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STRUCTURE AND DYNAMICS OF THE SOLAR CORONA OBSERVED DURING DIFFERENT PHASES OF THE SOLAR CYCLE

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Abstract. Study of the solar corona is very important from point of view of solar physic and solar-terrestrial relations. The solar corona is composed of both closed magnetic loops emerging from the photosphere and “open” magnetic field regions that form the heliosphere.

White light corona can be observed only during total solar eclipses (TSE) because its intensity is much lowerthan the brightness of the sky. Observations of the total solar eclipses (TSE) in 1990, 1999, 2006, 2008, 2009, 2012 and 2017, which are at different stages of the solar activity cycle, were conducted. Our expeditions and experiments were part of the Bulgarian National scientific program for observation of the specific total solar eclipse in collaboration with scientists from Russia, France and Egypt. The sites were chosen to be in the line of totality. We have made an analysis of the white light coronal structures and shape. Polar plumes, dome-shaped and “helmet” type structures are the basic coronal formations. They are evident from composited images of different number of negatives taken with a variety of exposures. Our composited images are compared with the images of the C2 coronagraph of Naval Research Laboratory’s LASCO instrument on ESA’s Solar and Heliospheric Observatory (SoHO).

The structure, shape and brightness of the solar corona significantly depend on the activity of the Sun. The corona is very bright and uniform at solar activity maximum. We can observe a lot of bright coronal streamers and other active regions on it. During minimum of the solar activity the corona becomes asymmetric - it stretches at the equator. The Ludendorff flattening index (ellipticity) is the first quantitative parameter introduced for analysis of the global structure of the solar corona. It is anticorrelated with solar activity and varies between minimum and maximum. Analysis of the ellipticity coefficient and phase of the solar cycle show that white light corona during the 2006, 2008, 2009 and 2017 TSE (2 different solar minima) is asymmetric in contrast to solar corona observed during the 1990, 1999 and 2012 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.

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

Introduction

Solar corona can be observed only during total solar eclipses (TSE) because its intensity is much lower than the brightness of the sky. 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.

White light corona is a result of scattering of photospheric light off electrons in the corona and dust in interplanetary space. 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 but they are closer to the Earth than the Moon and overoccult the sun, omitting from view exactly the inner corona.

The coronal light consists of **K-, F-, E-, T- corona**. These components are formed by very different mechanisms and have very different properties. K- (Kontinuierlich) corona is caused by scattering of photospheric light off rapidly-moving coronal electrons; F- (Fraunhofer) corona – by scattering of photospheric light off dust in interplanetary space between the orbits of Mercury and Earth; E- (Emission) corona – by actual emission of radiation by highly-ionized species in the corona; T- (thermal) corona – by thermal (largely infrared) emissions of interplanetary dust, usually the same dust that is causing the F-corona [*Golub and Pasachoff*, 1997].

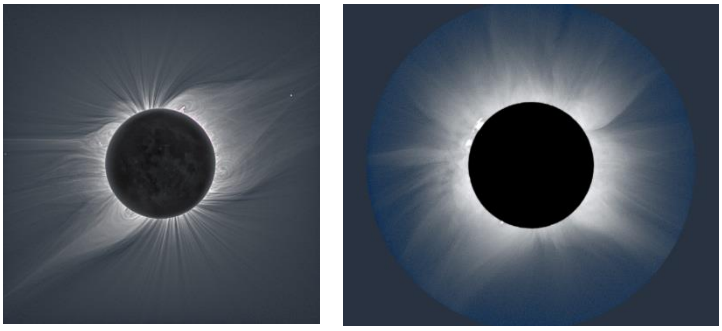
Primary source of information about distant regions of the middle and outer corona still remain optical observations of the so called **white-light corona**, formed from the K- and F- corona.

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.

Basic characteristics of the corona are controlled by changes in the configuration of the global magnetic field of the Sun. We know that, in general, large coronal streamers lie above the polarity-inversion lines of the large-scale magnetic field of the Sun marked by filaments and prominences [*Vsekhsvyatskiy et al.*, 1965]. That is why, studies of the solar corona shape give us information about long term variations and structure of its large scale magnetic fields.

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.



2008 minimum 1990 maximum

Figure 1. Solar corona during the 2008 TSE in minimum of the solar cycle and during the 1990 TSE in maximum solar activity.

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.

The minimum corona is much fainter and weaker than the maximum corona because of the absence of large active regions.

