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Photonic Crystals on the Wing

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14. ABSTRACT
In the last three years, two research groups, from the universities in Groningen, the Netherlands, and Exeter, UK, working on the natural photonics of animals, have been able to join forces thanks to the EOARD/AFOSR grant. The aim of the research project has been (and is) the elucidation of the optical mechanisms involved in animal coloration. Indeed, color is one of the important aspects that characterize an animal. As will be outlined below, during the past research period of three years, the collaborating teams have made considerable strides in advancing the field. Worldwide a rapidly increasing research activity can be observed in the area of animal coloration and the subsequent biomimetic applications of the discovered photonic design principles. We have now achieved a stage where we can well delineate the optical methods that animals use in making themselves colorful, or reversely, which tools they use for optimal camouflage. The near future will see further detailing of our present basic knowledge, and we expect that the focus will gradually shift to sophisticated technical applications and instruments. There were 49 publications produced from this Grant. Highlights and discoveries made during the grant period: 1) Characterized several photonic structures present in butterflies, beetles and birds; 2) Elucidated the unique properties of various photonic crystals: gyroids, fcc- and diamond-type, and quasi-ordered; 3) Characterized the scattering structures creating extreme whiteness; 4) Discovered that the unique, boomerang shape of Parotia breast feather barbule segments enables the creation of very rapidly changing color effects; 5) Found that thin film and multilayers of butterflies and beetles act as polarizer reflectors, which enable a secret signaling channel for conspecifics, invisible for predatory birds; 6) Developed a novel imaging scatterometer, which allowed the unprecedented characterization of the reflection properties of butterfly and beetle scales, as well as those of bird feathers and beetle elytra. Its successful use in the Groningen laboratory motivated the duplication of the instrument and its installation in Exeter. The instrument will also prove its value for the study of biomimetic applications.

15. SUBJECT TERMS
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Photonic crystals on the wing

Introduction

In the last three years, two research groups, from the universities in Groningen, the Netherlands, and Exeter, UK, working on the natural photonics of animals, have been able to join forces thanks to the EOARD/AFOSR grant. The aim of the research project has been (and is) the elucidation of the optical mechanisms involved in animal coloration. Indeed, color is one of the important aspects that characterizes an animal. As will be outlined below, during the past research period of three years, the collaborating teams have made considerable strides in advancing the field. Worldwide a rapidly increasing research activity can be observed in the area of animal coloration and the subsequent biomimetic applications of the discovered photonic design principles. We have now achieved a stage where we can well delineate the optical methods that animals use in making themselves colorful, or reversely, which tools they use for optimal camouflage. The near future will see further detailing of our present basic knowledge, and we expect that the focus will gradually shift to sophisticated technical applications and instruments.

Inevitably, animal bodies can only be visible when they emit light, either actively, as occurs by bioluminescence, or passively, by reflecting incident light. The latter occurs when materials exhibit a refractive index contrast, that is, when there are interfaces between media with different refractive indices. An important property of a reflecting surface is that the reflected light becomes distinctly polarized when the angle of light incidence increases. In other words, reflecting surfaces act as polarizer reflectors. Strong polarization dependence of the reflectance also occurs when the reflecting medium consists of intricate, periodic structures with periodicities on the order of the light wavelength. These structures, multilayers and photonic crystals, are often applied in coloring animal bodies. Polarization by animal surfaces and body structures has been a recurrent theme in our research.

The principles of animal coloration will be succinctly presented here. The principles will be illustrated with examples taken from insects (butterflies, beetles and weevils) as well as from birds. First, various cases of physical (or structural)

coloration will be considered and subsequently chemical (or pigmentary) coloration will be treated. Finally, a few cases where we discovered intricate combinations of structural and pigmentary colorations will be put in the limelight. An extensive scientific review article on these themes is envisaged.

