NRIAG Journal of Astronomy and Geophysics (2016) 5, 297–300

National Research Institute of Astronomy and Geophysics

NRIAG Journal of Astronomy and Geophysics

www.elsevier.com/locate/nrjag

REVIEW ARTICLE

White light coronal structures and flattening during six total solar eclipses

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Received 29 April 2016; revised 28 June 2016; accepted 9 August 2016
Available online 28 August 2016

KEYWORDS

Structure of the solar corona;
Total solar eclipse;
Flattening index

Abstract Solar corona is very important part of the solar atmosphere, which is not available every time and it is very difficult to observe it. From solar corona we can get more information about outer sun layers. Large-scale structure of the solar corona can be studied during total solar eclipses.

The structure, shape and brightness of the solar corona significantly change from eclipse to eclipse. They depend on activity of the sun. At maximum solar activity, the corona is very bright and uniform around the solar limb. There are a lot of bright coronal streamers and other active regions on it. During minimum of solar activity the solar corona stretches at the equator and become elliptical.

Flattening index is the first quantitative parameter introduced for analyses of the global structure of the solar corona. It varies with respect to the phase of the solar activity and sunspot number. In this paper we study the solar corona during the 1990, 1999, 2006, 2008, 2009 and 2012 total solar eclipses. We obtain flattening coefficients for all the six eclipses by using a new computer program. Our results are in a good agreement with published results.

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Peer review under responsibility of National Research Institute of Astronomy and Geophysics.

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http://dx.doi.org/10.1016/j.nrjag.2016.08.003
2090-9977

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1. Introduction

The total eclipse of the sun is truly a remarkable event not only because of the fact that the beautiful corona, prominences and all other associated phenomena are rendered visible, due to the hiding by the moon of the disk of the sun or the photosphere as it is called, but mainly because it enables astronomers to study these parts of the sun which are always invisible during bright sunshine, Madwar (1952).

The white-light corona, the outermost part of the atmosphere of the sun, has been observed photographically during the total eclipse of the sun since 1860 Pasachoff et al. (2007).

During the total solar eclipse, when the moon occults the sun for a few minutes we can observe the outer atmospheric layers of the sun, the chromosphere and the corona. The shape of the corona extends to several solar radii depending on the phase of sunspot cycle Marzouk (2013).

Markova et al. (1999) found that the structure of the corona is created by both the global and local magnetic fields. Structure and shape of the white-light corona during both total eclipses in 1997 and 1998 were of minimum type.

Rusin (2000) tried to express the shape and structure of the white light corona according to its brightness with three parameters: ellipticity, structure, and integral brightness. All these parameters are closely connected. They vary with the activity cycle phase, and reflect mainly the magnetic field of the sun, which is generated below the photosphere, in the convection zone, erupts through the photosphere and permeates the surface.

In this work we compare the defined features of the solar corona during six total solar eclipses (1990, 1999, 2006, 2008, 2009 and 2012) at different phases of the solar activity cycle. Also, we have calculated the flattening index of the solar corona during all eclipses by the help of a new computer program (Matlab R2012 language program).

2. Data used

The observations of total solar eclipses (TSEs) in 1990, 1999, 2006, 2008, 2009 and 2012 were conducted at different sites of the world.

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

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

March 29, 2006 – near the west border of Egypt, Salloum city, Egypt (Lat. = 31°34″3.23″N, Long. = 25°7′ 9.35′E, Alt. = 202 m).

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

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

The November 14, 2012 TSE was observed in the region of Mount Molloy, 150 km from Palm Cove, Cairns, Queensland, Australia (Lat. = 16°29′45.6″ S, Long. = 144°58′17.4″E, Alt. = 342 m).

