Solar Coronal Flattening during the Total Solar Eclipse of August 2017 from CATE Data

Jennifer Birriel
Joseph Teitloff
Department of Physics, Earth Science, and Space Systems Engineering, Morehead State University, 150 University Boulevard, Morehead, KY 40351; j.birriel@moreheadstate.edu

Received June 14, 2022; revised July 5, 2022; accepted July 8, 2022

Abstract The Continental-America Telescopic Eclipse (CATE) Experiment used a fleet of 68 identical telescopes spread along the line of totality to acquire images of the total solar eclipse on August 21, 2017. The original science goal was to construct a 90-minute, high-definition movie of the eclipse to examine the dynamics of the magnetic fields and plasmas in the solar corona. We used processed white light images from three CATE sites to examine the solar coronal flattening parameter, ε. The flattening parameters from sites 000 and 002, near the start of the eclipse, are the same as that measured for site 044b, the mid-point of the eclipse. Our average flattening parameter, ε = 0.24 ± 0.09, is consistent with values obtained by other observers for the 2017 solar eclipse. Furthermore, it is consistent with values obtained during other eclipses at the same solar phase as the 2017 eclipse, Φ = 0.789. These results represent yet another useful scientific result from the CATE Experiment.

1. Introduction

Solar magnetic variability is most readily observed by variations in sunspot number. Sunspot observations date back nearly 2,000 years, but the sunspot cycle was not discovered until 1844 by Heinrich Schwabe (Hathaway 2015). Other indicators of solar activity include changes in emission lines such as Fe XIV (530.3 nm) and Ca II K (396.85 nm) and disk radio emissions at 10.7 cm. Total eclipse observations since the mid-nineteenth have revealed changes in the shape of the solar white light corona; these changes also vary cyclically with solar activity (e.g., Pishkalo 2011; Rušin 2017; Pasachoff and Rušin 2022).

The white light solar corona is essentially created by the presence of helmet streamers around the circumference of the photosphere. During solar minimum these are limited to the equatorial regions of the solar disk, while during solar maximum helmet streamers are uniformly distributed around the solar disk. Since solar coronal structures such as helmet streamers and coronal holes are produced by the solar magnetic field extending above the photosphere, variations in the shape of the white light corona (WLC) makes them a useful indicator of solar activity.

In the early part of the 20th century, Hans Ludendorff developed a "flattening" coefficient to describe shape of the solar corona (Pishkalo 2011 and references therein). The so-called Ludendorff-index, ε, is defined as:

$$\varepsilon = \frac{d_e - d_p}{d_p} \qquad (1)$$

where d_e is the average equatorial diameter of the WLC and the d_p the average polar diameter. The average equatorial diameter, d_e, is determined by measuring the diameter of an isophote at the equator and the diameter of this same isophote at angles +22.5° and –22.5° from the equator. The average polar diameter is similarly defined. The solar flattening index increases in a linear fashion out to a distance of two solar radii and then rapidly falls off. The accepted methodology to determine $\varepsilon(2R_\odot)$ involves plotting measured values of ε for various isophotes as a function of $R/R_\odot$ and determining a linear fit to the data (e.g. Rušin 2017; Pishkalo 2011; Imaduddin *et al.* 2016).

