First observation of the fourth neutral polarization point in the atmosphere

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Received February 20, 2002; revised manuscript received April 30, 2002; accepted May 7, 2002

In the clear sky there are three commonly known loci, the Arago, Babinet, and Brewster neutral points, where the skylight is unpolarized. These peculiar celestial points, bearing the names of their discoverers, have been the subject of many ground-based investigations, because their positions are sensitive indicators of the amount and type of atmospheric turbidity. According to theoretical considerations and computer simulations, there should exist an additional neutral point approximately opposite to the Babinet point, which can be observed only at higher altitudes in the air or space. Until now, this anonymous "fourth" neutral point has not been observed during air- or space-borne polarimetric experiments and has been forgotten, in spite of the fact that the neutral points were a basic tool in atmospheric research for a century. Here, we report on the first observation of this fourth neutral point from a hot air balloon. Using 180°-field-of-view imaging polarimetry, we could observe the fourth neutral point at 450, 550, and 650 nm from different altitudes between 900 and 3500 m during and after sunrise at approximately 22°–40° below the anti-solar point along the anti-solar meridian, depending on the wavelength and solar elevation. We show that the fourth neutral point exists at the expected location and has characteristics similar to those of the Arago, Babinet, and Brewster points. We discuss why the fourth neutral point has not been observed in previous air- or space-borne polarimetric experiments. © 2002 Optical Society of America

OCIS codes: 010.3920, 100.0100, 120.5410, 260.5430, 280.0280, 290.1310.

1. INTRODUCTION

In the clear sky there are three commonly known loci, the Arago, Babinet, and Brewster neutral points, where the skylight is unpolarized.[1,2] The antecedents date back to 1809 when the French astronomer Dominique Francois Jean Arago discovered the partial linear polarization of skylight, and soon thereafter above the antisolar point he observed a neutral point, which nowadays bears his name.[3] In 1840 the French meteorologist Jacques Babinet discovered a second neutral point situated above the sun.[4] Since a neutral point existed above the sun, from considerations of symmetry, the Scottish physicist David Brewster predicted a third point of zero polarization positioned at a similar angular distance below the sun along the solar meridian. This celestial point, called nowadays the Brewster neutral point, was found in 1842 at the theoretically predicted position.[5] Only in 1846 could Babinet confirm the existence of the Brewster point.[6] Figures 1A and 1B show the normal positions of these three principal neutral points in the sky. Occasionally, some secondary neutral points have been observed under special conditions associated with reflections from water surfaces,[6,7] turbid atmospheres after volcanic eruptions,[8] or total solar eclipses.[9,10]

The principal neutral points have been the subject of many ground-based investigations, because their positions are sensitive indicators of the amount and type of atmospheric turbidity.[2] In the second half of the twentieth century, however, the neutral points have lost their importance in applied meteorology and have become a little used tool in meteorological research.[11] Theoretically, for reasons of symmetry, a further, fourth neutral point should exist below the anti-solar point (Fig. 1). However, it cannot be observed from the ground, because the region below the anti-solar point is either under the horizon (after sunrise, Figs. 1A and 1B) or, after sunset, in the shadow of the earth and thus the sub-anti-solar region is not illuminated by direct sunlight, which is the prerequisite of the occurrence of the fourth neutral point. The fourth neutral point may be observed only in the sunlit atmosphere and at appropriately high altitudes in the air (Fig. 1C) or space (Fig. 1D) somewhere below the anti-solar point.

The light field in the atmosphere can be divided into two components (Fig. 1): (i) The radiation scattered downward to the earth surface (downwelling light field) from the sunlit sky is called "skylight." (ii) The radiation directed to space (upwelling light field) and originating from scattering of sunlight in the atmosphere and reflection of light from the earth surface is termed "earthlight."[2] For a ground-based observer, the Arago, Babinet, and Brewster points are the neutral points of polarized skylight (Figs. 1A and 1B), but for an airborne observer, the Brewster and fourth neutral points are the neutral points of polarized earthlight (Fig. 1C), like the Arago and the fourth neutral points for a space-borne observer (Fig. 1D).

Until recently, no observation of the fourth neutral

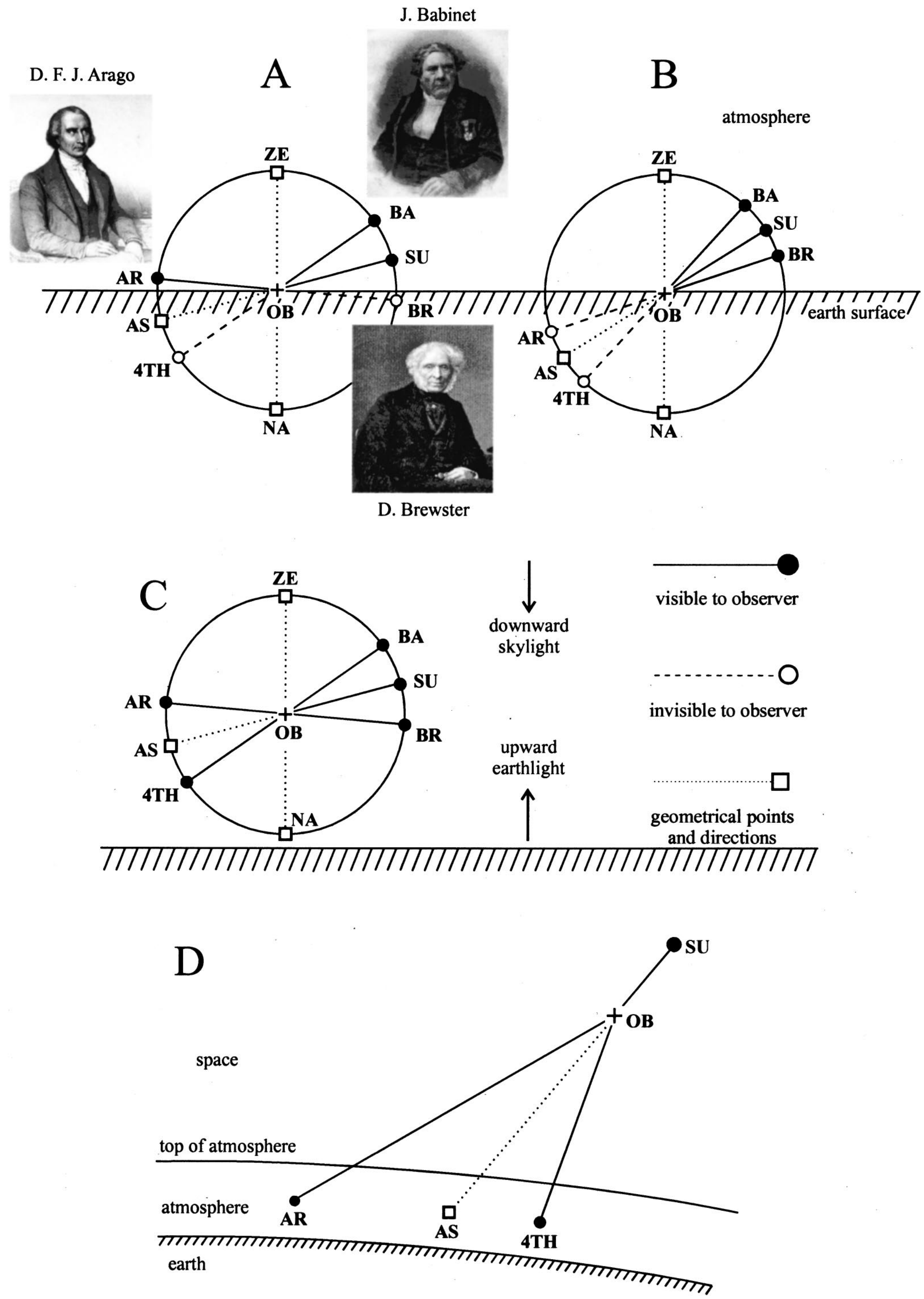

Fig. 1. A, B, schematic diagram showing the normal positions of the Arago (AR), Babinet (BA), and Brewster (BR) neutral points of skylight polarization in the vertical plane including the ground-based observer (OB), sun (SU), zenith (ZE), anti-solar point (AS), and nadir (NA). From the ground, only two neutral points are visible simultaneously: either the Arago and Babinet points (A, for lower solar elevations), or the Babinet and Brewster points (B, for higher solar elevations). From the ground, the fourth neutral point (4TH) is not visible. The insets are portraits of Dominique Francois Jean Arago (1786–1853), Jacques Babinet (1794–1872) and David Brewster (1781–1868), the discoverers of the neutral points. C, at an appropriately high altitude, all four neutral points can be observed simultaneously. Then the Arago and Babinet points are the neutral points of downwelling polarized skylight, while the Brewster and fourth neutral points are the neutral points of upwelling polarized earthlight. D, geometry of the space-borne observation of the Arago and fourth neutral points.

point has been reported, and so it has remained nameless. It could be called the "anti-Babinet point," because it is expected to be situated approximately opposite to the Babinet point (Fig. 1). Apparently, it has been overlooked in observational atmospheric optics, even though theoretical considerations[12] or model computations[13] have indicated its existence. It has been mentioned only occasionally in the literature; Rozenberg,[12] for example, called it "point observable from above," but it is not even mentioned in monographs on polarized light in Nature.[1,2,14]

With this in mind, on June 28 and August 25, 2001, we performed two hot air balloon flights over Hungary to observe the anonymous "fourth" neutral point. Using 180° field-of-view imaging polarimetry, we measured the patterns of the degree and angle of linear polarization of earthlight in the red (650 nm), green (550 nm), and blue (450 nm) ranges of the spectrum below the balloon's gondola as functions of the altitude and solar elevation. This technique has been proven to be an effective tool for quantitative studies of neutral points.[9,10,15–19] The aim of our first flight was to test the measuring apparatus on board and to check whether the 4000-m operational ceiling of the hot air balloon is enough to observe the fourth neutral point during and immediately after sunrise when the cloudless atmosphere is illuminated by approximately horizontally directed sunlight, which situation is ideal for this observation. Our first flight was successful, and we were able to observe the fourth neutral point. Then we performed a second flight to determine the lowest altitude at which the fourth neutral point can be still observed. We show here that the fourth neutral point exists at the expected location and has characteristics similar to those of the Arago, Babinet, and Brewster points. We shall discuss why the fourth neutral point has not been observed in previous air- or space-borne polarimetric experiments.