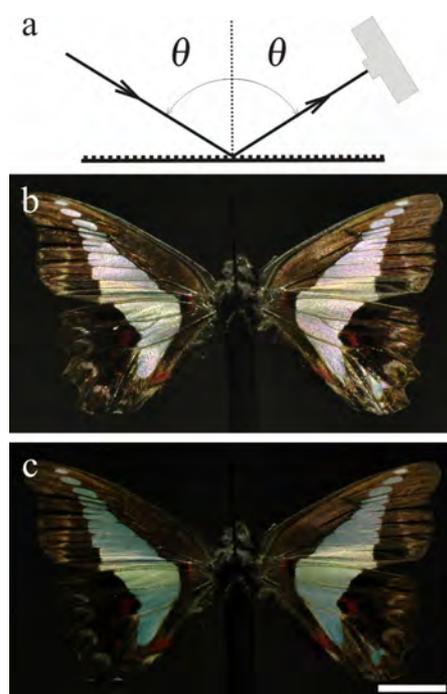


Fig. 1. Polarization of light reflected at the wing undersides of an intact *Graphium sarpedon* butterfly. **a** Diagram of the setup used to photograph the butterfly. The angle of light incidence as well as reflection was $\theta = 58^\circ$, and the plane of incidence was the sagittal symmetry plane of the butterfly's body. A linear polarization filter was put in front of the camera. **b** TE-light reflection. **c** TM-light reflection. Bar: 1 cm; from [48].

Thin films and multilayers

Distinct colors can be created with two interfaces a short distance apart, thus forming a thin film. Thin films are extensively encountered in butterfly wings and scales, as well as in bird feathers. The thickness of the thin film can rapidly vary, creating a broad-band, silvery reflection in some butterflies [19]; in others almost ideal thin films are created, as in the glass scales of the swordtail butterfly *Graphium sarpedon* [48], which act as polarizer reflectors (Fig. 1).

Coloration by thin film interference is well recognized in the feathers of birds. The main shaft of a bird feather is the rachis, which has serial paired branches, the barbs. The barbs possess further branches, the barbules, which are sectioned into segments. They have a thin envelope, the cortex, which acts as a thin film interference

reflector. Although the reflectance of a thin film is low, the neck feathers of for instance pigeons are conspicuously colored green and purple. Randomly arranged, heavily absorbing melanin-pigment granules inside the ovoid-shaped barbule segments create a black background against which the thin-film reflections stand out. Generally, not only barbule segments but also the barbs of bird feathers have a thin-film cortex, but the thickness is usually rather variable and of the order of several μm , so that on average a quite flat reflectance spectrum results. Nevertheless, the cortex layer bounding the bird feathers plays a considerable role in the feather reflectance properties, especially at larger angles of light incidence; an aspect that has been generally overlooked by birders [47].