The corona is the source of the fast and slow solar winds, and transient events like flares, jets, filament eruptions and coronal mass ejections (CMEs). Transient events can considerably change the structure of the corona, since, especially coronal mass ejections frequently lead to global magnetic re-organisation.

Coronal structures appear bright (arcades, loops, helmet streamers) or dark (coronal holes). Plasma density and temperature greatly depend on the magnetic field topology: bright features have closed magnetic structures (bipolar and active region loops), while dark coronal holes have an ”open” magnetic structure towards the interplanetary magnetic field.

“Helmet streamers” are connected with solar active regions, and are centered over sunspots or prominences. Above the helmet, a long, straight stalk continues outward, and remains untwisted even to a dozen solar radii.

Observations

Observations of the total solar eclipses (TSE) in 1990, 1999, 2006, 2008, 2009, 2012 and 2017 were conducted at different sites of the world, in the line of totality. Usually, the scientific programme of our expeditions includes different tasks:

Photometric investigation of the basic coronal structures in white light.
Spectrometric investigation of the solar corona.
Photometry of the sky illuminance with a LUX Pu 150 photometer.
Determining of the dynamics of basic micrometeorological parameters of the 2-meter ground atmospheric layer.
Astrometry of the TSE during its phase evolution
Observations of atmospheric optical effects during the TSE.

Here we consider the white light corona at different phases of the solar cycle.

July 20, 1990 – near the town of Kem, Karelia, Russia (φ = 64°57′ N, λ = 34°36′ E, Alt. = 165m). Maximum of the solar activity. Sunspot number SSN=104

August 11, 1999 - around the town of General Toshevo, Bulgaria (φ = 43°41.7′ N, λ = 28°11.5′ E, Alt. = 200m). Maximum of the solar activity. SSN=252

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

August 1, 2008 – near the town of Bijsk, Altay, Russia (φ = 51°58′ N, λ = 84°57′E, Alt. = 360m). Minimum of the solar activity. SSN=0

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. Minimum of the solar activity. SSN=0

November 14, 2012 - in the region of Mount Molloy, 150km from Palm Cove, Cairns, Queensland, Australia (φ = 16°29′45.6″ S, λ = 144°58′17.4″ E, Alt. = 342m). Maximum of the solar activity. SSN=133

August 21, 2017 - in the area of the town St. Joseph, USA, near the Missouri River (φ = 39°47′23.1″ N, λ = 94°52′42.6″ E, Alt. = 253m). Minimum of the solar activity. SSN=63

White light corona observations

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].

Solar corona photographs in white light during the 1990, 1999 and 2006 TSE were obtained by a large-aperture cameras (200/1000mm and telescope 150/2250mm Meniskas - Cassegrain), and telescopes-refractors (63/840mm) [*Stoev et al*., 2002]. **Black and white professional photographic films** Kodak T-MAX 200 Pro with unique structure were used.

During the 2008, 2009, 2012 and 2017 TSE, the white-light corona photographs were obtained with 250/2000mm, 300mm objectives, and 2000mm Macsutov - Cassegrain telescope using **high resolution digital cameras**. Photographs were taken with different exposures, from 1/2000 sec to 5 sec.

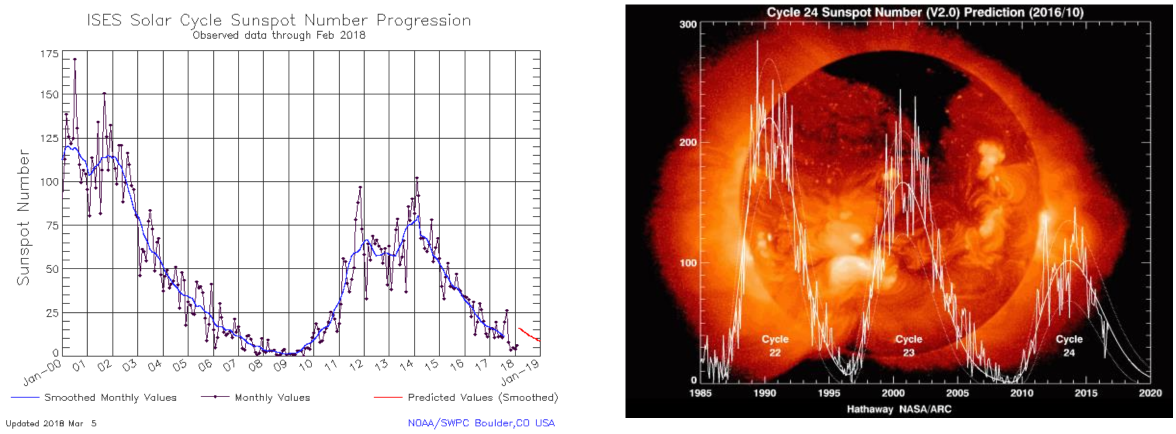


Figure 2. Solar cycle sunspot number progression.