2. MATERIALS AND METHODS

A. Conditions of the Hot Air Balloon Flights

We conducted two flights with a hot air balloon of the Hungarian Airlines Aero Club (MALÉV, Budapest). The operational ceiling of hot air balloons without oxygen masks for the crew is 4000 m above the ground level. The flights were performed on June 28 (local sunrise at 04:52 = local summer time = UTC + 2; crew: Attila Bakos, Balázs Bernáth, Gábor Horváth, Bence Suhai) and August 25 (local sunrise at 05:56; crew: A. Bakos, András Barta, B. Bernáth, G. Horváth) 2001. In both cases the balloon was launched before the local sunrise from the immediate vicinity of the Hungarian town Pákozd (47°13′N, 18°33′E; Fig. 2A). We chose this time for launching, because at sunrise (or sunset) the contribution of light reflected from the ground is small to the earthlight, which is dominated by atmospheric light scattering, especially for shorter (ultraviolet, blue) wavelengths. Furthermore, at sunrise (or sunset) the anti-solar point has a minimal (zero) elevation resulting in a maximal distance between the aerial observer and the earth surface in the predicted direction of the fourth neutral point (approximately 20°–35° below the anti-solar point). The first prerequisite of observation of the fourth neutral point is an appropriately thick air layer below the anti-solar point in which the sunlight can be backscattered toward the aerial observer (Fig. 1C). The second prerequisite is that this backscattered light must not be suppressed by the ground-reflected light. Thus the sunrise and sunset are ideal periods in which to observe the fourth neutral point. Depending on the meteorological conditions, a hot air balloon can climb to 4000 m within approximately 15–20 min, and to return to the ground requires approximately 20–25 min. Since hot air balloons must stay grounded from sunset until sunrise, and safe landing requires good visibility, one could not measure the polarization pattern of earthlight at sunset at high altitude. This is the reason we conducted the measurements at sunrise.

During the first flight the balloon drifted slowly southeast and landed in the immediate vicinity of the town Adony (47°06′N, 18°51.ᵐE), while during the second flight the balloon hovered approximately above Pákozd owing to calm weather conditions at the relatively low (below 1400 m) altitudes of this flight. Figure 2A shows the trajectory of the balloon on the map of Hungary during the first flight. In Fig. 2B the altitude of the balloon is seen as a function of time after sunrise for both flights. The altitudes and the points of time at which polarimetric measurements were done are represented by triangles in Fig. 2B. During the first flight, the minimum and maximum altitudes at which the polarization pattern of earthlight were measured were 2000 m and 3500 m, respectively. During the second flight, measurements were performed when the balloon hovered between 800 m and 1400 m. The angular elevation of the sun above the horizon versus time after sunrise was derived for the ground from the latitude and longitude of the launching site at Pákozd and from the time of the measurements. The dependence of the solar elevation on the change of the balloon's longitude and latitude (during the first flight) as well as altitude (during both flights) was negligible.

During both flights the atmosphere was slightly hazy but cloudless; the rising sun was not occluded by distant clouds. At Pákozd (launching site) and between Pákozd and Adony (landing site), the ground surface was a mixture of areas that are typical for agricultural cultivation: green grassland, fields, meadows, and ploughland with a mosaic pattern of different albedos. Near Pákozd there is Lake Velence partly occupied by areas of green reed and reed grass. During the second flight in some places there was a thin (2–5 m) fog layer immediately above the ground surface.

B. Measurement of the Polarization Patterns of Earthlight by 180°-Field-of-View Imaging Polarimetry

Our objective was to measure the degree and angle of linear polarization of the upwelling earthlight in the whole terrestrial hemisphere. For this purpose a 180°-field-of-view, rotating-analyzer imaging polarimeter was used. This instrument and its calibration are described in detail by Gál *et al.*[17] Here we mention only that the polarimeter is a roll-film photographic camera (Nikon F801) with a 180°-field-of-view fish-eye lens (Nikon Nikkor, focal length = 8 mm, f-number = 2.8) possessing a filter wheel with three linear polarizers (type: HNP′B, Polaroid Co.) with three different orientations of the transmission axis. We used Fujichrome Sensia II 100 ASA color reversal films. The down-facing polarimeter was mounted onto a holder, which hung on the outside of the gondola (Fig. 3A). The holder made it possible for the polarimeter to be slid up and down vertically. The verti-

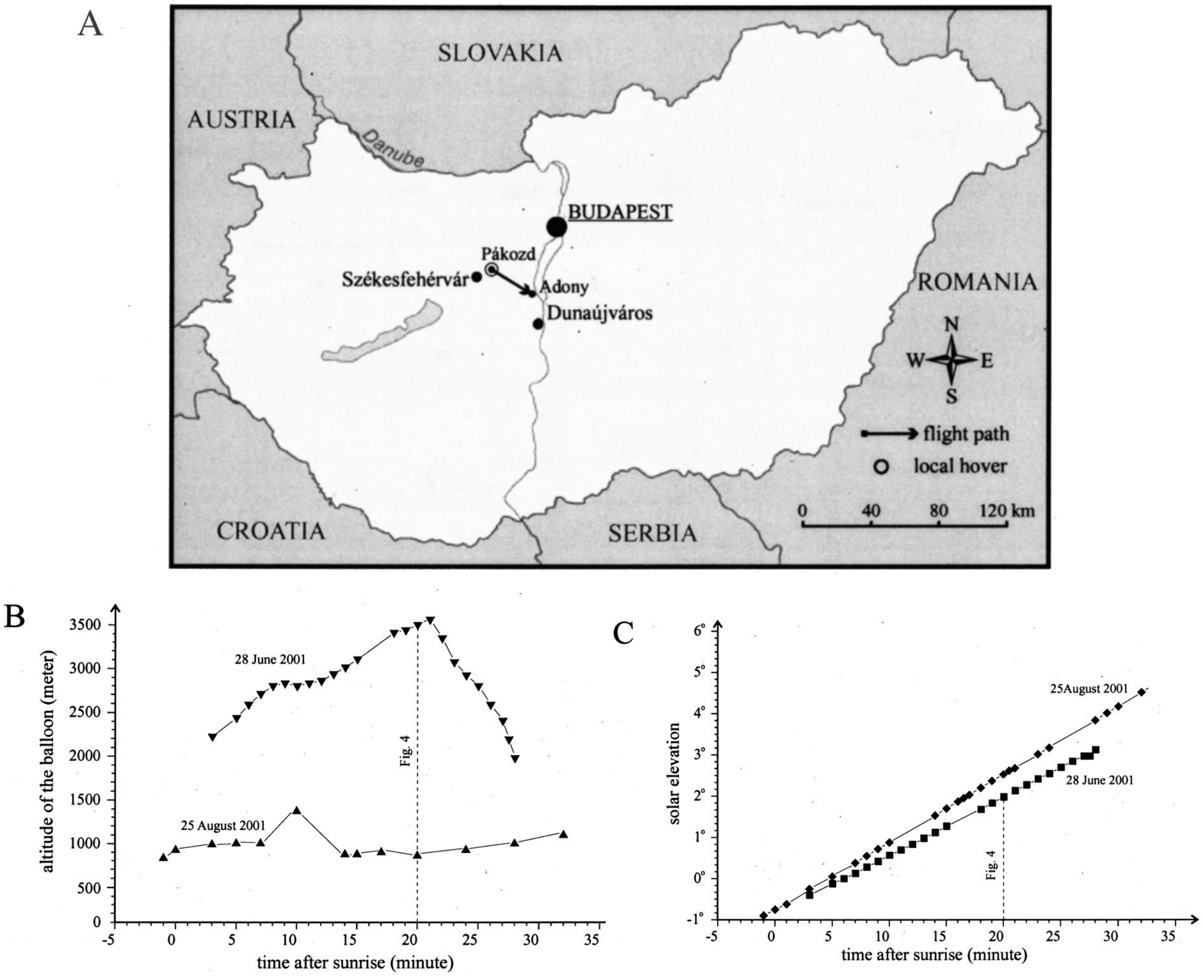

Fig. 2. Main parameters of our two hot air balloon flights conducted on June 28 (local sunrise at 04:52 = local summer time = UTC + 2) and August 25 (sunrise at 05:56) 2001 to measure the polarization patterns of upwelling earthlight and the characteristics of the fourth neutral point of atmospheric polarization. A, launching site (Pákozd, 47°13′N, 18°33′E), landing site (Adony, 47°06′N, 18°51′E), and trajectory of the first flight (hovering above the launching site during the second flight) on the map of Hungary. B, altitude of the balloon as a function of time after sunrise for both flights. Triangles, altitudes and points of time at which polarimetric measurements were done; dashed vertical line, measurement, the results of which are shown in Fig. 4.

