Antireflection of the Butterfly and Moth Wings through Microstructure

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Abstract. This article addresses two types of antireflection of wings of the lepidopteran insects (butterflies and moths). They are due to different microstructure in the wing surfaces. The first is minute indentations in the upper surfaces of scales. The examination of the upper and lower surfaces of scales suggests that the minute indentations in the upper surfaces of scales may inhibit the lepidopteran wings from showing mirror reflection. The second is a regular-hexagonal array of protuberances in the scaleless and transparent wing of *Cephonodes hylas*. The artificial *Cephonodes* wing without protuberances shows higher reflection in the broad wavelength range of light, which demonstrates that the protuberance array highly inhibits the *Cephonodes* wing from light reflection.

1. Introduction

Smooth cuticular surfaces of many insect bodies show mirror reflection, but wings of most lepidopteran insects (butterflies and moths) do not show it. Most lepidopteran wings are completely covered with abundant scales, which is not the case in many other insects. Thus, it is possible that scales may play some roles in inhibition of mirror reflection by lepidopteran wings. However, how scales inhibit mirror reflection has been scarcely addressed. In this article, this problem is addressed on the basis of some preliminary examination of light reflection and scale microstructure.

Another problem addressed in this article is antireflection of the transparent wing of a hawkmoth, *Cephonodes hylas*. This moth has transparent wings without scales, which is a rare case among lepidopteran insects. After scales are removed from wings of the majority of lepidopteran species, the wings without scales show mirror reflection. On the other hand, the *Cephonodes* wing without scales does not. YOSHIDA *et al.* (1996, 1997) reported that the *Cephonodes* wing has a highly ordered protuberance array in its surface and that the protuberance array functions as an excellent antireflective device in the broad wavelength range, which is reviewed in this article.

2. Inhibition of Mirror Reflection through Minute Indentations of a Scale Surface

2.1. *Reflection and microstructure in the wing surface of the small white cabbage butterfly, Pieris rapae*

Preliminary examination of wings of the small white cabbage butterfly, *Pieris rapae* (Fig. 1), was performed to study the relation between light reflection by the wing and the wing surface microstructure, as described below.

Since the *Pieris* wing are completely covered with scales, only upper surfaces of scales are visible (Fig. 2). They do not show mirror reflection (Fig. 3A). In Fig. 3A, a single scale is detached from the wing, and subsequently put on the wing surface. This scale is turned over, displaying its lower surface, and presents mirror reflection.

Another examination was made, as follows. Putting the sticky tape on the wing surface and subsequently detached it from the surface, the scales stuck to the tape are consequently removed from the wing surface, and the lower surfaces of the scales are exposed on the tape. These lower surfaces show mirror reflection (Fig. 3B), as the "turned-over" scale does in Fig. 3A.

Upper and lower surfaces of the *Pieris* scale are different in morphology. The upper surface presents mesh-like morphology (Fig. 4A), and the lower one (Fig. 4B) is much smoother than the upper one. As shown in the magnified view (Fig. 5), the upper surface has longitudinal ridges and transverse ribs connecting them (Fig. 5A), some pillars connect the upper and lower surfaces (Fig. 5B). The distance between the top of the longitudinal ridge and the lowest surface of the *Pieris* scale is about 1 μm (WAKU and KITAGAWA,
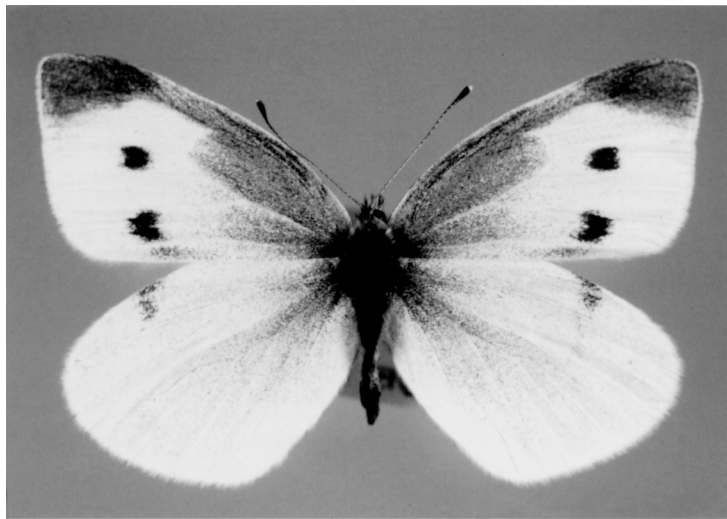

Fig. 1. *Pieris rapae* (female). The distance between the apical tips of the right and left forewings is about 4.7 cm.

1986). That is, the scales have minute indentations only in their upper surfaces, not in their lower ones.

The difference between the upper and lower surfaces of a scale, in reflection and microstructure, indicates that the minute indentations in the upper surfaces of scales may inhibit the lepidopteran wings from showing mirror reflection. Most lepidopterans do not present mirror reflection, as in *Pieris*, probably due to the scale microstructure similar to that of *Pieris*; the upper surface is indented and the lower one is smooth (DOWNEY and ALLYN, 1975; GHIRADELLA, 1998).