3. Flattening of the solar corona

Flattening of the solar corona (Ludendorf coefficient) ε characterizes the shape of the isophotes of the white-light solar corona. It increases monotonically from the limb to some distance r, which varies from eclipse to eclipse within the range of $\sim 1.4R_\odot$ to $\sim 2.2R_\odot$ and it is sensitive to the existence of coronal streamers at large heliographic latitudes. The rise of ε can be approximated with a linear function $\varepsilon = a + b\ (r - 1)$, where r is the mean equatorial radius of an isophote. The value $a + b$, equal to ε at $r = 2$, is just the classical parameter of Ludendorff. Flattening can be defined as:

$$\varepsilon = (r_e/r_p) - 1 \tag{1}$$

where r_e and r_p are the equatorial and polar distances of the isophotes from the center of the solar disk respectively.

Ludendorff (1928) made first quantitative analysis of the shape of the solar corona. He analyzed isophotes of coronal images and defined the averaged flattening of the solar corona by the formula:

$$\varepsilon = [(\mathrm{I} + \mathrm{II} + \mathrm{III})/(\mathrm{IV} + \mathrm{V} + \mathrm{VI})] - 1 \tag{2}$$

where I, II, II, . . . , VI designate six diameters of one and the same isophote separated at angles of $\pm 22.5°$.

4. Results and discussion

The most fundamental coronal characteristics (polar plumes, dome-shaped structures and helmet type streamers) have been observed on the images of the studied six total solar eclipses (1990, 1999, 2006, 2008, 2009 and 2012).

The total solar eclipses in 1990 and 1999 were during the maximum of the 22nd and 23rd solar activity cycles, respectively. These coronas show many streamers located at all azimuths around the occulted disk of the Sun (Fig. 1a and b).

The Total Solar Eclipse in 2006 occurred near the following minimum of the 23rd solar activity cycle. We can see in Fig. 1c stalks of helmet extend to 3 solar radii. The existence of different zones in the observed white light corona is clearly noticed.

According to the consensus reached by The Solar Cycle 24th Prediction Panel on May 8, 2009: the 24th solar cycle begins in December 2008. The 2008 total solar eclipse is on the minimum of solar cycle. Structures are also outlined on the composite image of the white-light corona - shape of the corona and number of streamers are different. The deviations of dome-shaped structures in western hemisphere are smaller than those in eastern one (see Fig. 1d).

The 2009 total solar eclipse is also in minimum but on the beginning of ascending branch of the 24th solar cycle. The quiet Sun corona shows larger helmet type streamers concen-

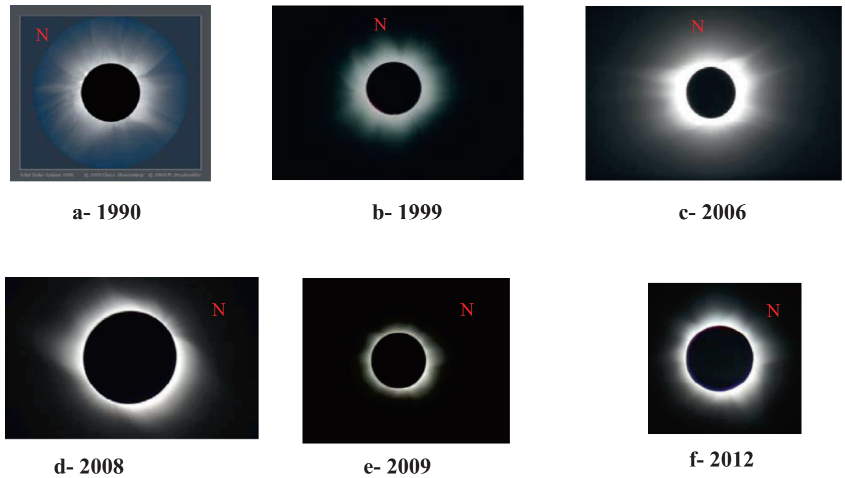

Figure 1 White-light solar corona during the six total solar eclipses, a – 1990, b – 1999, c – 2006, d – 2008, e – 2009, f – 2012.

trated in latitudes near the equator. Image of the white-light corona during the total solar eclipse 2009 (Fig. 1e) also shows the typical coronal structures. For 2012 total solar eclipse the white-light corona (Fig. 1f) is a typical maximum type. The active solar corona is full of structures. During sunspot maximum, the corona is very bright showing a uniform structure around the solar limb and bright coronal streamers, also other condensations associated with active regions are much conspicuous.