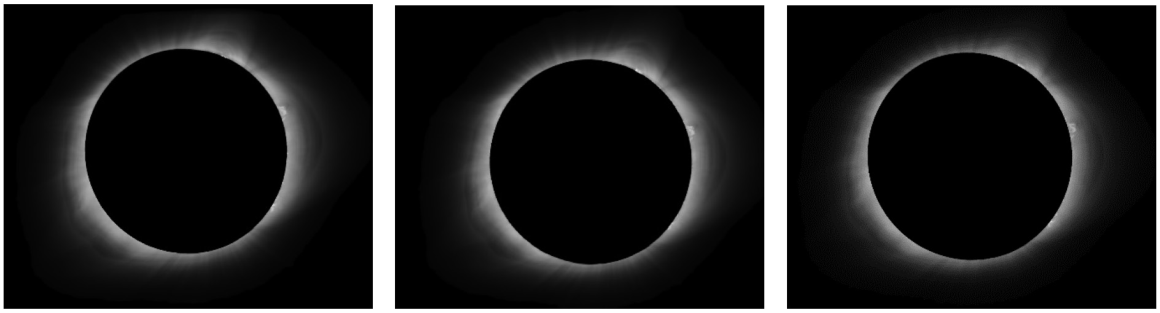
2. Observations and analysis

The Citizen CATE experiment is described in detail elsewhere (Penn *et al.* 2020); here we provide a brief overview of the essential instrumental components. Each site on the line of totality consisted of identical equipment which included an 80-mm diameter, 500-mm focal length APO refractor from Daystar fitted with a Thousand Oaks white light solar filter, #S4250. The mount was a Celestron Omni CG4, #915 with Celestron motor drive CG4, #93522. Images were acquired by a 5-Mpix CMOS camera, Pt Grey GS3-U3-51S5M-C which was controlled by an Arduino Uno. CATE data consist of white light images taken through a solar filter. Each site collected data for dark- and flat-field correcting. All sites collected a sequence of eight distinct exposures during totality: this resulted in hundreds of images from each site over the course of totality.

We used data from three CATE sites: two near the start of the eclipse—Site 000 in Weiser, Idaho, and Site 002 in Salem, Oregon—and one from the middle of the eclipse and the location with the longest duration of totality, Site 044 in Hopkinsville, Kentucky (Figure 1). These are the best images obtained at each site and are dark-corrected and flat field-processed. The CATE coronal isophotes agree in the overall shape found by Pasachoff and Rušin (2022) and Tsvetkov *et al.* (2019).

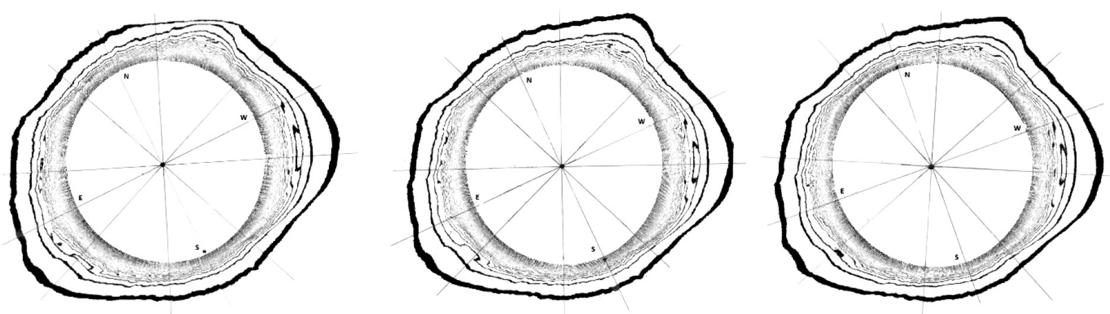
We used ImageJ software (Collins *et al.* 2017) to produce isophote images for each site, shown in Figure 2. Each isophote image was printed on paper: a protractor was used to measure angles and a ruler was used to measure isophote diameters. This method was suggested to us by Pishkalo (2021).

The measured radii for each image were used to compute flattening parameters which were then plotted as a function



(a) (b) (c)

Figure 1. White light images of totality from Sites (a) 000 Weiser, Idaho; (b) 002 Salem, Oregon; and (c) 044b Hopkinsville, Kentucky. Images are dark- and flat-field corrected. Note that the image for site 000 is slightly shifted and this results in a slight "clipping" in its outermost isophote as seen in Figure 2.



