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# Polarization neutral point pairs of the solar corona and the lunar disc observed during the total solar eclipse on 11 August 1999 in Hungary

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**During the total solar eclipses on 11 August 1999 in Kecel (Hungary) and on 29 March 2006 in Side (Turkey), two Hungarian groups performed full-sky imaging polarimetric measurements of the eclipsed sky. They observed the spatiotemporal change of the celestial polarization pattern and detected three polarization neutral points as well as two points with maximal polarization of the sky. Parallel to these studies, the polarization pattern in front of the lunar disc, the solar corona, and the surrounding sky have also been measured. During the total solar eclipse on 21 August 2017 in the USA (Rexburg–Idaho, Madras–Oregon), three American/international groups have measured the polarization characteristics of the full sky and the solar corona. The first group observed the spatiotemporal variation of the celestial polarization pattern, and the second group detected three polarization neutral points of the sky and observed two neutral points of the solar corona. The latter were named as Minnaert and van de Hulst neutral points. The third group observed two neutral points of the lunar disc. We have reanalyzed the earlier polarization patterns of the lunar disc, solar corona, and the surrounding sky measured during the Hungarian total eclipse on 11 August 1999. In these reanalyzed polarization patterns, all four neutral points observed during the eclipse on 21 August 2017 in the USA occur: the Minnaert/van de Hulst neutral point pair above/below the eclipsed Sun, where coronal polarization is canceled by sky polarization, and the northern and southern (unnamed) neutral points of the lunar disc, where the directions of polarization of coronal light and foreground skylight are perpendicular to each other with the same polarized intensity. We name the latter two polarization neutral points after Coulson and Vorobiev.** 

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## 1. INTRODUCTION

The investigation of the solar corona is very popular both in the scientific and amateur astronomy communities. This is because from the coronal characteristics conclusions can be drawn about solar activity, and some predictions of theoretical calculations and numerical simulations can be tested [1]. A brief review of the earlier polarization studies of the solar corona during eclipses is given in the Appendix A. The coronal light is composed of photons that are Thomson-scattered on free electrons and dust particles [2]. This scattered light is seen as a corona in the neighborhood of the Sun during total solar eclipses. The solar corona visible from the Earth's surface during total eclipses or through coronographs of high-altitude astronomical observatories or satellites has been the subject of many investigations [3–17]. On the basis of the polarization pattern of the solar corona, the electron density around the Sun can be calculated [13], which is an important parameter in solar physics. The polarization pattern of the corona changes from eclipse to eclipse, and it is an important part of the data basis related to the history of the Sun [1].

During the total solar eclipse on 11 August 1999 in Kecel (Hungary), Pomozi *et al.* [18] and Horváth *et al.* [19,20] performed the first successful full-sky imaging polarimetric measurements of the eclipsed sky: they observed the temporal change of the celestial polarization pattern and detected three polarization neutral points of the sky, one near the zenith and two near the horizon along the antisolar meridian. Parallel to this full-sky polarization imaging, they also measured the polarization pattern in front of the lunar disc eclipsing the Sun, the solar corona, and the surrounding sky. Some preliminary results of this corona observation have been published in a Hungarian paper [19] and in an English book chapter [21]. They demonstrated the well-known tangential (i.e., along a circle centered on the Sun eclipsed by the Moon) direction of polarization of the corona, the nearly homogeneous direction of polarization of the sky foreground dominating in the central region of the lunar disc, and the celestial area farther from the eclipsed Sun and the corona.

The full-sky imaging polarimetric measurements of this Hungarian group have been repeated successfully during the total solar eclipse on 29 March 2006 in Side (Turkey) by another Hungarian research group [22]: they registered again the spatiotemporal variation of sky polarization in much detail and observed the same three neutral points of the sky as detected in 1999 in Kecel (Hungary). Furthermore, they reported about two celestial points with maximal polarization.

These pioneering full-sky imaging polarimetric observations were fruitfully continued on 21 August 2017, when two American-international research groups successfully measured the polarization patterns of the full sky during the total solar eclipse in Rexburg (Idaho, USA) [23,24]. Eshelman *et al*. [23] observed very fine details of the spatiotemporal change of the polarization pattern of the sky and detected similar three neutral points as the Hungarian researchers in 1999. These observations confirmed that previously observed totality patterns [20,22] are general and not unique for each eclipse. Eshelman *et al*. [23] observed the transition of the neutral point from the zenith in totality to the normal Babinet point above the Sun after the third contact.

As a novelty compared to the eclipse observations in 1999 [18–20] and 2006 [22], Snik *et al*. [24] observed two polarization neutral points of the solar corona in Rexburg (Idaho, USA). Both neutral points were the result of the combination of the polarization patterns of the corona and the foreground atmosphere. They were named by Snik *et al*. [24] as Minnaert and van de Hulst neutral points after Marcel Gilles Jozef Minnaert (1893–1970) and Hendrik Christoffel van de Hulst (1918–2000), who both were famous researchers of the polarized solar corona [25,26] and atmospheric scattering [27–29].

