Solar Corona in White Light during Five Total Solar Eclipses

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Abstract. Solar corona in white light, at different stages of the solar activity cycle has been analyzed during the 1990, 1999, 2006, 2008 and 2009 total solar eclipses (TSEs).
Deviation of the coronal streamers from radial direction during minimum solar activity has been investigated. We have found that inclination of the streamers towards the equator is larger for the eclipses in deep solar minimum (2008 and 2009) in comparison with the 2006 TSE, which is also in minimum.
Values of the photometric flattening index at minimum of the solar cycle can be used for predictions of the amplitude of the cycle. We have made two estimations for the amplitude of the solar cycle 24 in terms of the smoothed monthly sunspot numbers using indices for TSEs before and after minimum - in 2008 and in 2009. The obtained values are 146±65 and 99,7±65, accordingly.

Introduction

Solar corona is the part of the solar atmosphere which is one of the most important from point of view of solar physic and solar-terrestrial relations. Solar wind is accelerated and the coronal mass ejection is formed in its inner part, which is difficult for observations and diagnostics. This transition of energy and matter from the photosphere through the chromosphere to the solar corona can be studied only during natural or artificial eclipses.

White light corona (WLC, the result of scattering of photospheric light off electrons in the corona and dust in interplanetary space) can be observed only during total solar eclipses because its intensity is much lower than the brightness of the sky. The orbital heliospheric observatories SoHO and STEREO, and the satellites Yohkoh,TRACE and CORONAS give the possibility of continuous investigation of the solar corona and the processes acting there but they are closer to the Earth than the Moon and overoccult the sun, omitting from view exactly the inner corona.

Solar eclipses are between two and five each year. Many occur over the oceans or distant places and it is very difficult to document them. Some are not total, being only partial or annular. Thus, a good opportunity for total solar eclipse observation comes along every only two or three years. The average duration of totality is only two to three minutes. That is why, studying changes in the corona from one eclipse observation to another will draw the picture of its evolution.

Eclipse observations are increasingly being used along with coronagraphic, filter, and x-ray and UV observations from space to give a more complete picture of the solar corona (Golub and Pasachoff, 1997).

Basic characteristics of the corona are controlled by the magnetic dynamo and its variations with the solar cycle. The equatorial plane of the dipole component of the solar magnetic field is regarded as principal plane of the solar corona with all its features. The position of this plane defines the orientation of the heliospheric current sheet and the outer solar corona in 3D space. Its inclination with respect to the solar equatorial plane varies from almost zero at solar minimum to almost 90° at solar maximum, which is the reason for fundamentally different appearance of the corona. The observed variety of solar corona forms is also determined by the variations of the current sheet orientation towards the earth due to solar rotation (Gulyaev, 2011,). Lifetime of these forms can be from less than one to more than several solar rotations.

Comparative analysis of the white light corona observations during 5 total solar eclipses (in 1990, 1999, 2006, 2008 and 2009), at different phases of the solar activity cycle is presented in this work. White light solar corona is examined using the inclination of streamers towards the equator and the photometrical flattening index or index of ellipticity of the solar corona.

Sites and observations

Observations of the total solar eclipses (TSE) in 1990, 1999, 2006, 2008 and 2009 were conducted at different sites of the world. Everywhere, our expeditions and experiments were part of the Bulgarian National scientific program for observation of the specific total solar eclipse. Sites were chosen to be in the line of totality.

July 20, 1990 – near the town of Kem, Karelia, Russia (φ = 64°57′ N, λ = 34°36′ E, Alt. = 165m).

August 11, 1999 - around the town of General Toshevo, Bulgaria (φ = 43°41.7′ N, λ = 28°11.5′ E, Alt. = 200m).

March 29, 2006 – near the town of Manavgat, Turkey (φ = 36°45′27.59″ N, λ = 31°27′14.11″ E, Alt. = 2m).