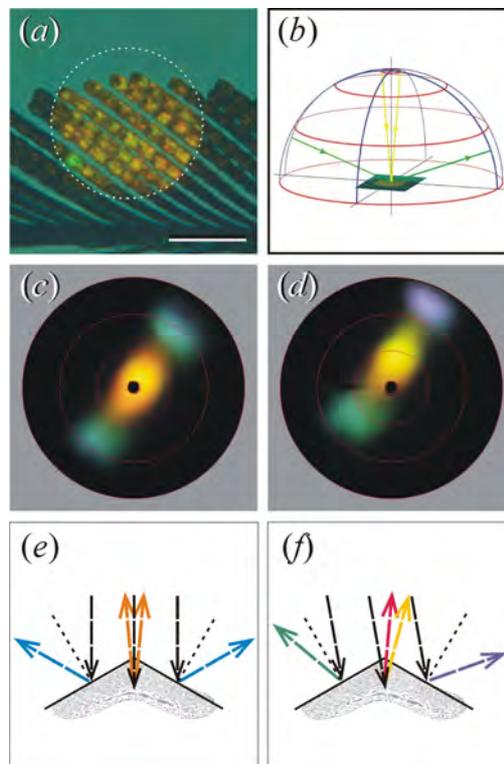


Fig. 2. Imaging scatterometry, which shows how a single barbule reflects light from a point source. The barbule acts as three separate colored mirrors, each reflecting light in a different direction. (a) A 200 μm diameter spot is illuminated with a narrow beam of white light; scale bar 100 μm . (b) Diagram of how light rays with angles of incidence 5° (yellow) or 70° (green) reflect from a plane surface with the same angle (indicated by the yellow and green arrows); the red circles indicate inclination angles of 5° , 30° , 60° and 90° . (c) The angular distribution of the scattered light by the barbule with about normal illumination. The red circles indicate inclination angles of 5° , 30° , 60° and 90° . The central black spot (approximating the circle with polar angle 5°) is due to the axial hole in the ellipsoidal mirror of the scatterometer. (d) The angular distribution of the scattered light from the barbule with illumination from an inclination angle of $\sim 20^\circ$. (e) Diagram explaining that the central yellow spot in (c) emerges from the melanin multilayers inside the barbule segments, acting as an interference reflector. The blue spots represent light beams reflected by the segment's cortex acting as an angled thin film reflector. (f) A similar diagram explaining how a shift in the direction of illumination results in the color changes of the reflected beams in (d), as expected for multilayer and thin film reflectors; from [40].

The thin film principle is applied in the breast feathers of the bird of paradise Lawes' Parotia in a very sophisticated way (Fig. 2). Here the barbule segments have a boomerang-shaped cross section. The segment cortex thickness is $\approx 0.35 \mu\text{m}$, causing a bluish reflection. The inner space of the barbules is filled with melanin pigment concentrated in rodlets that are neatly arranged in layers. The layers together create a strongly golden-yellow reflecting multilayer, which furthermore serves as a black background for the blue-reflecting thin-film cortex. The thin-film cortex and the interior multilayer together create very colorful feathers [40].

Multilayers creating bright iridescent green and purplish colors are realized in the elytra of *Chrysochroa* (jewel) beetles. The multilayers are extremely effective polarizer reflectors [37]. Perforated multilayers are present in the wing scales of lycaenid butterflies [21]. The amplitude and directionality of the reflections depend on the degree of the perforations. Multilayers are also realized in the ridges of the scales on the brightly blue wings of *Morpho* butterflies [17] and in the UV- or blue-reflecting wings of pierid butterflies [5,10,43,44]. The scale ridges are slender structures, however, so that diffraction plays an important role. Incident light is therefore reflected by *Morpho* scales into more or less smoothed diffraction patterns. These patterns could be well studied by a specially developed imaging scatterometer [17]. This instrument has demonstrated to be an immensely powerful tool for studying animal photonics; notably for the study of the optical properties of 3D structures [38].

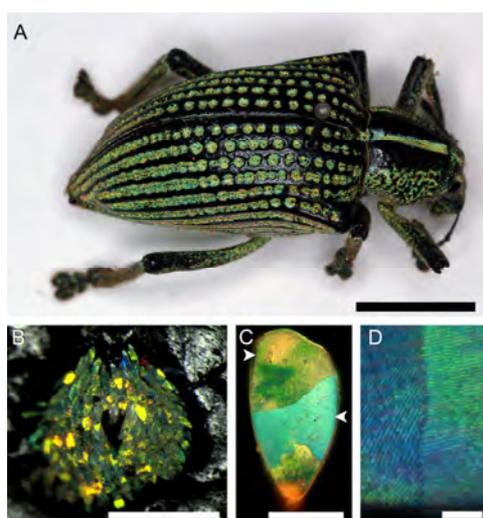


Fig. 3. The Diamond Weevil, *Entimus imperialis*, and its scale organization. **A** The intact animal with the black elytra studded with numerous yellow-green pits (bar: 1 cm). **B** A single pit as seen in an epillumination polarization microscope with polarizer and analyzer parallel (bar: 0.5 mm). **C** A single scale with a few differently colored domains (bar: 50 μm). **D** A domain border showing the difference in lamellar arrangements (bar: 5 μm); from [49].

Gyroids and diamond-type photonic crystals

Some lycaenid and papilionid butterflies have scales with extremely involved structures, namely gyroids. We have characterized in detail the reflection properties of these intriguing structures [6, 31]. Surprisingly, the scales, which are from a physics point of view built in an extremely sophisticated fashion, function for effectively camouflaging their owners against green foliage.