As another novelty compared to the corona observations of Horváth *et al*. [19] and Horváth and Varjú [21], Vorobiev *et al*. [3] observed two neutral points of the lunar disc during the total solar eclipse on 21 August 2017 in Madras (Oregon, USA). Because the field of view of the imaging polarimeter of Vorobiev *et al*. [3] was only $63' \times 63'$, they could not observe the Minnaert and van de Hulst neutral points.

When the first author (G.H.) of this paper had reviewed the manuscripts of Eshelman *et al*. [23] and Snik *et al*. [24], he decided to reanalyze the polarization patterns of the solar corona measured in 1999 in Kecel (Hungary). In this work, the results of this analysis are presented.

## 2. MATERIALS AND METHODS

The details of the total solar eclipse on 11 August 1999 in Kecel (Hungary) have been described elsewhere [18,20]. Here, we mention only that the corona polarization measurements have been performed in the immediate vicinity of the Hungarian village Kecel (46°32′N, 19°16′E) during the totality between 12:51:34 [local summer time = Universal Time Coordinated (UTC) + 2 h, second contact] and 12:53:56 (third contact). The time of mid-totality was 12:52:45 at a solar zenith distance of 32°. Furthermore, during the 11 August 1999 eclipse, the sky was very clear after the passage of a cold front. This circumstance was important, because the Hungarian researchers [18,20] performed temporally-modulated observations, which are vulnerable to errors when the skylight has temporal changes.

Using an exposure of 1/60 s, three polarization pictures were taken onto a Fujichrome Sensia II. (400 ASA) color reversal film about the lunar disc, solar corona, and sky foreground with a Nikon F801 camera equipped with a rotatable neutral density (grey) circular polarizer (Hama, mounted dichroic sheet polarizer, diameter = 62 mm, filtering linear polarization and converting it to circular polarization) and a refractive teleobjective (AF Nikkor, focal length = 75−300 mm zoom, $F = 4.0-5.6$, lens diameter = 62 mm). These three pictures taken with the same exposure corresponded to three different polarizer orientations (0°, 45°, 90° from the vertical). We have kept the teleobjective at 300 mm (at $F = 5.6$) with a field of view of about $2° \times 2°$. During the evaluation of the scanned (8 bit digitized, 700 pixel × 700 pixel, angular size of each pixel $= 2°/700 = 10.3''$) pictures, we selected the best recordings having the least over- and/or under-exposures. This best picture trio was taken at 12:52:35 very near to mid-totality (12:52:45). If the 8 bit digitized intensity value $0 \le I \le 255$ of a pixel in a given spectral [red (R), green (G), or blue (B)] range was smaller than 5, this pixel was considered to be underexposed, and if $I$ was larger than 250, the pixel was considered to be overexposed. In the best polarization picture trio, only the innermost annular region of the brightest part of the solar corona was overexposed, and under-exposure did not occur in the lunar disc or the surrounding sky.

Our rotating-analyzer film-camera-based photo-polarimeter was set on a tripod. The azimuth direction of the camera's optical axis was turned up to the azimuth of the solar meridian. Then, using a spirit-level (bubble-tube) fixed onto the camera's house, we oriented horizontally the camera's flat bottom. Finally, we elevated the optical axis of the camera up to the Sun so that the Moon-eclipsed solar disc got in the center of the camera's field of view. Thus, the left and right margins of the polarization pictures taken about the lunar disc, corona, and surrounding sky became vertical with an accuracy of ±0.5°. The effectively linear polarizer's transmission axis was aligned to $\beta = 0°$, 45°, and 90° relative to the vertical (= solar meridian) being parallel to the bottom-to-top axis of the camera, and the pictures were taken to ensure a modulation for linear polarization with the minimum three measurements. These three alignments were oriented manually with the rotation of the circular filter frame (containing three holes at 0°, 45°, and 90°, into which a spring-pressed small metal sphere could deepen) that ensured always the same ($\beta = 0° \pm 0.1°$, $45° \pm 0.1°$, $90° \pm 0.1°$) orientations of the polarizer. The local average degree $p_{\mathrm{ave}}$ and angle $\alpha_{\mathrm{ave}}$ of linear polarization were determined with averaging the digitized $I_\beta$ pixel-values (belonging to a given angle $\beta = 0°, 45°, 90°$ of the polarizer's transmission axis) in a window of $N$ pixel × $N$ pixel, then $p_{\mathrm{ave}}$ and $\alpha_{\mathrm{ave}}$ were calculated with the use of these averaged $I_{\beta,\mathrm{ave}}$ values. In the lunar disc,

$N$ was 6, whereas in the corona and the surrounding sky, $N$ was 12. The scanning, pixel-precise co-alignment and evaluation of the photographs were the same as in the case of the full-sky polarization pictures taken during the total solar eclipse on 11 August 1999 in Kecel (Hungary) [18,20,22].

