Significance of Light Polarization in the Behaviour of Certain Aquatic Insects and Sky-polarimetric Viking Navigation

SUMMARY OF PH.D. THESIS

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1. Introduction

The properties of originally unpolarized light can change in a variety of ways as a result of scattering, refraction or reflection. Although the polarization properties of light are practically imperceptibles for the human eyes, several arthropod species can detect and use them in their orientation processes. These facts inspired the widely discussed navigation theory that Viking sailors might have been able to orient themselves more or less precisely in the open sea with mysterious sunstones (i.e. calcite, tourmaline or cordierite crystals) on the basis of skylight polarization.

Our main goals were to measure the polarization characteristics of certain parts of the optical environment and by interpreting our results we also wanted to explain the behaviour of certain polarotactic aquatic insects. We also wanted to measure the accuracy of the second step of sky-polarimetric Viking navigation and test a previously unconceived navigation instrument, the twilight board. Our findings can help to understand the behaviour of polarotactic aquatic insects more precisely and find the answers to the still unproven questions related to the mysterious medieval open-sea navigation method of Viking sailors. Here I summarized our results, which have biological, atmospheric optical, meteorological and astronomical aspects.

2. Materials and Methods

In my Ph.D. thesis I present the results of two field experiments, in which we studied the polarotactic behaviour of *Ephoron virgo* [OLIVIER 1791] and *Caenis robusta* [EATON 1884] mayflies. We measured the reflection-polarization characteristics of light traps and torches used in these experiments by imaging polarimetry. During the mass swarming of *E. virgo*, we pointed the vertically polarized, horizontally polarized and unpolarised lightbeam of torches towards the swarm of mayflies flying above the river mid-line, and when they jammed around the torchlight, we took photographs of the attracted individuals. The photographs were evaluated with the software developed by Estrato Research and Development Ltd., which can count the white blobs of mayflies attracted by the torchlight. We studied the polarotactic reaction of *C. robusta* to vertically polarized, horizontally polarized and unpolarized light-traps and the captured individuals were counted later in the laboratory. It was enough and appropriate to use the binomial χ^2 test almost in all situations to obtain the significance of differences.

The polarization characteristics of the twilight sky at partial moon were measured with a full-sky polarimetric cloud detector constructed by Estrato Research and Development Ltd., and the anomalous celestial polarization patterns of the sunlit and moonlit smoky skies were measured by a full-sky imaging polarimeter. Based on previous literature data, we also analysed the role of these unusual celestial polarization characteristics in animal navigation.

In the second part of my Ph.D. thesis I tested a famous hypothesis, according to which the Viking sailors could have been able to analyse the celestial polarization characteristics by using sunstones and find the position of the sun covered by clouds or fog and then the North direction. We measured the accuracy of the second step of this hypothetic navigation method in a psychophysical experiment conducted in a planetarium with 11 male volunteer test persons, and from the measured errors we derived the accuracies of determining the North direction. We characterized the errors under various measurement situations by circular statistics. Our results were essential to establish the accuracy of the alleged sky-polarimetric Viking navigation and to judge the plausibility of this hypothesis.

According to the most accepted theory, the famous Uunartoq artefact fragment could be used as a sun-compass by Viking sailors in the Middle Ages. But Balázs Bernáth examined in detail this fragment and the scratches on it, and found a more sophisticated navigation toolkit optimized for use when the sun is close to the horizon, the twilight-board. To test his theory, we performed a psychophysical field experiment at dawn and dusk with six test persons and reconstructed medieval tools (two birefringent calcite crystals, a twilight compass and a shadow-stick) in clear weather at solar elevations lower than 10°. A magnetic compass with an opaque cover fixed on the dial plate served to measure the orientation error. After the test person oriented the twilight compass, the cover of the magnetic compass was carefully removed, and the dial plate was photographed from above. The error of true North was calculated by means of an image-processing software. We characterized the orientation errors under various measurement situations by circular statistics.

