Wing Scale Micro- and Nanostructure in Butterflies

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Budapest, Hungary

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Teams engaged in investigation of **natural photonic crystals**

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Layout of presentation

Introduction

Morphology of butterfly wings and scales

Typical microstructures of scales:

Urania-type and *Morpho*-type, U*rania*,-pepper-pot- type

Methods:

thermal and spectral measurements

light microscope, SEM and TEM investigation

Wing scale micro- and nanostructure in lycaenid buterflies

Comparison of the scale structures in different butterfly families

Summary

Polyommatus icarus - Common blue

male

female

female

Argynis aglaja - Dark green fritillary

People find a great pleasure in observing flashing flight, notifying the characteristic patterns and vivid coloration of butterflies' wings.

Photos: Dr Ivan Tomáš
Institute of Physics, Czech Republic, Prague

Chemical colours- arise from pigmentation

Natural pigments: *melanins (eumelanin, pheomelanin), pterins, flavonoids etc*

Produced colours: *black, brown, red, yellow, orange-yellow*

Physical colours - arise from micro- and nanostructures

Produced colours: *blue, violet, green*

Photonic Crystals

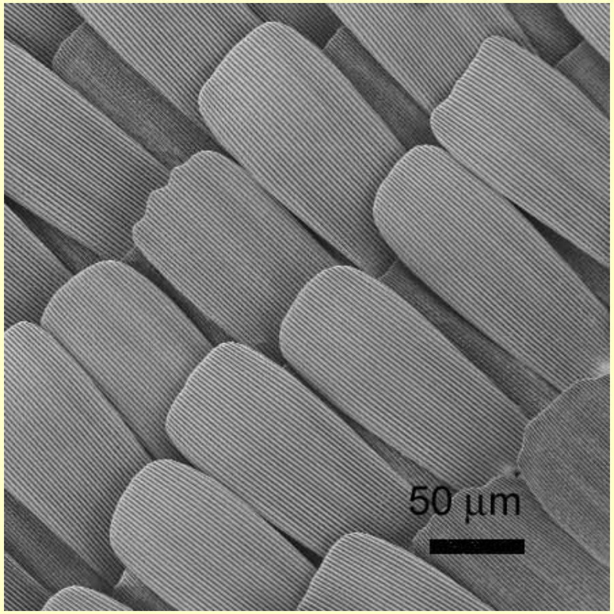
Photonic crystals are dielectric media exhibiting a periodic distribution of their refractive indexes. In photonic crystals same well-defined ranges of frequencies exist, in which light cannot propagate through the structure. Periodic ranges, called photonic band gaps prohibit electromagnetic wave propagation in the same way as semiconductors prohibit the propagation of quantum-mechanical electron waves in energy gaps. The light within the forbidden gap of an ideal photonic crystal is completely reflected by the structure.

The efforts made in the materials science for producing artificial photonic crystals are motivated by perspectives of applications in optical filtering and optical computing or in the design of very compact lasers.

Natural Photonic Crystals

Photonic crystal structures occur also in nature (beetles, algae, mineral opal). Butterfly wings are an excellent example of the living species that manipulate light in many ways. Among others wing scales can act as natural photonic crystals. Light interacts with three-dimensional micro- and nanostructures of the scales.

Typical **dimensions** of wings and their scales



Examples:

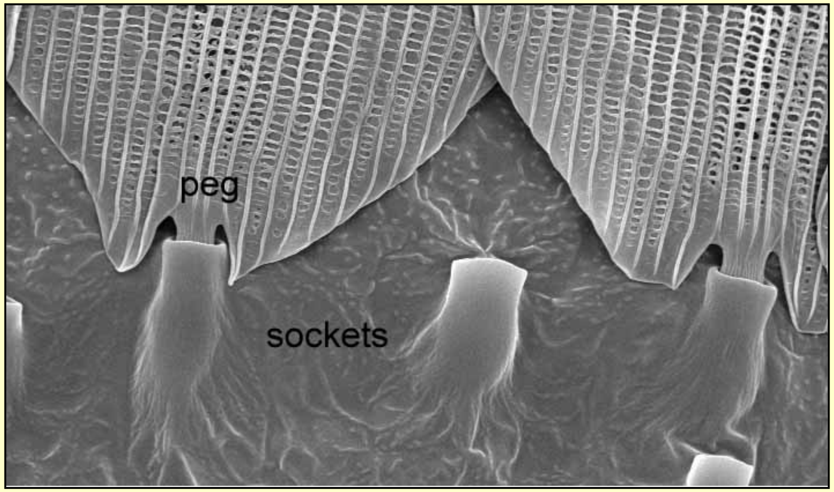
Queen Alexandra Birdwing butterfly of New Guinea *(Troides alexandrae)* wingspan ~30 cm

Western Pygmy Blue butterfly of North America (*Brephidium exile*) wingspan ~ 1 cm

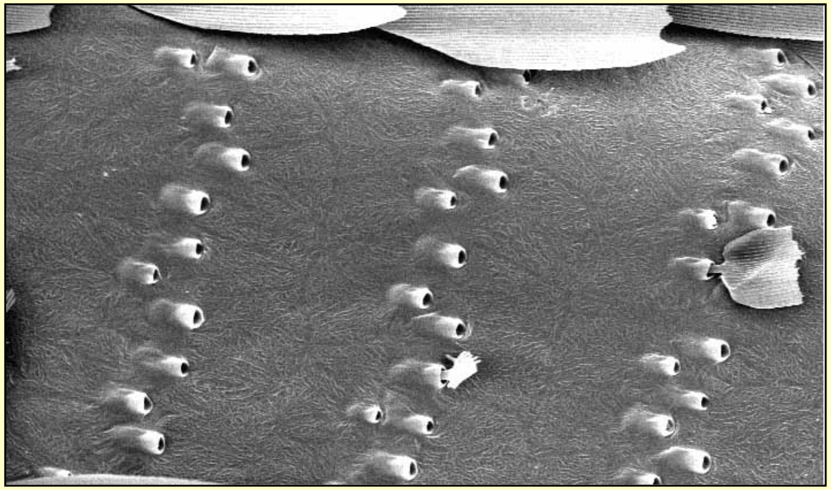
Scale width: 50 ~ 100 μm
Scale length: 150 ~ 200 μm

Scale **functions**: *pattern formation, pheromone dispersal, thermoregulation, visual signalling*

How the scale is attached to the wing membrane?

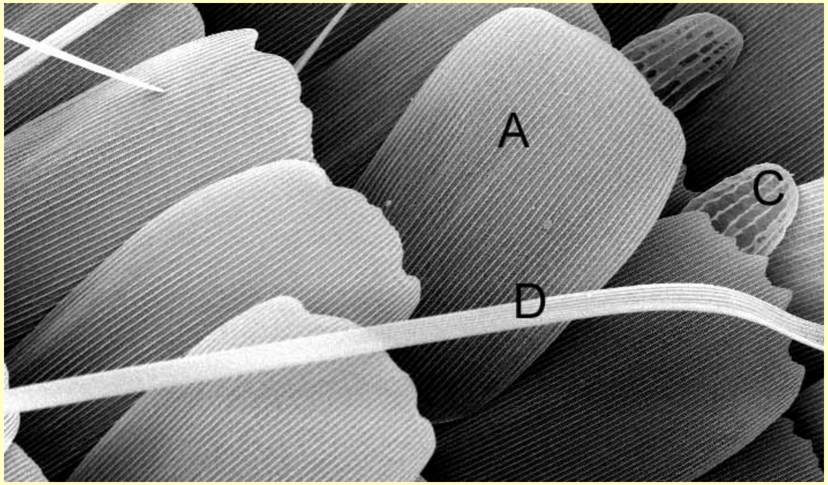


10 μm

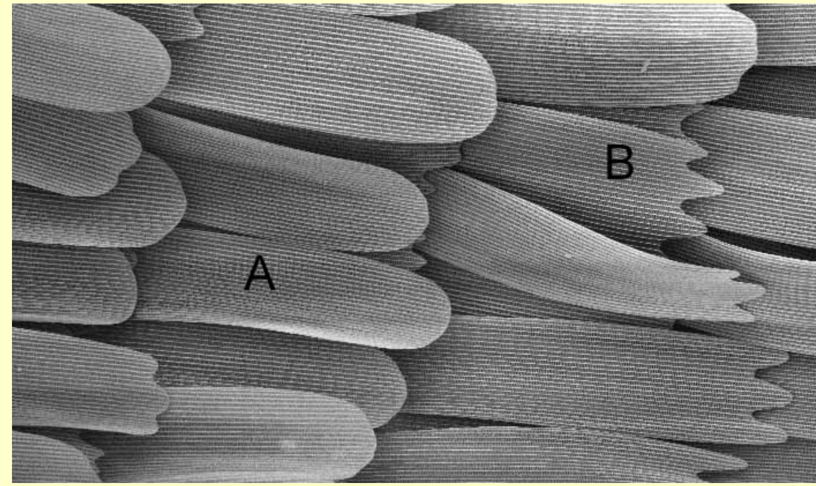


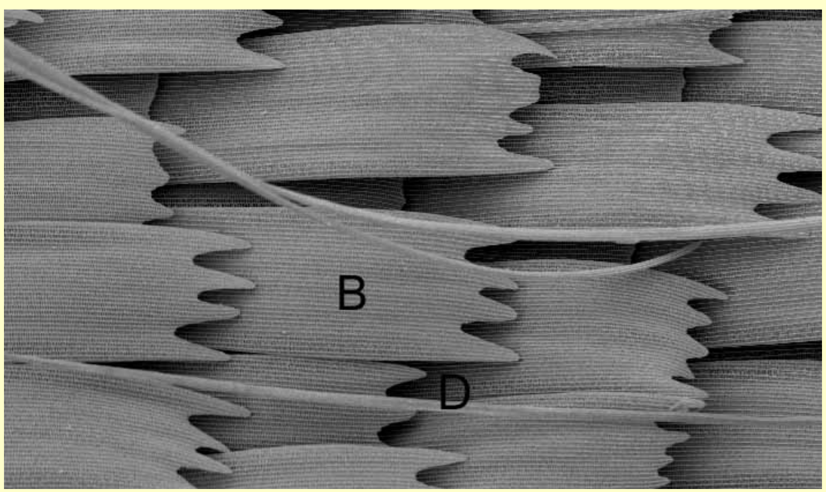
100 μm

Typical shapes of the scales



100 µm





Scales with:

A - rounded terminus

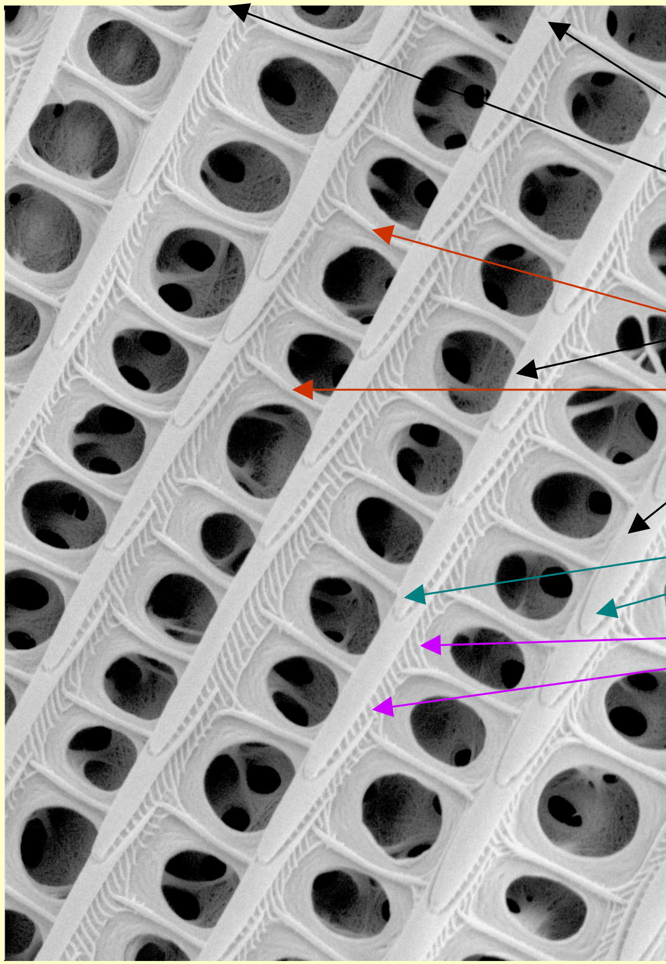
B - dentated (toothed) terminus

C - small androconia - scent scales

D - hair-like scales

Details of the scale structure

Luna moth (*Actias luna)*



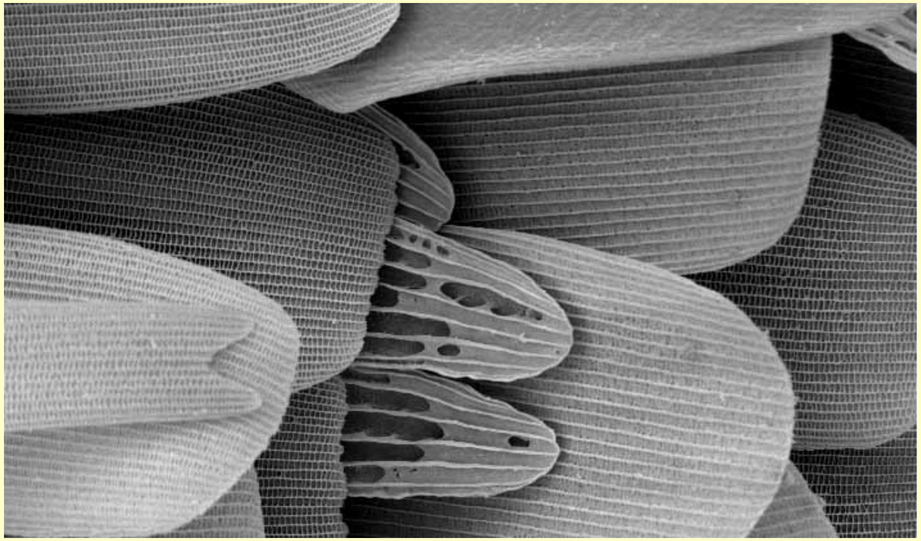
5 μm

Scales consist of a featureless reverse surface and a complex obverse surface with following elements:

- longitudinal ridges
- cross ribs
- scutes
- flutes

Longitudinal ridges and cross ribs form open cells so-called windows

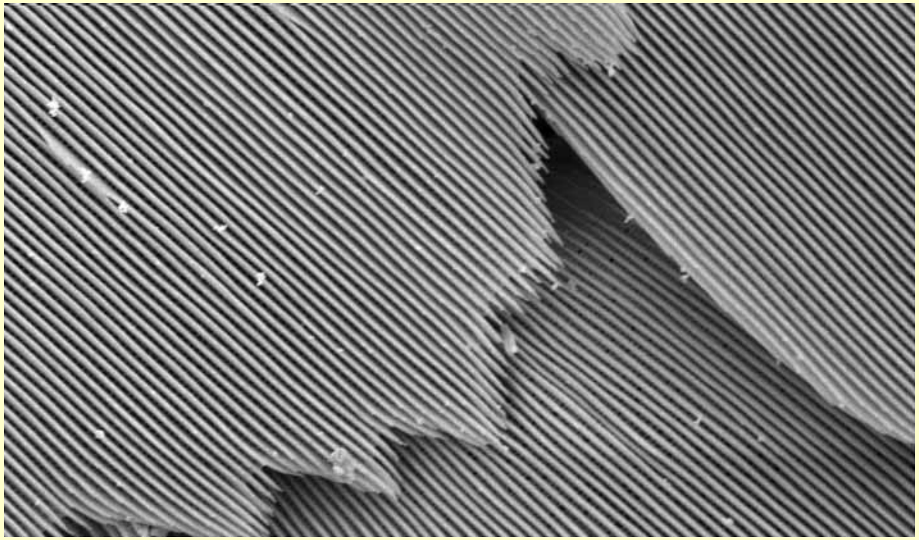
Typical microstructures of the scales



10 μm

Classical *Urania*-type scales

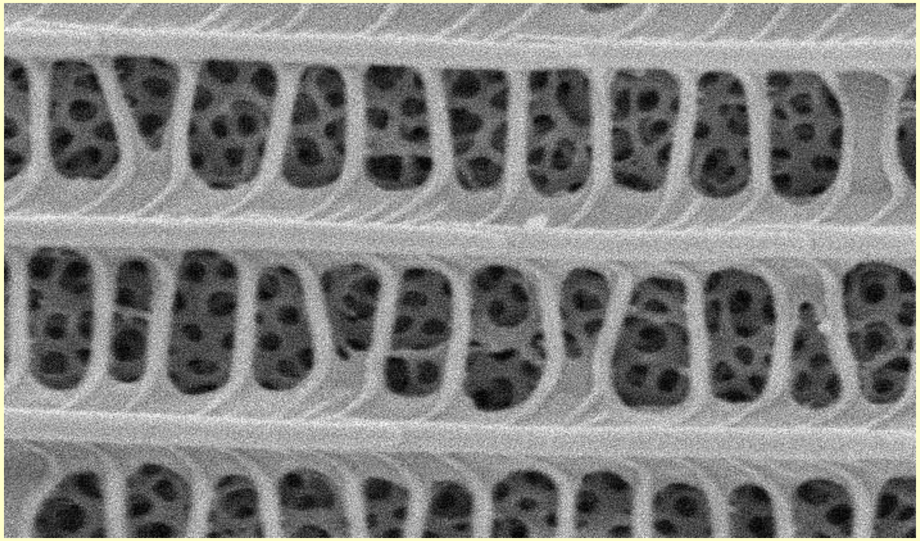
first observed in *Urania ripheus*



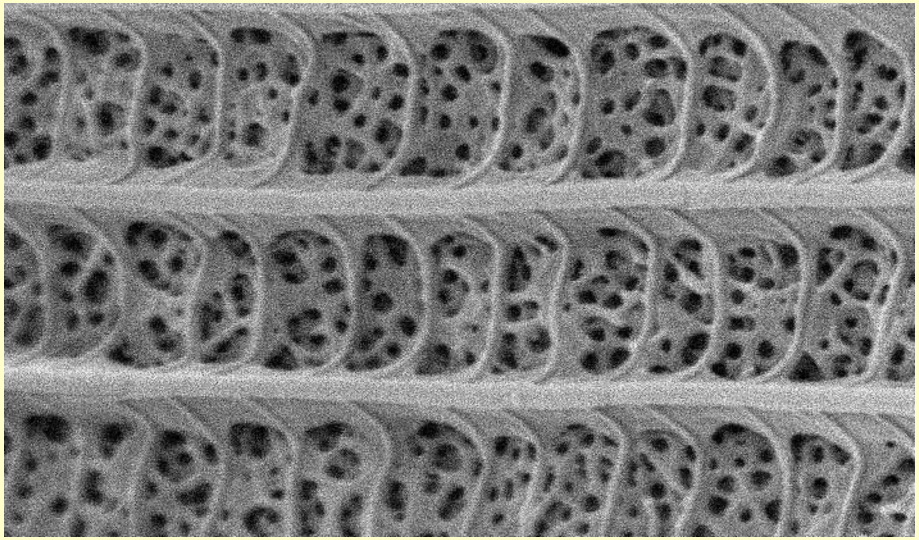
Classical *Morpho*-type scales

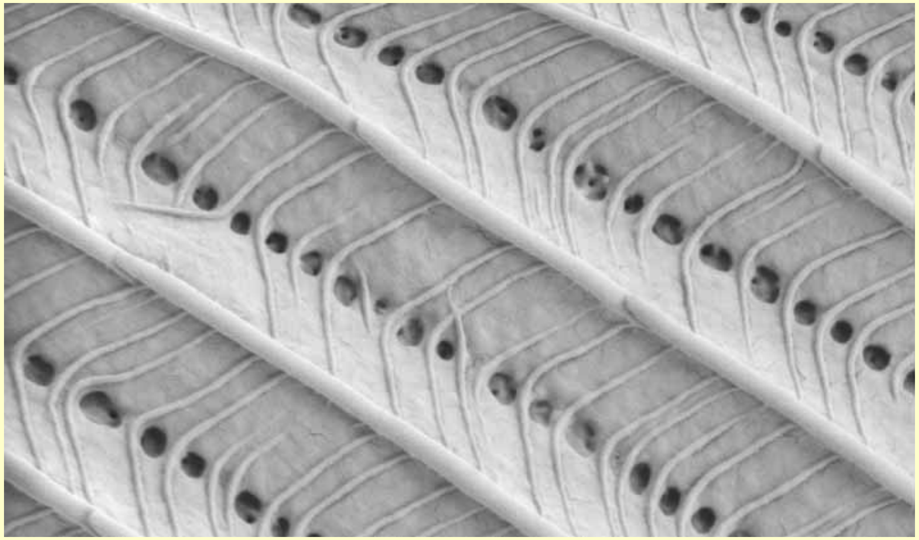
first observed in *Morpho menelaus*

The pepper-pot **nanostructure** of the *Urania* - type scales



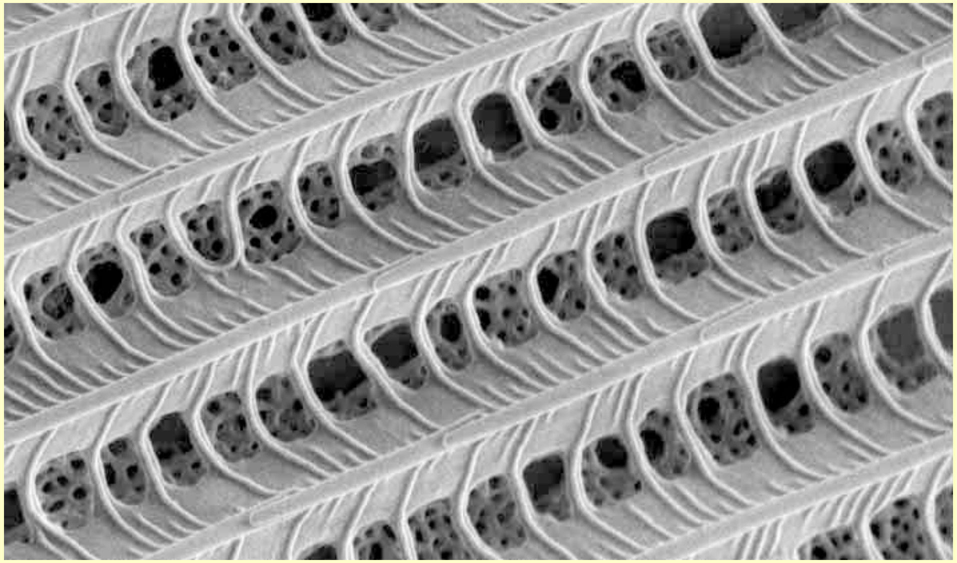
1 μm



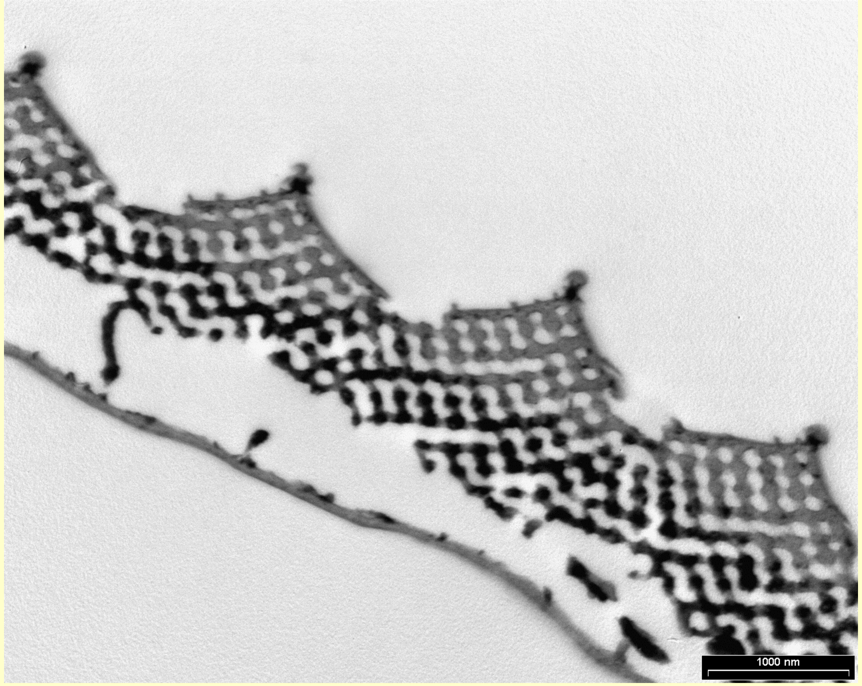


2 μm

The pepper-pot **nanostructure** of the *Urania* - type scales



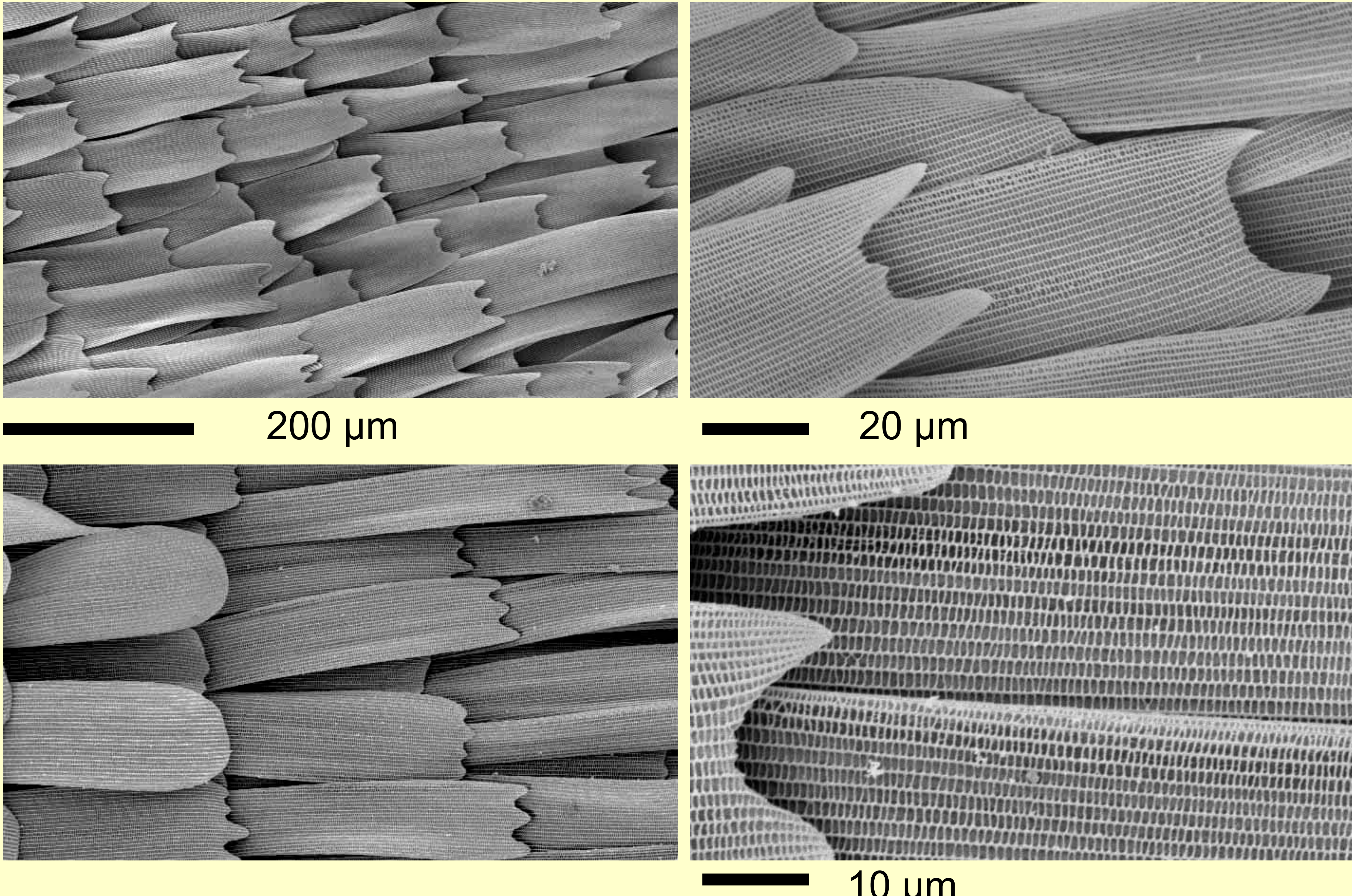
2 μm



1 μm

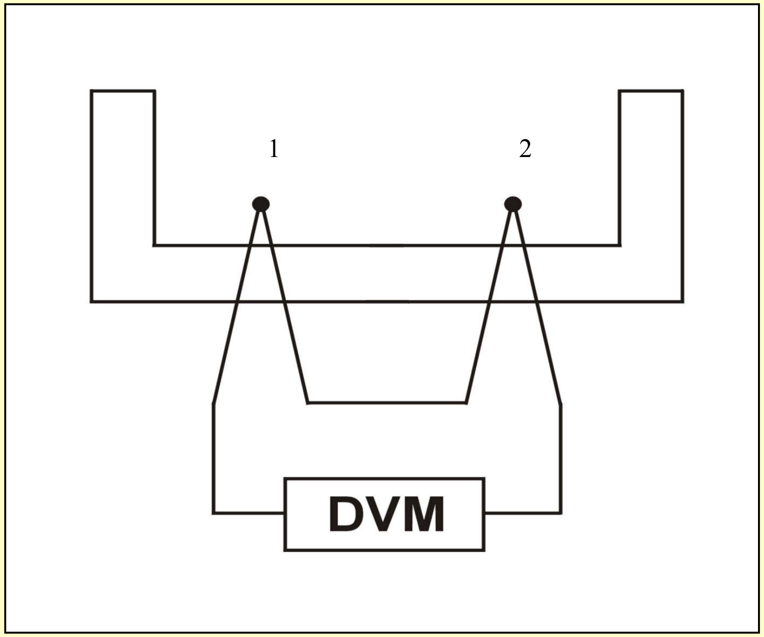
Scales with dentated terminus

different dentation and shape - similar net microstructure



Home-made setup for thermal measurements

Copper-constantan thermocouples measure the temperatures as a function of incident light power. The ratio of the wing temperatures as compared to the white paper was calculated according to the equation:

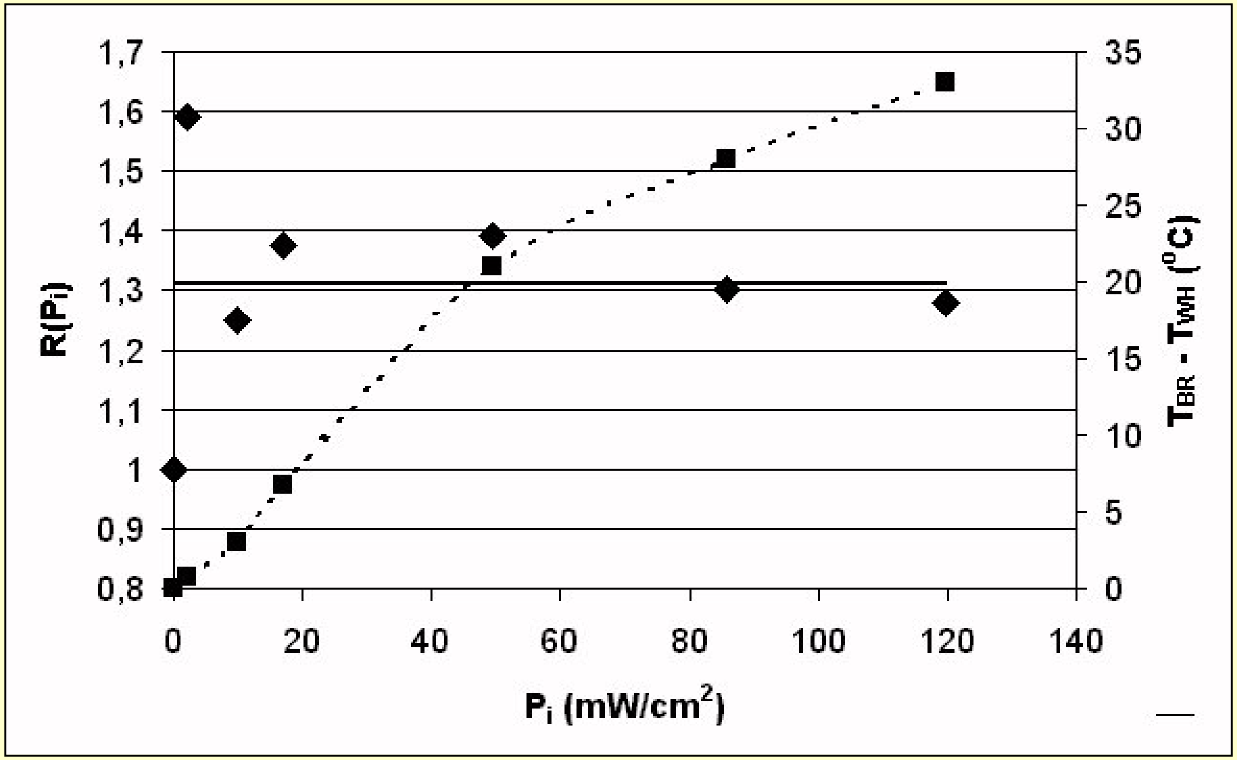


$$R = \frac{T_{BR} - T_{WH}}{T_{BL} - T_{WH}}$$

where T_{BR} is temperature of the brown butterfly wing,
T_{BL} is temperature of the blue butterfly wing,
T_{WH} is temperature of the white paper

Example of the thermal measurement

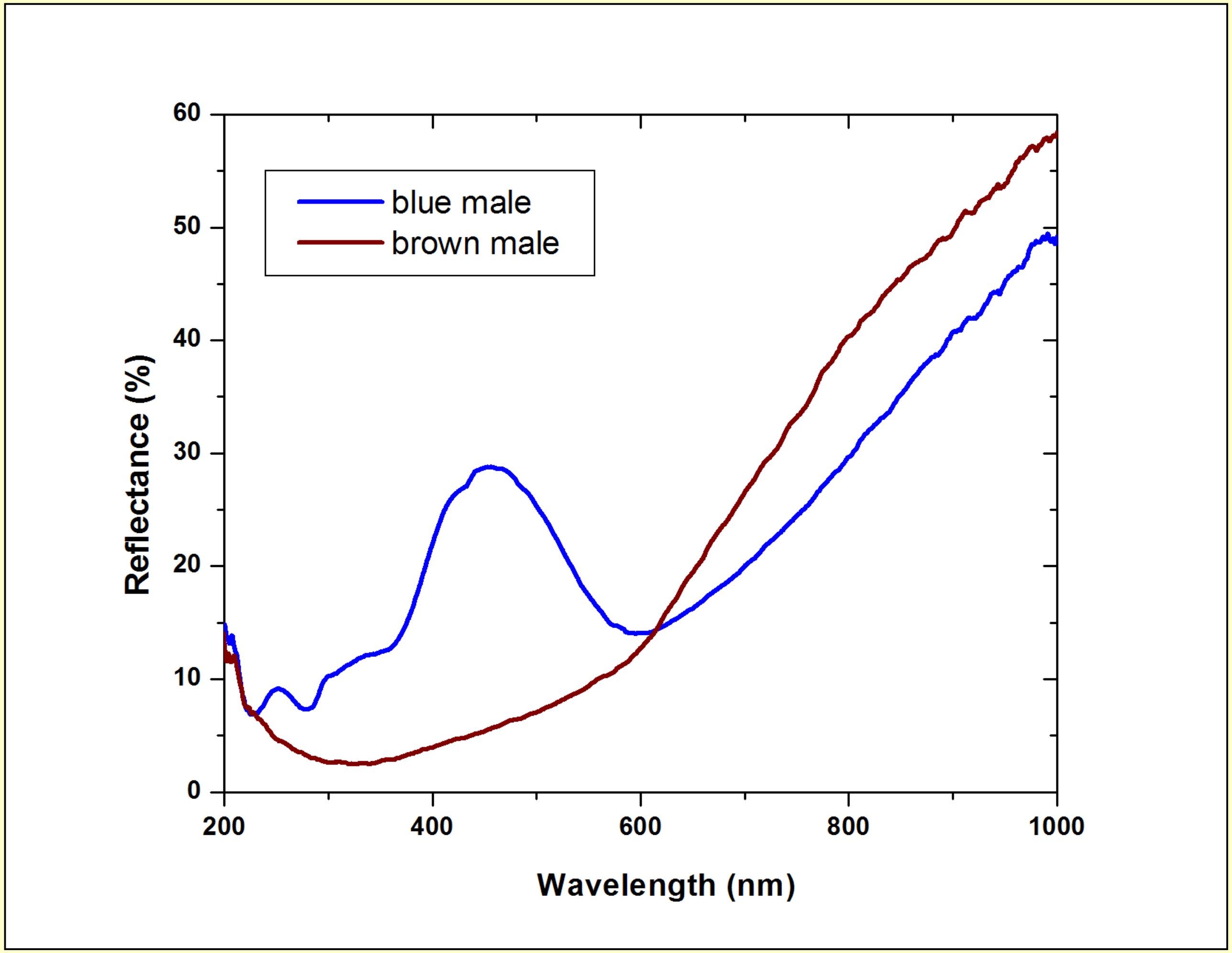
Temperature ratio as a function of the power light density and temperature difference between brown butterfly and white paper.

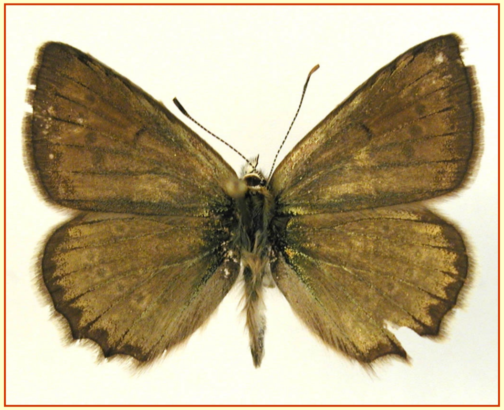


Spectral measurements

The AvaSpec-2048/2 Fiber Optic Spectrometer based on the AvaBench-75 symmetrical Czerny-Turner design with 2048 pixel CCD Detector Array was used for spectral measurements. This spectrometer enables application in the 200 – 1100 nm wavelength range. The reflection and transmission spectra can be measured on the whole wings or individual scales.

Reflection spectra measured on the wings of the blue and brown butterflies

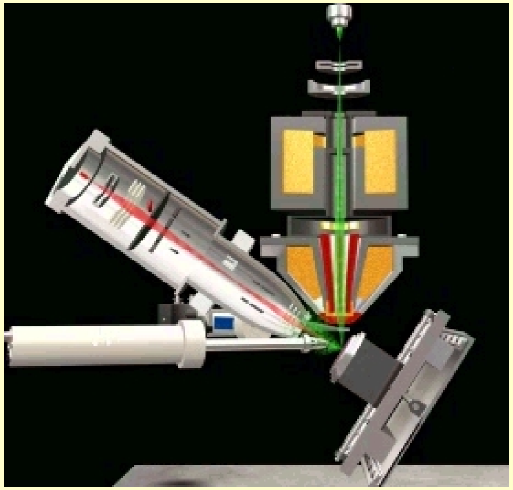


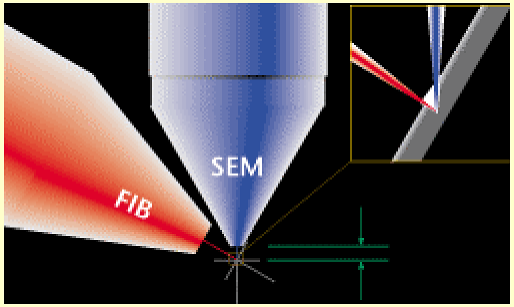


SEM / FESEM

LEO 1540 XB CrossBeam® workstation is a nanomachining and observation system. This workstation consists of the ultra high resolution Field Emission Scanning Electron Microscope (FESEM), Focused Ion Beam (FIB) column and multichanel Gas Injection System (GIS).