A partial polarimetric calibration was performed using an external rotatable linear polarizer (XP42-18 from ITOS, Mainz, Germany) transilluminated by unpolarized white light of a 500 W incandescent lamp. At the start, 10 depolarizing sand-abraded matte glass sheets were placed in the light beam between the lamp and the polarizer. Transposing more and more depolarizers from their original position to between the polarizer and the polarimeter, the degree of linear polarization $p$ of light received by the polarimeter could be decreased stepwise from 100% to 0%. The reproducibility error $\Delta\alpha$ of the angle of polarization $\alpha$ obtained during this calibration was smaller than $\pm 1°$ for $20\% \leq p \leq 100\%$, and $\Delta\alpha$ was not larger than $\pm 2°$ for $5\% \leq p \leq 20\%$. The reproducibility error $\Delta p$ of the degree of polarization $p$ was smaller than $\pm 1\%$ for $20\% \leq p \leq 100\%$, and $\Delta p$ was not larger than $\pm 2\%$ for $5\% \leq p \leq 20\%$. Radiometric calibration was not performed.

The red, green, and blue sensitivity maxima $\pm$ bandpass ($\lambda_{max} \pm \Delta\lambda$) of the used color reversal film (Fujichrome Sensia II, 400 ASA) were $650 \pm 30$ nm (red), $550 \pm 30$ nm (green), and $450 \pm 50$ nm (blue). The sensitivity curves of the R, G, B CCD sensors of the scanner (Hewlett-Packard ScanJet 6100C) had the following features: $660 \pm 40$ nm (R), $545 \pm 40$ nm (G), $450 \pm 40$ nm (B). Because the $\lambda_{max}$ and $\Delta\lambda$ values of the film and the scanner were very similar, the scanning procedure kept the spectral properties of the film. Thus, our polarimetry reflects well the polarization characteristics of a target (e.g., sky) in the R ($650 \pm 30$ nm), G ($550 \pm 30$ nm), and B ($450 \pm 50$ nm) range of the visible spectrum.

Because the best polarization pictures (with minimal underexposed and overexposed areas) were taken in the G ($550 \pm 30$ nm) spectral range, we present here only the polarization patterns in the green part of the spectrum. The polarization patterns were quite similar in the R ($650 \pm 30$ nm) and B ($450 \pm 50$ nm) spectral ranges.

## 3. RESULTS

Figure 1(A) shows the photograph of the lunar disc, solar corona, and the surrounding sky at 12:52:35 practically coinciding with the mid-totality (12:52:45) on 11 August 1999 in Kecel (Hungary). Although the lunar disc and the periphery of the picture are dark, they were not underexposed; thus, we could evaluate their three polarization pictures. Figure 1(B) displays the pattern of the degree of linear polarization $p$ measured in the G (550 nm) spectral range. The $p$-pattern of the corona was approximately rotational symmetric with some radial and tangential changes. As discussed by Vorobiev *et al*. [3], larger deviations from an exactly tangential direction of polarization pattern cannot occur in an optically thin corona. The small deviations from the ideally tangential polarization pattern observed by us in the solar corona during the eclipse on 11 August 1999 may be explained by the inevitable noise of the used film-based polarimetric technique.

Figure 2 represents the radial change of $p$ along lines tR and bL in Fig. 1(B) both directed $+5°$ clockwise from the vertical solar meridian measured in the G (550 nm). The maximum of $p$ was $p_{max} \approx 35\%$ at relative radius $\rho \approx +1.77$ (Fig. 2(A)) and $p_{max} \approx 31\%$ at $\rho \approx -1.75$ (Fig. 2(B)). The central circular region of the lunar disc had $p \approx 10\%$ which decreased to nearly zero in points $M_{North}$ and $M_{South}$ at $\rho(M_{North}) \approx +0.75$ and $\rho(M_{South}) \approx -0.71$ (Fig. 2). These points are the polarization neutral points observed also by Vorobiev *et al*. [3] during the total solar eclipse on 21 August 2017 in Madras (Oregon, USA). The surrounding sky had $p \approx 20\%-23\%$ which decreased to a minimum of approximately zero in points $C_{North}$ and $C_{South}$ at $\rho(C_{North}) \approx +2.27$ and $\rho(C_{South}) \approx -2.27$ (Fig. 2). With further decreasing relative radius after both neutral points, $p$ increased up to its maximum $p_{max}$ mentioned previously. The northern and southern neutral points $C_{North}$ and $C_{South}$ of the solar corona are the so-called Minnaert point and van de Hulst point, respectively, observed by Snik *et al*. [24] on 21 August 2017 in Rexburg (Idaho, USA).

Figure 1(C) shows the pattern of the direction (angle $\alpha$) of polarization of the lunar disc, solar corona, and their celestial surrounding measured in the G (550 nm). The direction of polarization of coronal light were approximately perpendicular to the radial direction, that is to the scattering plane. The slight tangential change of the angle of polarization $\alpha$ was due to the non-homogeneous structure of the corona. The surrounding sky and the circular central region of the lunar disc had an approximately homogeneous distribution of the direction of polarization with an angle $\alpha \approx +5°$ clockwise from the vertical solar meridian. On the other hand, the corona had tangential directions of polarization being nearly perpendicular to the local radius crossing the center of the lunar disc.

