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Research on Solar Corona during Total Solar Eclipses

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Abstract

Total solar eclipse observations have played a pivotal role in unveiling numerous secrets of the solar corona. From its initial identification in the 17th century to groundbreaking revelations about its million-degree temperatures in later centuries, eclipses have continued to provide key insights into the corona's dynamics and its dependence on solar activity cycles. Despite advancements in instrumentation and theoretical models, eclipses remain unparalleled opportunities for coronal research. Notably, the region of the corona most effectively observed from the ground during these events is inaccessible to any current space-based coronagraphs.

Our team have yet organized 7 scientific expeditions to observe total solar eclipses for the last 26 years. In the current paper we share our experience on the obtained research and conducted experiments underlining the point of continuing such observations today.

Keywords: expedition; eclipse; corona;

1. Introduction

The solar corona, the Sun's outermost atmospheric layer, presents a dynamic and captivating region of plasma with temperatures reaching millions of degrees Kelvin. Understanding its intricate structure and behavior remains one of the most compelling challenges in solar physics. Despite extensive research, fundamental questions persist –including the mechanisms behind coronal heating and the drivers of solar wind acceleration.

One of the rare opportunities to directly observe the solar corona in its full grandeur arises during total solar eclipses (TSEs). During these fleeting moments, the bright solar disk is obscured, revealing the fainter and more extended features of the corona. Such observations are crucial for gaining insights into the complex magnetic field structures and plasma flows that define this enigmatic region. Despite the remarkable advancements in coronagraph technology, eclipse observations remain indispensable. Space-based instruments often face limitations such as stray light contamination and constrained fields of view, which hinder the ability to capture the full extent of coronal structures close to the solar limb [Boe et al., 2021]. Furthermore, eclipses offer the unique advantage of capturing a broad spatial and spectral view of the corona under natural conditions, unaltered by instrumental limitations inherent to ground-based or spaceborne coronagraphs.

Unlike regular solar observations, TSEs allow the study of the corona from its innermost regions near the solar limb to its far-reaching outer extensions up to about 7 solar radii. This continuous view provides critical data for understanding the interactions between closed and open magnetic field lines, which influence the formation of different activity events as well as the solar wind. The highly dynamic environment of the corona also exhibits complex density and temperature variations, including loop structures, streamers, and polar plumes. Investigating these features is essential for unraveling the mechanisms behind the corona's extremely high temperatures and transient events.

Scientific expeditions during TSEs have long played an important role in probing the corona's mysteries. Usually, they are meticulously planned to optimize the collection of high-quality data. Researchers deploy specialized instruments to capture detailed information about the corona's composition, magnetic fields, and plasma dynamics. These expeditions often target remote locations along the narrow eclipse path, where weather conditions and atmospheric clarity are favorable. The data gathered during these brief but invaluable opportunities have led to numerous breakthroughs, including improved models of solar wind generation and advancements in space weather forecasting [Boe et al, 2021; Filipov et al., 2020; Pasachoff, 2017].

This paper explores the scientific significance of TSE observations and their indispensable role in advancing our understanding of the solar corona. By highlighting observational techniques, data acquisition strategies, and key findings, we aim to underscore the critical insights these unique events offer into the Sun's complex and dynamic outer atmosphere.

2. Total Solar Eclipse Expeditions

Our research focuses on leveraging these eclipse events to investigate the coronal structure, its dynamic properties, topology, and energetic processes. We employ an interdisciplinary approach that combines high-resolution imaging and detection of atmospheric changes by recording various meteorological parameters. By synthesizing observational data with theoretical insights, we aim to address key questions concerning both coronal properties and the Sun's influence on the heliosphere and, therefore, on our planet [Nikolov and Petrov, 2014].