August 1, 2008 – near the town of Bijsk, Altay, Russia (φ = 51°58′ N, λ = 84°57′E, Alt. = 360m).

July 22, 2009 - near the upper reservoir of the TianHuangPing Pumped Storage Power Station, China (φ = 30°28′14.2″ N, λ = 119°35′29.0″ E, Alt. = 909m), near the Shanghai Observatory, which belongs to the Chinese Academy of Science.

The white light corona observations during different years of total solar eclipses are made with different telescopes and cameras with different times of exposure. The experiments and observational equipment are described in Stoeva et al. (2011).

Results and analysis

Polar plumes, dome-shaped structures and "helmet" type structures are the basic coronal formations. They are evident from composite images of different number of negatives taken with a variety of exposures in white light (Stoev et al., 2002, Stoeva et al., 2008).

For studying the lifetime of coronal structures we have compared images of the white light corona from SOHO/LASCO 2 with an interval of ¼ period of the solar rotation – at the day of the eclipse, 7 days before and 7 days after the eclipse. Data available are for the eclipses in 1999, 2006, 2008 and 2009.

The total solar eclipses on July 20, 1990 and August 11, 1999 are during the maximum of the 22nd and 23rd solar activity cycle, respectively. These coronas show many streamers located at all azimuths around the occulted disk of the Sun (Fig. 1).

Fig. 2 shows three images of the WLC as obtained with SOHO/LASCO 2 with an interval of ¼ solar rotation period for the 1999 TSE. It is evident that corona is nearly one and the same for a half period, which is normal for solar maximum.

The 2006 TSE is in minimum - on the falling branch of the 23rd solar activity cycle. The 2008 TSE is also on the falling branch according to the consensus reached by The Solar Cycle 24 Prediction Panel on May 8, 2009**:** the 24th solar cycle begins in December 2008. The 2009 TSE is also in minimum but on the rising branch of the 24th solar cycle. The quiet Sun corona shows larger helmet-type streamers concentrated in latitudes near the equator between N45 and S45.

For the 2006 TSE, polar plumes are well developed in northern and southern hemisphere of the corona. Dome-shaped structures are displaced from 25° to 45° heliographic latitudes. The deviations from a radial direction in western hemisphere (21°) are greater than that in eastern one (8°).

Fig. 3 shows three images from LASCO2, SOHO with an interval of ¼ period for the 2006 TSE. Seven days before the eclipse there is no well developed streamers in the western hemisphere

For the 2008 TSE coronal structures are also outlined on the composite image of the white light corona, at heliographic latitudes from 19⁰ to 48⁰. The deviations in western hemisphere (9°) are smaller than that in eastern one (12⁰-18⁰).

Fig. 4 shows three images from LASCO2, SOHO with an interval of ¼ period for the 2008 TSE. One can see that shape of the corona and number of streamers is different and deviations from the radial direction in eastern hemisphere vary in the same range

Images of the white-light corona during the 2009 TSE also show the typical coronal structures. The deviations of the streamers from radial direction in western hemisphere are larger (28-34°) than that in eastern one (18-20°), as in 2006 TSE but with larger values.

Fig. 5 shows three images from LASCO2, SOHO with an interval of ¼ period for the 2009 TSE. Structure of the corona remains nearly one and the same

Studying the three TSEs during minimum of the solar activity cycle we found that deviation of the coronal streamers from radial direction or their inclination towards the equator is larger as a whole for the 2008 (Sunspot Number (SSN) at 2.5) and 2009 (SSN at 4.5) eclipses in comparison with the 2006 TSE (SSN at 17).

This fact can be explained with the low solar activity in 2008 and 2009 (deep solar minimum).

The Ludendorff flattening index (ellipticity) is the first quantitative parameter introduced for analyses of the global structure of the solar corona. It is anticorrelated with solar activity and varies between minimum (maximal value 0.4) and maximum (minimal value 0.0), within the limits of 0.2 (Van de Hulst, 1953, Gulyaev, 1997, Stoev et al., 2002, Pishkalo M., 2011).