Figure 3 displays the radial change of the angle of polarization $\alpha$ along lines tR and bL in Fig. 1(C) both directed $+5°$ clockwise from the vertical solar meridian measured in the G (550 nm). Crossing the northern and southern neutral points $C_{North}$ and $C_{South}$ of the solar corona at $\rho \approx +2.27$ (Fig. 3(A)) and $\rho \approx -2.27$ (Fig. 3(B)), respectively, the average $\alpha$ changes by 90°. The points $C_{North}$, $C_{South}$, $M_{North}$, and $M_{South}$ with minimum degree of linear polarization $p_{min} \approx 0\%-1\%$ (Fig. 2) can be considered as true neutral points, because the angle of polarization $\alpha$ changes by 90° (meaning a topological singularity) when crossing them along the radial lines tR and bL, respectively (Fig. 3).

Figure 1(D) represents the pattern of the direction of polarization of the lunar disc measured in the G (550 nm). Similar to the corona, the annular periphery of the lunar disc possessed nearly tangential direction of polarization, whereas the circular central lunar area had a nearly constant direction of polarization with angle of polarization $\alpha \approx +5°$ clockwise from the vertical solar meridian. Along lines tR and bL in Fig. 1(D) tilted by $+5°$ from the vertical solar meridian, the average $\alpha$ of the lunar disc changed by 90° in both the northern and southern neutral points $M_{North}$ and $M_{South}$ at $\rho \approx +0.75$ (Fig. 3(A)) and $\rho \approx -0.71$ (Fig. 3(B)), respectively.

The polarization characteristics of the corona were practically independent of the wavelength of light in the visible range of the spectrum. In August 1999, the activity of the Sun