Results and analysis

The 1990 and 1999 total solar eclipses are during the maximum of the 22nd and 23rd solar cycle.

The 2006 TSE is in the minimum - on the falling branch of the 23rd solar cycle.

The 2008 and 2009 TSE are also in minimum but on the rising branch of the 24th solar cycle. The 2012 eclipse is in very low maximum of the solar activity.

The 2017 eclipse is on the falling branch of the 24rd solar cycle.

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.

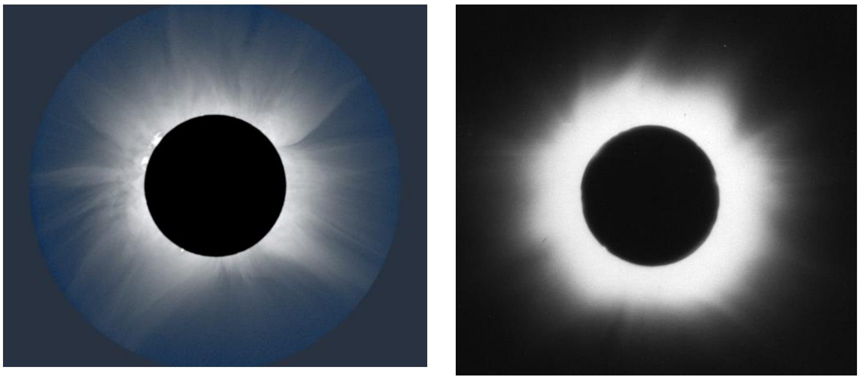


Figure 3. Solar corona from the total solar eclipse on **July 20, 1990 [***Miloslav Druckmüller*, 2004], left and **August 11, 1999 (**photograph in white light made by a great light power camera (200/1000 mm) - with 2 sec exposure).

Coronal streamers

During the 2006 TSE, all the basic coronal structures such, are evident from the composite image of 16 negatives taken with exposures from 1/2000 sec to 5 sec in white light [*Stoeva et al*., 2008].

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 25º to 45º heliographic latitudes. The deviations from a radial direction in western hemisphere (21º) are greater than that in eastern one (8º).

Figure 4. August 11, 1999 TSE. Black and white pencil drawing of the solar corona during the total phase, Zlatna Mychaylova. Equidencites.

Figure 5. March 29, 2006 TSE. Composite image of 16 negatives taken with exposures from 1/2000 sec to 5 sec in white light. Comparison of the white light corona with the steamer structure obtained by SoHO.

Comparisons are made with the steamer structure of the solar corona taken by SoHO and show that the basic streamer structures are identical.

For the 2008 TSE, coronal structures are also outlined on the composite image of the white light corona, at heliographic latitudes from 19º to 48º. The deviations in western hemisphere (9º) are smaller than that in eastern one (12-18º).

The total solar eclipse on July 22, 2009 has maximum duration of 6 min 39 sec and this is the longest totality for the last 2000 years.

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 (28-34º) than that in eastern one (18-20º), as in 2006 TSE but with larger values.

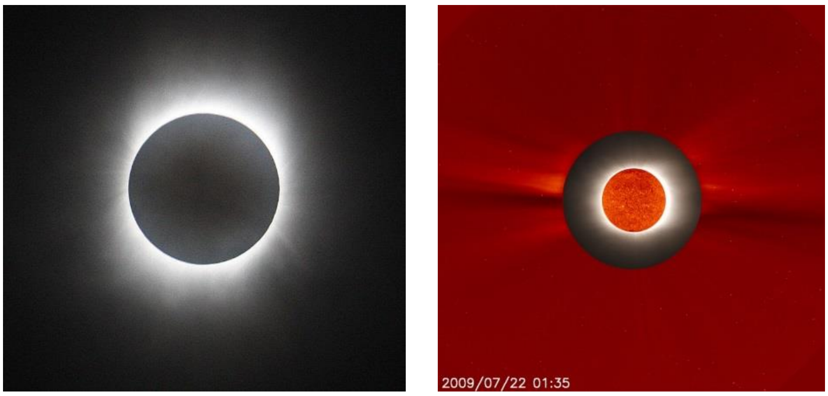


Figure 6. July 22, 2009 TSE - white light corona superimposed on an image of the Sun's outer corona taken by the Large Angle Spectrometric Coronagraph (LASCO) and shown in red false color (*right*).

