PROCEEDINGS OF SCIENCE

Polarization of the Daytime Sky

Yovelina Zinkova[a,*], Tsvetan Tsvetkov[a], Ruslan Zlatev[b] and Nikola Petrov[a]

a Institute of Astronomy and National Astronomical Observatory, Bulgarian Academy of Sciences, 72 Tsarigradsko shose blvd., Sofia, Bulgaria

b Independent researcher

E-mail: yzinkova@nao-rozhen.org, tstsvetkov@astro.bas.bg, nick@astro.bas.bg

Polarization is a property of light widely used as a source of additional information in astronomy. The primary source of polarization in the atmosphere is the scattering by gas molecules although meteorological conditions, sky pattern, underlying surface reflectance, etc. may influence the observed sky polarization. In order to explicate polarization measurements correctly, it is important to understand how partially polarized skylight varies. We present results for the daytime sky degree of polarization. Our equipment includes linear polarization filter attached to a photo camera as well as digital polarization camera. We determine the dependence of polarized daylight on the peculiarities of the landscape, altitude of the observer and the season.

11th International Conference of the Balkan Physical Union (BPU11),
28 August - 1 September 2022
Belgrade, Serbia

*Speaker

PoS(BPU11)040

1. Introduction

Talking about light, we most often bear in mind the electromagnetic radiation perceptible to our eyes. We distinguish colors, recognize different light phenomena, we know the laws of light. But we limit our conception to the capabilities of our eyes including only the so-called visible range of the electromagnetic spectrum (380 and 750 nm). Anyway, we can definitely say that the wave theory of light presented by Augustin Jean Fresnel (1788–1827) in the nineteenth century is one of the outstanding achievements in the physics of light. Through this theory it is possible to explain phenomena like interference, diffraction and polarization of light, i.e., light is primarily characterized by its wavelength, intensity and polarization.

Now there is hardly a book on optics that does not include an interpretation of the problems of light, related to polarization. Despite not everyone might realize it, our knowledge on polarized light has many practical applications in our modern times, e.g. in applied physics and in astronomy. Christian Huygens (1629-1695) was the first one to claim that light was not a scalar quantity based on his work on the propagation of light through crystals. It turned out that light had "sides" (in the words of Newton). This vectorial nature of light was called polarization [1]. Polarized light can be produced from the common physical processes that deviate light beams (absorption, refraction, reflection, diffraction, scattering or birefringence). For more than 150 years, our knowledge of polarization has been a crucial part of revealing the nature of many observational phenomena. The first important step in science regarding our knowledge of the polarization of light was made by Sir George Gabriel Stokes (1819–1903) in the middle of the nineteenth century [2]. He presented for the first time a mathematical description of any state of polarized light. He showed that unpolarized light and partially polarized light can be described by the wave theory of light. And what's more, he found that any state of polarized light could be completely described by four measurable quantities now known as the Stokes polarization parameters. The polarization is a property that characterizes the geometrical orientation of the oscillation of the electric field of light. Linear polarized light, for example, is light that oscillates only in one plane perpendicular to the direction of propagation.

Part of our scientific tasks are also related to observations and analysis of astronomical events, based on the polarized light we receive. One of our main subjects of study is related to determining the degree of polarization of white-light solar corona during total solar eclipses [3]. It consists of several different components according to the formation of their emission – E-, K-, F- and T-corona (E-corona – emission corona, radiation from highly ionized atoms/particles in the corona; K-corona – "continuum" corona, scattering of photons (photospheric light) by electrons in the corona; F-corona – "Fraunhofer" corona, scattering of photospheric light by dust particles; T-corona – "thermal" corona, mainly IR emission from interplanetary dust). The intensity of the corona is mainly determined by the intensity of the K and F components, which determines a fundamental question related to defining the boundary between the electron and dust components. Polarization observations are a key method for determining the intensity and shape of the electronic component of the solar corona during total solar eclipses [4]. They solve the questions of the electron density and temperature distribution in the solar corona [5, 6]. The electron density, on the other hand, is directly related to the phase of solar activity. But in addition to the coronal changes during the 11-year solar cycle, we observe a variety of manifestations of solar activity such as chromospheric bursts, bulge eruption, flares, coronal mass ejections

(CMEs), etc. [7, 8]. The surrounding magnetic structure of active solar processes and the magnetic reconnections of these structures determine the electron density in the solar corona (in particular). This is what makes this task contribute to the clarification of the physical nature of interaction of the solar plasma with the corresponding magnetic fields.