We have discovered diamond-type photonic crystals in the scales of the Diamond Weevil, *Entimus imperialis* (Fig. 3). The scales have large uniform domains allowing detailed characterization of the photonic properties. The recently completed analysis represents the most advanced study of a biological photonic crystal to date [49]. A surprising twist to this story is that, although the scales reflect light very effectively as well as directionally, the overall result for the weevil is that the scales together create a green color, closely matching foliage coloration.

Quasi-ordered photonic crystals

The weevil *Eupholus magnificus* (Fig. 4) has scales with ordered and quasi-ordered domains [42]. The difference in visual appearance is that ordered photonic crystals reflect light directionally, whilst reflections from quasi-ordered domains are diffuse.

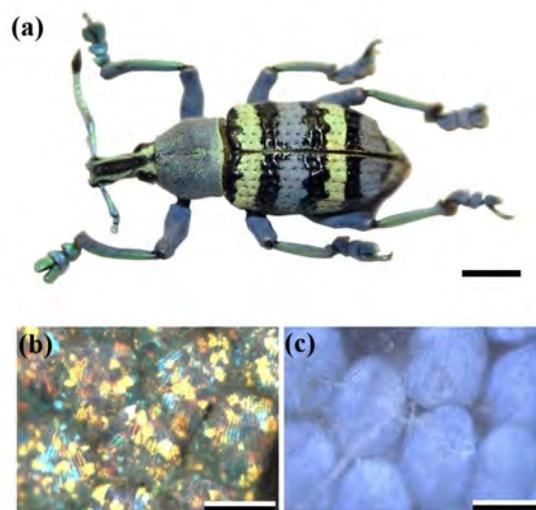


Fig. 4. The weevil *Eupholus magnificus*. (a) The elytra are marked by yellow and blue bands, with a diameter of a few mm, due to differently colored scales. The colored stripes alternate with dark bands where there are no scales present on the weevil's elytra: bar 4 mm. (b) Epi-illumination of the scales in the yellow elytral bands shows highly domained scales: bar 50 μm . (c) The scales in the blue bands are more or less homogenous in coloration: bar 50 μm ; from [42].

Many birds employ quasi-ordered structures to create colored barbs (Fig. 5). We have studied the barbs of the Common Kingfisher, and found that the barbs are distinctly iridescent. With random, natural illumination the iridescence becomes negligible [47].