cality of the optical axis of the fish-eye lens was checked by two orthogonal water levels on the camera and ensured by appropriate adjustments of the holder. Figure 3A depicts the geometry of the measurement. Performing the measurement in the gondola required strict choreography. One measurement section happened in the following way: (1) Leaning out cautiously from the gondola, and after setting the time of exposure and the aperture of the camera, the first member of the crew (G. Horváth) let down the polarimeter below the bottom level of the gondola. (2) Squatting in one of the corners of the gondola, the second member of the crew (B. Bernáth) reached out through an opening of the gondola to expose the film and rotate the filter wheel of the polarimeter three times. (3) Then the first person lifted the polarimeter, reset the time of exposure and the aperture, and lowered the polarimeter again. (4) In the meantime, the third member of the crew (B. Suhai or A. Barta) took note of the time of measurement, the aperture, the time of exposure, and the altitude of the balloon. The fourth member of the crew was the pilot (A. Bakos) of the hot air balloon.

The development, digitization, and evaluation of the polarization photographs of earthlight were performed in the laboratory. The whole procedure and its calibration are described in detail by Gál *et al.*[17] Here we mention only a special problem of the evaluation of the three polarization pictures arising from the aerial manner of the measurement from the gondola of a hot air balloon: During the 6 s of one measurement the gondola drifted a little and sometimes turned away, which resulted in more or less translations and rotations of the corresponding pixels of the three pictures relative to one another. The small spatial disparities (shifts) between the corresponding pixels induced by the drift caused small motion artifacts only in the polarization patterns of the ground surface but did not affect those of the atmospheric light scattering. This is apparent in Fig. 4, for example, where in the red spectral range small motion artifacts occur (Figs. 4H, 4I, 4J), which disappear in the blue part of the spectrum (Figs. 4B, 4C, 4D). However, the rotation of the corresponding pixels around the nadir due to the rotation of the gondola during measurements had to be compensated in many

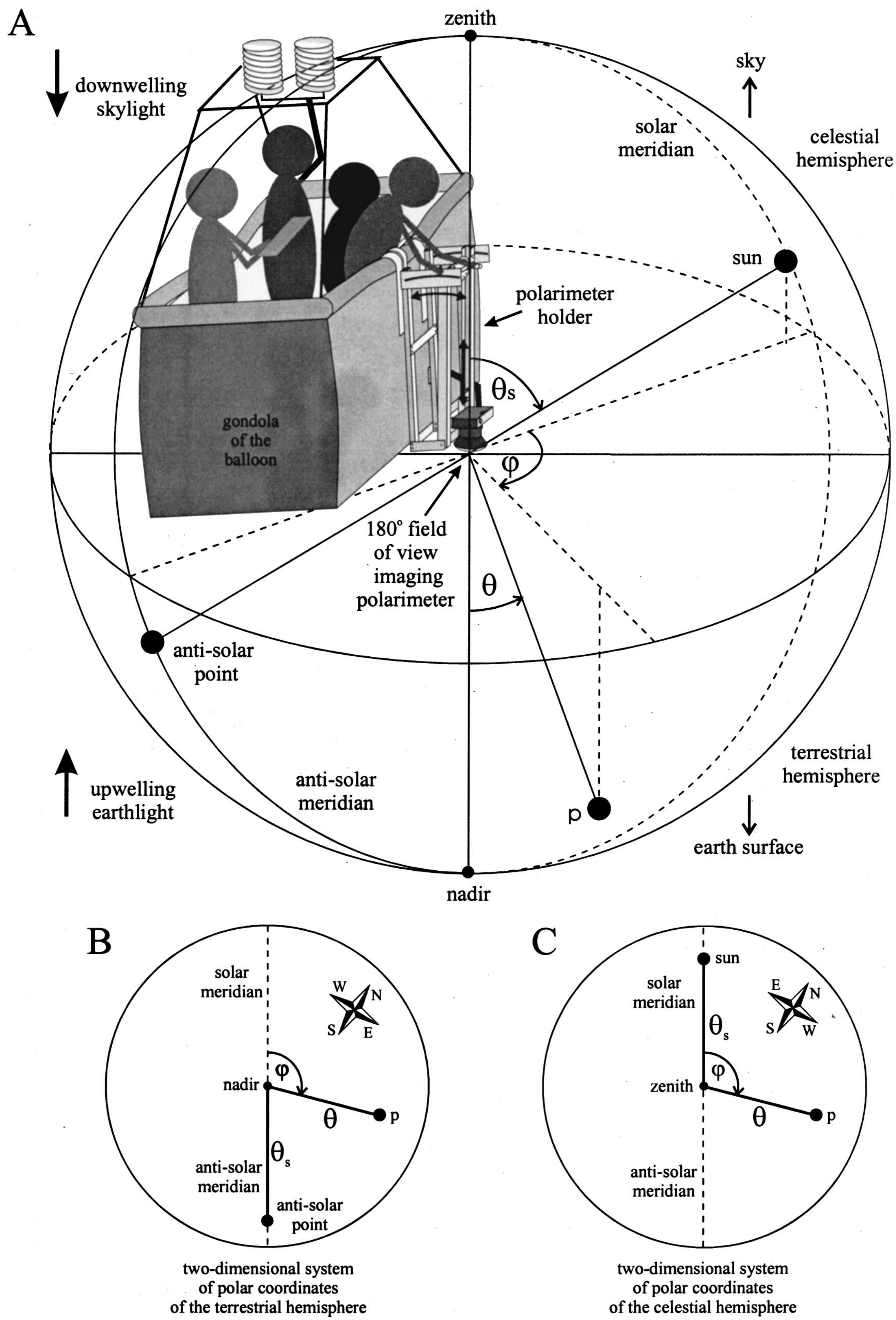

Fig. 3. A, Geometry of our polarimetric measurements in the gondola of a hot air balloon. B, C, two-dimensional system of polar coordinates of the terrestrial and celestial hemisphere in which the maps of Figs. 4 and 5 are represented. The azimuth angle φ is measured clockwise from the solar meridian, and the zenith or nadir angle θ is measured radially so that for the zenith or nadir, $\theta = 0°$ for the horizon $\theta = 90°$, and the radius from the zenith or nadir is proportional to θ. θ_s, solar zenith angle or nadir angle of the anti-solar point. Note that in map B the North, West, South, and East are represented on the compass rose as is usual in maps seen from above; but in map C East and West are transposed, because then we are looking up toward the celestial dome rather than down onto the ground.