The flattening index of the solar corona, which is largest at the activity minimum and vice versa, can be considered as an indirect characteristic of the polar magnetic field of the Sun, which is also largest at minimum according to dynamo theory. The amplitude of the toroidal magnetic field of the Sun (forms sunspots) in the activity maximum is determined by the poloidal magnetic field in the previous minimum. Pishkalo M. (2011) have obtained an equation for the best linear fit of the smoothed monthly sunspot number at cycle maxima W_{max} *vs.* the flattening index ε near cycle minima using data for 60 total solar eclipses:

$W_{max} = -2.8 + 466.1 \times \varepsilon$.

We have used this equation for calculating the amplitude of smoothed monthly sunspot number in the last solar cycle.

The TSE in 2008 is closer to the minimum of the solar activity – December 2008. Using the obtained flattening index of ε = 0.32 (very close to the value ε=0.29 of Rusin et al., 2010), it can be predicted that the amplitude of the current solar cycle will be 146±65 in terms of the smoothed monthly sunspot number – a value much higher than that of Pishkalo M. (2011) for the same eclipse.

The 2009 TSE is at the beginning of the solar cycle 24. Using this flattening index value - ε = 0.22 - we calculate a lower value - 99,7±65 - for the amplitude of the solar cycle 24, which is very close to the value preferred by Pishkalo M., 2011 - 95 ± 65, obtained for the 2008 TSE at ε = 0.21.

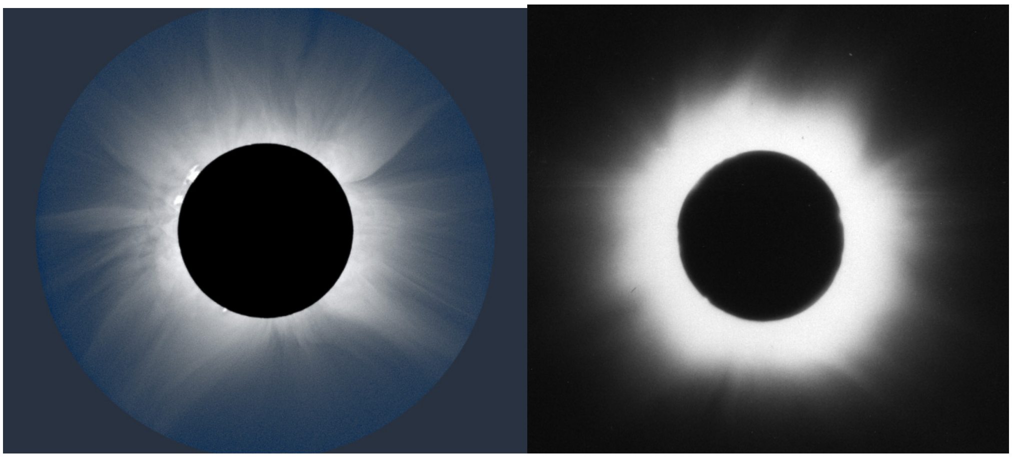


Fig.1. Helmet-type streamers and system of polar plumes are the basic details of the solar corona from the total solar eclipse on July 20, 1990 (Miloslav Druckmüller, 2004), left and August 11, 1999 (photograph in white light made by a great light power camera (200/1000 mm) with 2 sec exposure).

