The Iridescent Colours of Insects.

By H. ONSLOW.

I.—THE COLOURS OF "THIN FILMS."

IT is strange that the cause of the iridescent hues of insects and other animals should to a great extent still remain one of the unexplained problems of optics: theories have been advanced without end, but so far not one that is completely satisfactory. It is very significant that Prof. R. W. Wood, in speaking of certain metallic films the bright colours of which may be due to an exceedingly fine state of division, remarks: "There appears to be a large number of cases in which brilliant colours are shown which cannot be explained by any of the common laws of optics with which we are familiar. As far as I am aware, no very satisfactory explanation has ever been given of the colours of certain feathers and butterflies, and I strongly suspect there is some action of absorbing matter, in a state of very fine division, upon light waves, which is not yet completely understood."

This opinion is given in spite of the fact that no less an authority than Michelson declares that all the colours in question are surface colours; that is to say, they are due to selective metallic reflection, like the coloured surfaces of aniline dyes and metals. Nothing further is required to show how chaotic and contradictory is the present state of knowledge on this subject.

A discussion of the merits of the rival theories would not here be in place.[1] There will not, however, be much danger in venturing to predict that the almost infinite variety of iridescent colours depends upon every possible factor which can produce such colours. Neglecting the metallic films of Prof. Wood, just mentioned, and analogous cases, it is clear that the colours of insects must be caused in one of the following ways:—

(1) Pigmentation.
(2) Interference of light by "thin films" (as in the case of soap-bubbles).
(3) Diffraction of light by "gratings."
(4) Dispersion of light by prisms.
(5) The scattering of light by small particles (as in the blue of the sky).
(6) Selective metallic reflection (as in metals and aniline dyes).

In dealing with iridescent colours, the first possibility may be neglected, though pigments, such as yellow, are often found combined with structural colours, to form green and so forth.

The Interference of Light by "Thin Films."

This is well known to be the cause of the colour of soap-bubbles and oil films, and it certainly seems to offer one of the best explanations of the iridescence of insects. The late Lord Rayleigh has shown how the objections of Michelson may be met by postulating films of a peculiar structure. Also Biedermann has shown that when iridescent scales are placed in a highly refractive fluid, all colours disappear. This could not possibly occur if the colour were due to a substance resembling aniline dyes, for in these circumstances its body-colour would inevitably be seen by transmitted light. If, however, the colour were due to thin films of air separated by layers of chitin, this loss of colour is exactly what would be expected when the air-spaces were filled by a liquid; for the periodic structure would become a continuous medium. Moreover, Mallock has described how, by applying gentle pressure to scales, the colour fades, sometimes tending to return when the pressure is released. Naturally, if there are plates of chitin separated by air-films, such pressure would alter the spacing between the plates, and thus cause the colour to fade.

Since the minute structure of iridescent scales, etc., had never been examined, the present writer

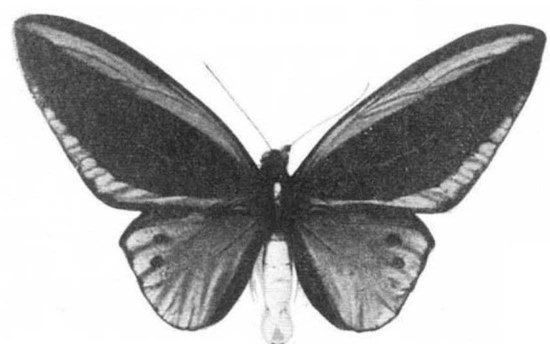

FIG. 1.—*Ornithoptera poseidon* ♂. Body yellow, wings emerald-green and black. (½ natural size.)

has carried out an extensive microscopical investigation in order to discover whether any light could be thrown on the question by this means. The varied types of the different structures found fully justified the expectation that a number of factors were involved, but though the colours of many scales could be accounted for by well-known laws, in other cases no explanation appeared adequate. A few instances will therefore be selected to illustrate the main types of iridescent colours found in insects.