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 toward 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).

According to Eqs. (1) and (2), we could calculate the flattening parameters by using a new computer program (Matlab R2012 language). The method we used to calculate the flattening index ε values is computerized by using Mathlab R2012 language program.

The contour maps (isophotes, equidensites) for six total solar eclipses (1990, 1999, 2006, 2008, 2009 and 2012) are shown in Fig. 2.

Table 1 shows values of the flattening coefficient ε calculated for the six total solar eclipses (1990, 1999, 2006, 2008, 2009 and 2012).

Pishkalo (2011) has compiled 170 values of the Ludendorff photometrical coefficient for 60 total solar eclipses from 1850 to 2010 and found that the flattening index values are in the range from 0 to 0.4. The flattening index decreases with the growth of the sunspot number.

Our results are in good agreement with the published one. For 1990 total solar eclipse we find that the flattening index ε is 0.11 and it is in agreement with Pishkalo (2011) and Stoeva et al. (2012) (equal 0.12).

As we see in Table 1 Pishkalo (2011), found that the flattening parameter during the total solar eclipse in 1999 is 0.04 and

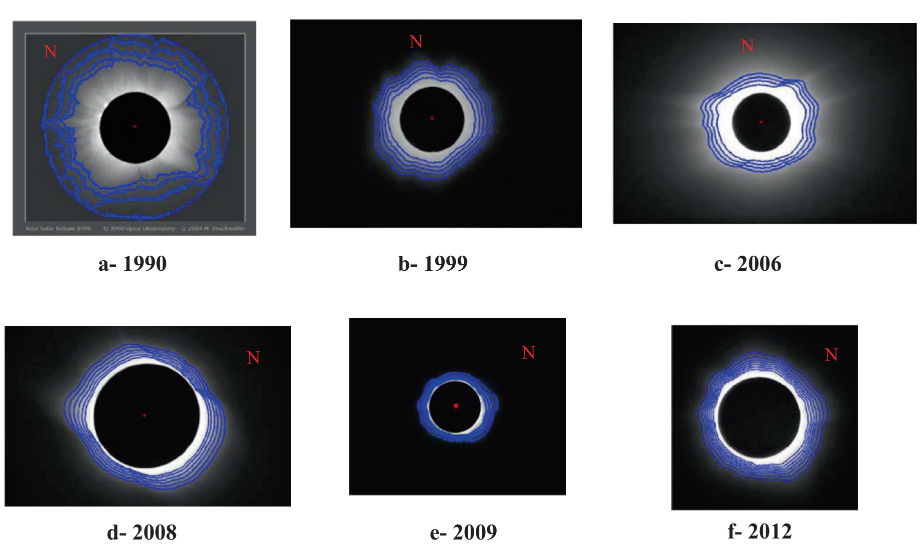

Figure 2 Equidensites of the solar corona derived by using the new Matlab R2012 language program for computing the Ludendorf flattening coefficient for six total solar eclipses: a – 1990, b – 1999, c – 2006, d – 2008, e – 2009, f – 2012.

Table 1 The flattening index ε for six total solar eclipses.

Eclipse year	Flattening index at $r = 2R_{\odot}$		Corona type
1990	0.12	Pishkalo (2011)	Before min of cycle 22 (May 1996)
	0.12	Stoeva et al. (2012)	
	0.11	This work	
1999	0.04	Pishkalo (2011)	After min of cycle 22 (May 1996)
	0.19	Stoeva et al. (2012)	
	0.20	This work	
2006	0.17	Pishkalo (2011) and Golub and Pasachoff (2009)	Before min of cycle 23 (Dec 2008)
	0.1	Stoeva et al. (2012)	
	0.16	This work	
2008	0.21	Pishkalo (2011)	Before min of cycle 23 (Dec 2008)
	0.32	Stoeva et al. (2012)	
	0.34	This work	
2009	0.24	Pishkalo (2011)	After min of cycle 23 (Dec 2008)
	0.22	Stoeva et al. (2012)	
	0.25	This work	
2012	–	Pishkalo (2011)	After min of cycle 23 (Dec 2008)
	0.024	Stoeva et al. (2012)	
	0.02	This work	

Stoeva et al. (2012) found it equal to 0.19, while in this work we have found it is equal to 0.2. It is in good agreement with the one published by Stoeva et al. (2012).