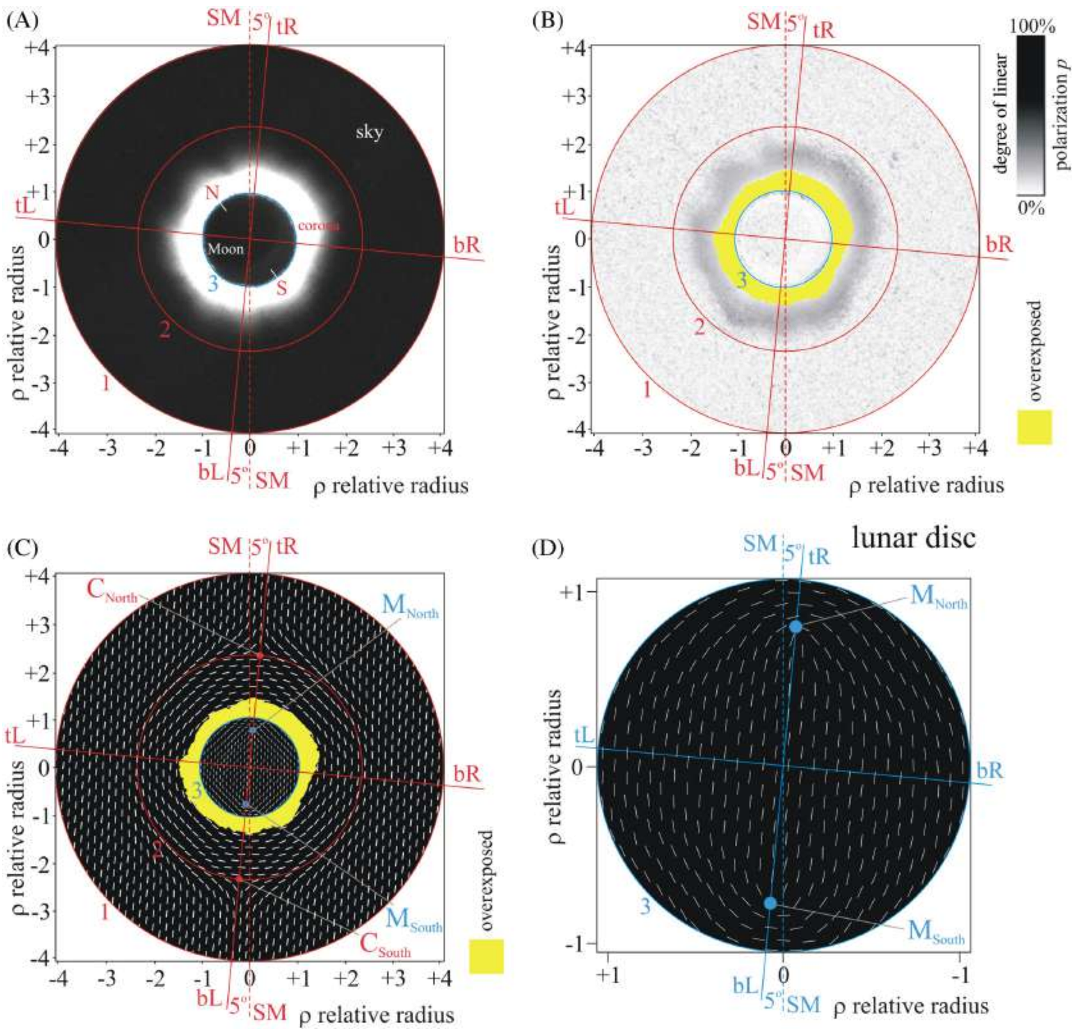


**Fig. 1.** (A) The lunar disc, the bright solar corona, and the surrounding sky photographed at 12:52:35 (= local summer time = UTC + 2 h) practically coinciding with the mid-totality (12:52:45) of the solar eclipse on 11 August 1999 in Kecel (46°32′N, 19°16′E, Hungary). In the lunar disc the North and South poles of the eclipsed Sun are marked by N and S. $\rho = r/r_{\mathrm{Moon}}$ is the relative radius, where $r_{\mathrm{Moon}}$ is the radius (in pixel) of the lunar disc, and $r$ is the radius (in pixel) from the center of the lunar disc. (B) Pattern of the degree of linear polarization $p$ measured in the green (550 nm) spectral range. (C) Pattern of the direction of polarization (white bars) measured in the green. $C_{\mathrm{North}}$: Minnaert neutral point of the corona (top right red dot). $C_{\mathrm{South}}$: van de Hulst neutral point of the corona (bottom left red dot). In panels B and C: the overexposed brightest part of the solar corona is shown by the yellow annulus. (D) Pattern of the direction of polarization (white bars) of the lunar disc measured in the green. $M_{\mathrm{North}}$: northern neutral point of the lunar disc (top right blue dot, suggested name: Coulson point). $M_{\mathrm{South}}$: southern neutral point of the lunar disc (bottom left blue dot, suggested name: Vorobiev point). In panels A–C: The outermost circle 1 represents the field of view of the camera. The innermost circle 3 is the perimeter of the Moon's disc. $C_{\mathrm{North}}$ and $C_{\mathrm{South}}$ are positioned approximately at the cross-points of lines tR, bL, and circle 2. In panels A–D: the dashed line SM represents the vertical solar meridian. Lines tR and bL cross the center of the lunar disc and are parallel to the average direction of polarization of the sky foreground that dominates the sky periphery and the central region of the lunar disc. Lines tL and bR are perpendicular to lines tR and bL and also cross the lunar disc's center.

was high, when the structure of the solar corona was relatively homogeneous and rotation symmetric, as is the usual case.

## 4. DISCUSSION

During total solar eclipses, polarization neutral points can occur where the tangential linear polarization of coronal light is canceled by the locally approximately homogeneous polarization of the foreground skylight. Although hints of such neutral points have been reported in [19,21,30–32], the first detailed observation of them above and below the eclipsed Sun (lunar disc) was published in [24] and their appearance within the lunar disc was reported in [3].

Although the total solar eclipse on 21 August 2017 in Rexburg (USA) [3,23,24] happened during a solar minimum, on 11 August 1999 in Kecel (Hungary), the activity of the Sun was near to its maximum [18,20]. For this case, a nearly rotational symmetric solar corona is typical. Furthermore, the polarization patterns presented here were measured at 12:52:35 almost coinciding with the mid-totality (12:52:45) in Kecel (46°32′N, 19°16′E, Hungary), when the light distribution of the lunar disc was also approximately rotation symmetric.