The first scientific observations of TSE ever made by Bulgarian astronomers dates back to 1961, when the lunar shadow passes through the northern part of our country. Unfortunately, no member of our team participated in the observations then, but we are provided with the original observations of this eclipse [Tsvetkov and Petrov, 2022]. Still, 38 years later - in 1999 the totality path crossed our territory once again. It was our first expedition for TSE observations, out of seven organized so far (Figure 1).

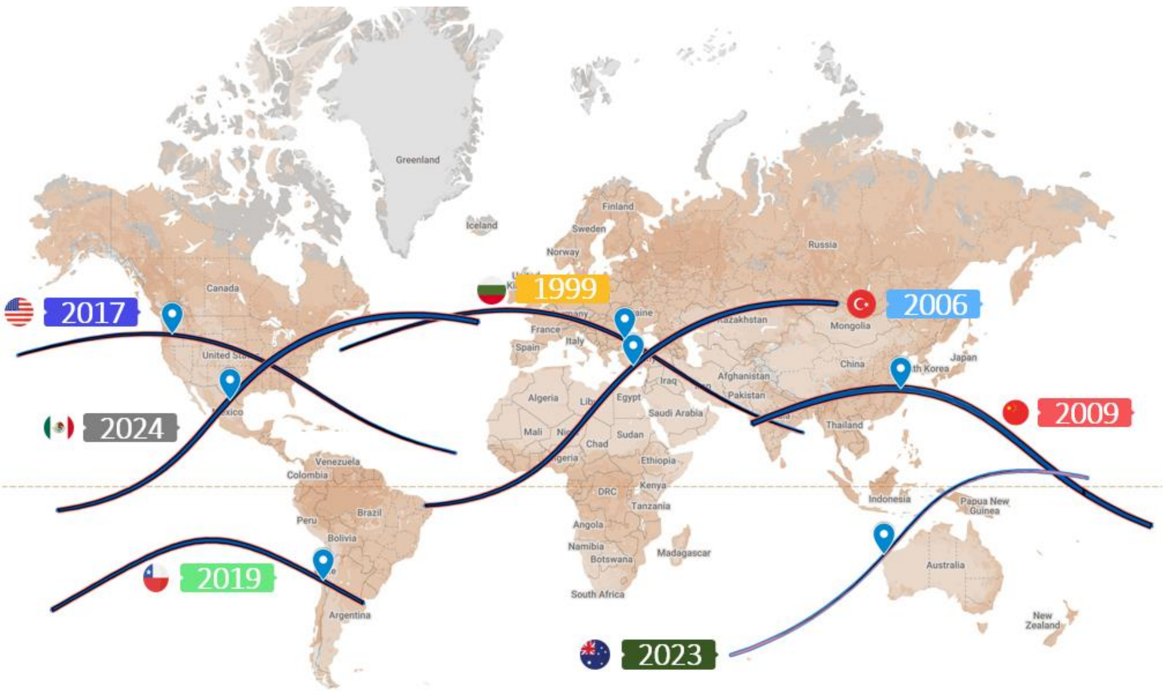

Figure 1. *Map of totality paths of all TSEs observed by our team with labels of observational site locations.*

Organizing TSE expeditions is a complex and demanding endeavor. Selecting an appropriate observation site requires careful consideration of multiple factors, including weather patterns, accessibility, and the path of totality. Often, this involves targeting remote locations where weather conditions are most favorable, necessitating extensive logistical planning to transport personnel and sensitive instruments. The challenges are compounded by the narrow time window of totality. Researchers must meticulously synchronize instrument setups and operational tasks to ensure that all planned measurements are successfully executed within this brief period.

