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Reflection-Polarization Pattern at Water Surfaces and Correction of a Common Representation of the Polarization Pattern of the Sky

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Many hydrophilous insects recognize water by the polarization of the reflected light [1]. When the water is illuminated by diffuse, nonpolarized sky light, the animals have a relatively simple polarization pattern to identify: all the e vectors in the reflected light are horizontal. But when the sky is clear and visibility good, very complicated polarization patterns can develop due to superposition of the polarization characteristics of the water surface and the partially reflected polarization pattern of the sky light.

We have calculated such patterns for an ideal water surface, and present them here. We also present a revised picture of the polarization of sky light. The drawing of the sky polarization pattern published in 1959 by Stockhammer [2], which has been reproduced in many review articles and textbooks (e.g. [3–6]), and the two-dimensional representation of the sky polarization pattern published by Wehner [7,8] contain an error in the directions of the e vectors. Here we correct this error.

For the calculations of reflection polarization the sky polarization pattern was slightly idealized; the lines of equal polarization were assumed to form exact circles around the position of the sun, as in Wehner's [9] three-dimensional polarization pattern, and the e vectors were assumed to be exactly aligned with these circles. Departures from this regular pattern in the vicinity of the sun (Babinet and Brewster neutral point) were disregarded. These departures are negligible because here the stronger polarization of the water surface predominates. The degree of polarization was approximated by $d = d_{max} \cdot \sin^2 \alpha/(1+\cos^2\alpha)$ (see [10], p. 288; α is the angular distance from the sun). For sun elevations of 0° (sun at the horizon), 30°, 60°, and 90°, d_{max} was taken to be 77, 70, 63, and 56%, respectively (see [10], p. 295). To calculate the reflection of the sky polarization pattern the appropriate Fresnel formulas were used ([11], p. 332).

With an ideal water surface under diffuse, unpolarized sky light, all the e vectors in the reflection-polarization pattern are arranged concentrically around the center of the pattern; that is, from the viewpoint of an observer they appear horizontal (Fig. 1a). Polarization is maximal at the Brewster angle $\Theta=53°$ (dotted line representing a degree of polarization $d=100\%$). The relative intensity of the reflected light is not shown in the figures. For unpolarized incident light it is 2% at $\Theta=0°$ (in the center of the pattern) and 7.6% at the Brewster angle; the amount of light reflected rises rapidly for $\Theta > 60°$, reaching 100% at $\Theta=90°$ (at the edge of the pattern).

With a clear, cloudless sky the polarization pattern visible over the water surface is considerably more complicated, because the polarization pattern of the sky itself contributes, to some extent,