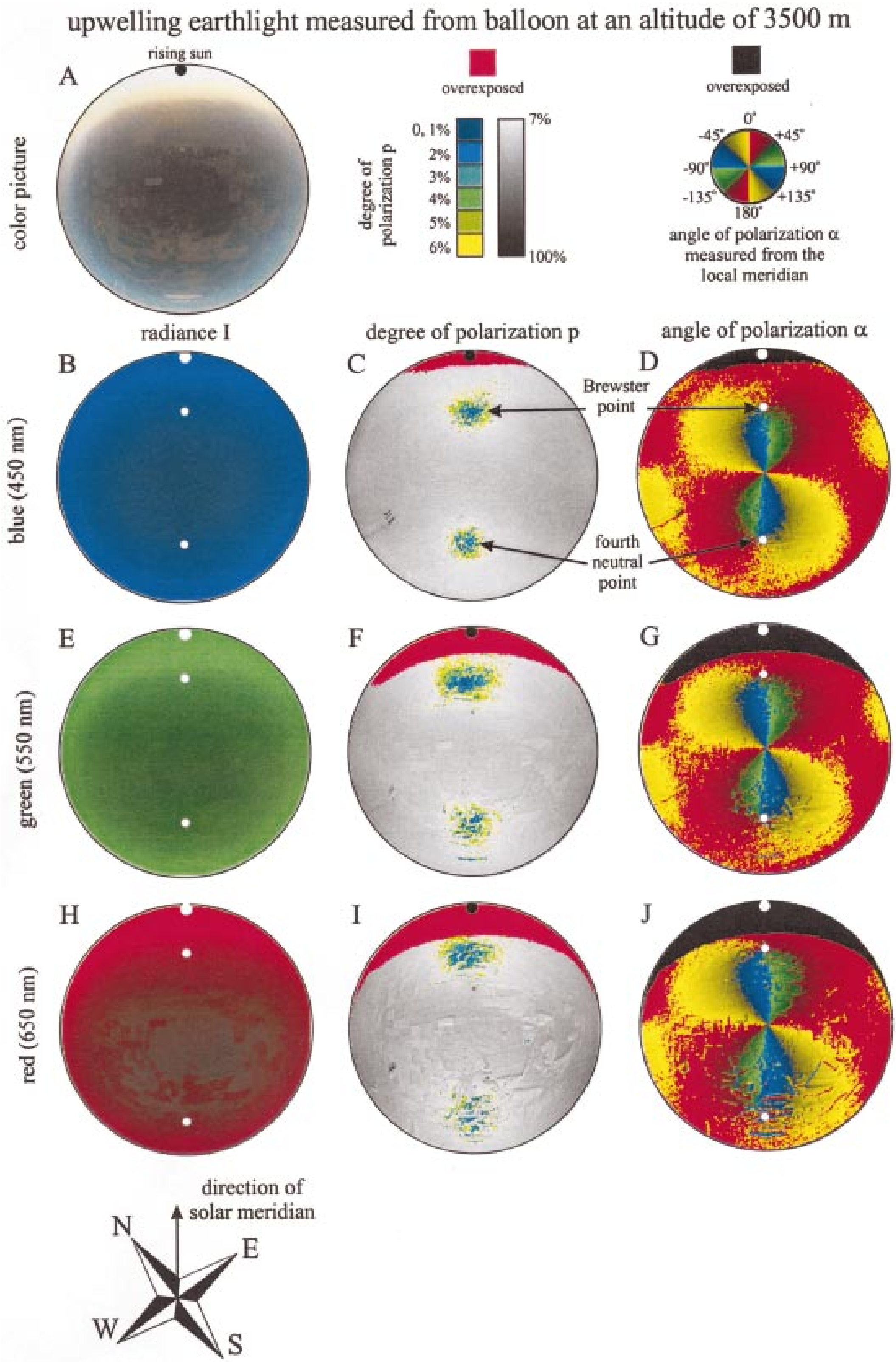

Fig. 4. 180°-field-of-view color photograph of the landscape below the gondola of the hot air balloon (A) and the patterns of radiance I (B, E, H), degree of linear polarization p (C, F, I), and angle of polarization α (D, G, J) of upwelling earthlight. Measurements were taken by using 180°-field-of-view imaging polarimetry at an altitude of 3500 m and a solar elevation of 3° for wavelengths of 450, 550, and 650 nm immediately after local sunrise (05:12; local summer time = UTC + 2; June 28, 2001). The position of the sun and the neutral points are indicated by dots. Time of exposure = 1/60 s, aperture = 2.8, color reversal film Fujichrome Sensia II, 100 ASA.

cases. This was done by taking the digitized, three-photograph set and rotating each picture about the nadir until selected common points of these pictures matched to within a pixel. For this purpose well-visible landmarks were selected in the pictures: small bright spots, road intersections, or the edges and angles of bright regions ofground surface. With our data collection system the degree of polarization p and angle of polarization α can be measured to an accuracy of approximately $\pm 1.5\%$ and $\pm 2°$, respectively.[17] The estimated accuracy to which the balloon rotations were corrected for is $\sim 1°$.

Figures 3B and 3C show the two-dimensional system of polar coordinates of the terrestrial and celestial hemisphere, respectively, used in the representation of the maps of polarization, in which the azimuth angle φ is measured clockwise from the solar meridian, and the zenith or nadir angle θ is measured radially so that for the zenith or nadir $\theta = 0°$, for the horizon $\theta = 90°$, and the radius from the zenith or nadir is proportional to θ. Note that in the patterns of the upwelling earthlight (terrestrial hemisphere) North, East, South, and West are represented on the compass rose as it is usual in maps seen from above, but in the patterns of the downwelling skylight (celestial hemisphere) East and West are transposed, because then we are looking up toward the celestial dome rather than down onto the ground.

C. Measurement of the Polarization Patterns of the Full Sky at Sunrise

To compare the neutral points of earthlight with those of skylight, from our archives we selected a set of polarization patterns of the full sky measured earlieearthlight. The neutral points are the result of second- r by the same 180° imaging polarimeter. The skylight measurement was performed from the ground on August 26, 1999 at local sunrise (06:00 = local summer time = UTC + 1, solar elevation = 0°) in the Tunisian Chott el Djerid (salt pan), 10 km from Kriz (33°52′N, 8°22′E) as described by Pomozi *et al.*[18] The desert ground was flat reddish/yellowish sand. The measured polarization patterns of skylight served as comparison with those of earthlight and to show the Arago and Babinet neutral points of skylight polarization, which are not visible on the earthlight patterns.

3. RESULTS

Figure 4 shows the patterns of the radiance I, degree p, and angle α of the linear polarization of earthlight measured by 180°-field-of-view imaging polarimetry at an altitude of 3500 m immediately after sunrise at a solar elevation of 3° in the red (650 nm), green (550 nm), and blue (450 nm) spectral ranges during the first flight on June 28, 2001. In the p patterns (Figs. 4C, 4F, 4I) two neutral points are clearly discernible in all three spectral ranges: The neutral point located along the solar meridian is the Brewster point, and the other along the anti-solar meridian is the fourth neutral point. At the center of both points, p is zero but gradually increases with radial distance from the point. In Figs. 4C, 4F, 4I low p values are coded by blue, green, and yellow colors, and the neutral points are positioned in the center of two regions of very low degrees of polarization. These weakly polarized areas are the most compact in the blue region of the spectrum and are the most diffuse in the red spectral range. The reason for this is that the longer the wavelength, the greater the contribution of ground-reflected light to the earthlight. The neutral points are the result of second- and higher-order scattering of sunlight in the atmosphere, and owing to the Rayleight law these higher-order scattering events dominate at shorter (ultraviolet, blue) wavelengths over ground reflection. At longer wavelengths the intensity of atmospheric scattering decreases and the relative influence of ground reflection increases, as can be well seen in the I patterns (Figs. 4B, 4E, 4H). This can also be seen in the p patterns: In the blue spectral range, p of earthlight changes smoothly and gradually as a function of the direction of view, while in the red range of the spectrum p changes suddenly at the edges of neighboring dark and bright regions of the ground.

In the α patterns (Figs. 4D, 4G, 4J) we see that both neutral points are positioned along the so-called "neutral lines" coinciding with the border line between the eight-shaped blue/green regions and the yellow/red areas, along which $\alpha = \pm 45°$ or $\pm 135°$ (Stokes parameter $Q = 0$). Generally, p is not equal to zero at neutral lines except as they intersect the solar and anti-solar meridian at the neutral points. On the other hand, crossing the neutral points along the solar or anti-solar meridian, α has a sudden change of 90°, because the polarization switches from "positive" (shaded with bright green and blue in the α patterns, and meaning direction of polarization perpendicular to the scattering plane determined by the observer, the sun, and the point observed) to "negative" (shaded with bright red and yellow, and meaning direction of polarization parallel to the scattering plane). Also in the α patterns we can see the increasing disturbing effect of ground-reflected light as the wavelength increases. The nadir angles of the Brewster and fourth neutral points determined on the basis of the p and α patterns in Fig. 4 are seen in Table 1. The general trend is that the shorter the wavelength, the closer the neutral points are located to the nadir, which phenomenon is explained in Section 4. We also evaluated many other imaging polarimetric measurements done at different altitudes between 2000 and 3500 m during our first flight (Fig. 2B), and we obtained results similar to those in Fig. 4: In all of these p and α patterns, the fourth neutral point as well as the Brewster point were visible in all three spectral ranges.

The aim of the second hot air balloon flight conducted on August 25, 2001 during and immediately after sunrise was to estimate the lowest altitude at which the fourth neutral point can be still observed. At an altitude of 900 m and at a solar elevation of 3° the fourth neutral point could still have been discerned in the polarization patterns measured at 450 and 550 nm. In the red (650 nm) range of the spectrum, the area of very low degrees of polarization around the expected position of the fourth neutral point was very diffuse, and only the Brewster point could be clearly observed in the p and α patterns. Owing to the low altitude, in the red spectral range the disturbing effect of ground reflection was so great and the relative contribution of atmospheric scattering to the earthlight was so small that the fourth neutral point was not yet seen clearly. Nevertheless, in the red spectral range there was a local minimum of p at the predicted position of the fourth neutral point. Under the meteorological conditions during the second flight, the lower limit of the altitude at which the fourth neutral point could be observed was ~ 900 m.

Table 1. Angular Distance of the Arago, Babinet, Brewster, and Fourth Neutral Points from the Nadir or the Zenith As Determined on the Basis of the Patterns of the Degree and Angle of Linear Polarization in Figs. 4 and 5 at 650, 550, and 450 nm

	Neutral Point			
	Skylight		Earthlight	
	° from Zenith		° from Nadir	
Spectral range (nm)	Arago	Babinet	Brewster	Fourth
Figs. 4, 6, 7 (3500 m)[a]				
650	—	—	56.3	65.3
550	—	—	51.1	49.8
450	—	—	46.6	49.2
Figs. 5, 6, 7 (ground)[a]				
650	70.7	59.0	—	—
550	64.4	61.6	—	—
450	68.1	65.5	—	—

[a] Altitude at which the measurement was done.