Different solar eclipses provide diverse observational opportunities, contributing to a more comprehensive understanding of the solar corona. Variability in elevation, solar altitude, and atmospheric conditions during each event offers distinct perspectives on coronal structures and dynamics (Table 1). This has always been a priority when planning our next expedition. For example, in Chile (2019) the Sun was setting at the end of the partial phase of the eclipse, while in Mexico (2024) it reached 70^{o} during the totality. To achieve statistically significant results, it is essential to gather data from multiple eclipses, allowing researchers to analyse variations and correlations across different conditions (different phases of the solar cycle, different locations and environment, etc.). Also, the eclipses in 1999 and 2017 (and the ones from 2006 and 2024, respectively) are identical since they are separated by one saros. This cumulative approach not only enhances the robustness of scientific findings but also provides more accurate and nuanced understanding of the Sun's outer atmosphere.

Table 1. *Details for the observational sites during the TSE expeditions of our team (1999 –2025).*

Date of the TSE	**Location**	**Coordinates**	**Elevation [m]**	**Duration of totality [s]**	**Sun's altitude [^{o}]**
11 August 1999	Bulgaria	43^{o} 32' 34.1" N 28^{o} 36' 16.0" E	0	142	59
29 March 2006	Turkiye	36^{o} 47' 10.1" N 31^{o} 23' 21.6" E	38	225	54
22 July 2009	China	30^{o} 28' 20.3" N 119^{o} 35' 31.1" E	1200	338	54
21 August 2017	USA	44^{o} 42' 11.6" N 120^{o} 47' 52.2" W	1200	124	42
2 July 2019	Chile	29^{o} 47' 32.1" S 70^{o} 53' 06.0" W	1450	135	13
20 April 2023	Australia	22^{o} 07' 21.9" S 114^{o} 05' 08.1" E	10	58	54
8 April 2024	Mexico	27^{o} 13' 15.2" N 101^{o} 43' 52.2" W	660	249	70

On the other hand, during more than 25 years of research during TSEs now, we have witnessed significant technological advancements that have greatly enhanced the accuracy and quality of data collected. Early expeditions relied on analog imaging systems and less sensitive detectors, which limited the resolution and scope of observations. However, with the advent of high-resolution digital imaging and modern instruments, we now capture more detailed measurements of coronal structures and dynamics, we can precisely track the meteorological parameters during the eclipse and try new approaches to previously obtained experiments. On our expedition to Australia (2023) we tested for the first time during an eclipse the capabilities of a digital polarization camera for the purposes of polarization studies of the corona [Zinkova et al., 2022]. All these improvements have had a profoundly positive impact on our research, allowing for deeper insights into the corona's behavior.

3. Scientific Research

Solar corona as being a part of the solar atmosphere is a dynamic layer [Pasachoff et al., 2007]. Its shape and structure changes depending on the phase of the solar cycle, the height above the solar limb and heliogrpahic coordinates we are observing it at [Priest, 2014]. White-light observations of the corona during TSEs provide invaluable insights into the Sun's outer atmosphere, having a long-standing history in solar research. The first photograph of a total solar eclipse in the middle of the 19th century provided unprecedented views of the corona, laying the foundation for modern solar physics [Rue, 1863]. Nowadays they may reveal detailed structures in the corona [Pasachoff and Rusin, 2022]. During the eclipses observed near solar minimum – from Turkiye (2006), China (2009), USA (2017) and Chile (2019), streamers at lower latitudes and polar plumes are clearly visible (Figure 2). Getting closer to periods of solar maximum, the shape of the corona becomes asymmetrical due to the influence of strong magnetic fields, but meanwhile more coronal formations appear. Although we have registered the presence of prominences in the corona on all expeditions, in 1999 (2 years before reaching the 23-rd solar maximum) they were the most numerous – 12. New digital cameras and image-processing techniques developed before the TSEs in 2017 and 2019 (also near the solar maximum) allowed revealing details about the connection between the prominences and surrounding cavities. Usually, these features are captured on composite images, which are result of combining lots of high-quality photos of the corona, taken with a variety of instruments and settings. Lenses with different focal length and diversified exposure times reveal different parts of the corona, enhancing our comprehension of its morphology and its variations with solar activity (Figure 2).