(a) (b) (c)

Figure 2. Isophotes for each site produced using ImageJ software (Collins *et al.* 2017): (a) 000 Weiser, Idaho; (b) 002 Salem, Oregon; and (c) 044b Hopkinsville, Kentucky. The solar orientation is indicated in each image as are the lines used to measure individual isophotes. The outermost isophote of site 000 is "clipped" at the northwest location due to a misalignment of the image on the camera chip.

of solar radius. The data are fit with a linear trendline and the resulting equation is used to calculate the solar flattening parameter $\varepsilon(2R_{\odot})$ for each site. Figure 3 shows the plots of data for each site.

3. Results and conclusion

Our results are summarized in Table 1. The average solar flattening parameter for the total solar eclipse of August 21, 2017, derived from CATE data is 0.24 ± 0.09. This result is in agreement with the value of 0.24 found by Pasachoff and Rušin (2022); it is also consistent with the results of Tsvetkov *et al.* (2019), who found a flattening parameter of 0.220 ± 0.002. (Our uncertainty is larger than Tsvetkov *et al.* for two reasons: our resolution is apparently lower and our isophotes do not extend out as far.)

As mentioned in the introduction, the flattening index varies with solar activity. The phase of the solar cycle is defined as from a historical perspective; the CATE data are consistent with historical measurements over the last century, as shown in Figure 4. The phase of the solar cycle is defined by:

$$\Phi = \frac{T - m_1}{m_2 - m_1} \tag{2}$$

where T is the time of observation, m_1 is the preceding minimum, and m_2 is the subsequent maximum (Rušin 2017); all of these values are in years and Φ ranges in value from 0 to +1. For the August 21, 2017, eclipse the solar phase was $\Phi = 0.789$. A historical plot of ε versus Φ (Figure 4) demonstrates that our value of $\varepsilon = 0.24$ is consistent with historical data at the same solar activity phase.

Citizen CATE participants consisted of both amateurs and professional scientists. As discussed by Stoev and Stoeva (2008), amateur observations of solar eclipses can provide useful scientific data regarding the structure of the solar corona in the form of solar flattening indices. Our results represent another useful contribution to solar eclipse science resulting from data derived largely by amateurs and students from the 2017 Citizen CATE project.

4. Acknowledgements

The authors wish to thank Matt Penn and Mike Conley for the use of CATE data from their sites. We are especially grateful to Matt Penn for processing all of the CATE data specifically used in this study. We thank Mykola Pishkalo for his advice and assistance in understanding how to make solar flattening parameter measurements. Finally, we thank Jay M. Paschoff and Vojtech Rušin for feedback that improved the quality of this paper.