To compare the polarization patterns of earthlight measured at near-zero solar elevations at sunrise with those of skylight when the sun is on the horizon, in Fig. 5 we present the polarization patterns of skylight, measured by 180° imaging polarimetry from the ground in the red (650 nm), green (550 nm), and blue (450 nm) spectral ranges on August 26, 1999 at sunrise in the Tunisian Chott el Djerid (a salt pan). Comparing Fig. 4 with Fig. 5, we can discern a great similarity between the polarization patterns. In all polarization patterns of Fig. 5 the Arago and Babinet points are clearly discernible, and these patterns possess qualitative features similar to those in Fig. 4. There are, of course, some quantitative differences between the polarization patterns of earthlight and skylight: First, at given angles from the solar meridian and the nadir/zenith, p of skylight is much higher than that of earthlight. Second, the neutral points of skylight polarization are located at greater angular distances from the zenith than those of earthlight from the nadir (see Table 1). Third, the change of polarization versus direction of view is smoother in the skylight patterns than it is in the earthlight patterns. One reason for these differences is that the polarization of the sky observed from the ground is the result of scattering of sunlight within the whole atmosphere, whereas the air layer below the balloon comprises only part of the earth's atmosphere. Another reason is that skylight has only one component (downwelling scattered light), whereas earthlight is the combination of light backscattered by the atmosphere and light reflected from the ground, the latter influencing strongly the upwelling radiation field.

Figures 6 and 7 show p and α of earthlight and skylight along the solar and anti-solar meridian measured in the red (650 nm), green (550 nm), and blue (450 nm) spectral ranges as a function of the viewing angle θ from the nadir or zenith. These data for the earthlight and skylight originate from the polarization patterns in Fig. 4 and Fig. 5, respectively. In the plots of Fig. 6 the local minima $p = 0$ at the neutral points and the maxima of p approximately at the nadir/zenith are clearly visible. The maximum p of earthlight is about one half or one third of that of skylight owing to the depolarizing effect of light reflected from the ground and multiple scattering from aerosols. The slight haze in the atmosphere during our balloon-borne measurements enhanced multiple scattering of the first component of earthlight, the sunlight scattered by aerosols, which resulted in a reduction of p of earthlight (Figs. 6A, 6C, 6E) and an increase in the area of negative polarization (Figs. 7A, 7C, 7E). The latter effect decreased the nadir angle of the Brewster and fourth neutral points (Table 1). The second component of earthlight, the sunlight reflected diffusely from the rough terrain, also suffered depolarization, which also decreased p of earthlight, especially at longer (green and red) wavelengths. These effects explain why earthlight was less polarized than skylight above the arid Tunisian desert and why the Arago and Babinet points of skylight polarization in Tunisia were nearer the horizon than the Brewster and fourth neutral points of earthlight polarization.

In Fig. 7 we can see that along the solar and anti-solar meridian, α of both earthlight and skylight is always approximately 90° (that is, perpendicular to the scattering plane, which means positive polarization) between the (fourth and Brewster as well as Arago and Babinet) neutral points, and passing the neutral points, α switches to approximately 0° and 180° (that is, parallel to the scattering plane, which means negative polarization). The noise of the measured α values is maximal at and near the neutral points owing to the very low degrees of polarization. In Figs. 6 and 7 the noise of both the p and the α plots of earthlight gradually increases from the blue to the red spectral range because of the increasing influence of ground-reflected light. Figure 8, summarizing the essence of our balloon-borne measurements, shows the three-dimensional distribution of polarization as well as the Arago and fourth neutral points observable around a hot air balloon at 3500 m and in the blue (450 nm) spectral range.

4. DISCUSSION

A. Origin and Characteristics of the Neutral Points

In the clear atmosphere, a neutral point occurs if the radiance of the normally positively polarized skylight or earthlight is matched exactly by an equal radiance of negatively polarized light. Multiple scattering of light causes negative polarization. The stronger the multiple scattering, the more negative polarization is introduced in the atmosphere and the more the neutral points are displaced from the sun or anti-solar point. The amount of multiple scattering is strongly affected by atmospheric turbidity.[2]

The different angular positions of the neutral points observed in the red, green, and blue ranges of the spectrum (Figs. 4 and 5, Table 1) are the consequence of the dispersion of polarization, the influence of wavelength-dependent ground reflection, and the spectral composition of direct sunlight. Under normal, clear atmospheric conditions and when the atmosphere is illuminated by sunlight (for higher solar elevations from the horizon) and

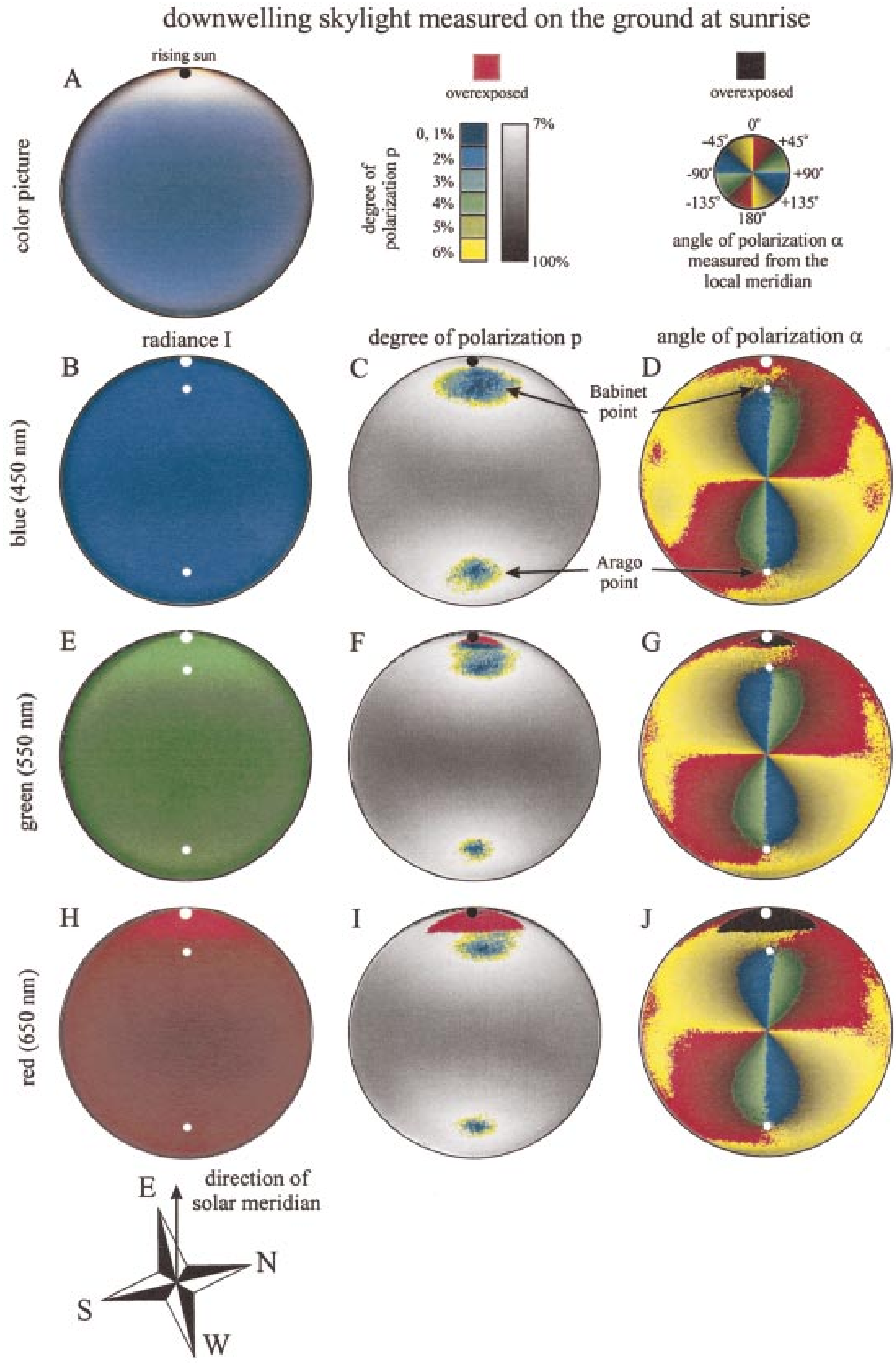

Fig. 5. As Fig. 4 for the full clear sky measured from the ground at local sunrise (August 26, 1999, 06:00 = local summer time = UTC + 1, solar elevation = 0°; Chott el Djerid, a salt pan, 10 km from Kriz, 33°52.ᵐN, 8°22.ᵐE, Tunisia). Note that on the compass rose East and West are transposed, because we are looking up toward the celestial dome rather than down toward the ground. Time of exposure = 1/60 s, aperture = 2.8, color reversal film Fujichrome Sensia II, 100 ASA.