FIB enables samples etching with Ga ions. (GIS) enables the enhanced etch, metal and insulator deposition.





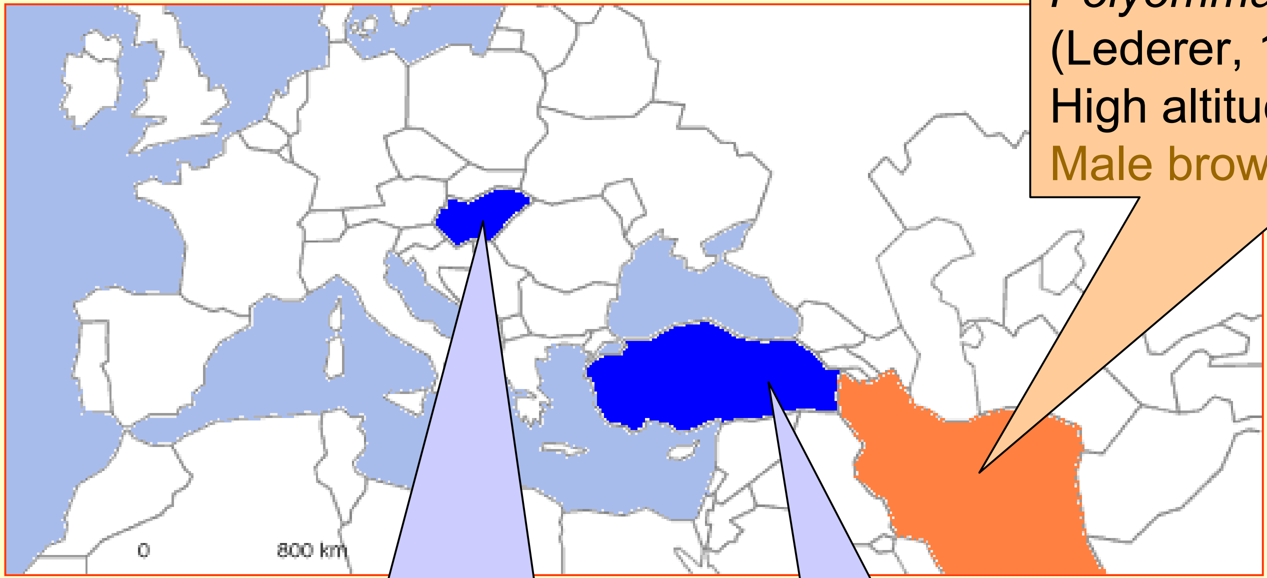
Investigations on butterflies belonging to family Lycaenidae

The objects of our investigations were scientific specimens originating from the collections of the Hungarian Natural History Museum. The individual specimens were collected in the field, pinned, set, desiccated and scientifically labeled, then curated in a systematic collection.

The **aim** of our study was to investigate the correlation between structural colour and scale morphology. We have started our investigation with Blue Lycaenid Butterflies (tribe Polyommatini) that generally possess structural colours and display striking sexual dimorphism. Females belonging to this tribe are generally brown. Males are usually blue.

We concentrated on the study of the phenomenon termed by Bálint and Johnson* as **discolouration**. It means that the sister species of a butterfly possessing vivid structural colour on the dorsal wing surfaces lost the colouration and became brown. The phenomenon is observed in geographical or environmental conditions extreme for butterflies. According to our findings, discolouration plays an important role in adaptive thermoregulation, which gives higher rate for the survival of the individual butterfly, and its population in extreme conditions.

* Zs. Bálint & K. Johnson: Neue Entomologische Nachrichten No. 68 (1997).

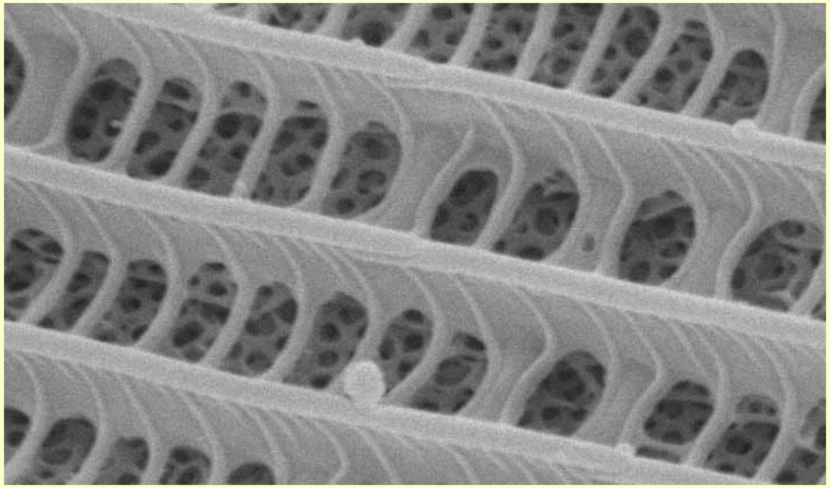


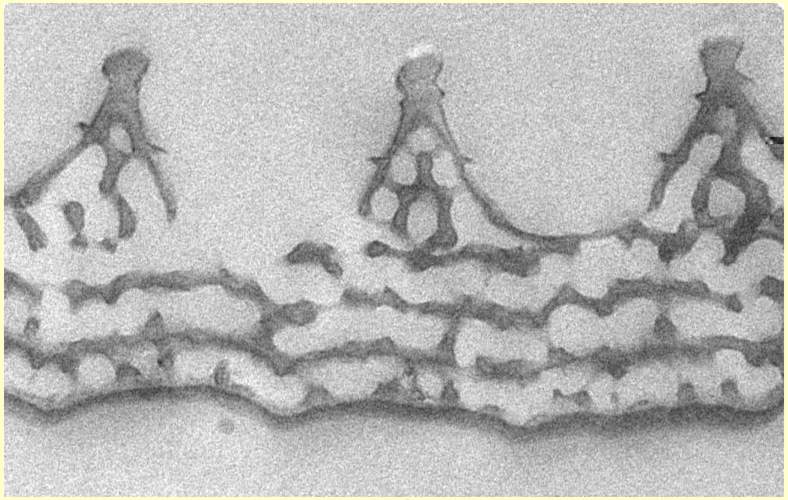
Polyommatus marcidus
(Lederer, 1872)
High altitude: Elburs, Iran
Male brown, Female brown

Polyommatus daphnis
(Denis et Schiffermüller, 1775)
Low altitude: Pannonia
Male blue, Female brown

Polyommatus daphnis
(Denis et Schiffermüller, 1775)
Low altitude: Anatolia
Male blue, Female brown

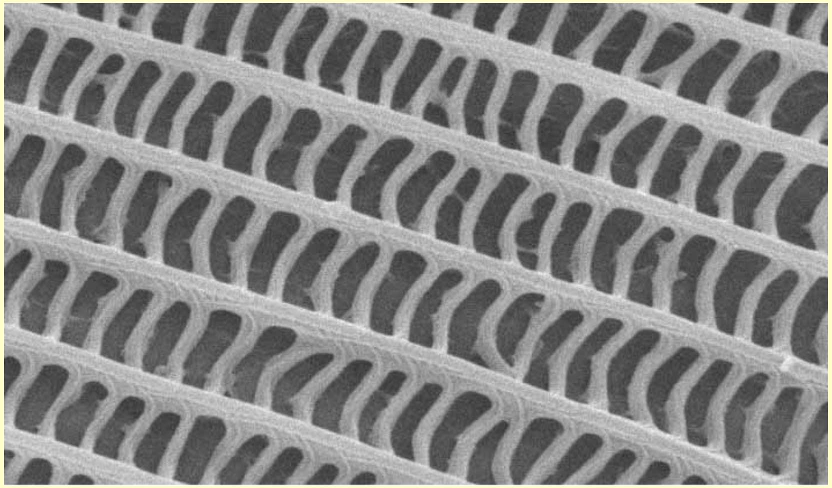
Polyommatus daphnis, blue male - pepper-pot