2.2. Comparison between primitive and advanced lepidopteran scales

Unlike the wings of the majority of lepidopterans, the *Eriocrania* wing presents mirror reflection (Fig. 6). The upper surfaces of the *Eriocrania* scales have no indentations like those in *Pieris* (Fig. 7), which is consistent with the suggestion in *Pieris* that the minute indentations may inhibit the scale from showing mirror reflection but the smooth surfaces do not. The smooth upper surfaces of scales is characteristic of species in *Micropterygidae* and *Eriocraniidae*, which are small and primitive among lepidopteran insects (KRISTENSEN, 1970).

The *Eriocrania* wing is covered with pale and dark brown scales. However, in the mirror reflection area of Fig. 6, some blue scales and violet ones are scattered. Change of the incident light angle or the viewing one elicits change of the reflection area and the scale color. Generation of the glittering blue and violet can be accounted for by "thin-film reflection mechanism" (LAND, 1972), as follows. In primitive lepidopterans, upper and
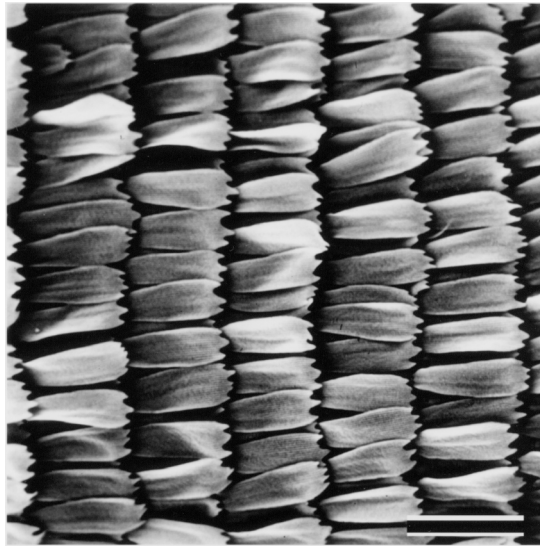

Fig. 2. Scanning electron micrograph of scales in the right wing of *Pieris rapae* (female). Distal is to the right. This direction is the same as in Figs. 3–5 and 7. Bar: 100 μm.
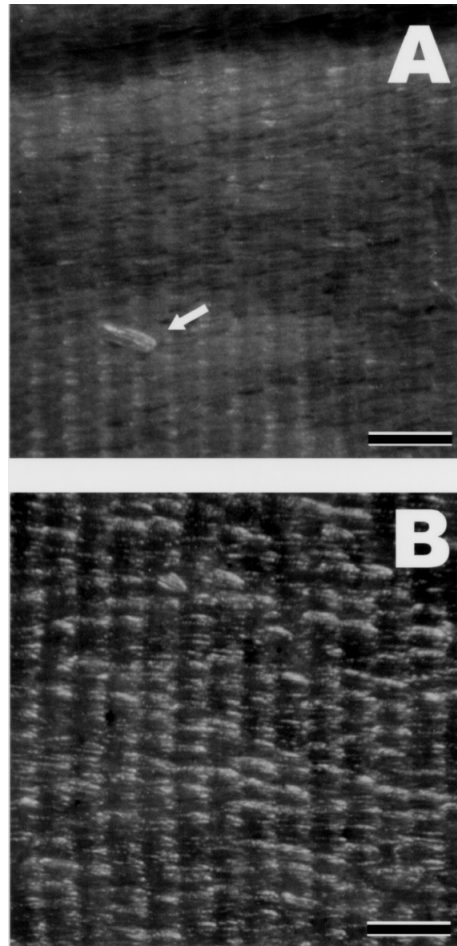
Fig. 3. Photographs of wing scales under a dissecting microscope. Bar: 200 μm. (A) Scales in the upper wing surface. Only a single scale, indicated by an arrow, displays its lower surface (see the text). (B) Scales stuck to the tape.