Morpho menelaus.—The brilliant blue-green of this wonderful insect is well known. It is given by two layers of scales—section *1a*, Fig. 2, the pale blue upper layer, which shows the anomaly of appearing blue both by transmitted and by reflected light (NATURE, vol. ciii., p. 84, April, 1919), and section *1b*, Fig. 2, the deep blue lower layer of scales, which bears a very curious periodic structure. This structure, best seen in transverse sections of the scales, is shown in Fig. 2, *1b*. The films of transparent chitin, *a*, here appear as pillars, and between them there are films of air, *af*. Seen in longitudinal section, these pillars become long,

[1] "On a Periodic Structure in Certain Insect Scales, and the Cause of their Iridescent Colours." By H. Onslow. Read before the Royal Society on January 29, 1920.

narrow strips of chitin, *a*, Fig. 2, *1c*. The chief peculiarity of these films is that they are placed at right angles, and not parallel, to the surface of the scale or wing, as may clearly be seen from the sections. This results in an obvious consequence, which goes far to prove that the plates are the true cause of colour. It has always been said that the colour of iridescent insects changes towards the violet end of the spectrum, like a flat soap film, when the wing is turned from the normal to grazing incidence. This should be true if the colour were produced by films parallel to the wing surface, but if they were at right angles to it, the reverse should be the case; that is to say, the colour should approach the red end of the spectrum as the angle reaches the grazing incidence.

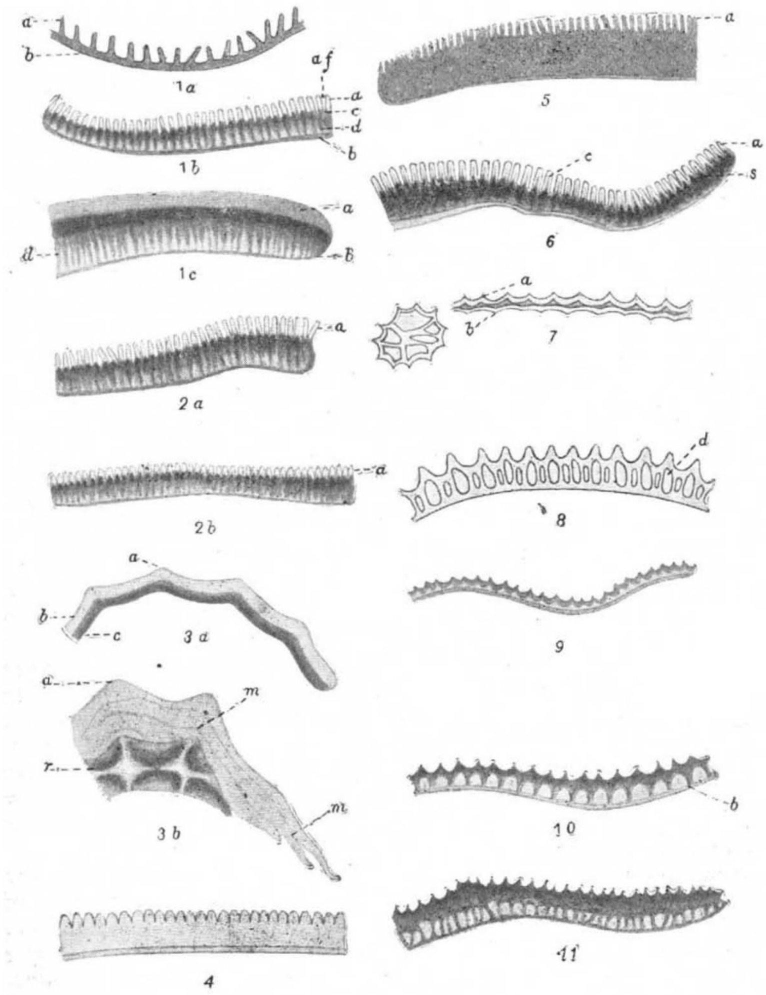

FIG. 2.