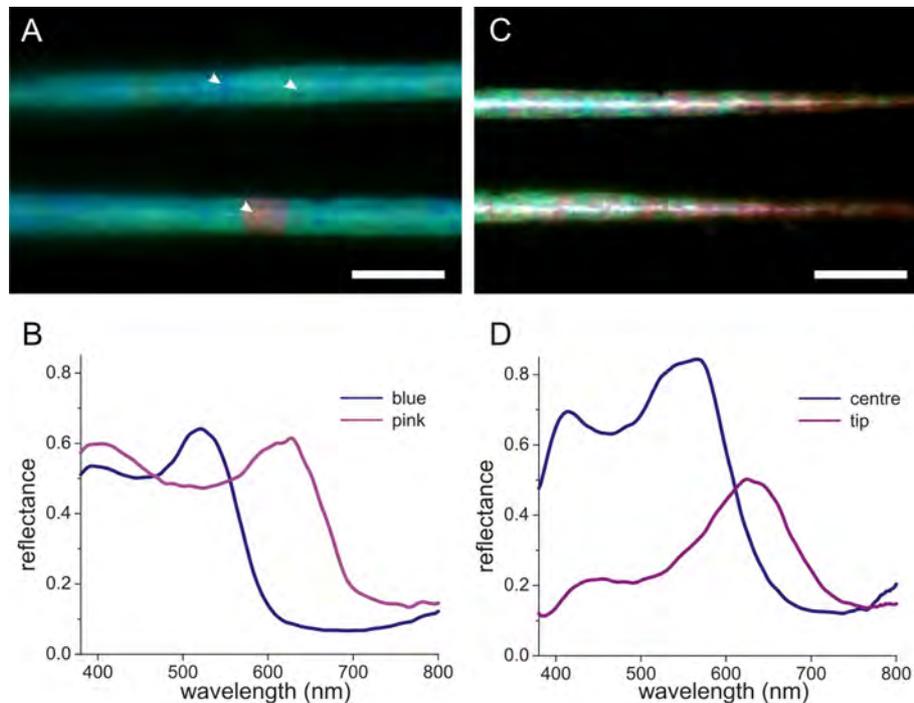


Fig. 5. Variations in the structural coloration of the barbs of the Common Kingfisher, *Alcedo atthis*. (A) Back feather barbs with mainly similar bluish color cells. Occasionally an aberrant cell with a different color (here pinkish) occurs. The vacuoles are distinguishable as dark areas with a central bright spot (arrowheads). Bar: 50 μm . (B) Reflectance spectra measured from small areas ($\sim 5 \times 5 \mu\text{m}^2$) of a blue and the pink area of the barbs of (A). (C) Barbs of a head feather with blue-green cells in the central feather area (left), but towards the tip the colour changes towards brown-red. Bar: 100 μm . (D) Reflectance spectra from the central and tip area of the barbs of (C); from [47].

Random scattering and pigments

Randomly organized structures will scatter incident light diffusely. Certain white beetles appear to have scales with very efficiently arranged random structures causing intense white, diffuse coloration. The discovered organization principles have important technical ramifications, for instance for the paper industry [1,24,30].

Scattering structures that contain pigments become colored, due to spectrally selective absorption. Pigmentary coloration is widespread in the animal kingdom, especially in butterflies and birds [2,3,7,9,34,46,47]. Papilionid butterflies of the *nireus* group (Fig. 6) appear to employ pigments in combination with regularly organized structures to tune the spectral reflections [2,3,4,20,34,45,46].

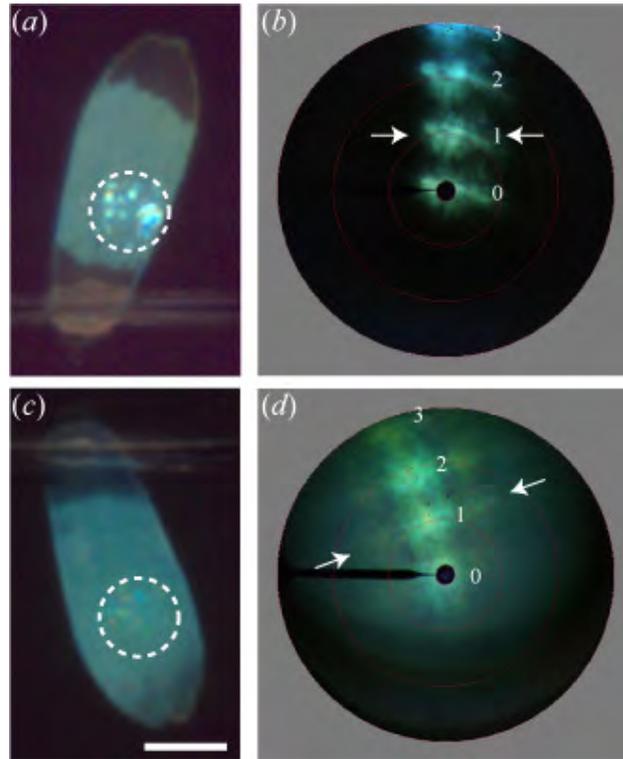


Fig. 6. Near-field (*a*, *c*) and superimposed far-field scatterograms (*b*, *d*) for the underside (*a*, *b*) and upperside (*c*, *d*) of a single scale of *P. epiphorbas*. A scale area with $\sim 40 \mu\text{m}$ diameter (dashed circle) was illuminated with a narrow-aperture (5°) white beam. The scale was rotated in three steps of 15° (from normal (0°), to 15° , 30° , and 45° ; numbered 0, 1, 2, 3, respectively), causing a change of 30° in the direction of the reflected light beam (from normal (0°), to 30° , 60° , and 90°); the arrows indicate the 15° step. The red circles indicate angular directions with respect to the axis of 5° , 30° , 60° , and 90° (scale bar in *a* and *c*: $50 \mu\text{m}$); from [46].