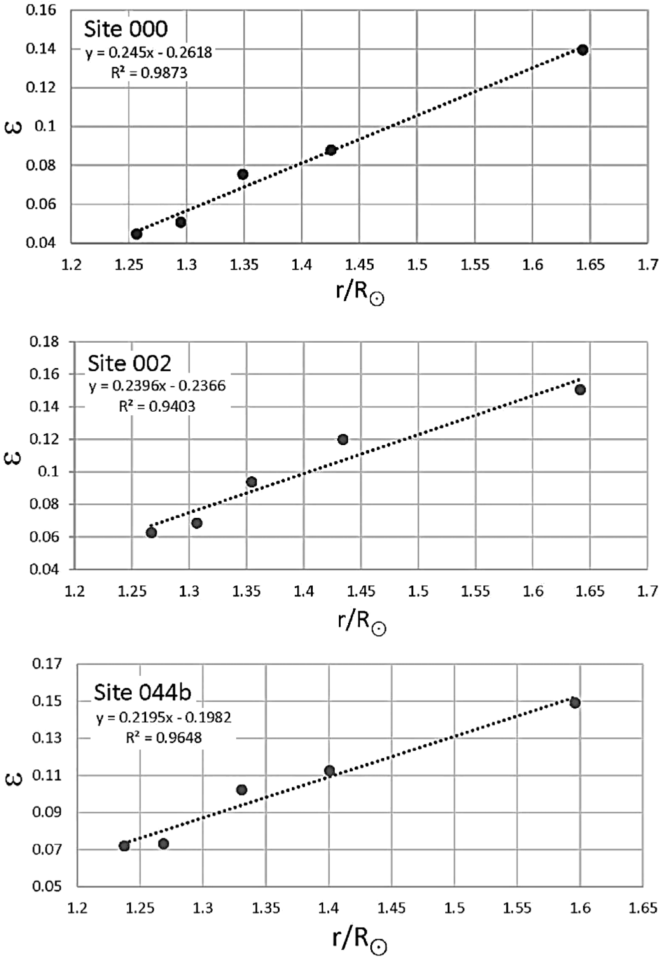


Figure 3. Plots of Ludendorff flattening parameter, ε, as a function of heliocentric radial distance.

Table 1. Solar Flattening Parameters Derived from selected CATE data.

Site No. (Location)	*Observer*	$\varepsilon(2R_\odot)$
000 (Idaho)	Matthew Penn	0.23 ± 0.04
002 (Oregon)	Mike Conley	0.24 ± 0.09
044b (Kentucky)	Birriel, Birriel, Yess	0.24 ± 0.06

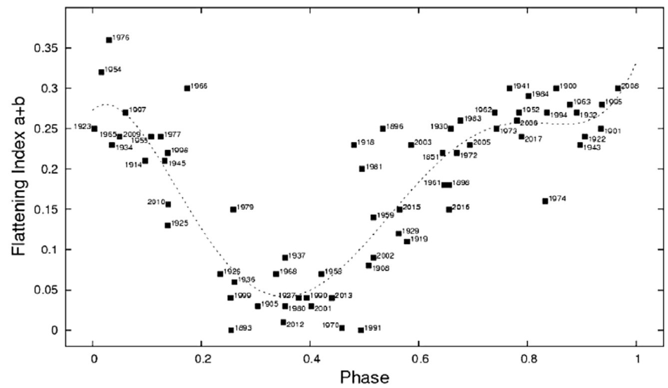


Figure 4. A plot of historical values of solar flattening, ε, versus solar activity phase, Φ. The red squares indicate flattening parameters for Cycle 24. (Reprinted by permission from Springer Nature, *Solar Physics*, "The Flattening Index of the Eclipse White-Light Corona and Magnetic Fields," J. M. Pasachoff and V. Rušin, 2022.)

References

Collins, K. A., Kielkopf, J. F., Stassun1, K. G., and Hessman, F. V. 2017, *Astron. J.*, **153**, 77 (https://www.astro.louisville.edu/software/astroimagej).

Hathaway, D. H., 2015, *Living Rev. Sol. Phys.*, **12**, 4.

Imaduddin, I., Akbar, E. I., and Putri, G. P. 2016, *J. Phys. Conf. Ser.*, **771**, 012008.

Pasachoff, J. M., and Rušin, V. 2022, *Sol. Phys.*, **297**, 28.

Penn, Matthew, *et al.* 2020, *Publ. Astron. Soc. Pacific*, **132**, 014201.

Pishkalo, M. I. 2011, *Sol. Phys.*, **270**, 347.

Pishkalo, M. I. 2021, private communication (October 10, 2021).

Rušin, V. 2017, *Sol. Phys.*, **292**, 24.

Stoev, A. D., and Stoeva, P. V. 2008, *Adv. Space Res.*, **42**, 1806.

Tsvetkov, T., Miteva, R., Ivanov, E., Popov, V., Nakeva, Y., Bojevski, L., Damm, T., and Petrov, N. 2019, in *Space, Ecology, Safety—SES 2019*, eds. P. Getsov, G. Mardirossian, Ts. Srebrova, Space Research and Technology Institute, Bulgarian Academy of Sciences, Sofia, 52.