3. Results

3.1. A polarotactic reaction of mayflies helping to avoid unsuitable habitats

- We found that *E. virgo* and *C. robusta* mayflies are attracted less to vertically polarized light than to horizontally polarized and unpolarized one.
- We pointed out that this polarotactic behaviour helps mayflies to stay above the highly and horizontally polarized water surfaces and to avoid unsuitable habitats, such as the riparian vegetation, which reflects weakly and non-horizontally polarized light.

- We found that the attractiveness of mayflies to differently polarized lights depends on intensity and species.

3.2. Anomalous celestial twilight polarization at partial moon and possible implications for animal orientation

- We found that the celestial polarization pattern is temporarily irregular at partial moon immediately after sunset or before sunrise, because in that case the intensities of scattered sunlight and moonlight are comparable but the solar-antisolar and lunar-antilunar meridians do not overlap.
- We observed that the neutral points of the twilight sky at partial moon are unusually positioned off the solar-antisolar and lunar-antilunar meridians.
- We pointed out that when scattered moonlight and sunlight compete, the symmetry axis of sky polarization is intermediate in such a way that it switches from the lunar-antilunar meridian to the solar-antisolar meridian prior to sunrise, and *vice versa*, from the solar-antisolar meridian to the lunar-antilunar meridian after sunset. At the same time the duration of this transient period highly depends on latitudes.
- We found that the maximum degree of polarization of light from the twilight sky decreases during this transient period, which can be explained by the multiple scattering of sunlight and moonlight in the atmosphere.
- We pointed out that these atmospheric optical phenomena during the irregular polarization transition between sunlit and moonlit skies may have possible implications for the orientation of polarization-sensitive crepuscular and/or nocturnal animals. Moreover, the duration of this transient period can considerably increase at higher latitudes when the celestial trajectory of the sun and moon runs for a long time near the horizon.

3.3. Anomalous celestial polarization caused by forest fire smoke and possible implications for orientation

- Using full-sky imaging polarimetry, we compared the celestial polarization patterns of clear and smoky moonlit skies.
- We showed that the sky polarization pattern, which is necessary for orientation of many polarization-sensitive animal species, can change drastically when the sky is covered by forest fire smoke, also in case of sunlit and moonlit skies.

- We found that due to the presence of smoke particles, the maxium degree of linear polarization of skylight and the angular distance between the unpolarized neutral points have also reduced.

3.4. Accuracy of the second step of sky-polarimetric Viking navigation

- We measured the error function of the second step of sky-polarimetric Viking navigation in a psychophysical experiment conducted in a planetarium. From the measured sun localization errors, we derived the accuracies of determining the North direction.
- We pointed out that if a Viking navigator cannot choose two nearby sky points for the sunstone analysis because of foggy or cloudy meteorological conditions, he has to determine the celestial polarization characteristics at distant celestial points. In this case he has to rotate his head a lot, which leads to inaccuracies in the estimation of angles and directions on the sky dome. We found that the navigator can determine the above-horizon intersection of the two celestial great circles more easily if the two selected sky points are closer to each other and the sun, and these three celestial points have higher elevations.
- We also found that the most precise North determination happened at the highest solar elevation and the inaccuracy of this navigation method can be higher when the two selected celestial points are far from the sun and the angle between the planes of the two celestial great circles increases. These findings can be explained by the limited field of view of the human eye.

3.5. Twilight board as a possible tool for sky-polarimetric Viking navigation

- We successfully tested a previously unconceived solar navigation method aided by a shadow-stick, a pair of calcite sunstones and a sun-compass, optimized for use when the sky is clear and the sun is close to the horizon.
- We found that the accuracy of this navigation method is incomparable to that of modern direction-finder instruments and highly depends on the meteorological conditions, the azimuth and elevation of the sun and the estimation method of a verdant or a qualified navigator.