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=0) and 2009 (SSN=0) eclipses in comparison with the 2006 TSE (SSN=31).

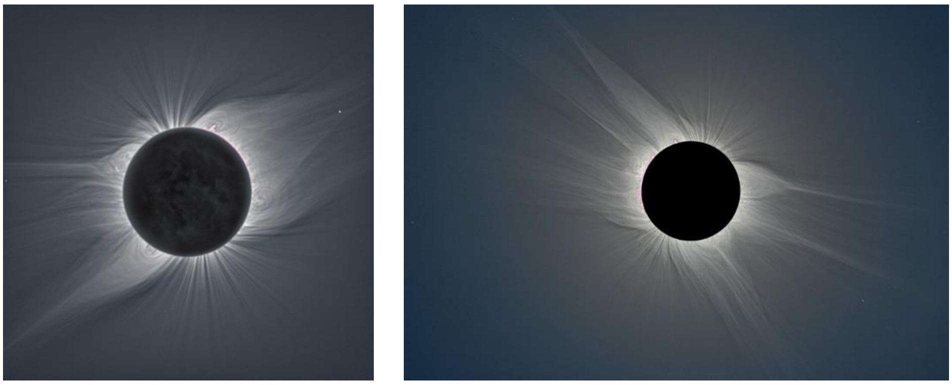


Figure 7. Coronal streamers during the August 1, 2008 (*left*) and March 29, 2006 (*right*) TSE in white light.

This fact can be explained with the low solar activity in 2008 and 2009 (deep solar minimum). For studying the corona of the sun during a very low maximum in the solar activity Russian-French-Bulgarian expedition was organized for observation of the November 14, 2012 total solar eclipse in Australia. Different experiments were conducted in the region of Mount Molloy, 150 km from Palm Cove, Cairns, Queensland.

Composite eclipse image consists from 16 images of different exposures made during the expedition of Space Research and Technology Institute, BAS (P. Stoeva and A. Stoev) and, Lebedev Physical Institute, RAS, Moscow (S. Kuzin and A. Percov).

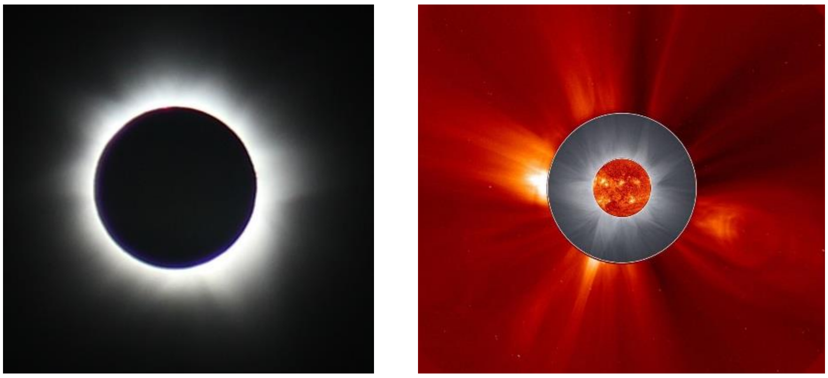


Figure 8. White light corona during the November 14, 2012 total solar eclipse, Australia, photographed with a 300 mm objective (*left*). Eclipse composite image between a SOHO/EIT image in helium radiation at 304Å in the ultraviolet (central image) and an outer-corona image from SOHO/LASCO (*right*).

Total solar eclipse on August 21, 2017 has been the first in the United States since 99 years and crosses the country from Oregon to South Carolina. We partly managed to observe the phenomenon due to suddenly changed weather conditions, but we received wonderful photographs from our American colleagues.

The Megafilm project (*http://eclipsemega.movie*) has been successfully completed, where people from across the US send photographs or videos to a Google-related system to make them accessible to everyone.