lower layers of most scales have almost no gap (KRISTENSEN, 1970). Brown pigments, synthesized in the scale forming cell, is assumed to be distributed between these layers, and to function as a light absorbing filter. The scale layer in *Eriocrania semipurpurella* is about 80 nm in thickness (KRISTENSEN, 1970). Assuming the refractive index to be 1.6 (GHIRADELLA *et al*., 1972), the optical thickness of the layer is estimated to be about 130 nm. When the incident light is perpendicular to the "thin-film" surface, the light with the wavelength of four times of the optical thickness of the "film" is strongly reflected through interference. In the reflection oblique to the film, the light with the wavelength shorter than that of the preceding perpendicular case is strongly reflected. In the reflection perpendicular
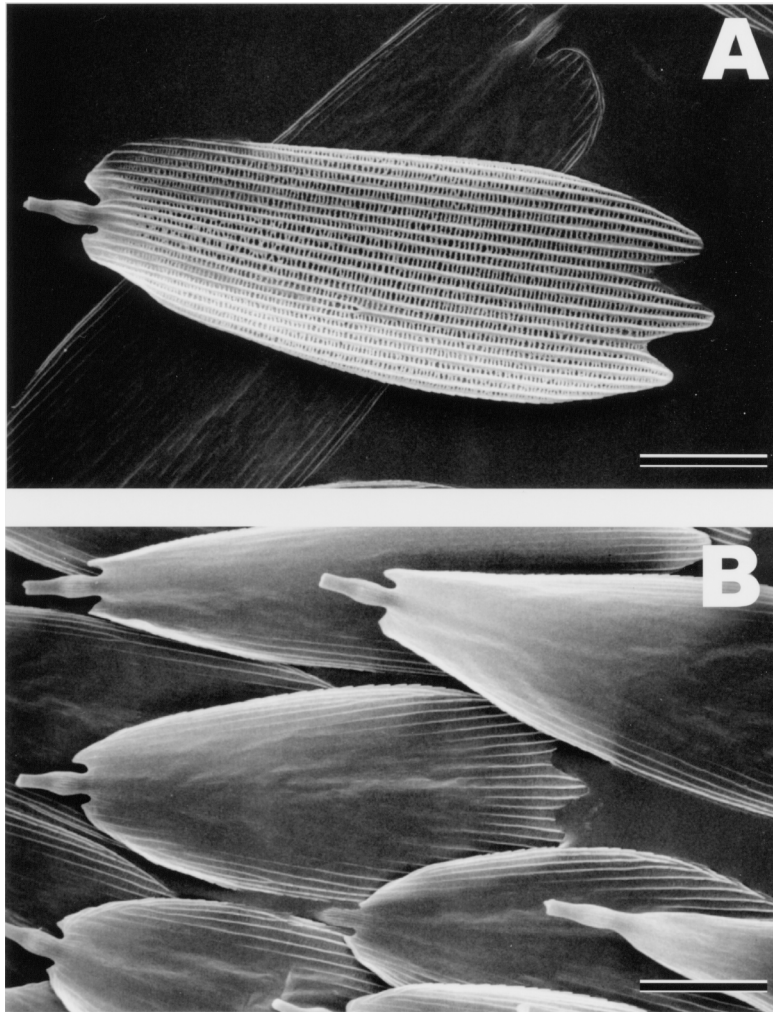
Fig. 4. Scanning electron micrographs of the *Pieris* scale. Bar: 10 μm. (A) Upper surface. (B) Lower surface.

to the film with 130 nm in optical thickness, the light with 520 nm wavelength, that is bluish green, is strongly reflected, while the light with shorter than 520 nm, including violet and ultra-violet, is strongly reflected in the reflection oblique to the film. Thus, it is likely that blue and violet generation in the glittering scales of Fig. 6 is approximately accounted for by this "thin-film reflection mechanism" based on the scale microstructure of *Eriocrania*. As described above, the indentations of the upper layers of the scales in advanced lepidopteran wings probably contribute to inhibition of the mirror reflection. These indentations also eliminate the "thin film" interference condition through deformation of the film structure. Thus, the scale indentations in advanced lepidopterans seem to contribute
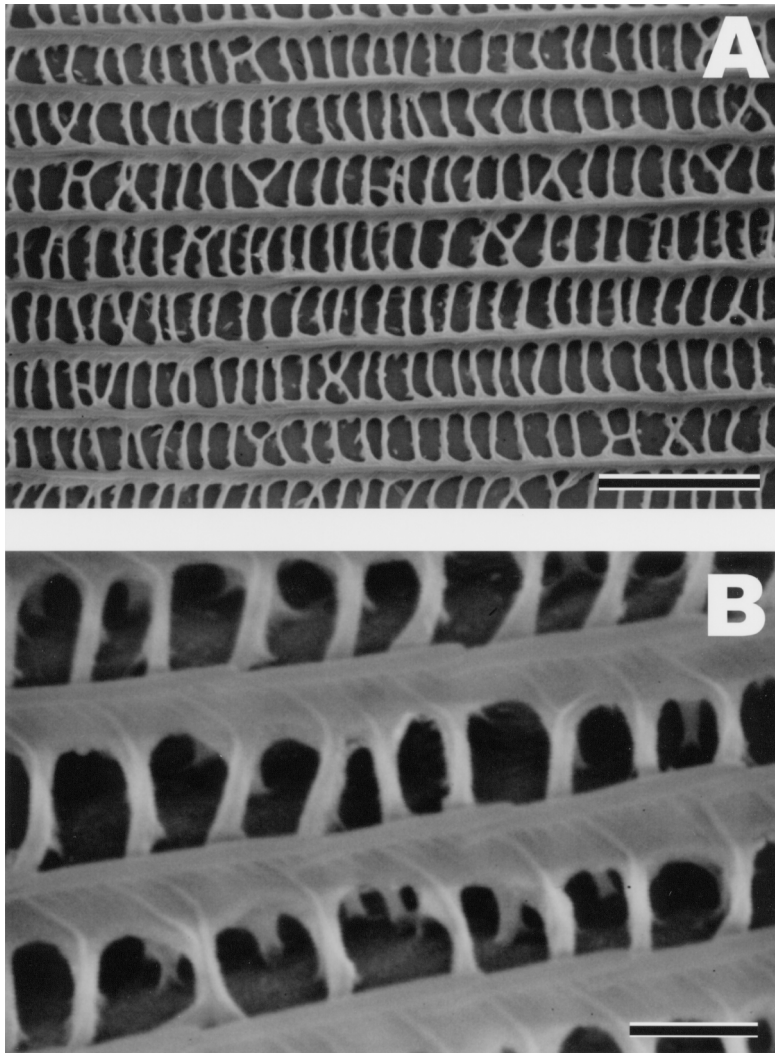
Fig. 5. Magnified views of scanning electron micrographs of the upper surface of the *Pieris* scale. (A) Upper view. Bar: 5 μm. (B) Oblique view. Bar: 1 μm.