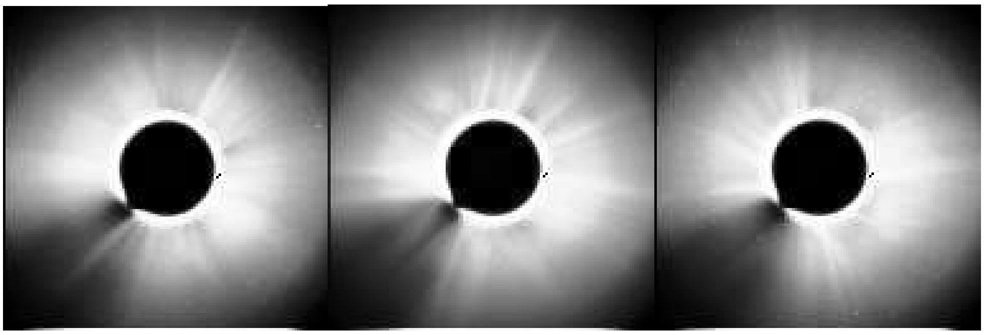
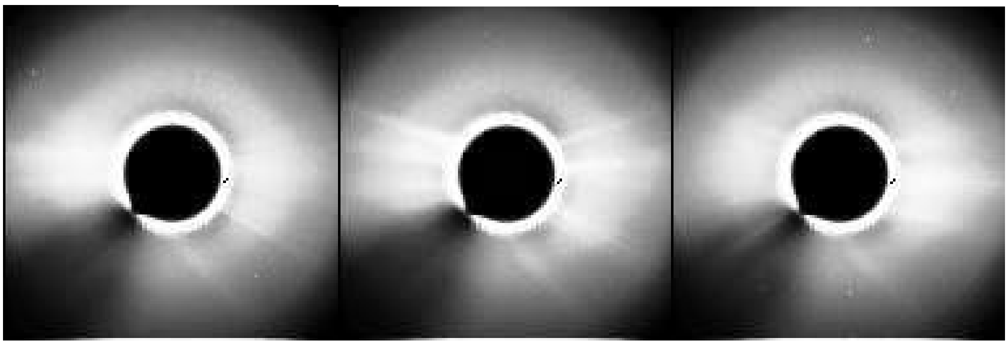
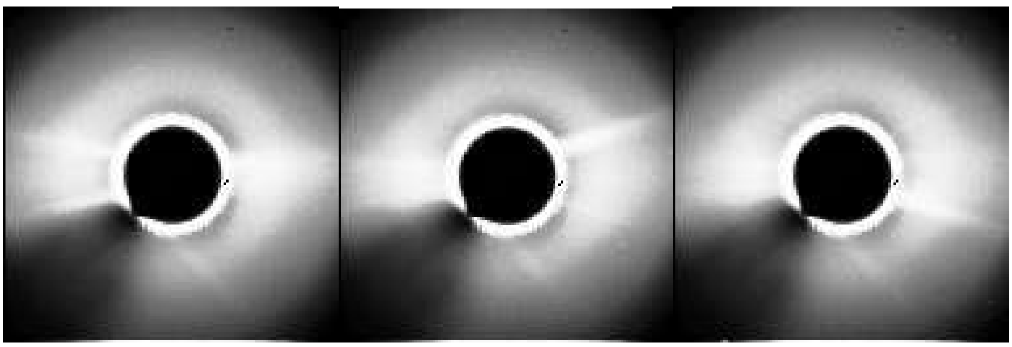


Fig.2. WLC as obtained with SOHO/LASCO 2 with an interval of ¼ period for the 1999 TSE



22.03.2006 29.03.2006 05.04.2006

Fig.3. WLC as obtained with SOHO/LASCO 2 with an interval of ¼ period for the 2006 TSE



25.07.2008 01.08.2008 08.08.2008

Fig.4. WLC as obtained with SOHO/LASCO 2 with an interval of ¼ period for the 2008 TSE