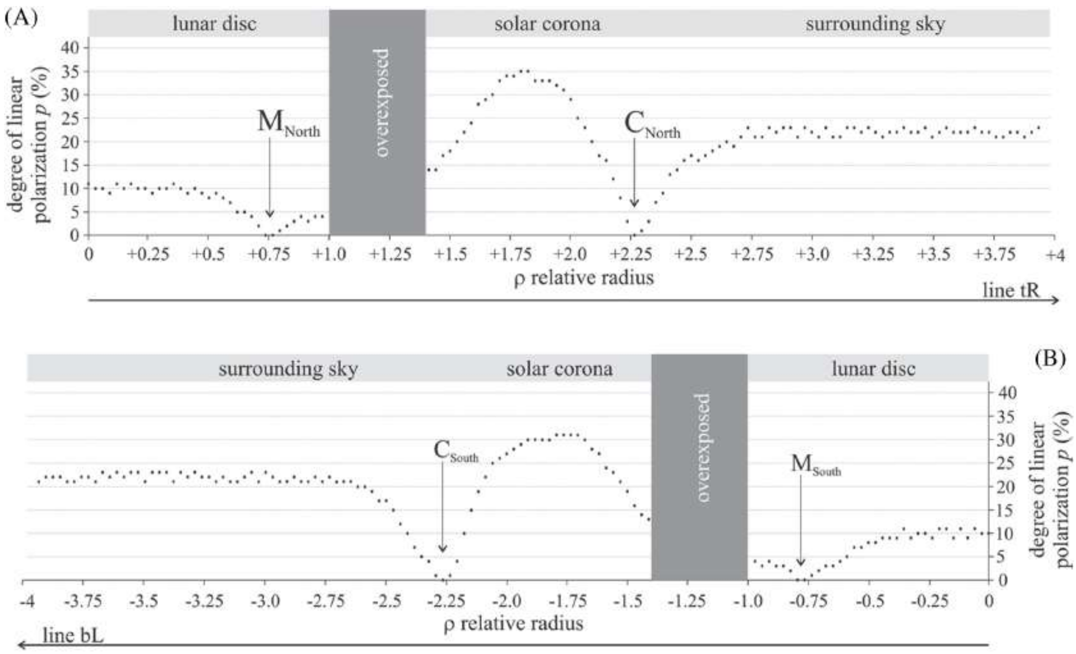


**Fig. 2.** (A) Degree of linear polarization $p$ (%) as a function of the relative radius $\rho = r/r_{\text{Moon}}$ along line tR in Fig. 1(B), where $r_{\text{Moon}}$ is the radius (in pixel) of the lunar disc, and $r$ is the radius (in pixel) from the center of the lunar disc. $p$ is minimal (approximately zero) at the neutral points $M_{\text{North}}$ (northern neutral point of the lunar disc) and $C_{\text{North}}$ (northern neutral point of the solar corona). $M_{\text{North}}$ and $C_{\text{North}}$ are at $\rho(M_{\text{North}}) \approx +0.75$ and $\rho(C_{\text{North}}) \approx +2.27$. (B) Degree of linear polarization $p$ (%) along line bL in Fig. 1(B). $p$ is minimal (nearly zero) at the neutral points $M_{\text{South}}$ (southern neutral point of the lunar disc) and $C_{\text{South}}$ (southern neutral point of the solar corona). $M_{\text{South}}$ and $C_{\text{South}}$ are at $\rho(M_{\text{South}}) \approx -0.71$ and $\rho(C_{\text{South}}) \approx -2.27$.

These rotation symmetric light conditions may be the main reason for the central symmetric positions of the observed neutral point pairs $C_{\text{North}}/C_{\text{South}}$ and $M_{\text{North}}/M_{\text{South}}$ relative to the center of the lunar disc (Figs. 1(C), 1(D), 2, and 3).

According to Snik *et al*. [24] and Vorobiev *et al*. [3], during the totality of solar eclipses, the net celestial polarization is the result of the superposition of the polarization of coronal light and foreground skylight. At mid-totality of the eclipse on 11 August 1999 in Kecel (Hungary), the angle of polarization of the sky foreground was $\alpha \approx +5°$ from the vertical solar meridian in both the central region of the lunar disc and the surrounding sky within the field of view of our polarimeter. This homogeneous polarization was combined with the tangential polarization of the solar corona. One of the consequences of this combination was the appearance of the polarization neutral point pair $M_{\text{North}}$ and $M_{\text{South}}$ of the lunar disc as well as the neutral point pair $C_{\text{North}}$ and $C_{\text{South}}$ of the solar corona (Figs. 1(C), 1(D), 2, and 3) where the coronal polarization was canceled by the polarization of sky foreground. The northern neutral point $C_{\text{North}}$ and the southern neutral point $C_{\text{South}}$ observed above and below the eclipsed Sun during the eclipse on 21 August 2017 in Rexburg (Idaho, USA) were named by Snik *et al*. [24] as Minnaert point and van de Hulst point, respectively. Vorobiev *et al*. [3] and we in the present work observed that the sky polarization in front of the Moon has lower degrees of polarization than elsewhere. This effect hints at some depolarization due to scattered coronal light.

Although the anonymous neutral points $M_{\text{North}}$ and $M_{\text{South}}$ of the lunar disc have been also observed by Vorobiev *et al*. [3] during the 21 August 2017 eclipse in Madras (Oregon, USA), they did not suggest names of them. Because both neutral points have also been detected in the polarization patterns measured on 11 August 1999 in Kecel (Hungary) and presented in this work, we suggest naming $M_{\text{North}}$ the "Coulson neutral point" after the late Kinsell L. Coulson (1916-1999). He was a famous meteorologist of various celestial and astronomical polarization phenomena, including solar eclipses [33–39]. We also propose naming $M_{\text{South}}$ the "Vorobiev neutral point" after Dmitry Vorobiev, because he and his colleagues have first reported on it [3].

During the eclipse on 21 August 2017 in Rexburg (Idaho, USA), Snik *et al*. [24] observed the Minnaert ($C_{\text{North}}$) and van de Hulst ($C_{\text{South}}$) neutral points of the solar corona at relative radii $\rho(C_{\text{North}}) \approx +3$ and $\rho(C_{\text{South}}) \approx -3$, whereas we detected these points at $\rho(C_{\text{North}}) \approx +2.27$ and $\rho(C_{\text{South}}) \approx -2.27$ (Fig. 2). On the other hand, on 21 August 2017 in Madras (Oregon, USA) Vorobiev *et al*. [3] observed the northern $M_{\text{North}}$ and southern $M_{\text{South}}$ neutral points of the lunar disc at $\rho(M_{\text{North}}) \approx +0.75$ and $\rho(M_{\text{South}}) \approx -0.75$, whereas we detected these points at $\rho(M_{\text{North}}) \approx +0.75$ and $\rho(M_{\text{South}}) \approx -0.71$ (Fig. 2). Snik *et al*. [24] detected nearly ($\pm 1°$) vertical (= solar meridian) polarization of the sky foreground in Rexburg (Idaho, USA), whereas Vorobiev *et al*. [3] observed a foreground sky polarization tilted by 7° (B) and 18° (R) anti-clockwise from the vertical in the central region of the lunar disc in Madras (Oregon, USA). During the eclipse on 11 August 1999 in Kecel (Hungary), the polarization of the sky foreground was tilted about 5° clockwise (G) from the vertical solar meridian both in the central region of the lunar disc and the surrounding sky (Figs. 1(C), 1(D), and 3). On 21 August 2017, the maximum degree of polarization of the solar corona