not only to inhibition of the mirror reflection but also to inhibition of the interference color generation shown in the primitive lepidopteran scales.

Primitive lepidopterans are generally small; for instance, the primitive *Eriocrania* is compared with the advanced *Pieris* in Fig. 8. The majority of advanced lepidopterans have the wings without mirror reflection probably due to the scale microstructure. If large lepidopterans had glittering and colorful wings such as the *Eriocrania* one, they would be easily detected by their enemies. Thus, it is likely that the scale microstructure in advanced
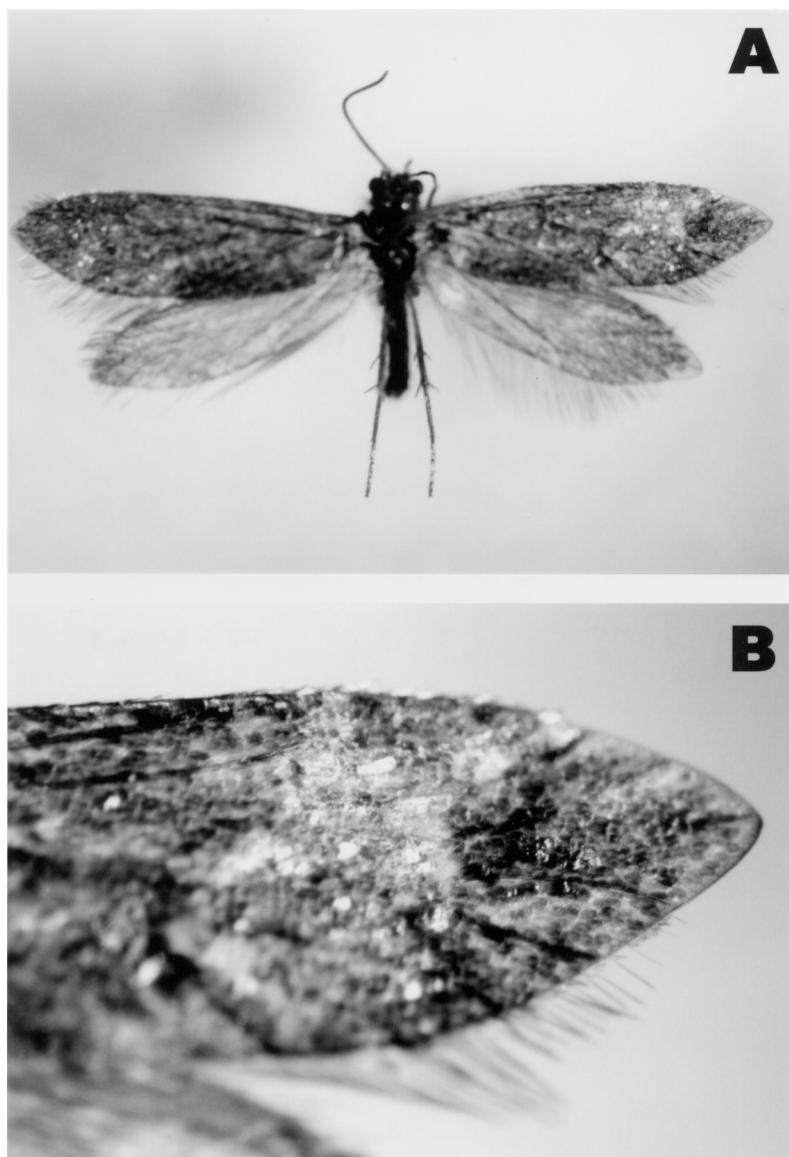
Fig. 6. *Eriocrania* sp. Its species name has not yet be established. (A) Whole view. The distance between the apical tips of the right and left forewings is about 0.9 cm. (B) Mirror reflection in the right wing. The reflection area depends on the light direction.
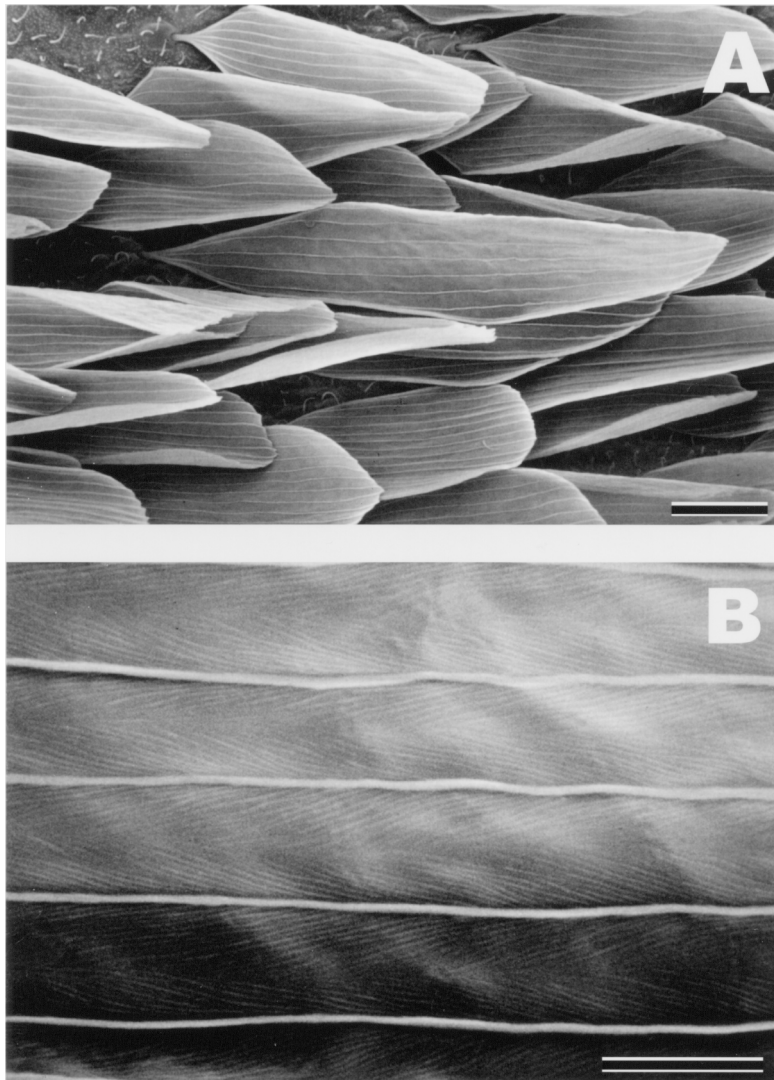
Fig. 7. Scanning electron micrographs of the *Eriocrania* scale. (A) Scales in the upper wing surface. Bar: 20 μm. (B) Magnified view of a scale. Bar: 5 μm.