the ground reflection is approximately independent of wavelength (for colorless grounds covered by snow or gray/white sand, black soil, for example), a general rule is that the shorter the wavelength of light, the lower the degree of skylight polarization.[2] There is little spectral dependency at wavelengths $\lambda > 500$ nm but strong dispersion for shorter wavelengths. The strong decrease of p toward shorter wavelengths is due mainly to multiple scattering, because p resulting from a single-scattering event is independent of λ. At shorter wavelengths multiple scattering reduces p, increasing the magnitude of negative polarization and thus shifting the positions of

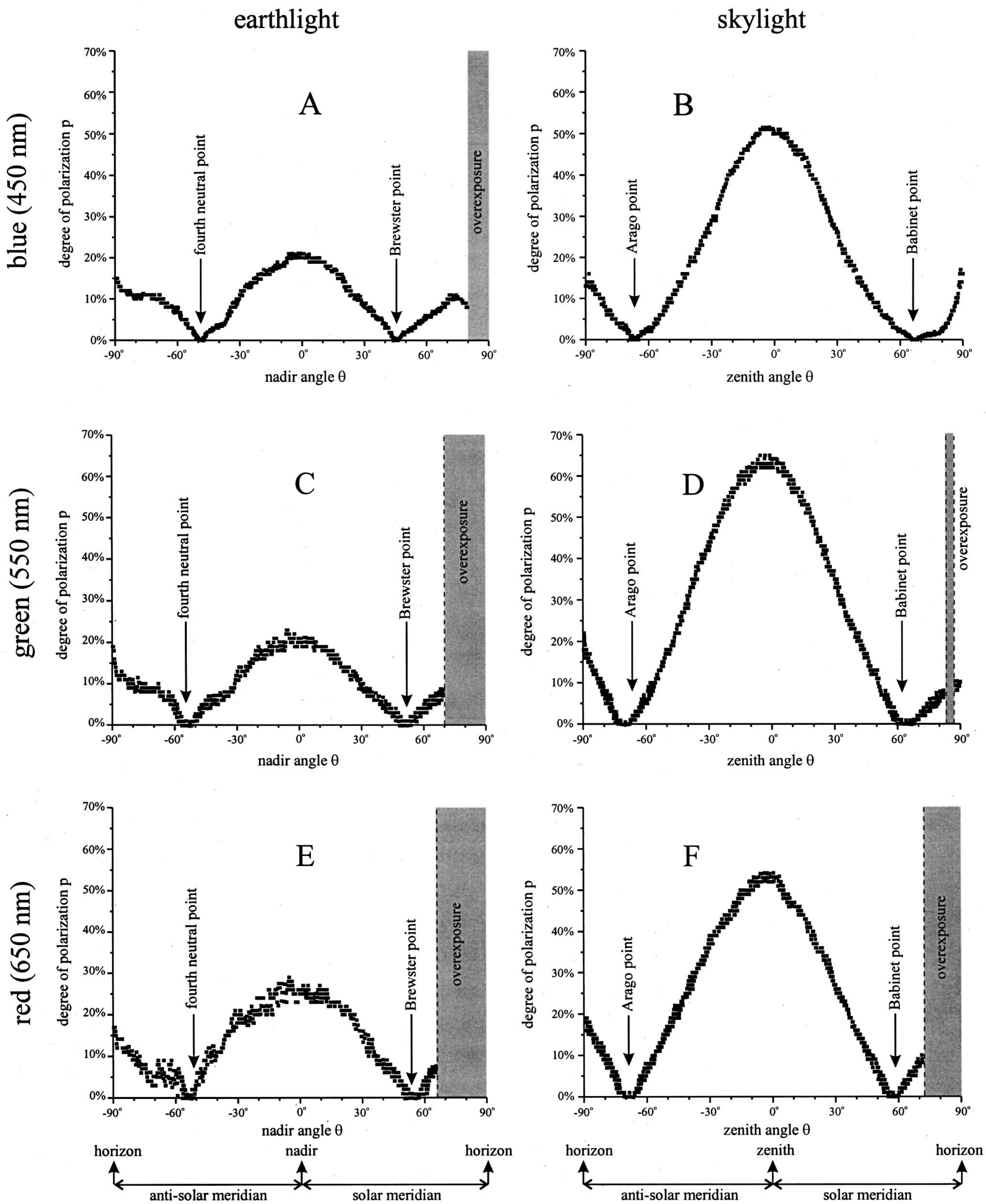

Fig. 6. Degree of linear polarization p of earthlight (A, C, E) and skylight (B, D, F) along the solar and anti-solar meridian measured in the red (650 nm), green (550 nm), and blue (450 nm) spectral ranges as a function of the nadir/zenith angle θ. Data for earthlight and skylight originate from the polarization patterns in Fig. 4 and Fig. 5, respectively. Gray stripes show the overexposed areas.

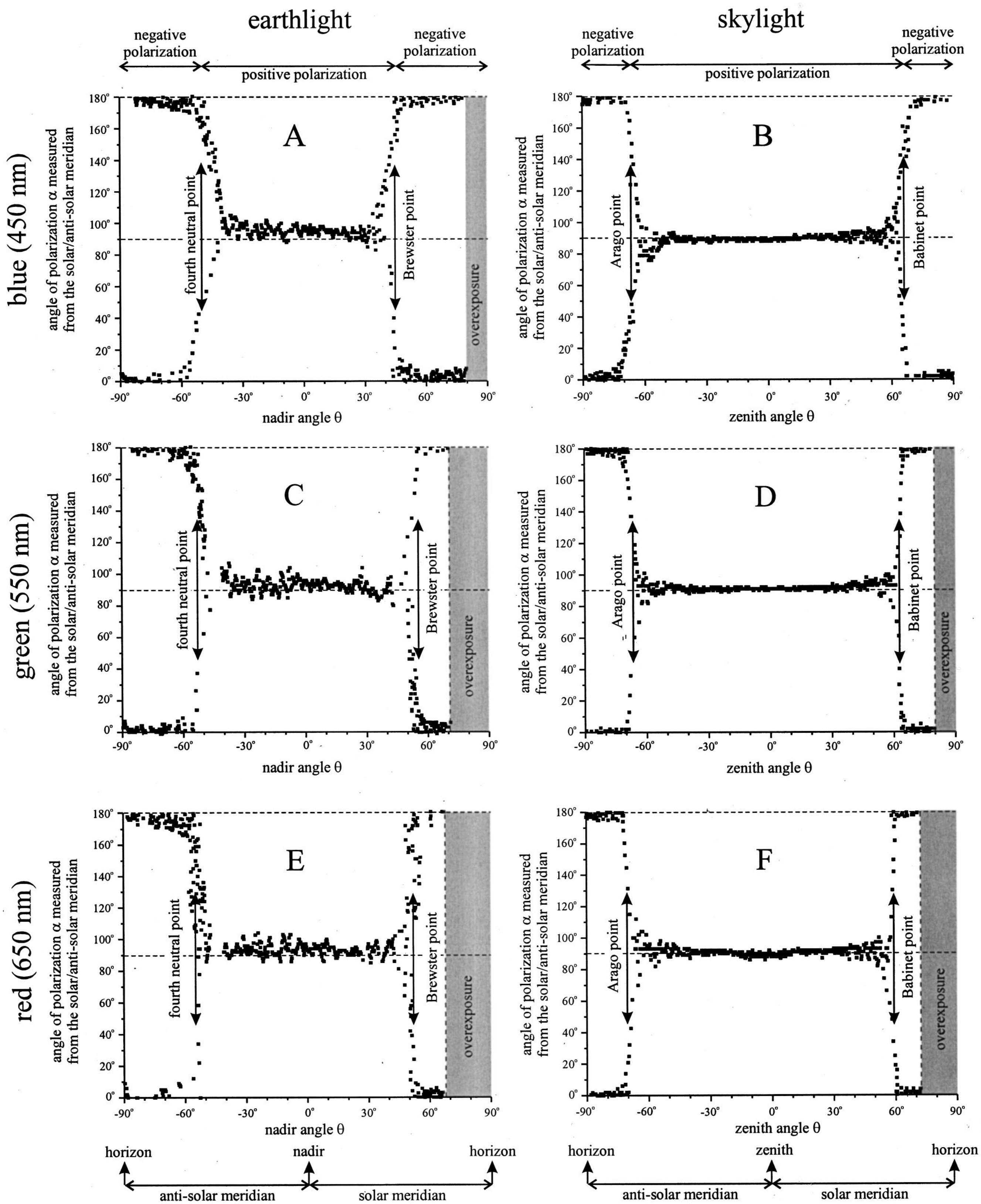

Fig. 7. As Fig. 6 for angle of polarization α of earthlight and skylight measured from the solar/anti-solar meridian.

the neutral points farther away from the sun or anti-solar point. Thus the region of negative polarization surrounding the sun and anti-solar point is much more extended in the short-wavelength (ultraviolet and blue) than in the long-wavelength (green and red) range of the spectrum. This is why under these conditions the angular distances of the neutral points from the sun or anti-solar point increase as the wavelength decreases. Then the Arago, Babinet, Brewster, and fourth neutral points are nearest the zenith or nadir in the blue spectral range; in the green range they are positioned slightly farther away from the zenith or nadir, and in the red range their angular distance from the zenith or nadir is the greatest.