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 =0) and 2009 (SSN = 0), and 2017 (SSN =63) eclipses in comparison with the 2006 TSE (SSN =31). This fact can be explained with the low solar activity in 2008, 2009, and in the following minimum in 2017 (deep solar minimum).

Flattening index

The Luddendorf flattening index (ellipticity) is the first quantitative parameter introduced for analyses of the global structure of the solar corona. It increases monotonically from the limb to some distance r, which varies from eclipse to eclipse within the range of ~1.4 $R_\odot$ to ~2.2 $R_\odot$ and it is sensitive to existence of coronal streamers at large heliographic latitudes.

This ellipticity coefficient show that corona is very round at solar maximum, when streamers emerge from so many latitudes, and it is much more elliptical at solar minimum, when only a few streamers are visible at the equator.

This way, the Luddendorf flattening coefficient shows the cycle of solar activity [*Van de Hulst*, 1953; *Gulyaev*, 1997; *Stoev et al*., 2002].

For determining of the flattening ε the formula of *Ludendorf* [1928] has been applied

$$\varepsilon = \frac{d_0 + d_1 + d_2}{D_0 + D_1 + D_2} - 1$$

where d_0 is the equatorial equidensity diameter, d_1 and d_2 are the diameters placed at angles of ± 22.5° in relation to d_0; D_0 is the diameter of equidensities passing through the solar poles and D_1 and D_2 are the diameters tilted to D_0 at angles of ± 22.5°. The flattening ε, which characterizes the solar corona type, is calculated at a distance of 2 $R_\odot$ from the solar disk centre – a way to remove the effect of the F-corona.

The phase of the solar activity cycle can be calculated using the formula of *Bernheimer* [1938]:

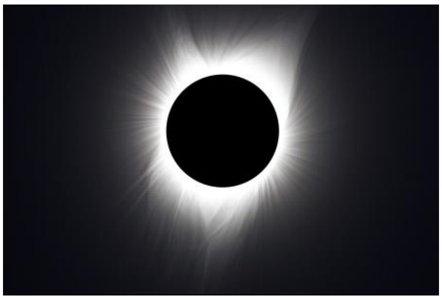


Figure 9. Solar corona on August 21, 2017 in minimum of the solar activity.

$$\Phi = \frac{T - T_{\min}}{|T_{\max} - T_{\min}|}$$

where T is the moment of the total solar eclipse, T_{min} and T_{max} are the nearest minimum and maximum of the corresponding solar cycles. The phase is calculated by linear interpolation between the closest maximum (Φ=1) and closest minimum (Φ=0). The sign + or – is assigned according to the rising and falling branch of the solar cycle, respectively.

Table 1. The solar corona flattening index ε and the solar cycle phase Φ for seven total solar eclipses.

Year	**1990**	**1999**	**2006**	**2008**
Sunspot N	104	252	31	0
ε	0.090	0.190	0.098	0.320
Φ	- 0.85	0.75	- 0.25	- 0.04
Corona Type	Before min (May 1996)	After min (May 1996)	Before min (Dec 2008)	Before min (Dec 2008)

Year	**2009**	**2012**	**2017**
Sunspot N	0	133	63
ε	0.22	0.024	0.270
Φ	0.12	0.87	- 0.6
Corona Type	After min (Dec 2008)	After min (Dec 2008)	After max (Apr 2014)

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:

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

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.

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. The average value is 122.85. Mean value of the sunspot number in April 2014, determinead as maximum of the Solar cycle 24 is SSN=112.46, which is very close to the obtained value.

Other investigations conducted during total solar eclipses:

1. Astrometry of the Total Solar Eclipse phenomenon.
2. Photometry of the solar corona in the green coronal line (photos with a narrow green filter λ = 5303Å).
3. Corona Spectrometry (Green Coronal Line).
4. Meteorology of the ground atmospheric layer (2 meters).
5. Photometry of the sky illumination during the phase evolution of the Total Solar Eclipse.

Conclusion

We have made an analysis of the white light coronal structures and shape during the seven total solar eclipses, which are at different stages of the solar activity cycle. Ground based composite images are compared with images from space observatories: Solar Ultraviolet Imager (SUVI) from NOAA/NASA's GOES-16 (inside the black and white corona) and C2 coronagraph of Naval Research Laboratory's LASCO instrument on ESA's Solar and Heliospheric Observatory (SoHO).

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, 2009 and 2017 eclipses (deep solar minimum) in comparison with the 2006 TSE, which is at comparatively larger solar activity.