lepidopterans may give a concealing effect against their predators and parasites. On the contrary, the minority of advanced lepidopterans, such as the *Morpho* butterflies, have highly reflective wings of which scale microstructure is specialized to give high reflection through constructive interference. In the *Morpho* butterflies, however, not all parts of their wings are reflective. The *Morpho* butterflies cover the reflective parts of their wings with
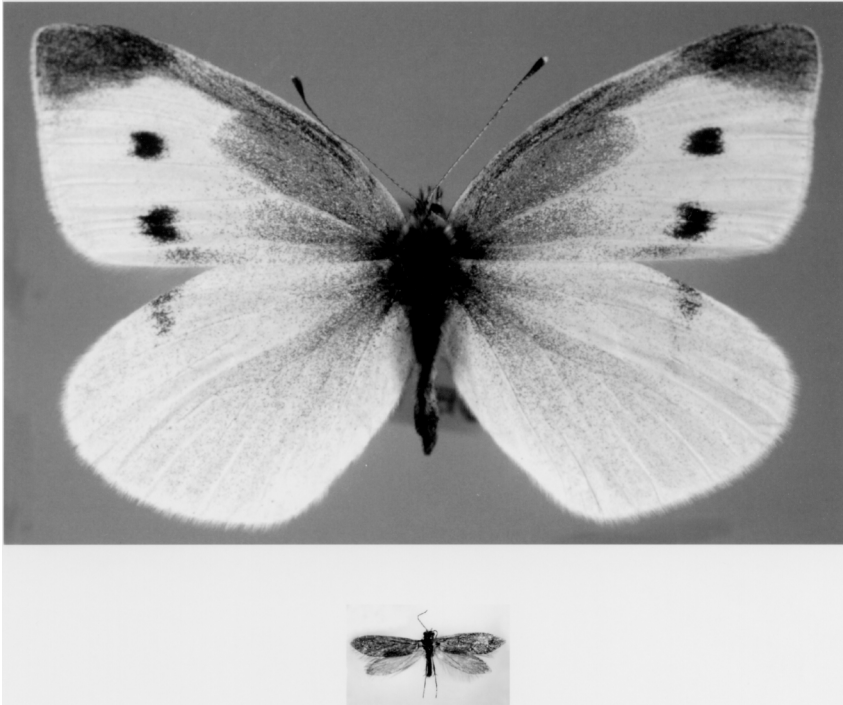
Fig. 8. *Pieris rapae* (upper) and *Eriocrania* sp. (lower). They are the same specimens as in Figs. 1 and 6, respectively.

the other non-reflective ones in their resting posture, and it is pointed out that a sudden exposure of the reflective part of the wing, elicited by wing movement, may startle potential predators (NIJHOUT, 1991). It is possible that the reflective wings in the advanced lepidopterans may generally play some roles in their survival, as suggested in the *Morpho* butterflies.