These features are more or less modified by wavelength-dependent reflection of light from the ground. If in a given spectral range the reflectivity of the ground is much higher than in other parts of the spectrum, in this spectral range the relatively greater amount of ground-reflected light strongly alters the skylight and earthlight polarization and the positions of the neutral points: If the ground-reflected light is horizontally (positively), vertically (negatively) polarized, or unpolarized, it reduces, enhances, or does not alter the area of the negatively polarized region of the atmosphere around the sun and anti-solar point, and therefore it decreases, increases, or does not change the angular distance of the neutral points from the sun or anti-solar point, respectively.

At sunset and sunrise, the spectral composition of direct sunlight differs considerably from that during the day, and the proportion of longer (yellow, orange, red) wavelengths is increased. This phenomenon also changes the skylight and earthlight polarization as well as the neutral point positions. A rare but similar effect occurs after volcanic eruptions, when the wavelength-dependent absorption and scattering on the aerial particles of volcanic debris significantly modify the spectral composition of direct sunlight.[2]

In the sky above the Tunisian desert, where the skylight polarization patterns in Fig. 5 and plots of Figs. 6B, 6D, 6F and 7B, 7D, 7F were measured, p of skylight was

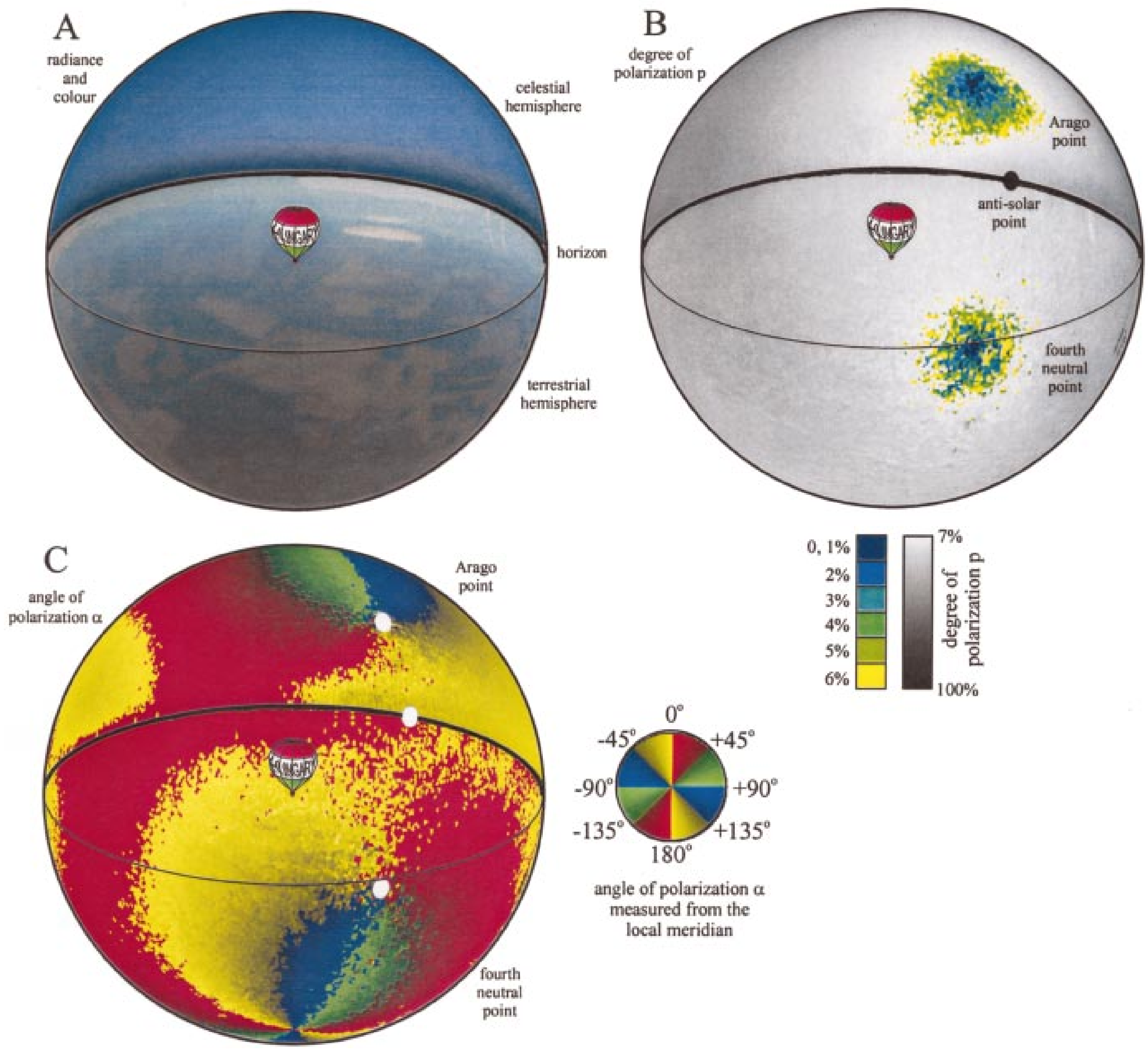

Fig. 8. Three-dimensional spatial distribution of radiance and color (A), degree (B), and angle (C) of linear polarization as well as the Arago and fourth neutral points observable around a hot air balloon at 450 nm and at an altitude of 3500 m. Each sphere in the picture is the combination of the patterns of parts A, C, D in Figs. 4 and 5.

highest in the green spectral range rather than in the red. The reason for this anomaly is that the ground was reddish/yellowish sand, and thus the amount of light reflected from the ground was largest in the red spectral range, which decreased p of skylight in this part of the spectrum. This wavelength-dependent ground reflection and the reddish/orange direct sunlight at sunrise also influenced the positions of the Arago and Babinet points. The same phenomenon was observed by Horváth *et al.*[20] as well as by Horváth and Wehner[21] during the videopolarimetric study of the Arago point at sunset, at another place in the reddish Tunisian desert in 1996.

In the case of our balloon-borne observation of the Brewster and fourth neutral points, the characteristics and observability of both neutral points depend strongly on the altitude of the observer and the features of the underlying ground surface: Compared with the atmospheric contribution to polarized earthlight, the relative surface contribution is the smallest for the shorter (ultraviolet and blue) wavelengths and increases toward longer wavelengths. The higher the albedo of the surface in a given spectral range, the greater the contribution of ground reflection to the polarized earthlight. The fourth neutral point can be observed only at higher altitudes (>900 m) from balloons, aircrafts, or satellites but not from higher mountains, because the shadow of mountains excludes direct sunlight from the region of the atmosphere below the anti-solar point. From higher mountains or towers, however, the negative polarization of earthlight can be well observed below the horizon.[22]

B. Why Has the Fourth Neutral Point Not Been Observed in Previous Air- or Space-Borne Polarimetric Experiments?

In the past, several air-borne (balloon- or aircraft-borne) and space-borne polarimetric measurements have been performed that could have made it possible to observe the fourth neutral point. Thus, it is rather surprising that no explicit, definite experimental evidence of the existence of this anonymous neutral point has been reported until our observations. The reasons are manifold:

1. Earthlight contains a significant component due to scattering by the atmosphere, besides that due to surface reflection. For remotely sensed surface characterization and discrimination, however, such atmospheric contamination of the radiation field has generally been minimized or corrected for by use of radiative transfer models applicable to the conditions of observation.[2] Since the polarization of sunlight due to atmospheric scattering is responsible for the origin of neutral points, the fourth neutral point had little chance to be observed in air- or space-borne remote sensing measurements in which the atmospheric component of earthlight was minimized or corrected for to promote the observation of surface features.

2. The first attempt to measure the polarization of earthlight was made by Rao[23]: his balloon-based measurements, performed over the White Sands area (New Mexico), exhibited depolarization of the molecular scattering by a Lambertian ground; thus the fourth neutral point was not observable. The first extensive measurements of earthlight polarization were made during four Space Shuttle missions, and a preliminary presentation was made by Coulson *et al.*[24] Photographs were taken of the earth surface with a pair of cameras, each of which contained a linearly polarizing filter with different orientation of the transmission axis. Some qualitative data could have been deduced from the comparison of these polarization picture pairs. This qualitative technique is one of the forerunners of imaging polarimetry. Since for a complete imaging polarimetry three polarization pictures are needed if the circular polarization is negligible, this qualitative method is inappropriate for the space-borne observation of the fourth neutral point.

3. Herman *et al.*[25] performed a balloon-borne experiment to measure the radiance and degree of linear polarization of sunlight scattered by the stratospheric aerosol at near-infrared (850 and 1650 nm) wavelengths at an altitude of 20 km. Since only circular scans were done in a nearly ($\pm 0.1°$) horizontal plane with a narrow- (2°) field-of-view point-source polarimeter when the sun was just at the horizon, the fourth neutral point, located at sunrise or sunset approximately 20°–30° below the anti-solar point, could not have been investigated with this polarimeter.