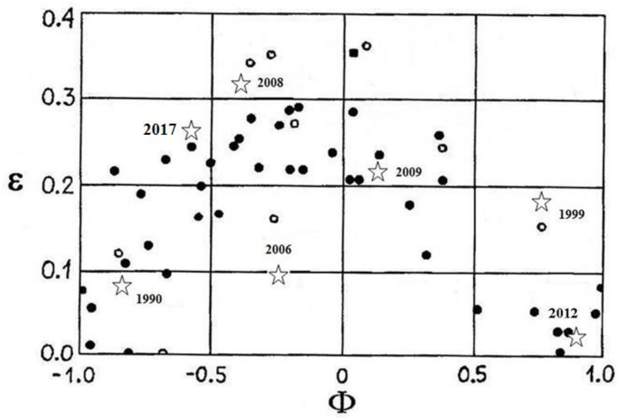


Figure 10. The solar corona flattening indices ε as a function of the solar cycle phase Φ for seven TSEs are shown as white stars. Other plots are results by *Gulyaev* [1997] who uses data for 51 solar eclipses.

Analysis of the Ludendorf flattening index and phase of the solar cycle show that white light corona during the 2006, 2008, 2009 and 2017 TSE (solar minimum) is asymmetric in contrast to solar corona observed during the 1990, 1999 and 2012 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 (mean value is 122.85). Mean value of the sunspot number in April 2014, determinead as maximum of the Solar cycle 24 is SSN=112.46.

References

Bernheimer W. E., 1938, "Sunspot activity and the form of the solar corona". M.N.R.A.S., 98, 598.

Druckmüller Miloslav, 2004, Eclipse Photography Home Page, *http://www.zam.fme.vutbr.cz/~druck/eclipse/Ecl1990/Incor/0-info.htm*

Ludendorff, H., Sitzungsber. Preuss. Akad. Wiss. Phys.-Math. Kl., 16, 1928, 185.

Golub, L., Pasachoff, J.M., "The Solar Corona". Cambridge University Press, Cambridge, 1997, 259.

Gulyaev, R. "Solar cycle variation of the solar corona shape. A new outlook", *Astron. Astrophys. Transactions*, 13, 1997, pp 137-144.

Gulyaev, R. "Investigations of the solar corona using the solar eclipse observations in IZMIRAN", *Geomagnetism and Aeronomy*, vol. 51, N 2, 2011, pp 174-181.

Pishkalo, M., "Flattening Index of the Solar Corona and the Solar Cycle", *Solar Phys*, 270, 2011, 347–363, DOI 10.1007/s11207-011-9749-y

Rušin, V., Druckmüller, M., Aniol, P., Minarovjech,M., Saniga,M., Miki´c, Z., *et al.*: 2010, *Astron. Astrophys.*513, A45.

Stoev, A., Y. Shopov, P. Muglova, N. Kiskinova, Yu. Varbanova, Zl. Michaylova, R. Velkov, "Structure of the solar corona during the 1999 total solar eclipse", In *First Results of 1999 Total Solar Eclipse Observations*, Edited by D.N.Mishev and K.J.H. Phillips, Professor Marin Drinov Publishing House, Sofia, 2002, pp 143-150.

Stoeva, P., A. Stoev, S. Kuzin, Y. Shopov, N. Kiskinova, N. Stoyanov, A. Pertsov," Investigation of the white light coronal structure during the total solar eclipse on March 29, 2006", International Symposium on Recent Observations and Simulations of the Sun-Earth System, Varna, Bulgaria, 17 – 22 September 2006, doi:10.1016/j.jastp.2007.08.051, Journal of Atmospheric and Solar-Terrestrial Physics v. 70, 2008, pp. 414–419

Stoeva, P., A. Stoev, S. Kuzin, "White light corona at different phases of the solar cycle", Sun and Geosphere, 6(1), 2011, pp 33-35, ISSN 1819-0839.

Van de Hulst, H.C., "The Chromosphere and the Corona", In *The Sun*, ed G. P. Kuiper, University of Chicago Press, Chicago, 1953.

Vsekhsvyatskiy, S. K., G. M. Nikolskiy, V. I. Ivanchuk, A. T. Nesmyanovich, et al., Solar Corona and Corpuscular Radiation in the Interplanetary Space (in Russian), Kiev, Naukova Dumka, 293 p., 1965.