3.   Antireflection through a Highly Ordered Array of Submicron-Sized Protuberances in the Wing of *Cephonodes hylas*

Most lepidopetran wings are completely covered with scales, while a few lepidopteran species have no scales in minor or major parts of their wings. A hawkmoth, *Cephonodes hylas*, has no scales in almost all region of its wing surface, except for the narrow region along its wing margin and wing veins (Fig. 9). Since the *Cephonodes* wing is fairly transparent, it is hard to detect it by naked eye while it is being fluttered. What mechanism is involved in such high transparency of the *Cephonodes* wing? It is because antireflection through the indentations of the wing surface contributes to the high transparency of the *Cephonodes* wing, as described below.
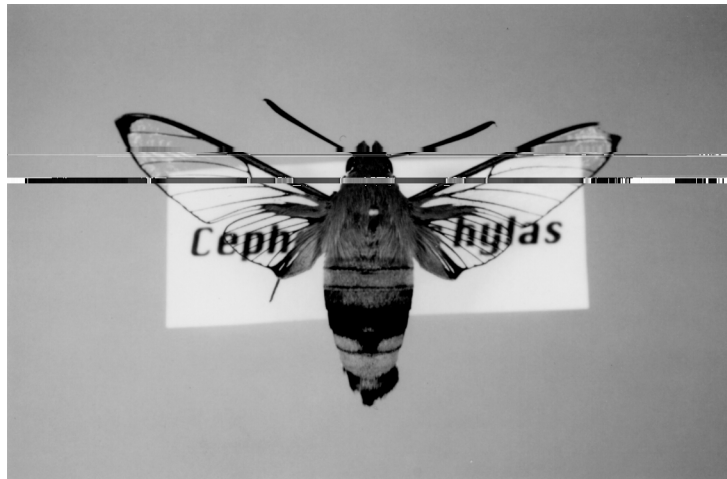
Fig. 9. *Cephonodes hylas*. Distance between the apical tips of the right and left forewings is about 6.2 cm.

3.1. Protuberance array in the wing surface

YOSHIDA *et al*. (1996) reported that the *Cephonodes* wing has a regular-hexagonal array of protuberances in the surface of its transparent region (Fig. 10). Each protuberance is dome-shaped with a constriction around its middle height, and about 250 nm high. The center-to-center distance between adjacent protuberances is about 200 nm. Many other lepidopteran wings have protuberances similar to those of the *Cephonodes* wing (DOWNEY and ALLYN, 1975; ALLYN *et al*., 1982), but such a closely packed and highly ordered array as in *Cephonodes* was the first finding in the lepidopteran wings.

However, the protuberance array with the same morphology as in *Cephonodes* had already been discovered in the corneal surface of some insect eyes, including lepidoptera, by BERNHARD and MILLER (1962). Two points are slightly different from the *Cephonodes* wing protuberance; first, the corneal protuberance is 200 nm high (*Cephonodes*: 250 nm), and second, it has no constriction along its side.