For solving such observational problems, photographic methods of capturing the solar corona using linear polarization filters, Wollaston prism or Nicol prism were used until recently [4, 9]. These methods have shown their effectiveness and results, but they have some disadvantages. Mechanical inaccuracies, slowing down in frame acquisition process or in the calibration during processing can often happen. Modern digital cameras (used in last 30 years) offer some solutions to these problems, but do not solve them completely. We present our first observations using digital polarization camera on the daytime sky. We test if such cameras could be a good solution to our questions related to solar corona polarization during total solar eclipses.

2. Observations and results

The degree of polarization is one of the main properties of light. It can be a tool for solving questions with application in the modern industrial world. The possibilities of the new digital cameras, especially the polarization ones, are a new method of inspection with high precision and productivity. But also, such cameras could have applications in many scientific studies.

We did our first tests and evaluated the capabilities of SVS Vistek exo253ZGE polarization camera. It uses Sony CMOS type technology, which implies the possibility of precise short exposures up to 10 fps. Camera resolution is 12.3 MP (4096x3000 px) and pixel size is 3.45 x 3.45 µm. A four-directional polarization square filter array is overlaid directly on top of the pixel array and beneath the micro lenses (Figure 1). It consists of repeated 2x2 patterns of grid polarizers with four different angles at 0°, 45°, 135° and 90°. Each polarizer filters the incoming light so only the polarization components perpendicular to the grid orientation can pass through and be detected by the underlying photodiode. Thus, a four directional polarization image can be captured in one shot.

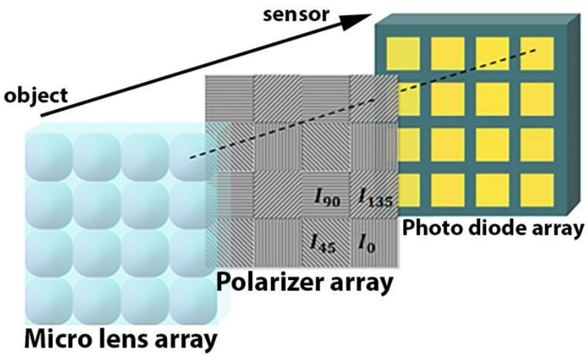

Figure 1. Scheme of the four-directional polarization square filter array – 2x2 filter array with 4 polarization grid orientations (Source: https://www.svs-vistek.com/en).

Our first experiments with the polarization camera were performed during the day with a last quarter moon on 2022 August 19, 07:30 UT. It is well-known that the moonlight is partially linearly polarized except at full moon, when it is unpolarized [10]. It becomes polarized after scattering off gas molecules in the upper layers of Earth's atmosphere. The observations were obtained at the National Astronomical Observatory (NAO) Rozhen at altitude of 1730 m, clear (cloudless) sky, 50% relative humidity (average for the time of the experiment). First of all, our goal was to evaluate the field of view for lenses with different focal lengths (for 70 mm lens and 200 mm lens) that we usually use during total solar eclipses. For the day of our experiment angular separation between the centers of solar and lunar disk was 90°. This implies maximum values for the degree of polarization in the central part of the lunar disk, as well as in the daytime sky around the Moon. The average value of the degree of polarization of the daytime sky during our experiment is 60% for the two optical systems. The error we determine based on the average noise deviation is ±1%. The highest value of polarized light from the central illuminated part of the lunar disk reaches a value of 45%. The polarization angle of both the daytime sky and the lunar disk is +15°. These results are shown in Figure 2 that includes raw image, polarization degree image, and polarization angle (from left to right). The image was obtained with a 200 mm lens for better resolution and better visualization, but the polarization parameters do not change when using a 70 mm lens. In the extreme areas around the limb of the lunar disc, areas not corresponding to real values are noticed – these are overexposed areas.