4. Publications

4.1. Publications representing the basis of the dissertation

[1] **Farkas A.**, Száz D., Egri Á., Barta A., Mészáros Á., Hegedüs R., Horváth G., Kriska G. (2016): Mayflies are least attracted to vertical polarization: A polarotactic reaction helping to avoid unsuitable habitats. *Physiology and Behavior, 163,* 219–227. (D1, IF: 2,976)

[2] Barta A., **Farkas A.**, Száz D., Egri Á., Barta P., Kovács J., Csák B., Jankovics I., Szabó G., Horváth G. (2014): Polarization transition between sunlit and moonlit skies with possible implications for animal orientation and Viking navigation: anomalous celestial twilight polarization at partial moon. *Applied Optics, 53, 23,* 5193–5204. (Q1, IF: 1,649)

[3] **Farkas A.**, Száz D., Egri Á., Blahó M., Barta A., Nehéz D., Bernáth B., Horváth G. (2014): Accuracy of sun localization in the second step of sky-polarimetric Viking navigation for north determination: a planetarium experiment. *Journal of the Optical Society of America A, 31,* 1645–1656. (Q1, IF: 1,448)

[4] Bernáth B., **Farkas A.**, Száz D., Blahó M., Egri Á., Barta A., S. Åkesson, Horváth G. (2014): How could the Viking sun compass be used with sunstones before and after sunset? Twilight board as a new interpretation of the Uunartoq artefact fragment. *Proceedings of the Royal Society A, 470, 2166,* article no. 20130787. (Q1, IF: 1,998)

4.2. Additional publications relating to the dissertation in English

[5] Horváth G., **Farkas A.**, Bernáth B. (2014): *Sky-polarimetric Viking Navigation*. In: *Polarized Light and Polarization Vision in Animal Sciences*. (Ed.: Horváth G.) Springer Series in Vision Research. Springer-Verlag: Heidelberg, Berlin, New York. pp. 603–635.

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[7] Åkesson S., Odin C., Hegedüs R., Ilieva M., Sjöholm C., **Farkas A.**, Horváth G. (2015): Avian compass calibration: comparative experiments with diurnal and nocturnal passerine migrants in South Sweden. *Biology Open, 4, 1,* 35–47.

[8] Száz D., Horváth G., Barta A., Robertson B., **Farkas A.**, Egri Á., Tarjányi N., Rácz G., Kriska G. (2015): Lamp-lit bridges as dual light-traps for the night-swarming mayfly, *Ephoron virgo*: Interaction of polarized and unpolarized light. *Public Library of Science ONE, 10, 3,* article no. e0121194.

[9] Száz D., **Farkas A.**, Blahó M., Barta A., Egri Á., Kretzer B., Hegedüs T., Jäger Z., Horváth G. (2016): Adjustment errors of sunstones in the first step of sky-polarimetric Viking navigation: Studies with dichroic cordierite/tourmaline and birefringent calcite crystals. *Royal Society Open Science, 3,* article no. 150406.

[10] Száz D., **Farkas A.**, Barta A., Kretzer B., Egri Á, Horváth G. (2016): North error estimation based on solar elevation errors in the third step of sky-polarimetric Viking navigation. *Proceedings of the Royal Society A, 472,* article no. 20160171.

[11] Egri Á., **Farkas A.**, Kriska G., Horváth G. (2016): Polarization sensitivity in Collembola: An experimental study of polarotaxis in the water-surface-inhabiting springtail *Podura aquatica*. *Journal of Experimental Biology, 219, 16,* 2567–2576.

[12] Száz D., Mihályi D., **Farkas A.**, Egri Á., Barta A., Kriska G., Robertson, B., Horváth G. (2016): Polarized light pollution of matte solar panels: Anti-reflective photovoltaics reduce polarized light pollution but benefit only some aquatic insects. *Journal of Insect Conservation, 20, 4,* 663–675.