4. Using the polarimetric device developed by Herman *et al.*,[25] Deuzé *et al.*[26] performed a balloon-borne experiment for directional observations of the radiance and the degree of polarization of earthlight. This apparatus with a 2° field of view was adapted to polarimetric measurements at near-infrared (850 and 1650 nm) wavelengths scanning in a vertical plane. A sun pointer allowed the gondola of the balloon to be stabilized at a given azimuth; thus polarimetric measurements were made in a vertical plane that departed from the solar/anti-solar point's vertical plane by ~8°. In a vertical scan performed at altitudes of approximately 28–31 km, there were two local minima of the degree of polarization of earthlight [Deuzé *et al.*,[26] p. 98, plot $P(\theta)$ of sequence (a) in Fig. 4]: one minimum in forward scattering (~25° below the sun) and another minimum in backward scattering (~25° below the anti-solar point). The former and the latter minima of the degree of polarization were observed near the Brewster point and the fourth neutral point, respectively. If the plane of the scan had been exactly the solar/anti-solar point's vertical, Deuzé *et al.*[26] could have observed the fourth neutral point.

5. The POLDER (Polarization and Directionality of Earth's Reflectances) instrument was designed to measure the directionality and polarization of the solar radiation scattered by the earth-atmosphere system.[27] An air-borne simulator of the instrument has also been developed, and experimental air-borne campaigns have been conducted, as well. Three of the channels (443, 670, 865 nm) measured the linear polarization of the incident light. This was achieved by three measurements with polarizers turned by steps of 60°. A combination of the three measurements yielded the Stokes parameters I, Q, U, from which the total radiance $L = I$, the linearly polarized radiance (the product of the total radiance and the degree of linear polarization) $L_{\mathrm{pol}} = (Q^2 + U^2)^{1/2}$, and the angle of polarization were deduced. The POLDER team prefers to use polarized radiance—which is nearly additive with respect to the contributions of molecules,

aerosols, and land surfaces—rather than degree of polarization, where polarized and unpolarized light are mixed ambiguously. Thus, in the publications of the POLDER-team, color-coded maps of the radiance and polarized radiance have been used (see, e.g., Fig. 6 in Ref. 28, p. 145). Neutral points along the anti-solar meridian above and below the anti-solar point never show up explicitly in the POLDER maps of the polarized radiance. In these pictures, around the anti-solar point there is usually an extended circular or elliptic (dark-gray or black) spot representing zero and very low values of polarized radiance at all three (443, 670, 865 nm) wavelengths. Farther away from the anti-solar point, the picture gradually becomes brighter and the color more bluish because of the gradually increasing polarized radiance, especially in the blue (443 nm) spectral range owing to molecular scattering. At a given wavelength, the polarized radiance is zero at the Brewster and fourth neutral point, the position of which depends on wavelength (see Fig. 4 and Table 1). These neutral points show up strikingly in the map of the degree of linear polarization p measured at any wavelength if very low p values (0%, 1%, 2%, 3% ,...) are coded and visualized by strongly contrasting colors. In the maps of polarized radiance used by the POLDER team, three colored dark (almost black) spots should be seen at the positions of the Brewster and fourth neutral point at the three (443, 670, 865 nm) wavelengths. These dark-colored spots are, however always merged into the great dark spot around the anti-solar point, since the zero and the very low values of polarized radiance are coded by the same very-dark-gray shades. On the other hand, the information available in the angle of polarization was practically not used by the POLDER team; we do not know of any published map of the angle of polarization measured by the POLDER instrument.

6. Using the Mie theory, Bréon *et al.*[13] computed the polarized phase function $Q(\gamma)$ for 12 different aerosol models as a function of scattering angle γ. $Q(\gamma)$ is the product of the phase function and the degree of linear polarization. In their model they used different size distributions and refractive indices of the aerosol particles. $Q(\gamma)$ is negative when the direction of polarization is parallel to the plane of scattering and positive when it is perpendicular. Where the polarized phase function switches from negative to positive $[Q(\gamma^*) = 0]$ there is a neutral point. Depending on the model parameters, in the 12 $Q(\gamma)$ plots computed by Bréon *et al.*[13] (Fig. 1b, p. 17188), $Q(\gamma^*) = 0$ for different scattering angles γ_1^* and γ_2^*, where $10° < \gamma_1^* < 55°$ and $120° < \gamma_2^* < 170°$. The neutral point at γ_1^* and γ_2^* corresponds to the Brewster and the fourth neutral point, respectively. Although from these numerical calculations a neutral point of earthlight polarization below the anti-solar point can be deduced and predicted, in their numerous publications the POLDER team never noted explicitly the existence of this neutral point and did not mention that it might correspond to the fourth principal neutral point. The closest comment regarding this neutral point was made by Deuzé *et al.*[28] (pp. 144–145) where they noted for their numerical results that "near a scattering angle 150° the polarized reflectance equaled the molecular reflectance; the aerosols exhibited zero polarization for a 150° scattering angle, and for larger scattering angles, the aerosol polarization increased again, with the polarization direction parallel to the scattering plane ..."

Judging from their publications, the fourth as well as the Brewster neutral point seemed to escape the attention of the POLDER team. Obviously, they used the polarization data collected by the POLDER instrument for practical, applied meteorological purposes. Nevertheless, the polarization data sensed remotely by the air-borne as well as the space-borne version of the POLDER instrument should latently contain the fourth neutral point of the normal clear sunlit atmosphere: The maps of the degree and angle of linear polarization measured at the three (443, 670, 865 nm) wavelengths should have been calculated and visualized in a format similar to that presented in this work.

7. Finally, we would like to note that Lynch[29] unquestionably found the existence of the fourth neutral point during his airborne observations, but never published his results, because his calibrations were unsatisfactory.

5. CONCLUSIONS

We conclude that the results of our two balloon-borne imaging polarimetric measurements provided convincing quantitative evidence of the existence of the fourth principal neutral point within the clear sunlit atmosphere. The fourth neutral point was observed from different altitudes between 900 and 3500 m during and immediately after sunrise at the theoretically predicted position, at approximately 22°–40° below the anti-solar point along the anti-solar meridian, depending on the wavelength.

The fourth neutral point has characteristics similar to those of the Arago, Babinet, and Brewster points: (i) It is located along the anti-solar meridian at the edge of the areas of positive and negative polarization of earthlight; (ii) at sunrise, it is at about the same angular distance below the anti-solar point as the Brewster point is below the sun; (iii) its nadir angle decreases as the wavelength decreases; (iv) its position and the polarization characteristics of earthlight around it are influenced by ground reflection, the effect of which decreases as the altitude increases and/or the wavelength decreases; (v) its nadir angle is decreased by multiple scattering on atmospheric aerosols, increasing the areas of negative polarization of earthlight.

The balloon-borne observations on the Brewster and fourth neutral points are consistent with our earlier ground-based observations on the Arago, Babinet, and Brewster points performed with video polarimetry[20,21] or with full-sky imaging polarimetry.[9,10,15–19]

The fourth neutral point was not observed during earlier air- or space-borne polarimetric experiments and/or it escaped the attention of researchers, because (a) some of these measurements were performed at longer (red or infrared) wavelengths to minimize the contribution of the molecular scattering at the shorter (ultraviolet, blue) wavelengths; (b) the previous techniques were not adequate to measure neutral points; (c) the routinely used point-source scanning polarimeters were not pointed toward the fourth neutral point; (d) neutral points did not show up explicitly in the polarization maps owing to an inadequate, disadvantageous color coding and displaying of the measured polarization data.

According to Coulson[2] (p. 242), "more attention has been paid to the measurement of the positions of the Arago, Babinet, and Brewster points than to any other feature of skylight polarization." This statement is now rounded off by our first observation, visualization, and characterization of the fourth neutral point reported 193 and 162 years after the discovery of the Arago point and the Babinet point, respectively, and 160 years following the first observation of the Brewster point.

ACKNOWLEDGMENTS

Part of this work was done at the Department of Cognitive Neuroscience of the University of Tübingen, Germany. Our research was supported by a 12-month Humboldt fellowship from the German Alexander von Humboldt Foundation and by an István Széchenyi scholarship from the Hungarian Ministry of Education to G. Horváth and by grant 31-43317.95 from the Swiss National Science Foundation to R. Wehner. We are grateful to Attila Bakos (balloon pilot), István Cseraljai, Ernő Svájer, and Ottó Bogdányi (Hot Air Ballooning Department, Hungarian Airlines Aero Club MALÉV, Budapest) for their assistance during the balloon flights. Many thanks are due to Sándor Hopp and Endre Berecz (Mechanical Workshop, Eötvös University, Budapest) for constructing the polarimeter holder and to Ákos Horváth, meteorologist (Meteorological Observatory, Siófok), for his help prior to our balloon flights. Thanks are due to Günther P. Können and David K. Lynch for their valuable comments on an earlier version of the manuscript.

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29. D. K. Lynch (David.K.Lynch@aero.org) wrote to G. Horvath on 26 November 2001: "The 4th neutral point has been a favorite topic of mine for some years, yet I have never published the results. I have observed it twice, once in 1983 and again in 1994 from aircraft, but I have not published the results because my calibrations were not too good. The existence, however, is certain."