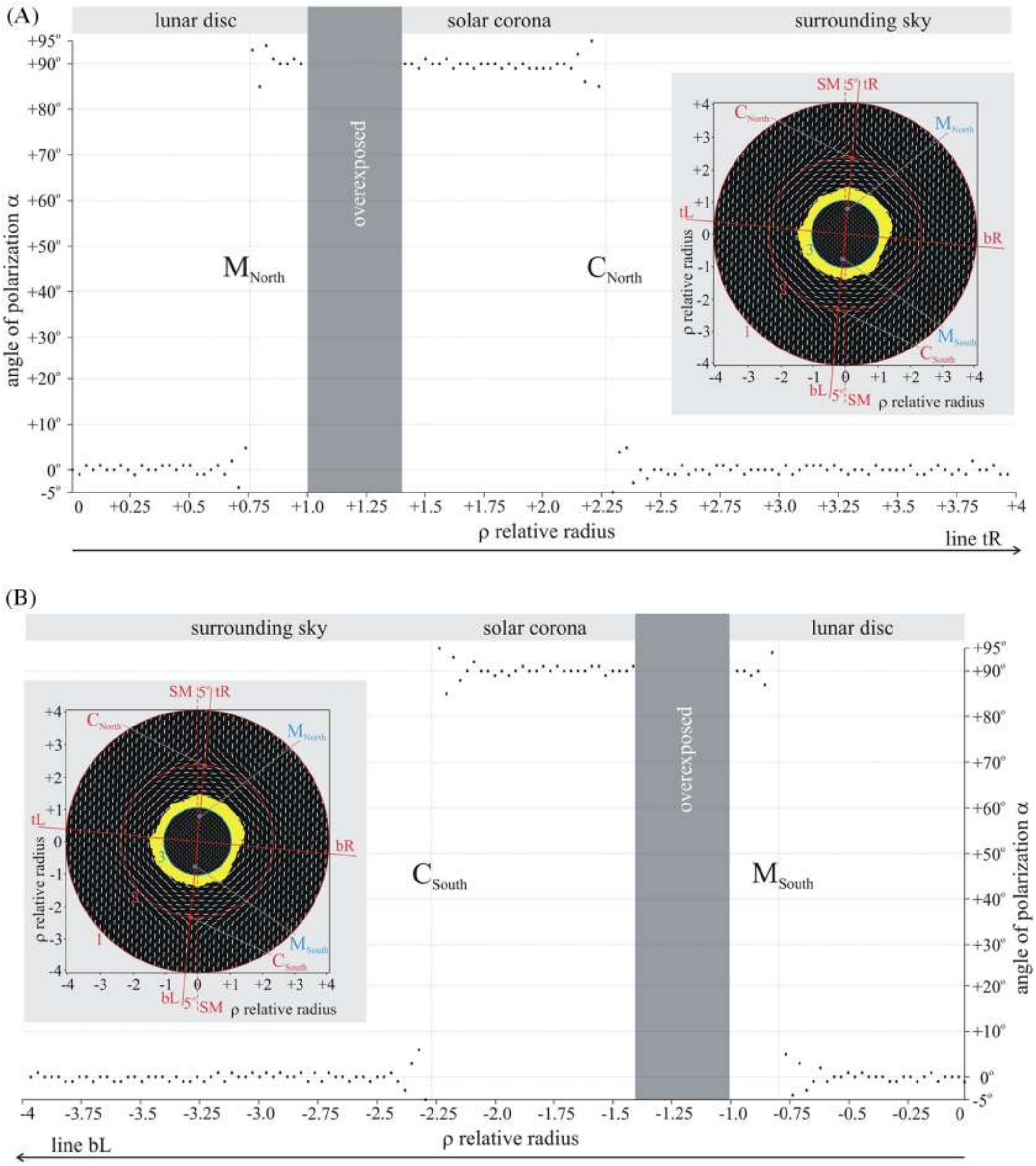


**Fig. 3.** (A) Angle of polarization $\alpha$ (dots) clockwise from line tR in Fig. 1(C) as a function of the relative radius $\rho = r/r_{Moon}$ along tR. The average $\alpha$ changes by 90° at the neutral points $M_{North}$ (northern neutral point of the lunar disc at $\rho \approx +0.75$) and $C_{North}$ (northern neutral point of the solar corona at $\rho \approx +2.27$). (B) Angle of polarization $\alpha$ clockwise from line bL in Fig. 1(C) as a function of $\rho$ along bL. The average $\alpha$ changes by 90° at the neutral points $M_{South}$ (southern neutral point of the lunar disc at $\rho \approx -0.71$) and $C_{South}$ (southern neutral point of the solar corona at $\rho \approx -2.27$). For the sake of a better visualization, Fig. 1(C) is inserted in both the A and B panels.

was $p_{max} \approx 56\%$ in the G [24] and $\approx 47\%$ in the B and R [3], whereas on 11 August 1999, $p_{max} \approx 31\%-35\%$ was measured in the G. On 21 August 2017 in Rexburg (Idaho, USA), the degree of polarization of the surrounding sky was 25%–29% in the G [23,24], whereas on 11 August 1999 in Kecel (Hungary), it was 20%–23% (Fig. 2).