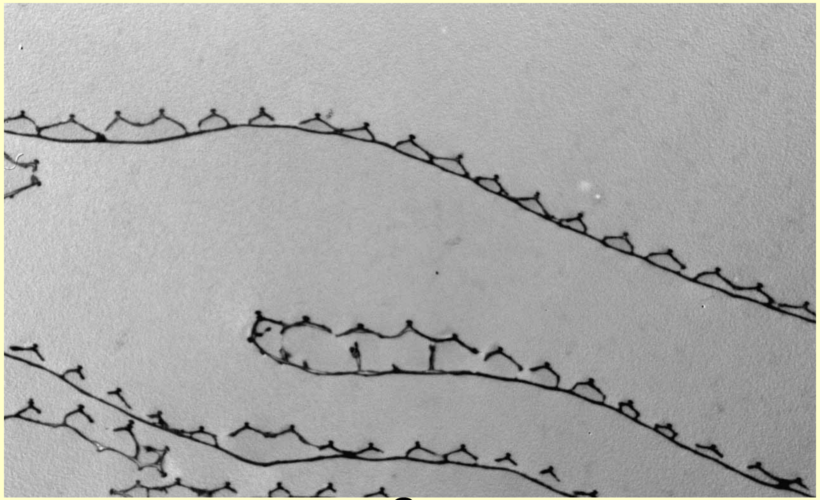


1 μm

Polyommatus marcidus, brown male -net structure



1 μm

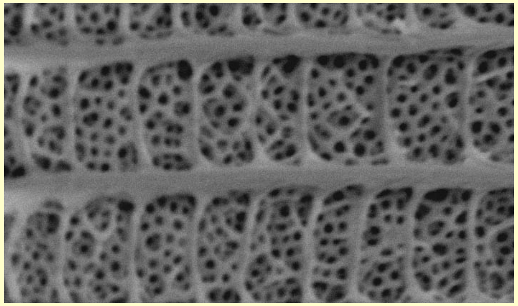


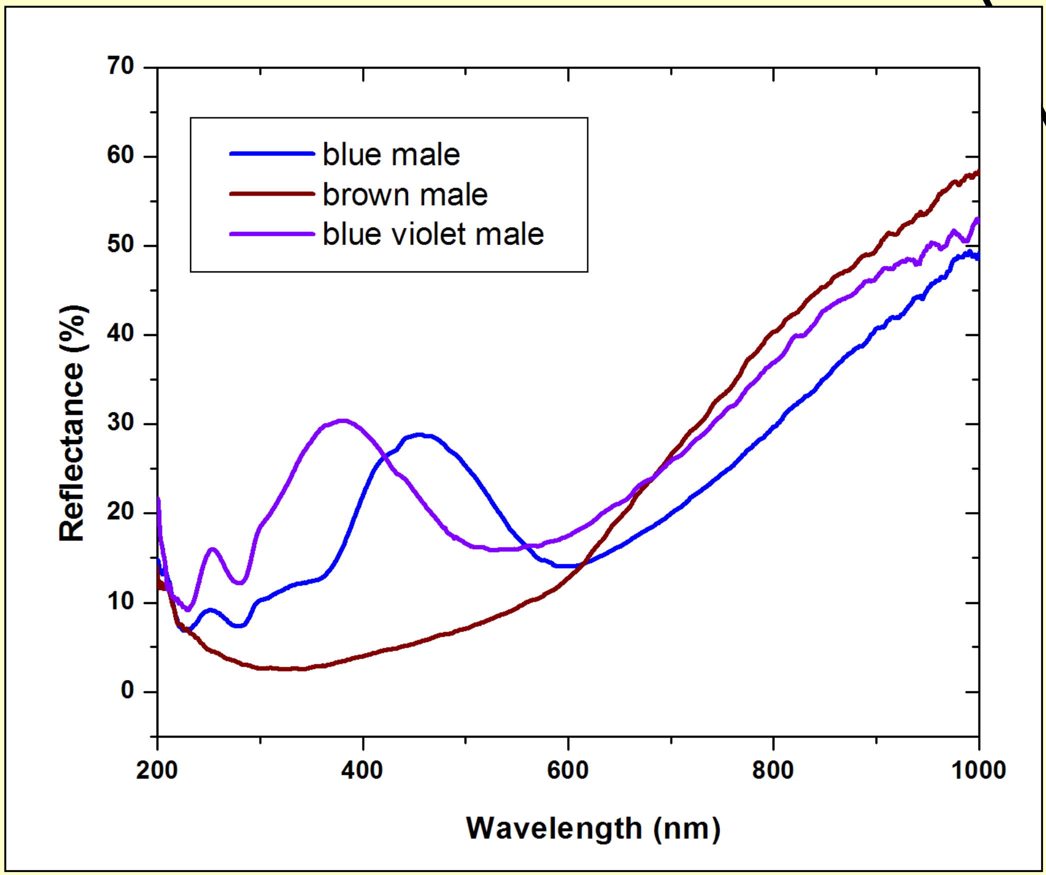
2 μm

Dependence between nanostructure and reflectance

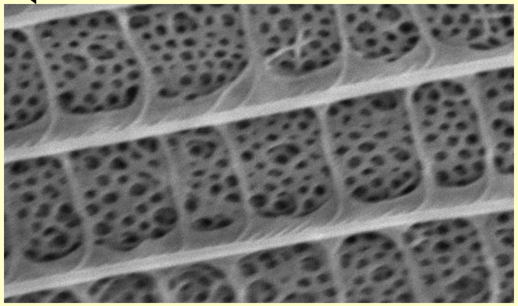
pepper-pot structure

blue male





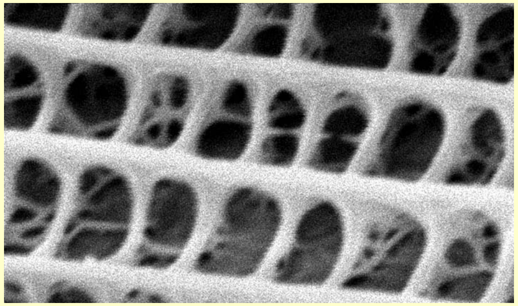
Polyommatus daphnis



blue-violet male

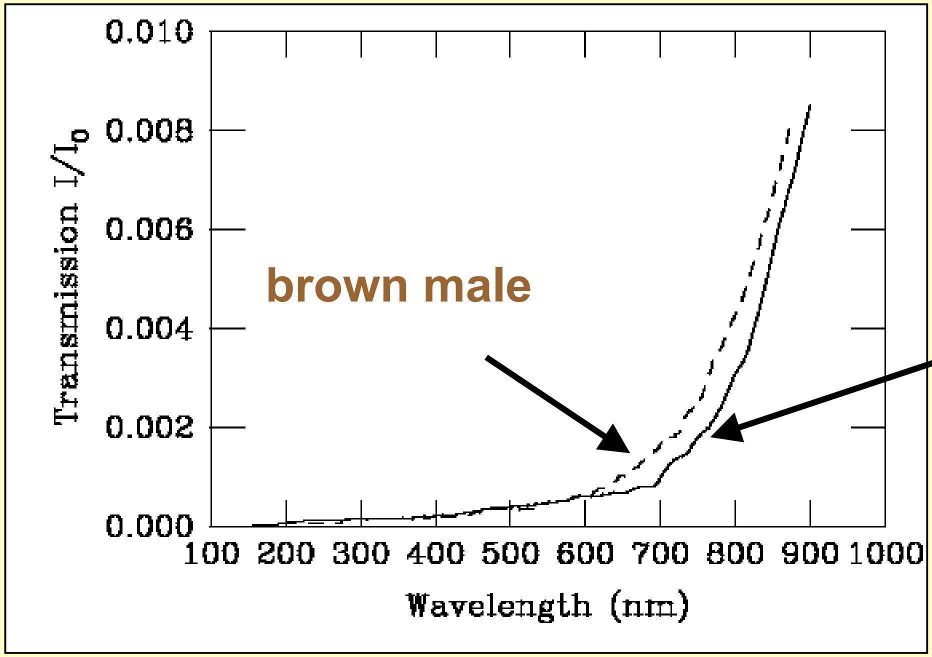
Polyommatus marcidus

brown male



loss of pepper-pot structure

Transmission spectra of the blue and brown butterfly wings



Three layers influence the **transmission** of the light:

scales on the dorsal side of the wing, wing membrane, scales on the ventral side of the wing.

Transmitted light intensity is negligibly small; no significant difference in the transmission values is found between brown and blue wings.

Incident light is either **reflected** by the scales on the dorsal side or **absorbed** by three layers.

Model and computer simulation

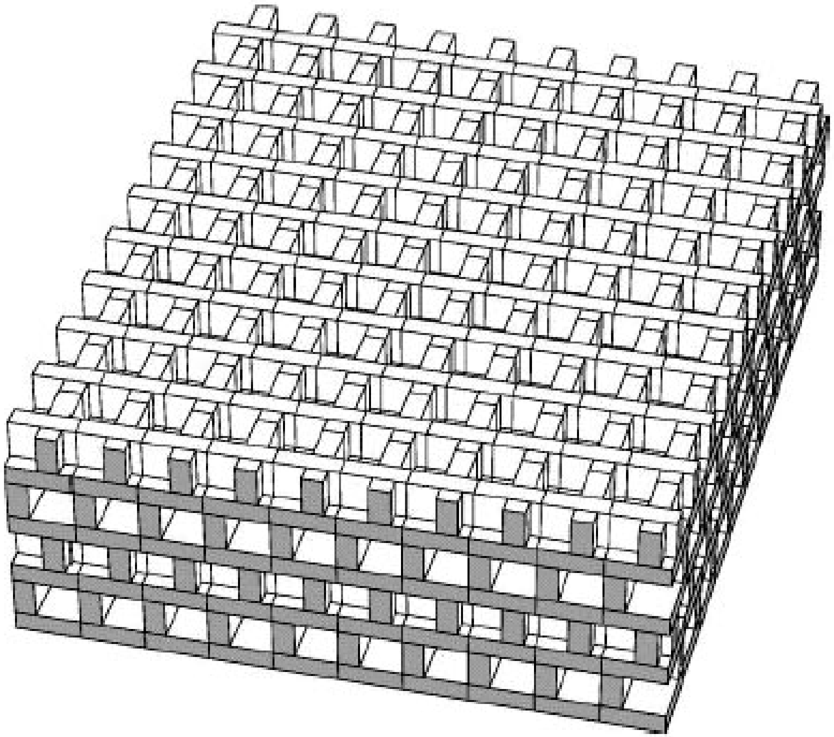


FIG. 8. Model structure built on the basis of high-resolution SEM images used in the computer simulation of the photonic crystal. The periodic structure is made of two identical layers, each 0.2 μm thick. All chitin walls (dielectric constant $2.25+0.1i$) are assumed to have a mean thickness of 0.066 μm. The lateral unit cell is rectangular, 0.24 μm by 0.2 μm.