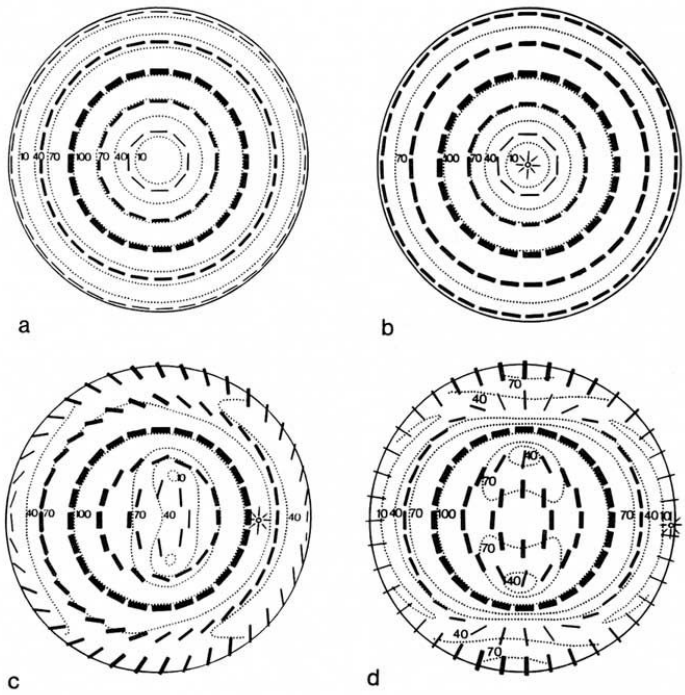

Fig. 1. Polarization pattern of an ideal water surface (a) in diffuse, nonpolarized sky light and under a clear, cloudless sky with the sun at the elevations 90° (b), 30° (c) and 0° (d). In the center of the pattern the observer is looking straight down at the water surface ($\Theta=0°$), and at the periphery the direction of view is $\Theta=90°$ to the vertical. *Dotted*: lines of equal degree of polarization d, showing the value of d for each line. The thickness of the bars for the e vectors is proportional to the degree of polarization

to the reflection-polarization pattern. Figure 2a shows the sky polarization pattern for a sun elevation of 30°. This is the corrected form of Stockhammer's pattern[1] (Fig. 2b; see also legend).

When the sun is at the zenith, the band of strongest polarization in the sky polarization pattern, 90° away from the sun, is parallel to the horizon; the e vectors in this zone are now horizontal and add to the polarization with horizontal e vectors in the reflection-polarization pattern, even in regions apart from the Brewster angle (Fig. 1b). The closer the sun comes to the horizon, the steeper is the slope of the band of strongest polarization in the sky, and the greater the departure of the e vectors from horizontal in the polarization pattern of the water surface. In the extreme case, when the sun is at the horizon (Fig. 1d), vertical (radial in Fig. 1) e vectors can appear. However, such discrepancies from the otherwise dominant horizontal e-vector orientation occur only in regions apart from the Brewster angle – regions in which the band of strongest polarization is reflected by the water surface – and at the horizon (at the periphery of the pattern). Here the degree of polarization is lower than in the region of the Brewster angle.

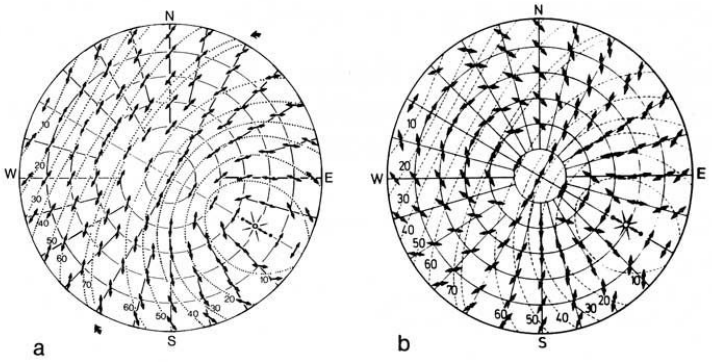

Fig. 2. a) Polarization pattern of the sky, with the sun at 30° elevation. The pattern corresponds to that of Stockhammer [2] (b) with the e-vector directions corrected by reflection about the meridians. *Circles*: elevation at 15° intervals, *dotted*: lines of equal degree of polarization, *arrows* outside the pattern point to the band of strongest polarization (d=70%). It is located 90° away from the sun. Lines of equal polarization pass across the sky approx imately concentrically around the sun, and the e vectors are approximately tangential to such circles. In the two-dimensional representation, therefore, the e vectors must be approx imately parallel to the dotted lines and cannot in some cases lie nearly perpendicular to them, as in Stockhammer's diagram

For a long time it has been considered unlikely that animals could orient to the polarization of light reflected from shiny, nonmetallic surfaces, because "this reflection polarization varies too much in space and time" ([2], see also [10]). Many hydrophilous insects do orient to reflection-polarization, however, at least to the extent that it guides them to their habitat [1]. The more complicated pattern associated with low elevation of the sun causes no great problems, for the following reason. It has been shown for *Notonecta* [12] that a polarizing horizontal surface with vertical e-vector direction is entirely ignored. Reflecting surfaces are interpreted as water when the horizontal e-vector component predominates. Over bodies of still water such zones are present even when the sun is low, at least on the side toward the sun and on the opposite side.

