shadow bands before and after the totality during different solar eclipses. The direction of propagation is measured from North (clockwise).

	1999 August 11		2006 March 29		2019 August 21	
Characteristics	before	after	before	after	before	after
Duration [s]	88	62''	133	148	45	40
Width [mm]	10-17	10-17	18	16	60	60
Distance [mm]	62	57	30-80	13-55	50	30
Direction [°]	18	13	330	307	80	80
Velocity [m s^{-1}]	0.5	0.5	2-4	2-4	2.37	1.56

To investigate a possible relation between the atmospheric conditions near the ground and the behavior of the shadow bands during the 2019 July 2 TSE we also performed a monitoring of eclipse meteorology. To track the changes in the surface air temperature we situated 2 teams 1 km away from each other. The results obtained by the first team are shown in Fig. 3. They measured 3.5 °C temperature drop during the eclipse with the minimum values reached 9 minutes after the totality, while the second one registered 2 °C decrease and lowest temperature 28 minutes after the totality. These differences in the results may be explained by the local peculiarities of the landscape around the observational spots as well as by the different instruments used.

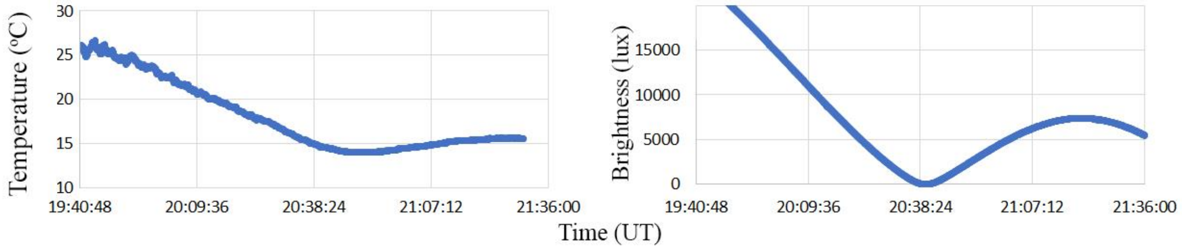

Fig. 3. The changes of the temperature (left panel) and the brightness (right panel) during 2019 July 2 TSE, observed from Atacama Desert, Chile. Given times are in UT as the totality is observed between 20:38 and 20:41 UT.

The wind properties are monitored using Gill Windsonic anemometer with 0.25 s time cadence between two consecutive measurements. The data registered 2 minutes before and after the totality (in the period of shadow bands observations) are presented as wind rose diagrams in Fig. 4. The change of the wind direction before and after the totality from primary eastern to northwestern is evident. The average wind speed also varied – from 2.37 m s^{-1} in the moments before the totality to 1.56 m s^{-1} after.

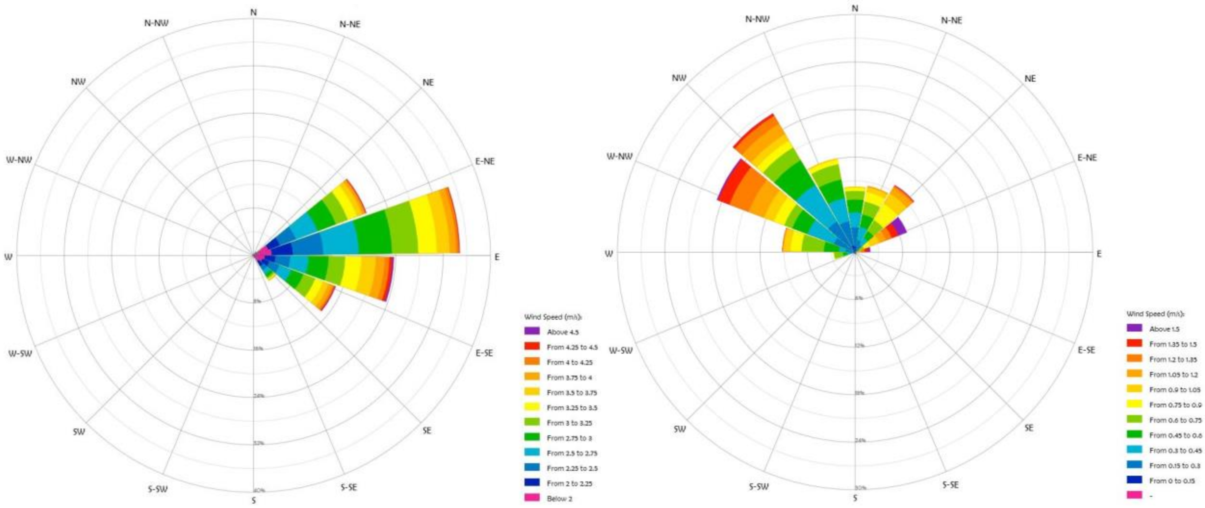

Fig. 4. Wind rose diagram showing the direction of propagation and the speed of the wind detected 2 minutes before (left panel) and after (right panel) the totality

The observed decrement of the wind speed before and after the totality coincides with an increase of the period between the bands detected after performing a fast Fourier transform of the observational data – from 0.53 s (before the totality) to 0.63 s (after the totality). These facts support the hypothesis for a possible influence of the ground level wind's atmospheric scintillation on the pattern of the shadow bands.

Conclusions

We present summarized results from observations performed during four total solar eclipses – 1999 August 11 (Bulgaria), 2006 March 29 (Turkey), 2017 August 21 (USA), 2019 July 2 (Chile), regarding the flattening of the white-light solar corona and eclipse meteorology in terms of shadow bands monitoring.

Our results for the Ludendorff flattening index and its changes in different phases of the solar cycle are presented. A prediction of the maximum amplitude of the sunspot numbers for the 25th solar cycle, based on the flattening index claims that we are about to face a less powerful solar cycle with W_{max}= 56±65.

The properties of the shadow bands observed during 3 TSEs are summarized and these from the 2019 TSE are compared to the changes of the atmospheric conditions (temperature, wind speed and direction, etc.). Our results can be considered as a confirmation of the hypothesis for a possible influence of the ground level of the shadow bands propagation.

Acknowledgements

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