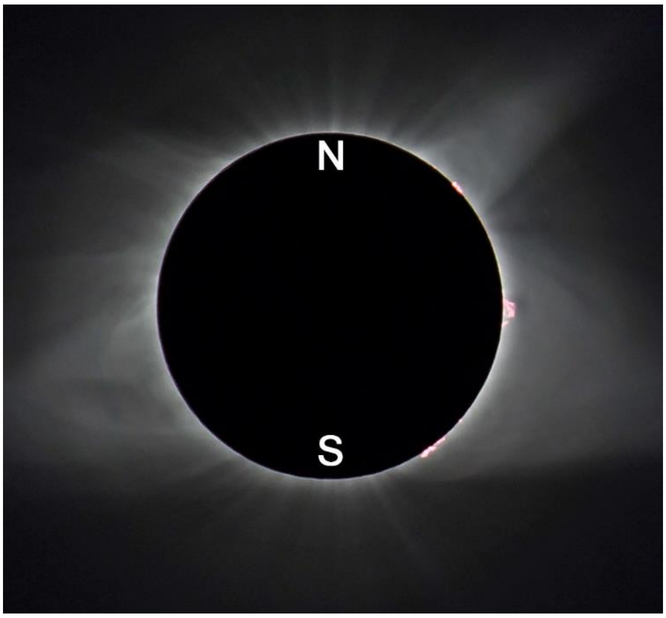

Figure 2. *A composite image of the corona from the TSE on 2017 August 21 (USA).*

Eclipse observations remain the sole method for capturing white-light data from the crucial lower and middle coronal regions as they host the formation of the solar wind and encompass the lower sections of coronal structures at least until coronal observations become feasible from the Moon or through tandem spacecraft equipped with a distant occulter [Pasachoff, 2017].

Polarimetric observations in white light allow scientists to separate the K-corona (arising from Thomson scattering by free electrons) from the F-corona (resulting from sunlight scattering by interplanetary dust). The intensity of the polarized light directly correlates with the number of free electrons along the line of sight, which enables mapping electron density distributions in the corona. Understanding how electron density varies across different regions of the corona is essential for pinpointing the sources of solar wind streams [Liang et al., 2023]. Electron density data, when combined with temperature and magnetic field measurements, help refine models of coronal heating mechanisms. Eclipse-based polarimetric observations often capture the inner corona, which is difficult to observe even with advanced spaceborne coronagraphs [Boe et al., 2021]. This provides unique, high-resolution data to improve and validate findings from space missions.

We obtain the polarimetric experiment during every expedition [Merzlyakov et al., 2019] collecting sufficient data that is about to be summarized. On Figure 3 we show the result of polarimetric observations of the corona during the eclipse in 2023 (Australia). Our data allowed separation of the polarized light or the so-called K-corona (right) from the total coronal white-light emission (left).