1a, Upper scale of *Morpho menelaus*. *a*, striæ; *b*, lower membrane.
1b, Lower scale of *M. menelaus*. *af*, air-film; *a*, chitin film; *c*, pigmented striæ; *d*, bands of chitin joining upper and lower membranes; *b*, lower membrane.
1c, Longitudinal section of the last. *a*, chitin film seen from the side.
2a, Central spot of *Chlorippe laurentia*. *a*, tall films of chitin.
2b, Periphery of the above, showing *a*, bosses of chitin.
3a, Scale of *Papilio ulysses* showing *a*, wave like striæ; *b*, transparent layer of chitin; *c*, pigmented layer of chitin.
3b, Diagonal section of the same. *a*, striæ; *r*, pigmented portion of striæ; *mm*, films of chitin.
4, Blue scale of *Ornithop era urvilliana*. The chitin is colourless.
5, Green scale of *O. posei..on*. The whole scale, including the chitin films *a*, contains a yellow pigment.
6, Magenta scale of *Callitaera esmeralda*, showing granular pigment *s*; and a cleft, or division *c*, in the films of chitin *a*.
7, Section through scale, and tip of scale of *Salamis parhassus*. *a*, upper membrane; *b*, lower membrane.
8, Metallic golden scale of *Dione juno*. *d*, large air-space.
9. Iridescent scale of *Lycaena icarus* stained with carbol-fuchsin.
10, Black under-scale of *Urania fulgens*. *b*, transparent, iridescent membrane.
11, Partially depigmented scale of *Euploea deione*.
All these sections were drawn to the scale $\mu = 1 \cdot 5$ mm. with Zeiss 2 mm. apochromat, N.A. 1·4, and Comp. Oc.

The variation of colour in a number of insects was measured in wave-lengths, and most of them were found to fall into two groups—(*a*) those with the periodic structure just described, which at grazing incidence reflected the longest waves, and (*b*) those without this structure, which reflected the shortest waves when in the same position. Further, it was possible to show that the distance between two consecutive plates of chitin was from $0 \cdot 6\mu$ to $1 \cdot 0\mu$,[2] and since the chitin plates often show a line of cleavage, *c*, Fig. 2, section 6, so that they appear double, this space may contain two films of chitin and one of air. Thus the plates may be of the most efficient thickness for producing colour (*i.e.* one-half wave-length), which for chitin is $0 \cdot 17\mu$, and for air $0 \cdot 25\mu$, or $0 \cdot 6\mu$ for the three plates.

Chlorippe laurentia.—The edges of the dull green patches on this insect's wings are brown at normal incidence, but the whole area becomes a brilliant green at grazing incidence. This illustrates the effect of the height of the chitin plates on the quality and saturation of the colour. The central area, which is always green, is shown in section *2a*, Fig. 2, where the chitin plates are the usual height. In the area which is brown at normal incidence, section *2b*, Fig. 2, the chitin plates, *a*, have become merely bosses. If a ray must traverse three or four films to give a certain depth of colour, it is obvious that, in the case of section *2b*, it will do this only at very oblique incidence; whereas, in section *2a*, this will happen with rays more nearly normal to the surface.

Ornithoptera poseidon (Fig. 1).—The males of this gorgeous species, and of the even more remarkable *O. paradisea* (Fig. 3), are emerald-green, and they illustrate the effect of combining structural and pigmentary colours. The narrow plates of chitin, *a*, seen in section 5 of Fig. 2, produce a blue colour, but the body of the scale is dyed by a bright yellow pigment, the colour of picric acid. This pigment extends into the chitin

[2] $1\mu = \frac{1}{1000}$ mm. The sections in Fig. 2 were all drawn to the scale $\mu = 1 \cdot 5$ mm., so that the relative distances may be seen at a glance.

plates themselves, so that they also are yellow. The addition of this pigment converts the blue into a green, and the effect of suppressing it is seen in *O. urvilliana*, a powdery blue insect, a section of which, *4*, is shown in Fig. 2. It is pale blue on the upper surface, probably because the chitin plates are broad, but underneath, where the plates are like those in section *5*, and contain a little yellow pigment, it is pale green. In some other insects

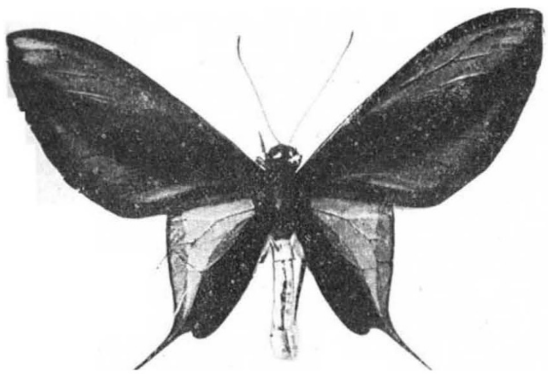

FIG. 3.—*Ornithoptera paradisea* ♂. Body and hind-wings gold fore-wings green and black. (½ natural size.)

the pigment is granular, as at *s*, in section *6*, being situated in the body of the scale, but not in the chitin plates. This is the case with those Pierids which have magenta tips to their fore-wings, as well as with the beautiful purple-eyed *Callitaera esmeralda*, which has scaleless but iridescent fore-wings (Fig. 5).