[13] Horváth G., Takács P., Kretzer B., Szilasi S., Száz D., **Farkas A.**, Barta A. (2017): Celestial polarization patterns sufficient for Viking navigation with the naked eye: Detectability of Haidinger's brushes on the sky versus meteorological conditions. *Royal Society Open Science, 4,* article no. 160688.

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[15] Száz D., **Farkas A.**, Barta A., Kretzer B., Blahó M., Egri Á, Szabó G., Horváth G. (2017): Accuracy of the hypothetical sky-polarimetric Viking navigation versus sky conditions: revealing solar elevations and cloudinesses favourable for this navigation method. *Proceedings of the Royal Society A, 473,* article no. 20170358.

4.3. Additional publications relating to the dissertation in Hungarian

[M-1] Horváth G., Blahó M., Herczeg T., Száz D., Czinke L., Barta A., Egri Á., **Farkas A.**, Tarjányi N., Kriska Gy. (2015): Matt fekete autók poláros fényszennyezése: a matt bevonat sem környezetbarát. I. rész. *Fizikai Szemle, 65, 1,* 7–9., II. rész. *Fizikai Szemle, 65, 2,* 38–41.

[M-2] Horváth G., **Farkas A.**, Száz D., Egri Á., Barta A., Barta P., Kovács J., Csák B., Jankovics I., Szabó Gy. (2015): A Hold és Nap által megvilágított égbolt polarizációátmenete biológiai vonatkozásokkal: a szürkületi ég rendellenes polarizációja részleges holdfázis idején. *Fizikai Szemle, 65, 3,* 74–82.

[M-3] Bernáth B., **Farkas A.**, Horváth G. (2015): Navigáció égre néző vikingekkel. 1. rész: Alkonyfény-iránytű. *Élet és Tudomány, 70, 10,* 307–309.

[M-4] **Farkas A.**, Kriska Gy., Herczeg T., Horváth G. (2015): Navigáció égre néző vikingekkel 2. rész: Jég és föld között. *Élet és Tudomány, 70, 15,* 464–466.

[M-5] Bernáth B., **Farkas A.**, Horváth G. (2015): Navigáció égre néző vikingekkel 3. rész: Hol vagyok? Merre tartok? *Élet és Tudomány, 70, 20,* 623–625.

[M-6] Barta A., **Farkas A.**, Horváth G. (2015): Navigáció égre néző vikingekkel 4. rész: Útmutató fénytünemények. *Élet és Tudomány, 70, 25,* 790–792.

[M-7] Horváth G., Egri Á., Barta A., **Farkas A.** (2015): Navigáció égre néző vikingekkel 5. rész: Napkővel három lépésben. *Élet és Tudomány, 70, 32,* 1008–1010.

[M-8] Hegedüs R., **Farkas A.**, Horváth G. (2015): Navigáció égre néző vikingekkel 6. rész: A napkőhasználat légköroptikai feltételei. *Élet és Tudomány, 70, 36,* 1142–1144.

[M-9] **Farkas A.**, Nehéz D., Horváth G. (2015): Navigáció égre néző vikingekkel 7. rész: Napkeresés a planetáriumban. *Élet és Tudomány, 70, 44,* 1385–1387.

[M-10] Száz D., **Farkas A.**, Blahó M., Kretzer B., Horváth G. (2015): Navigáció égre néző vikingekkel 8. rész: Kristályrejtély. *Élet és Tudomány, 70, 50,* 1577–1579.

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[M-12] **Farkas A.** (2015): A dunavirág fénybörtöne. *A Földgömb, 33, 296,* 46–55.

[M-13] **Farkas A.**, Trupka Z. (2015): Szennyező fény. A világítás csillagászati és ökológiai árnyoldalai. *A Földgömb, 33, 299,* 72–85.

[M-14] Száz D., **Farkas A.**, Horváth G. (2016): Navigáció égre néző vikingekkel 9. rész: Napmagasságbecslés. *Élet és Tudomány, 71, 39,* 1235–1237.

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