For 2006 total solar eclipse, Stoeva et al. (2012), defined the value of the solar coronal flattening ε = 0.1. Pishkalo (2011) and Golub and Pasachoff (2009) found that the flattening index ε during the total solar eclipse in 2006 is 0.17. Our value for the flattening index ε during the total solar eclipse in 2006 is defined to be 0.16, and it is matched with the published one by Pishkalo (2011) and Golub and Pasachoff (2009).

The flattening index ε during the total solar eclipse in 2008 was calculated by Pishkalo (2011) and he found it equal to 0.21, while Stoeva et al. (2012) found it equal to 0.32. Our value matches with the one published by Stoeva et al. (2012), and it is equal to 0.34.

Pishkalo (2011) showed that the flattening index ε during the total solar eclipse in 2009 is 0.24, while Stoeva et al. (2012) found it equal to 0.22 and in this work we have found it equal to 0.25 and it is in agreement with the published values.

Finally, the flattening index ε during the 2012 total solar eclipse has been calculated by Stoeva et al. (2012) and they found it equal to 0.02. Here, we find it equal to 0.024.

The solar corona flattening coefficient ε as a function of the total solar eclipse year is depicted on the diagram in Fig. 3.

As we see in Fig. 3 the comparison is made between our results and the published ones with polynomial fitting. The curve for Pishkalo, 2011 is not complete because there are no data for the 2012 solar eclipse. It is evident that our results are in good agreement with the published ones.

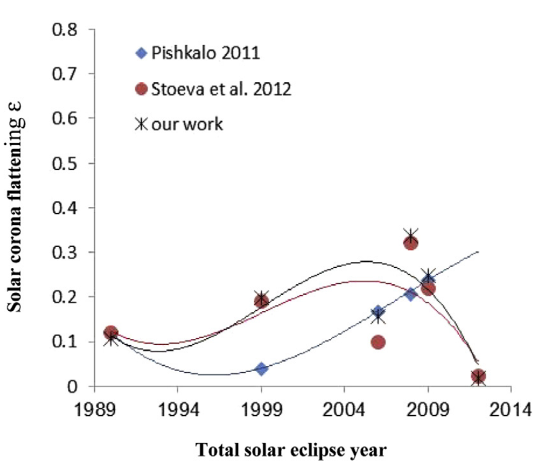

Figure 3 The solar corona flattening ε as a function of the total solar eclipse year for six eclipses obtained in this work, by Stoeva et al. (2012), and Pishkalo (2011).

5. Conclusions

The most fundamental coronal characteristics (polar plumes, coronal cavities and arcades, coronal holes, streamers) have been observed in the photographs of six total solar eclipses (1990, 1999, 2006, 2008, 2009 and 2012).

The calculated Ludendorf flattening coefficient shows that white-light corona during the 1990, 1999, and 2012 total solar eclipses is symmetric (solar corona maximum), while white light coronal observations during the, 2006, 2008 and 2009 total solar eclipses are asymmetric (solar corona minimum).

We obtain value for the flattening index ε in 1990 TSE (0.11), which is in a good agreement with the results of Pishkalo (2011) and Stoeva et al. (2012). Value for the flattening index during the 1999 TSE is consistent with the one published by Stoeva et al. (2012). For the 2006 TSE, ε value is in agreement with that of Pishkalo (2011) and Golub and Pasachoff (2009). The flattening index value during the 2008 TSE correlate with that published by Stoeva et al. (2012). For the 2009 TSE the value obtained in this work for the flattening index is in agreement with the one published by Pishkalo (2011) and Stoeva et al. (2012). Finally, for the 2012 total solar eclipse we obtain flattening index ε value which is in consistent with that of Stoeva et al. (2012).

In general, our new computerized method for calculation of the flattening coefficient ε gives values, which are in consistent with the published ones.

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