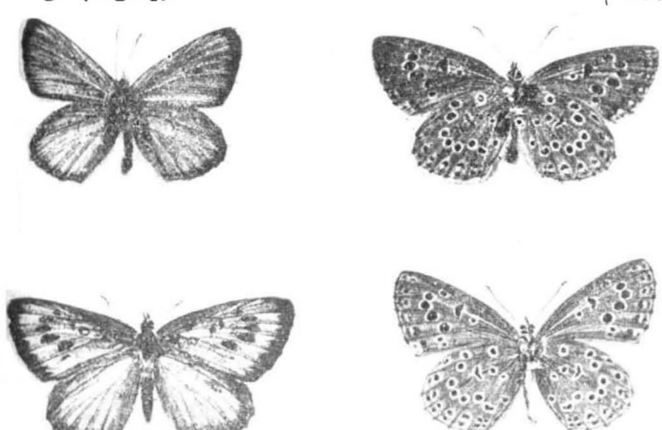

FIG. 4.—*Nomiades arion* (the Large Blue). Male and female, and under-sides of same. Natural size.)

Black is naturally a very important pigment, for it often serves the purpose of absorbing white light, which otherwise, being reflected, would greatly desaturate the colour. Thus the white spots in many insects, such as *Morpho cypris*, have exactly the same structure as the deep blue parts, except for the absence of the absorbent backing of black pigment in the lower layers of the scale.

Papilio ulysses.—The insects the colour of which changes towards the violet at grazing incidence do not have a periodic structure such as that described; but they invariably exhibit a somewhat thick superficial layer of clear chitin. The scales of many iridescent Papilios belong to this group, as, for example, the satin-blue scales of *P. ulysses*, section *3a*, Fig. 2. The layer of chitin, *b*, is clearly too thick to cause colour, and no finer structure could be made out, even with an objective capable

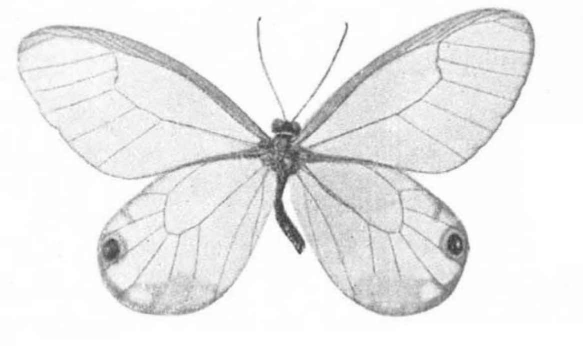

FIG. 5.—*Callitaera esmeralda.* The wings are scaleless and faintly iridescent. The eyes of the hind-wings are magenta. (Natural size.)

of separating the rulings of a grating $0{\cdot}21\mu$ apart. This is less than one-half the mean wave-length in air, which seems to preclude the existence of air-films. Nevertheless, the surface layer might contain three or four half-wave-length plates of chitin, placed exceedingly close together, though not actually in optical contact. It is, however, doubtful whether in this case pressure experiments and immersion in highly refractive fluids would produce the effects observed.

Very strong confirmation of the existence of a periodic structure, of some description, parallel to the surface, can be obtained by cutting oblique sections of *P. ulysses*. These sections, *3b* (Fig. 2), show the ragged edges of three or four layers of chitin, *mm*, which come into focus successively on lowering the objective.

Salamis parhassus.—There are some insects, like the pale pink *Salamis parhassus*, which have scales that might owe their colour to the thin double membranes of which they are composed, *a* and *b*, section *7* (Fig. 2). If these single films of chitin really cause the colour, it is difficult to account for the uniformity of shade, which ought to vary with the inevitable differences of thickness inherent in an organic film. Such variegated colours are actually found in the lower membrane of many black scales, such as those of *Urania fulgens*, *b*, section *10* (Fig. 2).

There are, however, other insects, such as many Lycænids (Figs. 4 and 6), the iridescent scales of which have membranes too thick to produce colour, though no finer structure can anywhere be made out, section 9 (Fig. 2).