L. P. Biró *et al.* “Role of photonic-crystal-type structures in the thermal regulation of a Lycaenid butterfly sister species pair”, Physical Review E 67, 021907 (2003)

Calculated

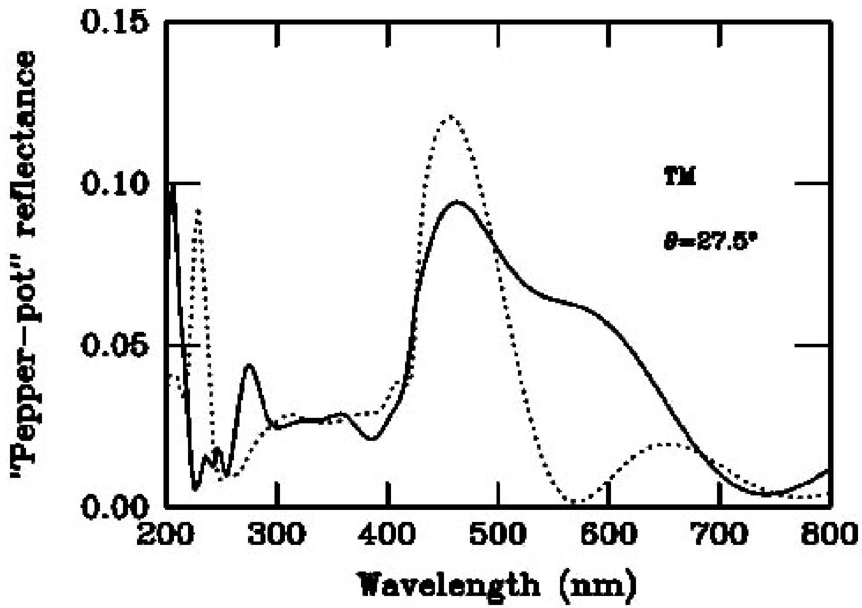


FIG. 9. Reflectance values (solid line) of the pepper-pot structure as calculated from the computer model (see Fig. 8), to be correlated with the measurements described in Fig. 3. The dotted line refers to a second, independent model, where parallelepipedic cavities are replaced by ellipsoids.

Measured

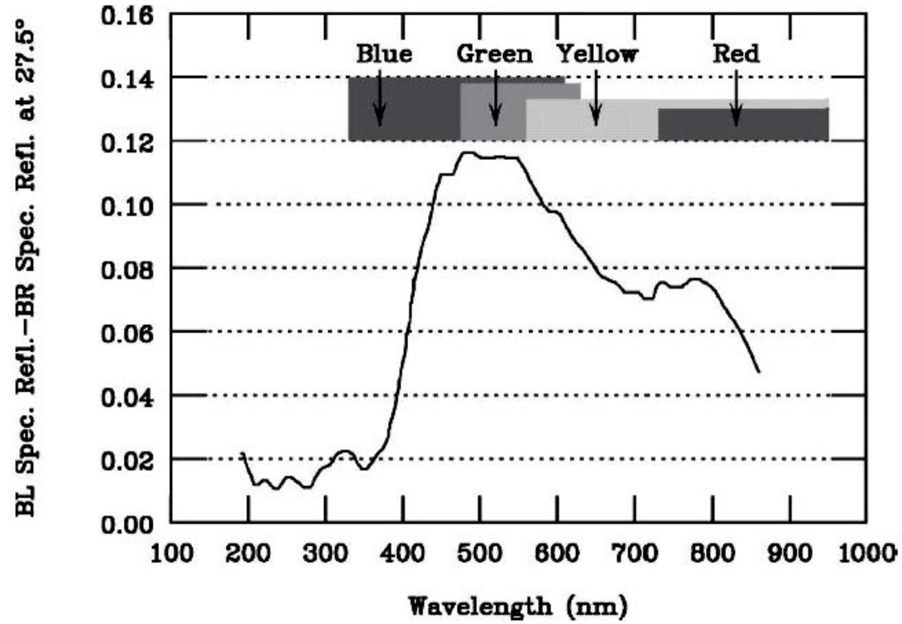


FIG. 3. Specular reflectance difference of the blue (BL) and brown (BR) male butterfly wings, measured at 27.5°. The spectral regions in which the colored glass filters have a transmission higher than 50% are indicated.

All these measurements and observations allow us to **conclude** that:

The **absence** of the pepper-pot nanostructure is equal with the lack of the photonic crystal function.

The **discoloured** males are able to use solar radiation in a more efficient way.

Polyommatus marcidus populations live in Elburs region in relatively high altitudes, more than 2500 m above see level, where the UV and blue parts of the solar spectrum are more intense than in the lowland. Particularly these parts of the solar spectrum are used efficiently by discoloured species.

Due to **discolouration** brown individuals have a better chance to survive and reproduce.

Comparison of scales in butterflies living in temperate climate and in high Andes

We posed the following questions:

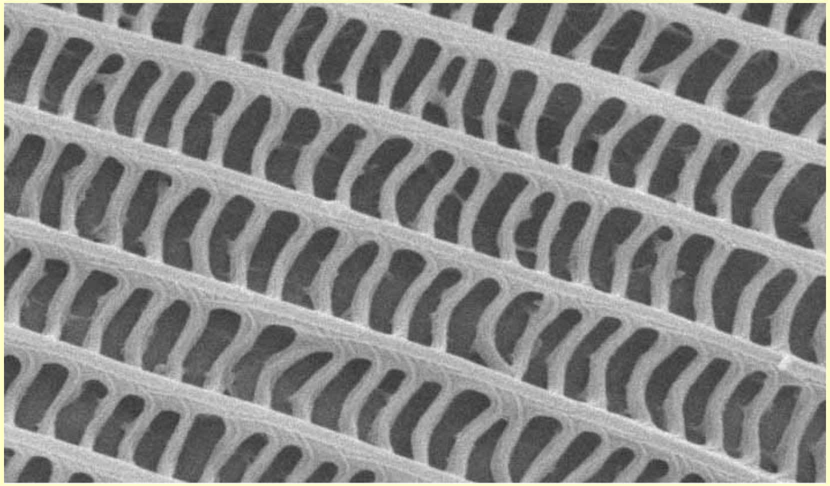
(1) What are the scale micro- and nanostructural differences between the discoloured and the coloured species?

(2) If there are changes, what are the possible explanations?

(3) Is there any correlation between structural colours and the ecology of the species involved?

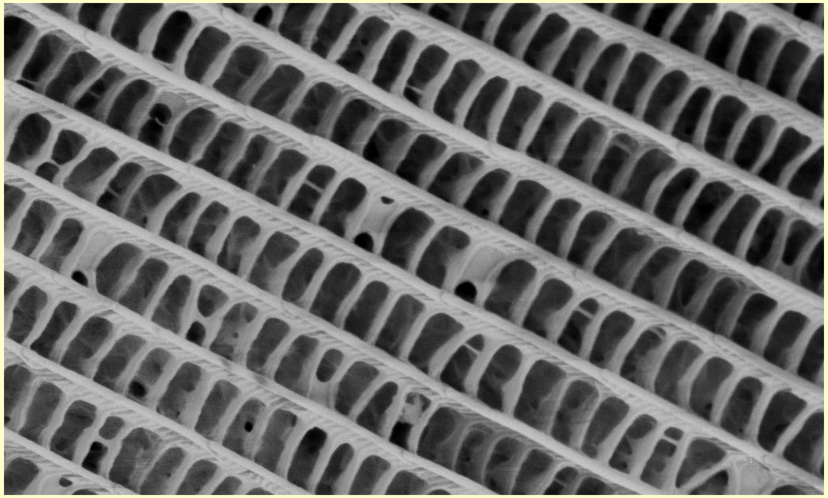
Comparison of scales in butterflies living in temperate climate and in high Andes

Scales of discolored butterflies



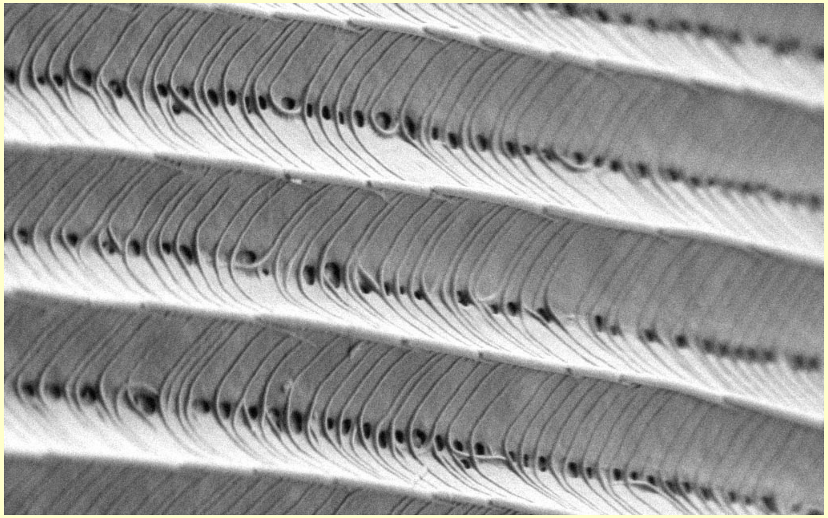
Polyommatus marcidus, brown
(Iran, 2500 m above see level)

Thecloxurina atymna, (Ecuador, 3400 m above see level)



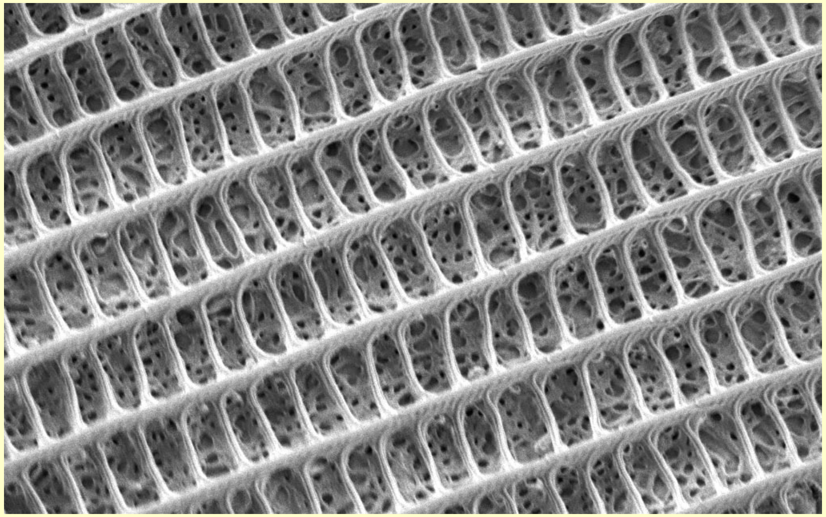
Comparison of scales in butterflies living in temperate climate and in high Andes