3.2. Antireflection through a protuberance array

Subsequent to the discovery of the corneal protuberance array, BERNHARD *et al*. (1963, 1965) studied a function of this protuberance array, and suggested that it has a function of antireflection of light, mainly based on the results obtained from the model experiment. They made a model in which the protuberance array size is scaled up; magnified to about 10^5 times. The model was made of a paraffin-beeswax mixture whose refractive index of 1.5 is approximately the same as that of the corneal cuticle. They measured microwave reflectance by the model with or without the protuberance array, and obtained the results indicating that the protuberance array decreases the microwave reflectance in the broad wavelength range. Scaling down the model size into the actual size of the corneal protuberance array, wavelength of the electromagnetic wave is consequently
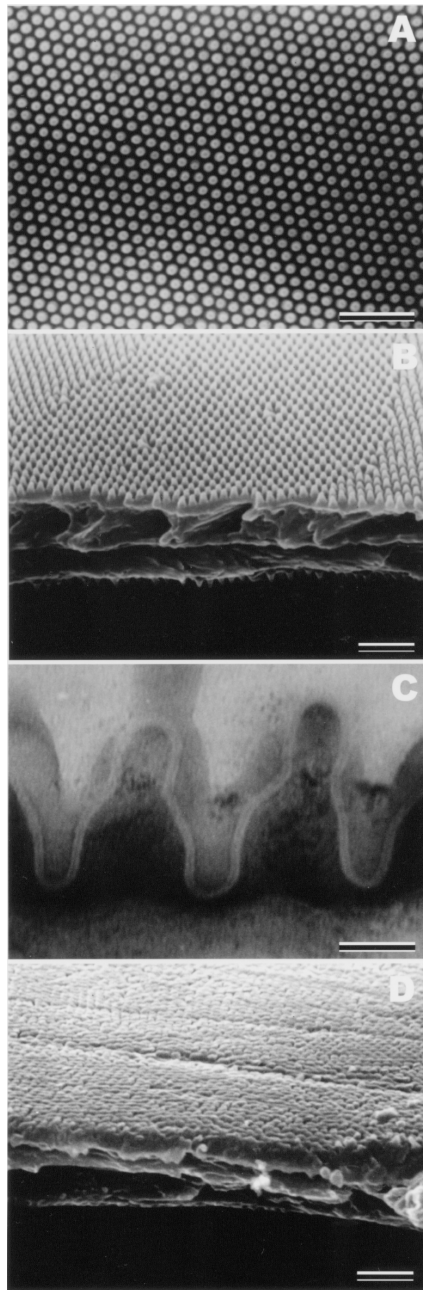
Fig. 10. Protuberance array in the *Cephonodes* wing. (A) Scanning electron micrograph of the upper view of the wing. Bar: 1 μm. (B) Scanning electron micrograph of the oblique view of the wing cut with scissors. Bar: 1 μm. (C) Transmission electron micrograph of the cross section of the wing, presenting side views of the protuberances. Bar: 0.1 μm. (D) Scanning electron micrograph of the oblique view of the "smooth" wing cut with scissors. Bar: 1 μm.
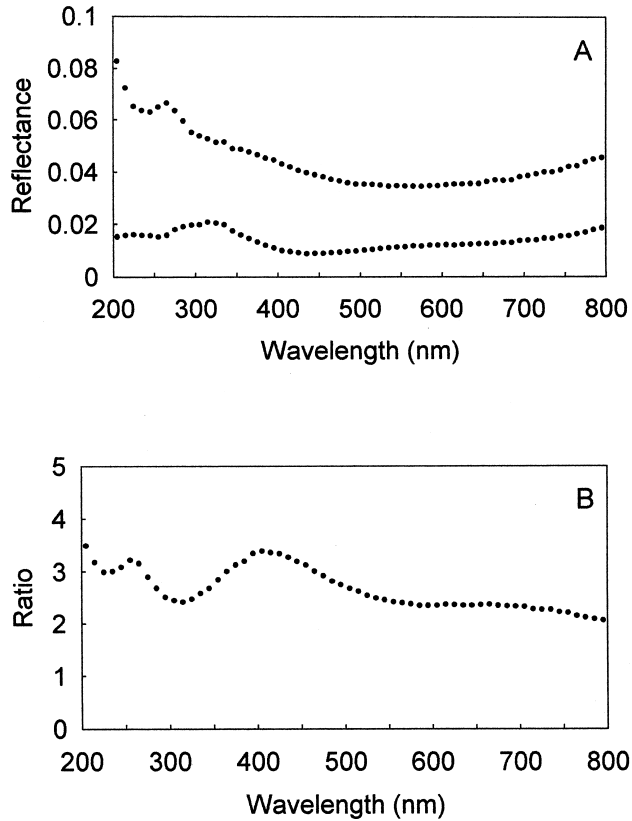
Fig. 11. (A) Representative reflectance spectra of the intact wing with protuberances (lower trace) and the "smooth" wing after crushing its protuberances (upper trace). (B) Spectrum of the reflectance ratio of the "smooth" wing to the intact one. All dots are the average of six wings.

decreased from that of microwaves to that of light waves. Thus, it is assumed that the protuberance array of the insect cornea may decrease light reflectance in the broad wavelength range.

The model protuberance is shaped like a cone and made of a paraffin-beeswax mixture, while the actual one is like a dome and made of a cuticle. The model is about 10^5 times larger than the actual size. To study a function of the protuberance array more reliably, an experiment with an actual cornea or wing would rather be preferable. In *Cephonodes*, an artificial "smooth" wing with much lower protuberances could be made without damaging the wing shape (Fig. 10D). Light reflectance was measured with both the intact wing and the artificial "smooth" one, and the results were compared with each other. As shown in Fig. 11, reflectance increased more in the "smooth" wing (after crushing the protuberances) than in the intact wing in the applied wavelength range from 200 nm to 800 nm. This indicates that the protuberance array functions as a broad-band antireflective device, as
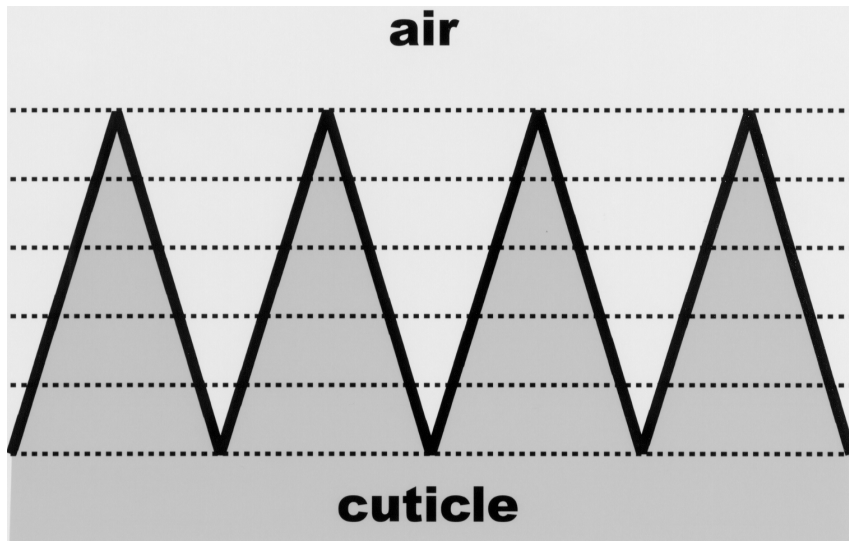
Fig. 12. Schematic figure of the side view of the protuberance array. Since each protuberance is too small to detect with visible light, the protuberance array can be viewed as transparent coating on the corneal surface. The refractive index is 1.0 (air) over the coating and 1.6 (cuticle) below it. The coating is divided into five layers in this figure, and the lower layer has a larger proportion of cuticle to air.