The characteristics of sky polarization and the positions of the previously mentioned four neutral points during an eclipse depend on the structure of the solar corona, atmospheric aerosols and clouds, albedo distribution of the Earth's surface, and the geometry of the umbra (i.e., Moon's shadow). The differences in the polarization characteristics of the lunar disc, solar corona, and sky foreground measured during the 1999 (present paper) and 2017 [3,24] total solar eclipses may be the result of the different solar zenith distances (in 1999: 32°, in 2017: 42°), meteorological, surface, umbral, and coronal conditions.

The formation of the Coulson and Vorobiev neutral points of the lunar disc light from the corona and/or the Earth's atmosphere scattered inside the polarimeter could play an important role. In principle, no coronal light could be present in front of the lunar disc, and there would be a sharp transition from sky polarization in front of the solar disc to the much brighter inner corona. The tangentially polarized light inside the lunar disc is therefore scattered light from the solar corona, either by forward scattering in the Earth's atmosphere or inside the polarimeter. These neutral points are observed by three different imaging polarimeters [3,19,21,24]. An interesting task of future studies could be to determine how the position of these neutral points depends on the imaging instrument and/or the coronal brightness, and further, what role does forward scattering in the Earth's atmosphere play in this phenomenon.

## APPENDIX A

### BRIEF REVIEW OF EARLIER POLARIZATION STUDIES OF THE SOLAR CORONA DURING ECLIPSES

The first polarization observation of the solar corona was performed by Arago in 1842, and in 1851, Edlund detected the coronal radial polarization ([40], pp. 2-3). The Thomson scattering of sunlight by free electrons occurs below about 5 solar radii from the center of the Sun. Polarimetric measurements serve mainly for estimation of the electron density in coronal streamers ([40], pp. 147-172).

Using a polarigraph (three polarizing plates with transmission axes rotated by 60° relative to each other, and a reflecting analyzer), Zakharin [4] studied the degree and direction of linear polarization of the corona during the total eclipse on 19 June 1936 in Kalenoe (Kazakhstan, formerly USSR).

With the use of a photoelectric polarimeter, Dollfus [5] investigated the corona during the total eclipse on 29 September 1956 in the Pic du Midi Observatory (France).

Using infrared polarimetry, Leroy and Ratier [6] studied the polarization of the K-corona and the surrounding sky during the total eclipse on 29 September 1956 in the Pic du Midi Observatory (France).

With the use of a radially graded neutral density grey filter and a rotatable linear polarizer, Koutchmy and Laffineur [7] measured the radiance and polarization of the corona during the total eclipse on 22 September 1968 in Yurgamish (Siberia, Russia, formerly USSR).

Using a photographic polarimeter based on a Savart plate, Beckers and Wagner [8] detected very weak linear polarization of the coronal and prominent emission lines during the total eclipse on 7 March 1970 in the High-Altitude Observatory in Quiechapa (Oaxaca, Mexico).

Koutchmy and Schatten [9] photographed the corona through a neutral density grey filter equipped with a rotatable linear polarizer during the total eclipse on 7 March 1970 in El Gramel (Oaxaca, Mexico). They investigated the radial and tangential polarization of the K and F corona between 1 and 6 solar radii.

During the Mexican total eclipse on 7 March 1970, Saito [10] took three regular and four polarized photographs of the corona up to 5 solar radii from the center of the Sun through a radially graded neutral density grey filter and a rotatable linearly polarizing filter.

Koutchmy [11] studied the polarization of the corona during the total eclipse on 30 June 1973 in Moussoro (Chad, Africa). He used a telescope mounted with a radially graded neutral density grey filter and a rotatable linearly polarizing filter.

With the use of a telescope mounted with a rotatable linear polarizer with four different transmission axes, Dürst [12] measured the polarization characteristics of the corona up to 3.3 solar radii during the total eclipse on 16 February 1980 in Yellapur (India).

Using a telescope mounted with a rotatable linear polarizer with four different transmission axes, Sivaraman *et al*. [13] measured the degree of linear polarization of the corona during the total eclipse on 16 February 1980 in Hosur and Jawalgere (near Bangalore, India). From the coronal radiance and polarization, they derived the electron density up to 2.5 solar radii from the center of the eclipsed Sun.

Badalyan *et al*. [14] compared the optical (radiance, degree, and direction of polarization) and magnetic characteristics of the corona measured during the total eclipse on 11 July 1991 in La Paz (Mexico).

Sykora *et al*. [15] reviewed the polarization characteristics of the corona measured during the total eclipses on 30 June 1973, 16 February 1980, and 11 July 1991 in three different sites.

During the total eclipse on 26 February 1998 in Curacao (Dutch Antillas), Gabryl *et al*. [16] measured the radiance and polarization of the corona and derived the coronal electron density. They used a telescope mounted with a rotatable linear polarizer.

Using a spectro-imaging polarimeter, Qu *et al*. [17] studied the corona during the total eclipse on 2 November 2013 in Gabon (Africa).

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**Data Availability.** Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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