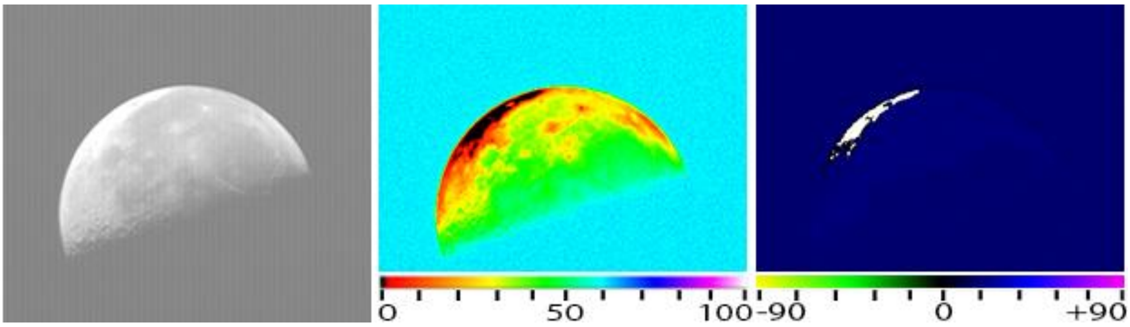

Figure 2. Raw black and white image of the Moon (left), the same image but after transformation, showing a sky polarization gradient of about 60% and in the central part of the lunar disk about 45% (center) and again the same image, but after transformation for polarization angle - almost constant: + 15° (right).

We performed another experiment to determine the polarized light of the daytime sky over a large time interval (from 7:30 to 15:30 UT). The skylight is partially polarized, due to the sunlight scattered by the atmospheric particles, air molecules, water, dust, and aerosols. According to the Rayleigh scattering theory, the polarization pattern of skylight is mainly determined by the solar position. Again the same 70 mm and 200 mm lenses were used (Figure 3). The degree of polarization was determined as an average of the values measured in five squares (5x5 px each) – one located in the center at each image and four at a distance of 500 px (for 70 mm image) and 175 px (for 200 mm image) in four directions (above, below, left and right) from the central square. During the observations, the optical systems were constantly pointed to the north, 40° above the horizon. The expected changes in degree of polarization and angle of polarization should be determined solely by the movement of the Sun across the sky, other atmospheric conditions being constant. Unfortunately, after 9:00 UT cumulus clouds began to appear in the sky. Despite moments of clear sky in the shooting areas, our treatments show non-uniform deviations in time.

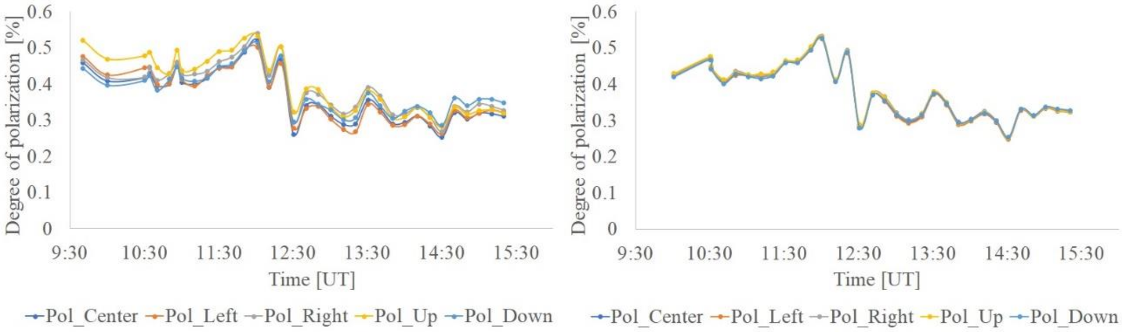

Figure 3. Total results for degree of polarization for all 33 images taken in period of 6 hours on 2022 August 19 from NAO Rozhen with 70 mm (left) and 200 mm lens (right).

Due to the different focal length of the lenses, we obtained slight offsets for the values of the degree of polarization at the shorter focal lens (70 mm) for different parts of the sensor's matrix – up to 6%. With longer focal length, the lens did not show such error. In experimental observations of the Moon during the full moon on 2022 September 30 with 70 mm, 200 mm and 600 mm focal length, we obtain the same values for the degree of polarization (Figure 4).