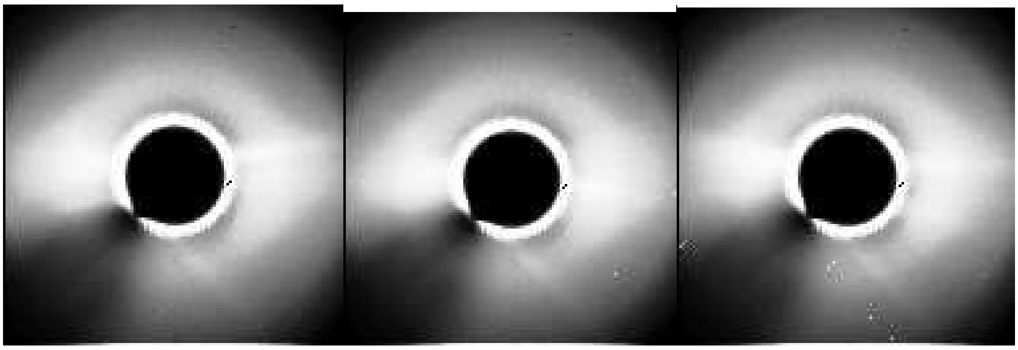


Fig.5. WLC as obtained with SOHO/LASCO 2 with an interval of ¼ period for the 2009 TSE.

Table 1 The solar corona flattening ε and the solar cycle phase Φ for five total solar eclipses

Year	1990	1999	2006	2008	2009
ε	0.090	0.190	0.098	0.320	0.22
Φ	- 0.85	0.75	- 0.25	- 0.04	0.12
Corona Type	Before min (May 1996)	After min (May 1996)	Before min (Dec 2008)	Before min (Dec 2008)	After min (Dec 2008)

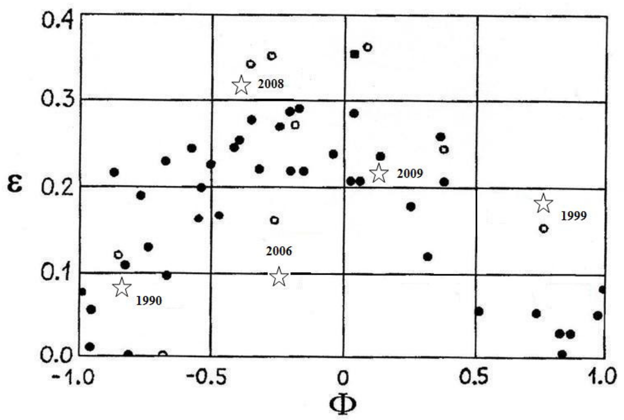


Fig. 6. The solar corona flattening indices ε as a function of the solar cycle phase Φ for five TSEs are shown as white stars. Other plots are results by Gulyaev (1997) who uses data for 51 solar eclipses.

Conclusion

We have made an analysis of the white light coronal structures and shape during the 1990, 1999, 2006, 2008 and 2009 total solar eclipses, which are at different stages of the solar activity cycle. We have examined the corona using the inclination of streamers and the flattening index.

Three of the investigated TSEs are during minimum of the solar activity cycle. We have found that deviation of the coronal streamers from radial direction or their inclination towards the equator is larger as a whole for the 2008 (SSN at 2.5) and 2009 (SSN at 4.5) eclipses (deep solar minimum) in comparison with the 2006 TSE, which is at comparatively larger solar activity (SSN at 17).

Analysis of the Ludendorf flattening index and phase of the solar cycle show that white light corona during the 2006, 2008 and 2009 TSE (solar minimum) is asymmetric in contrast to solar corona observed during the 1990 and 1999 total solar eclipses (solar maximum). Moreover, value of the photometric flattening index at a cycle minimum can be used to forecast the amplitude of the cycle. We have made two estimations for the amplitude of the solar cycle 24 in terms of the smoothed monthly sunspot numbers using indices for TSEs in 2008 (ε = 0.32, 4 months before solar cycle minimum in December 2008) and in 2009 (ε = 0.22, 7 months after the minimum) - 146±65 and 99,7±65 accordingly.

These results can contribute to development of contemporary notion of the physical characteristics, shape and structure of the solar corona and its evolution with the solar activity cycle.

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