Euploea deione.—There is one large group of insects of considerable interest, the colour of which cannot be accounted for in any way. This group includes the dark purples and deep, glossy blues and greens of all the most sombre iridescent insects, such as the Purple Emperor (*Apatura iris*), the Scarlet Tiger (*Callimorpha dominula*), the Purple Hairstreak (*Zephyrus quercus*), and many exotic species. Any one of these, such as the section of *Euploea deione*, 11 (Fig. 2), shows no difference from the black, non-iridescent scales immediately beneath them. They are all so densely pigmented that nothing can be made out until they are bleached, and even then a thin cuticle only sometimes appears. Were it not for the fact that the colours disappear under pressure and in refractive fluids, it might be thought that the iridescence was due to selective metallic reflection, as will be shown to be probably the case in most scaleless beetles.

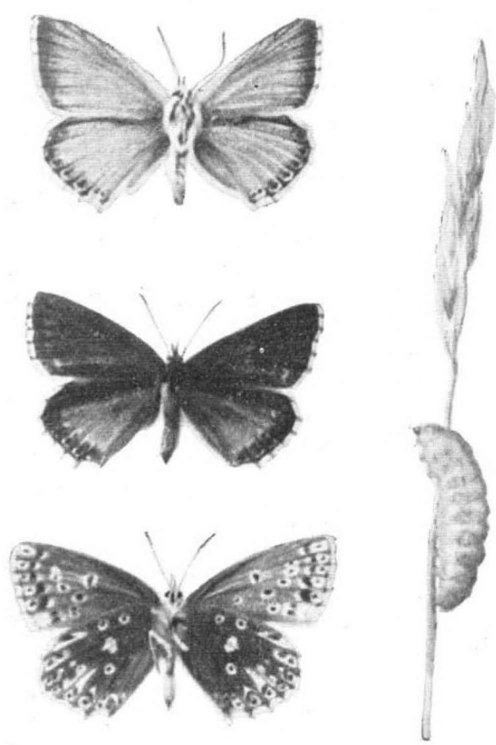

FIG. 6 *Lycaena corydon* (the Chalk Hill Blue). Male, female, under-side of female and larva. (Natural size.)

Dione juno.—Scarcely less puzzling are the metallic greenish-gold and silver scales of many Plusia, such as the Burnished Brass Moth (*Plusia chrysitis*). Section 8, Fig. 2, shows the golden scale of the tropical insect *Dione juno*, which has no structure that can adequately account for the colour, since it is identical with the scales in the adjoining brown areas, except for the absence of the pigment. To produce anything approaching metallic reflection a highly polished surface would be necessary, as well as a large number of air-spaces not more than the diameter of a few air-molecules in thickness. The effect of a highly polished surface is seen in the scales of the Coppers, as, for instance, the Small Copper (*Chrysophanus phlaeas*), which has ordinary scales containing a granular orange pigment, yet appearing almost iridescent. The only trustworthy evidence of true iridescence is, of course, the change of colour seen on altering the angle of the incident light.

(To be continued.)

Ballistic Calculations.

By D. R. HARTREE.

THE purpose of the present article is to give an outline of the more important methods of numerical solution of the various problems of external ballistics—that is to say, problems connected with the resisted motion of a shell after leaving a gun. Most of the methods to be mentioned were developed during the war, either for working out range tables or other information to be used in the field, or for analysing a trial shoot.

The problems that arise may conveniently be divided into two groups, comprising what are sometimes known as primary and secondary problems, the theoretical and practical treatments of which proceed on rather different lines. The primary problems are those which involve the calculation of the performance of a gun, or rather its shell, under ideal conditions, such as still air, a standard muzzle velocity, and so on. The secondary problems are those in which we are concerned with the calculation of the corrections to be applied to the solutions of the primary problems to allow for the departure of actual conditions from the ideal.

A very important simplification is introduced by assuming that the forces due to the motion of the shell through the air consist only of a resistance in a direction opposite to the direction of the motion of the shell relative to the air. Lack of trustworthy information until recently about the other forces made this the only possible course. Some account of these forces and their effects is given in a recent issue of NATURE.[1]

Making this assumption, and neglecting the effect of earth rotation (which may be considered as a secondary problem), it appears that the trajectories concerned in any primary problem lie entirely in the vertical plane containing the initial direction of motion. For this reason they are known as "plane trajectories."

The retardation due to air resistance R acting

[1] See NATURE, June 10, "The Dynamics of Shell Flight," by R. H. Fowler.