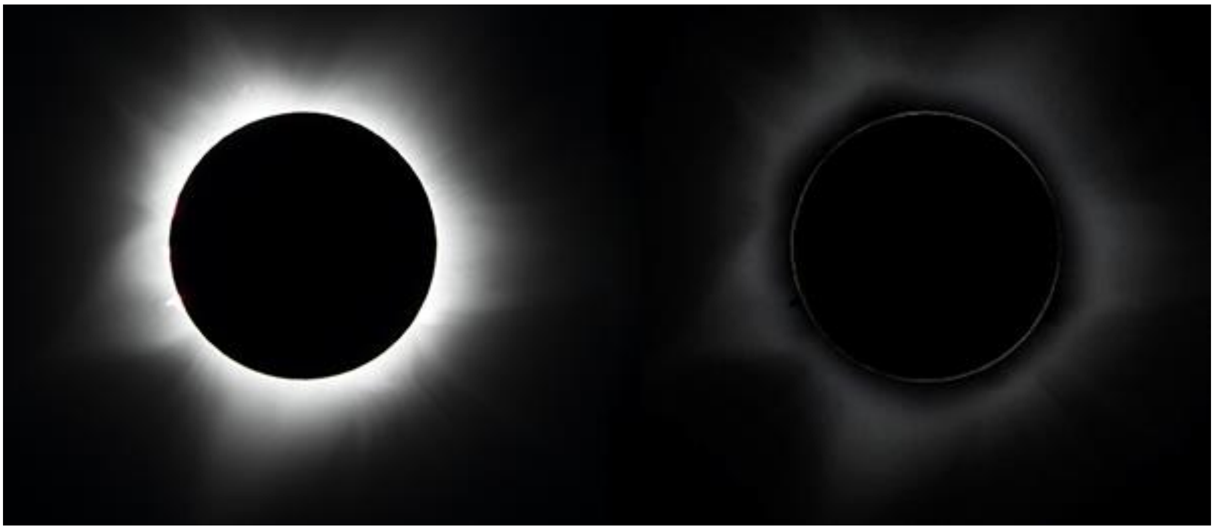

Figure 3. *White-light (left) vs. polarized (right) solar corona from the TSE on 20 April 2023 (Australia). Original images are taken with 600 mm lens and exposure time of 1/100 s.*

TSEs are not only interesting for the scientist studying the Sun, since they also have a noticeable impact on Earth's environment, particularly in terms of meteorological changes. During an eclipse, rapid fluctuations in solar radiation can lead to a temporary drop in temperature, changes in wind speed and direction, and variations in atmospheric pressure [Harrison and Hanna, 2016]. These phenomena often create localized cooling effects, providing valuable opportunities for studying atmospheric dynamics and the interplay between solar radiation and weather systems.

We tracked atmospheric conditions during every TSE, but since 2017 we included not only a temperature and humidity data logger, but also an anemometer measuring the wind velocity and direction. The biggest temperature drop we recorded during a totality happened in 2024 (Mexico) – 5.3 ^{o}C. A year earlier in 2023 (Australia) the temperature dropped 3.5 ^{o}C, while in 2019 (Chile) – only 1.6 ^{o}C.

On the other hand, by taking into account the meteorological parameters during the eclipse and comparing them to the shadow bands before and after the totality, we check the hypothesis about the role of the near-ground atmosphere on the shadow bands' patterns we observe. Since in this paper we are focused on the coronal research, more about our other experiments can be found in Zlatev et al. [2020].

In the future, we plan to continue working on the listed experiments in order to accumulate additional data that will help to obtain better quality results, as well as to add some new studies. For our next expedition, we plan to make a new attempt to register the outer boundary of the dust-free zone in the solar corona by detecting resonant emission of atoms and low-charged ions as a sign of the sublimation process of solid neutral particles from the S-corona.

4. Conclusions

TSEs remain invaluable events for advancing our understanding of the solar corona. Despite the significant progress made with spaceborne instruments, these natural phenomena still offer opportunities for observing regions of the corona that are otherwise inaccessible. The combination of high-resolution imaging, polarimetric data, and comprehensive observational campaigns during eclipses has contributed to refining our understanding of coronal structures, plasma dynamics and underlying physical processes. Additionally, eclipse observations continue to provide complementary data that enhance and validate findings from both theoretical models and space-based missions.

For more than quarter a century now our team organized 7 expeditions for observations of TSEs collecting in overall more than 20 minutes of totality for revealing the mysteries of the eclipsed Sun. In the near future our eyes are on the upcoming eclipse on 12 August 2026. This event will be particularly significant for mainland Europe, as it will be the first TSE visible there in the 21st century. The maximum duration of totality is expected to be approximately 2 minutes and 18 seconds with the point of greatest eclipse located between the coasts of Greenland and Iceland. We already started working on the organization of this expedition, since we consider the study of TSEs as a cornerstone of solar research, yielding crucial insights into one of the most dynamic and complex regions of the solar atmosphere.

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