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[1] Stockhammer based his polarization pattern on the data of Sekera. Sekera (cf. [13]) represented the e-vector directions in a rather obscure way, as lines of equal deviation of the plane of polarization from the vertical plane. In transferring the angles so indicated to the radii of polar-coordinate paper, Stockhammer reversed the direction of rotation. As a result, all the e-vectors appear reflected about the radial coordinates. Although Wehner [9] represented the sky polarization pattern correctly and in the first easily understandable form, with three-dimensional diagrams, some of the two-dimensional polarization patterns he published later [7, 8] exhibit the same peculiarities as Stockhammer's pattern. Here the source of error was that the e-vector directions were determined by looking up at the dome of the sky, but then plotted in a polar-coordinate system that shows the dome as if it were viewed from above (Wehner, personal communication). Again, the result is a reflection of the e vectors at the meridians. Inferences about the orientation mechanism of bees are not affected by this plotting procedure in any way, because the bee's internal representation of the polarization pattern takes the same form.

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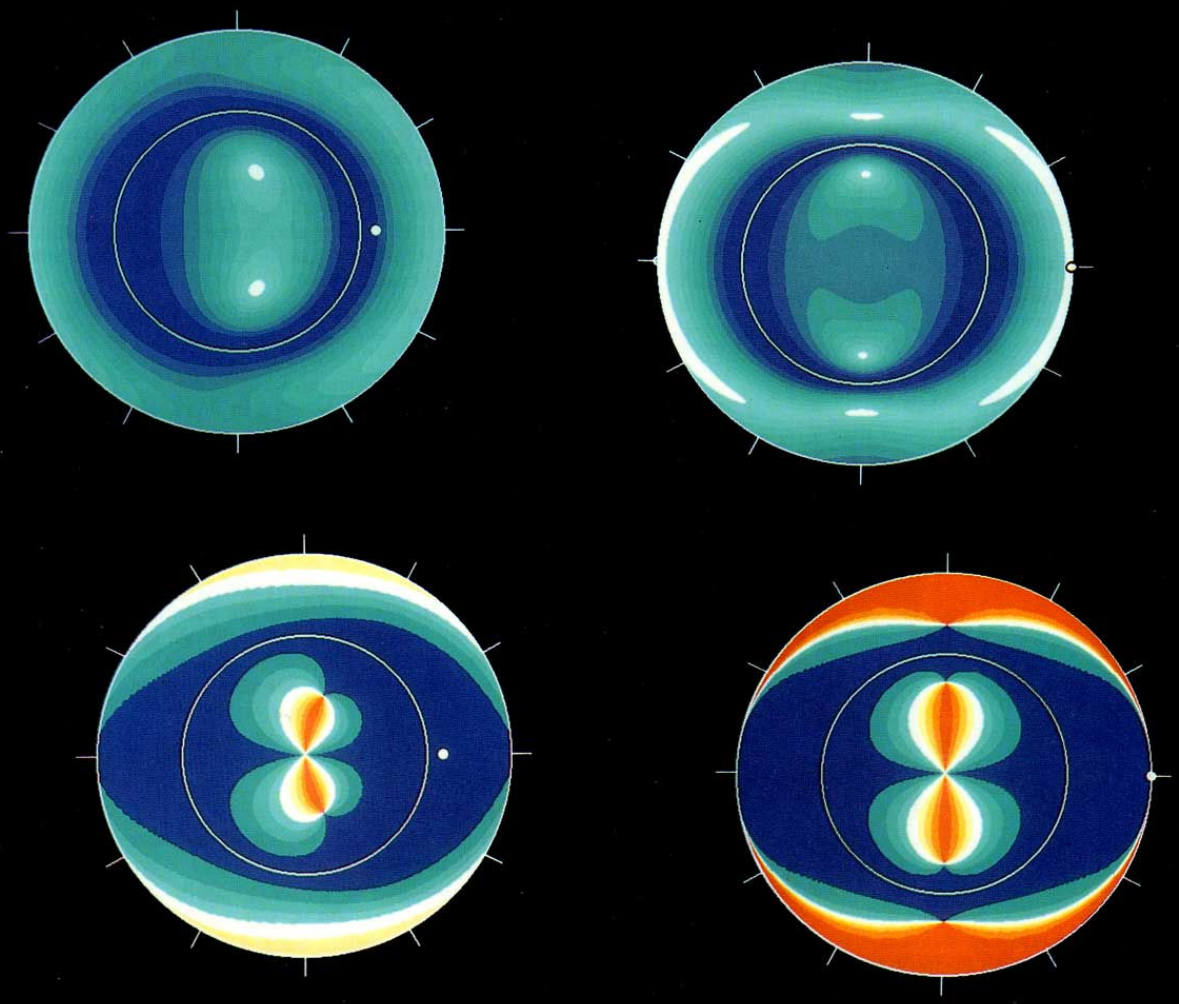