indicated by the model experiment in the corneal protuberance array. The reflectance ratio of the "smooth" wing to that of the intact one is around 2.1–3.5 in the *Cephonodes* wing, which is roughly equal to that in the model experiment by BERNHARD *et al.* (1965). It is likely that the protuberance shape difference between a dome and a cone may not affect the efficiency of antireflection.

BERNHARD *et al.* (1965) explained the antireflection mechanism of the protuberance array by viewing the protuberance array as the effective antireflective coating in which the refractive index smoothly changes through the protuberance array, from that of air to that of a cuticle, as illustrated in Fig. 12. According to the theory by BLAISSE (1950), this type of coating is antireflective in broad range of electromagnetic wavelength. Each protuberance is assumed to be a unit of an antireflective device. Viewing the bottoms as the boundaries between adjacent protuberances, the protuberances arranged regular-hexagonally is most closely packed in two-dimensional space (Fig. 13). BERNHARD *et al.* (1963) described that the thickness of the antireflective coating should be about half a wavelength for the middle of the spectrum concerned. Thus, it is likely that the protuberance array may be the most effective antireflective coating to the visible light in terms of both size and density of the antireflective unit. Since antireflection of light consequently increases transmission of light, the high transparency of the *Cephonodes* wing is probably due to this extremely effective antireflective coating of the protuberance array. This highly transparent wing, hard to be distinguished from its background, would give a good concealing effect to *Cephonodes*.
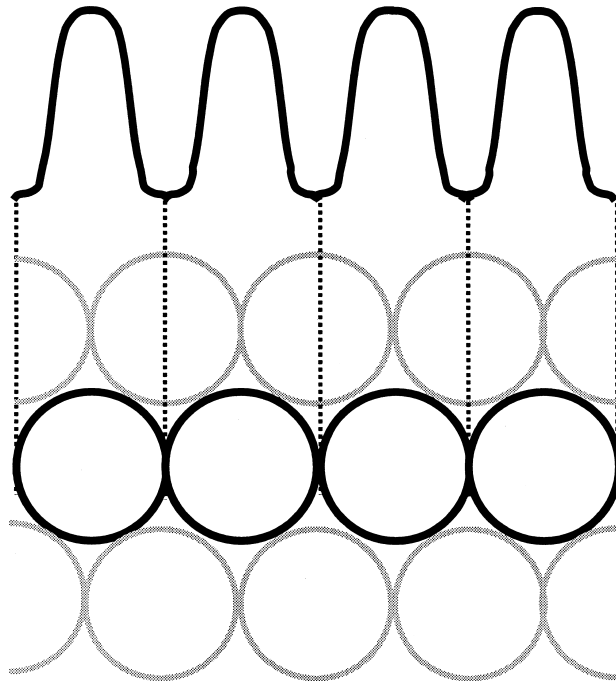
Fig. 13. Schematic figure of the protuberance arrangement. The upper part of the figure shows the side view of
     the protuberances in a row, and the lower one shows the upper views of the circumferences of the
     protuberance bases. Faded circles in the lower part are those of the protuberances in adjacent rows.

4. Concluding Remarks

In this article, two types of antireflection of lepidopteran wings were addressed. The
first type is due to the indentations of scales, and the second one is due to the protuberance
array in the scaleless and transparent wing.

A several kinds of particular scale microstructure which generate colors, have been
studied; those colors are generated by interference or scattering of light (GHIRADELLA *et
al.*, 1972; HUXLEY, 1975, 1976; HUXLEY and CARTER, 1981). On the other hand, a relation
of scale microstructure to antireflection of light has been scarcely addressed. Although
preliminary examination which suggests antireflective effect of the scale indentations is
described in this article, a quantitative study should be performed for further elucidation
of this problem.

The protuberance array of the *Cephonodes* wing is an excellent antireflective device
of light, which is a rare case in lepidopteran wings. This structure was first discovered in
the corneal surfaces in some insect eyes, and has stimulated antireflection technology. IBN-
ELHAJ and SCHADT (2001) produced high-performance and low-cost antireflective films,
which would be applicable to a wide variety of instruments. The author hopes that some

novel microstructures in insect bodies will be discovered and subsequently stimulate some new scientific and technological studies, including optical ones, in future.

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