Vision

Animal colorations are presumably tuned to the spectral properties of animal visual systems. A number of visual studies have been performed in parallel with the coloration studies [4,5,8,12,22,33,39,41]. Our work on butterflies indicates that related species can apply quite different optical methods, that is, use different pigments and/or photonic crystals, for achieving similar coloration results, which conforms with the general view that the spectral properties of the visual systems of related species are similar.

Highlights and discoveries made during the grant period

- We have characterized several photonic structures present in butterflies, beetles and birds.

- We elucidated the unique properties of various photonic crystals: gyroids, fcc- and diamond-type, and quasi-ordered.
- We characterized the scattering structures creating extreme whiteness.
- We discovered that the unique, boomerang shape of *Parotia* breast feather barbule segments enables the creation of very rapidly changing color effects.
- We found that thin film and multilayers of butterflies and beetles act as polarizer reflectors, which enable a secret signalling channel for conspecifics, invisible for predatory birds.
- We developed, thanks to the support by the EOARD/AFOSR grant, a novel imaging scatterometer (Fig. 7), which allowed the unprecedented characterization of the reflection properties of butterfly and beetle scales, as well as those of bird feathers and beetle elytra. Its successful use in the Groningen laboratory motivated the duplication of the instrument and its installation in Exeter. The instrument will also prove its value for the study of biomimetic applications.

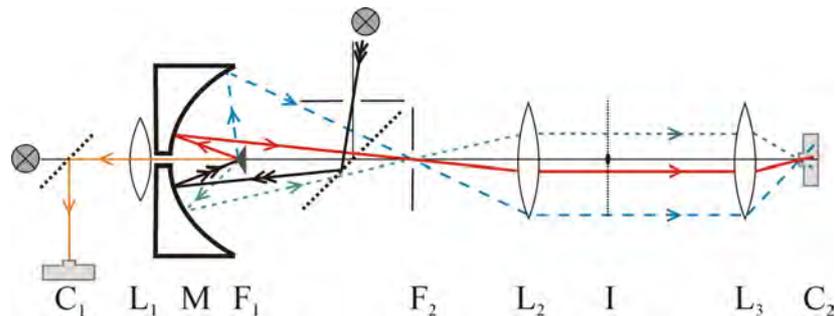


Fig. 7. Simplified diagram of the imaging scatterometer. The object is positioned in F_1 , the first focal point of ellipsoidal mirror M , and a light beam is directed from a certain angle to the object. The object is observed and imaged, via a small axial hole in mirror M , by lens L_1 and camera C_1 . Light reflected from the object is focused by the ellipsoidal mirror at its second focal point, F_2 , which coincides with the front focal point of lens L_2 , so that the distribution of the scattered light at infinity is projected in the back focal plane of the lens, I . This plane is imaged by lens L_3 at camera C_2 ; from [17].

- We have presented our work at numerous meetings and in research institutes, e.g. of the American Physical Society (Portland, March 2010), the International meeting of Natural photonics (Shanghai, June 2011), SOAR (State of the Art Review) meetings in Southampton (September 2009, June 2011), Eglin AFB and Wright-Patterson AFB (March 2010). A large delegation of the two collaborating teams will participate in the Geometry of Interfaces meeting in Primosten (Croatia; October 2011).

The above summary of the research outcomes is far from exhaustive. The publications listed below [put in the text numbered between brackets] will serve to provide detailed information for the interested reader.

Groningen/Exeter 3 August 2011

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Computational Physics
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Published papers during the grant period

2007

1. Vukusic P, Hallam B, Noyes J. (2007) Brilliant whiteness in ultrathin beetle scales. *Science* 315:348.
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