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Titelbild

Polarisationsmuster einer Wasserfläche bei einer Sonnenhöhe von 30° (links) und von 0° (rechts). Kleiner heller Kreis: Position des Spiegelbildes der Sonne; weißer durchgezogener Kreis: Brewster Winkel (53° von der vertikalen Blickrichtung in der Mitte der Abbildungen entfernt); oben: Polarisationsgrad *d*, je dunkler der Blauton, desto höher ist *d* (90–100 % beim tiefsten Blau, 0–10 % bei Weiß); unten: Richtung der e-Vektoren. Beim tiefsten Blauton beträgt die Abweichung von der horizontalen Richtung weniger als 10 %, bei Weiß 45 ± 5 %, bei Rot > 80 %, d.h. die e-Vektoren sind hier fast vertikal ausgerichtet. Wasserinsekten interpretieren reflektiertes, polarisiertes Licht als Wasser, wenn die horizontale e-Vektorkomponente überwiegt. Das ist in den Zonen der Fall, die in den unteren Abbildungen mit Blautönen wiedergegeben sind. Vgl. S. 82 dieses Heftes

Reichel, N.
Umweltbildung – ein neues Instrument zur Wiederbelebung der Studienreform?

In den 70er Jahren standen Reformen im Bildungswesen unter dem Motto „Mehr Demokratie wagen". Heute heißt das Zauberwort der Bildungsreform „Umweltbildung". Der Artikel analysiert die Lage der Umweltbildung an Hochschulen und macht Vorschläge zu einer Ökologisierung universitärer Forschung und Lehre. Er hebt hervor, daß Umweltbildung an Hochschulen nur gelingen kann, wenn vorhandene Ansätze zu interdisziplinären und gleichzeitig praxisbezogenen Zugängen zur Behandlung des Gegenstandes „Umwelt" gestärkt werden. Der Artikel fordert schließlich eine breite Diskussion über die Umweltbildung, die zweite Chance einer wirksamen Studienreform.

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Sengstock, K., Ertmer, W.
Die Kühlung von Atomen in den μ-Kelvin-Bereich durch Laserlicht

Die in den letzten Jahren entwickelten Methoden zur Manipulation und Kühlung der Bewegungsfreiheitsgrade neutraler Atome eröffnen neue Perspektiven in Atomphysik und Quantenoptik. Durch Einstrahlung von Laserlicht ist es möglich, atomare Ensembles abzubremsen, in kleinen Volumina einzufangen und ihre Bewegung bis an die quantentheoretischen Grenzen auszudämpfen. Die physikalischen Grundlagen und theoretischen Grenzen der Erzeugung ultrakalter Atome werden diskutiert und einige der möglichen Anwendungen vorgestellt.

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Zippel, H. P.
Historische Aspekte der Forschung über das Riechsystem von Wirbeltieren

Diese historische Übersicht stellt die grandiosen Untersuchungen von M. Schultze im 19. Jahrhundert in den Vordergrund. Seine Darstellungen enthalten viele methodische Details, grundsätzliche Auseinandersetzungen mit gängigen Lehrmeinungen und genaue Beschreibungen der Riechschleimhaut bei Wirbeltieren. Seine sorgfältig gewonnenen Erkenntnisse wurden von späteren Untersuchern mit Hochachtung erwähnt und sind auch heute noch weitestgehend gültig.

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