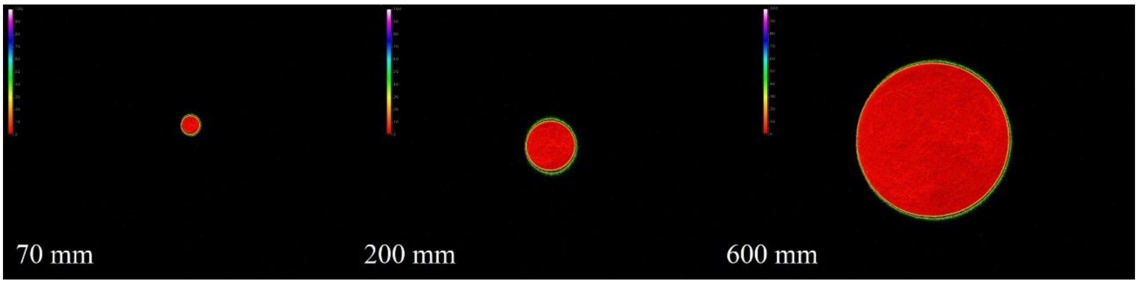

Figure 4. The degree of polarization using different lenses.

The reflected sunlight during a full moon is important to us because it is comparable to the intensity of the solar corona during a total solar eclipse. With the images obtained with the 600 mm lens, a more detailed investigation of the areas of lunar surface is possible. The values of the degree of polarization are in the interval 0.5-4%. This corresponds to the results obtained by other researchers [11]. Of course, here we pay more attention to the technical capabilities of the polarization camera, and a detailed study is our upcoming task.

3. Conclusions

Our tests of the polarization camera for solving scientific tasks demonstrate promising results. The usage of such camera for astronomical purposes seems plausible. First results of our experiments show that the camera could be used for photographing total solar eclipses. Benefits of this method are simultaneous observations at four different angles of polarization, time saving and error reducing. For polarized observations of solar eclipses, it is important to use lenses with longer focal length to reduce the influence of the position of the corona on the image. As with other sensors, light coming from a large angle of incidence will create crosstalk between the pixels and worsen the image. To prevent the crosstalk, we recommend using a larger focal length and/or a smaller aperture.

When studying the direction of polarization, the value may change depending on the angle of incidence. However, this is not the only factor. The angle of the object, the F-number of the lens and the polarization of the light source also have an impact. Finally, the results depend on the entire system and its application.

Acknowledgements

This study is supported by the National Science Fund of Bulgaria with contract No. KP- 06-H28/4 and the joint project of cooperation between IANAO, Bulgarian Academy of Sciences and the Department of Astronomy, Faculty of Mathematics, University of Belgrade, Serbian Academy of Sciences and Arts P-04/04.02.2020.

References

[1] D. Goldstein, 2003, *Polarized Light Second Edition*, Marcel Dekker Inc., Chapter 3.

[2] G. G. Stokes, 1851, *On the Composition and Resolution of Streams of Polarized Light from different Sources*, *Trans. Cambridge Philos. Soc.* **9**, 399.

[3] V. L. Merzlyakov, Ts. Tsvetkov, L. I. Starkova, R. Miteva, 2019, *Polarization of White-Light Solar Corona and Sky Polarization Effect During Total Solar Eclipse on March 29, 2006*, *SAJ* **199**, 83-87.

[4] M. Schmidt, 1953, *Brightness, polarization and electron density of streamers in the solar corona*, *BANS* **12**, 61.

[5] K. Saito, M. Makita, K. Nishi, S. Hata, 1970, *A non-spherical axisymmetric model of the solar K corona of the minimum type*, *Ann Tokyo Astron Obs*., *2nd ser.* **12** (2), 51-173.

[6] O. G. Badalyan, 1996, *Temperature and Density in the Middle Corona Through the Activity Cycle Determined from White Light Observations*, *AApTr* **9** (3), 205-223.

[7] Ts. Tsvetkov, R. Miteva, N. Petrov, 2018, *On the relationship between filaments and solar energetic particles, JASTP* **179**, 1-10.

[8] Ts. Tsvetkov, N. Petrov, 2020, *Quasiperiodic Velocity Fluctuations in Eruptive Prominences Observed by AIA/SDO, ApJ* **893** (1), id.40, 7.

[9] W. M. Cohn, 1938, *Polarization of the Solar Corona in the Total Eclipses of 1932 and 1934*, *ApJ* **87**, 284.

[10] S. F. Pellicori, 1971, Polarizing properties of pulverized materials with special reference to the lunar surface, Applied Optics 10, 270 – 285.

[11] M. Jeong et al., 2015, *Multi-Band Polarimetry of the Lunar Surface. I. Global Properties, ApJS* **221**,16.