Scales with **structural colour**



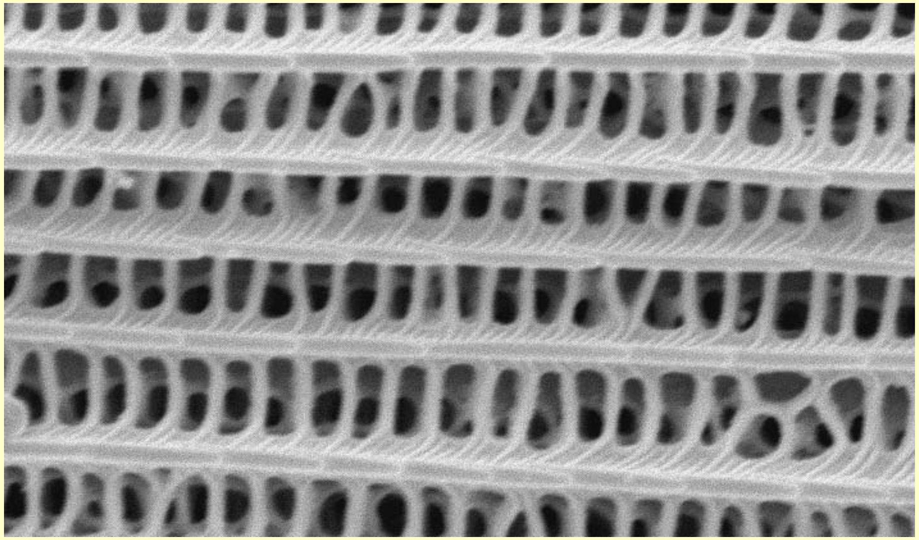
Thecloxurina loxurina,

(Ecuador, 1700 m above see level)



Red scales with gold glance

Lycaena virgaureae



The material laying below the microcells possesses larger circular openings than in the structures of butterflies generating blue or green structural colors. Therefore we believe that this kind of microstructure is connected with coppery or goldish wing coloration.

Comparison of the wing scales in *Morpho* butterflies

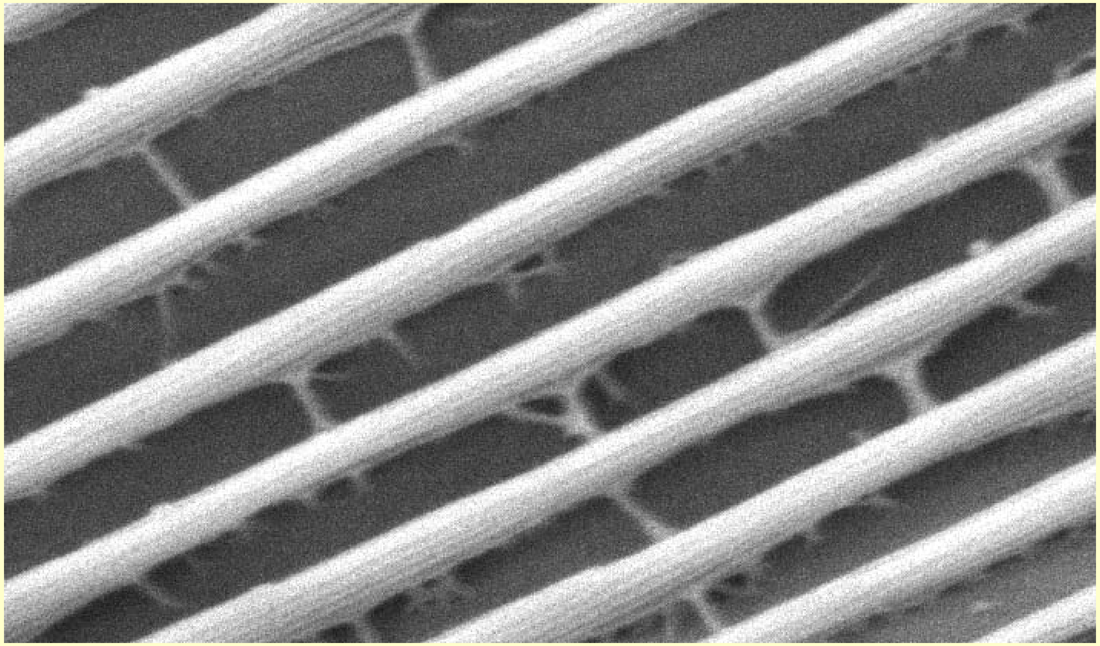
Morpho-type scales exist also in lycaenid butterflies.*

What kind of scale structure possess *Morpho* species without structural colour?

* R. J. D. Tilley & J. N. Eliot: Trans. lepid. Soc. Japan Vol. 53 (2002) p. 153

Scale microstructure in different *Morphos* (Nymphalidae)

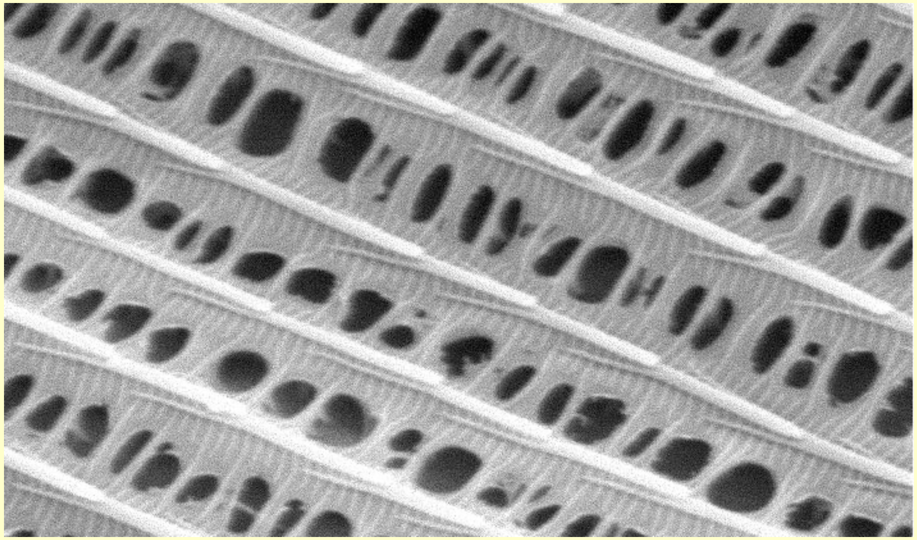
Morpho thamyris blue male, (structural colour)



2 μm

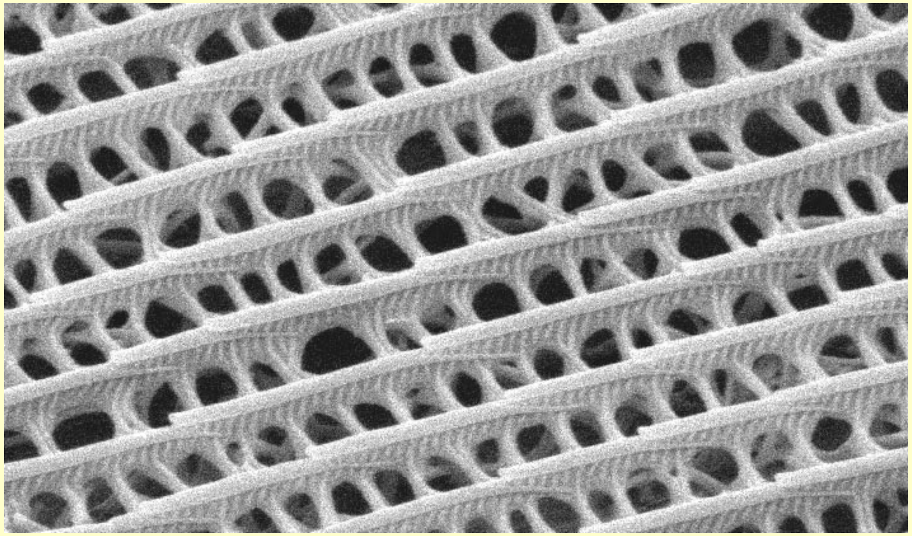
Typical *Morpho*-type structure generated by flutes situated on the sides of longitudinal ridges

Scale microstructure **transitions** between *Urania*- and *Morpho*-types in Morphos (Nymphalidae)



Morpho laetus pearl white male

Morpho cisseis brown male



Scale microstructure **transitions** between *Urania*- and *Morpho*-types in Morphos (Nymphalidae

In the case of Morphos, only scales with *Morpho*-type structures have been recorded. We have found out that a wide array of structures are exsisting in discoloured species, including the *Urania*-type with remnants of pepper-pot nanostructures.

The *Morpho* species without structural colours we have examined are considered as advanced butterflies according to the most recent phylogenetic approach of the genus. The absence of the structural colours seems to be also an important tool in the evolution of the large *Morpho* butterflies.

Therefore we conclude that structural colour manipulation is a plausible and general instrument in the evolution of the butterflies.

Summary

Using scanning electron microscope we were able to find out that absence or change of structural colours in butterflies is caused by qualitative or quantitative change of nanostructures in the body of the individual scales.

This change seems to be an important step in the evolution of the generic lineage having species with structural colours. The discoloured species indicate that the lineage pioneers a habitat, which is novel for the genus.

We can see that there are wide arrays of nanostructures working like natural photonic crystals. The scales without photonic-crystal type nanostructures seem to be relatively uniform even in families, which are not closely related.

The absence of photonic-crystal type nanostructures appears in many butterfly lineages, therefore we hypothesize that this convergent phenomenon is an effective instrument of the biological evolution.

Our study has revealed that there is a deep intertwining between physics and biology. Walking on this path and exploring butterflies new ideas and results can emerge in both of these disciplines.

The work was supported by Hungarian Scientific Research Fund (T-042972). The authors acknowledge support from Belgian FNRS within the framework of scientific exchange programs with the Hungarian Academy of Sciences.

Thank you for your attention!