生物策略表

類別	生物策略 (Strategy)
生物策略 STRATEGY	鱗片的微構造減少反射 (Scale microstructures reduce reflection)
生物系統 LIVING SYSTEM	西非加蓬噝蝰 *Bitis rhinoceros* (West African gaboon viper)
功能類別 FUNCTIONS	#獲得、吸收、或過濾能量 #改變光線/顏色 #Capture, absorb, or filter energy #Modify light/ color
作用機制標題	蛇類鱗片上微米及奈米級結構透過減少光反射造成極黑顏色 (Micro-and nano-structures on snake scale create ultra-blackness by reducing light reflection.)
生物系統/作用機制示意圖	 Source: https://upload.wikimedia.org/wikipedia/commons/thumb/d/d6/Viperidae_-_Bitis_gabonica_rhinoceros.JPG/1280px-Viperidae_-_Bitis_gabonica_rhinoceros.JPG

作用機制摘要說明 (SUMMARY OF FUNCTIONING MECHANISMS)

西非加蓬噝蝰 (West African Gaboon Viper) 的偽裝 (camouflage) 非常有名。皮膚上幾何形狀的深淺色彩，使這種蛇在森林地面上幾乎無法被看見。另外，這種蝰蛇皮膚上的深色部分有一種獨特的黑色，稱為「極黑」(ultra black)，使牠更加難以被發現。當一般的黑色表面吸收大部分照射到的光線時，仍有一部分光線會不被吸收然後反射回觀察者處。然而這種蝰蛇的黑色鱗片幾乎不會反射光線，有著黑色天鵝絨般的外觀。即使蛇的鱗片確實含有色素，但形成這種極黑色的秘密在於其每片鱗片表面的微米及奈米層級構造 (micro- and nano-structure)。透過阻止光線反射，這些表面構造增加了色素對光線的吸收，產生了更深沉的黑色。

產生這種獨特色彩的方式稱為「結構色」(structural color)。科學家發現這種類型的顏色在很多動物及某些植物中都有產生，例如藍閃蝶 (*Morpho* butterfly) 鮮艷的藍色以及表皮帶有虹光 (iridescence) 的莓果。我們日常生活中看到的色彩大部分都是由色素而不是結構所造成。色素是會吸收某些波長光線的化學分子。而在結構色中，表面材料的形狀透過反射部分但非全部波長的光線來建構色彩。這導致特定顏色的產生。

是哪種結構能夠產生像加蓬噝蝰般的黑色磨砂表面呢？這種蝰蛇黑色鱗片的特徵是有著多層次的微米及奈米構造表面。鱗片表面披覆著 30 μm 高的脊狀構造 (ridges)，研究人員稱之為「葉片狀」(leaf-like) 構造。這種微構造的表面有著更加細小，高度大約為 600 nm 的紋飾 (crests)。葉片狀突出物之間的區域披著毛茸狀的隆凸 (protuberance, 或稱小刺 spinules)。這些結構的大小與可見光的波長範圍(280-700 nm) 類似。

這種微觀構造透過減少光線反射來產生蝰蛇中的極黑色彩。如果光線照射在光滑的表面，光線通常會反射回觀察者處。然而鱗片上的結構，被認為會把光波導向到蝰蛇的皮膚而不是觀察者。每當光線照射到這些微米/奈米構造時，部分會被吸收而剩餘的會被反射。這些剛被反射的光線照射到其它微米/奈米構造時，導致更多的光線被吸收而剩餘的又被反射。這過程一直重覆使反射的光線逐次變少，直到沒有更多的光線可以被反射。到最後，只有非常少的光線反射到觀察者處。一個研究證實了天鵝絨黑色的鱗片比淺色鱗片，在紫外光到接近紅外光的波長範圍中，會少四倍的光線反射。這種光線反射的減少導致蝰蛇黑色皮膚上獨特天鵝絨質感的產生。因為這種微觀表面構造，蝰蛇的皮膚不會是光亮的，使牠能有效地捕捉獵物或躲避掠食者。

The West African Gaboon Viper is famous for its camouflage. Geometric patterns of dark and light coloration on its skin make the snake nearly invisible against the forest floor. Moreover, the dark sections of the viper's skin have a unique blackness called "ultra black," which makes the snake even harder to spot. While ordinary black surfaces absorb most of the light that hits them, some light escapes and is reflected back to the viewer. This viper's black scales, however, reflect almost no light, taking on a velvet-like appearance. Though the snake's scales do contain pigments, the secret to this ultra-blacknesses lies in the micro- and nano-structure on each scale's surface. By preventing reflection, these surface structures enhance the light absorption of the pigments, creating an even darker black.

The way in which this unique coloration is created is called "structural color." Scientists have discovered this kind of color production across many animals and some plants, such as the vibrant blue of the Morpho butterfly and the iridescent skin of berries. Most of the colors we see on a daily basis are likely caused by pigments rather than structures. Pigments are chemical molecules that absorb light of certain wavelengths. In the case of structural color, on the other hand, the shape of the surface material creates color by reflecting some but not all wavelengths of light. This leads to production of a certain coloration.

What kind of structures can create a matte black surface like that of the Gaboon Viper? The viper's black scales feature a hierarchical micro- and nanostructured surface. They are covered with 30 μm tall ridges, which are described by researchers as "leaf-like" structures. The surface of this microstructure has even tinier crests that are about 600 nm tall. Areas between the leaf-like projections are covered with hair-like protuberances (spinules). The size of these structures is similar to that of visible wavelengths of light (380-700 nm).

This microscopic structure creates ultra blackness in the viper by reducing light reflection. If light hits a smooth surface, it is usually reflected back to the viewer. The structures on the scale, however, are thought to guide light waves toward the viper's skin instead of the viewer. Each time that light hits one of these micro/nano-structures, some is absorbed and the rest is reflected. The newly reflected light hits other micro/nano-structures, with some more light being absorbed and the remainder being reflected. This process repeats itself with less and less light being reflected each time until no more light can be reflected. By the end, very little light is reflected to the viewer. One study shows that velvet black scales reflect four times less light than pale scales do in the UV to near IR range. This reduced light reflection results in the unique velvet appearance of the viper's black skin. Because of its microscopic surface structure, the viper's skin is not glossy, allowing it to effectively hunt for prey and evade predators.

文獻引用 (REFERENCES)

西非加蓬噝蝰蛻皮的掃瞄式電子顯微鏡影像，證實了鱗片表面構造與色彩的形成相吻合。黑色區域的特徵是有著多層次微米及奈米構造。它們披覆有數種紋飾所組成的葉狀微構造。從頂端測量，葉狀微構造的平均高度為 30±4 μm (mean±s.d.) 且平均密度為 1900±100 mm^{-2}。這些構造被分岔的奈米尺度脊狀構造所包覆。脊狀構造的平均高度為 600±10 nm，厚度為 60±10 nm，以及在分岔之後有 330±50 nm 的平行間隔。它們的方向是與向著頂端的葉狀構造的輪廓線 (contour lines) 所垂直。脊狀構造規律地與支柱 (struts) 所連接。(Spinner et al. 2013: 2-3)

入射光 (incident light) 被奈米及微米層級的表面不規則性所多次反射與散射 (scattered)。在任何情況下，部分的入射光（或是之前被結構散射及反射的光線）會被皮膚最表層沉積的黑色素所吸收 (Spinner et al. 2013: 4)。

然而，我們的數據證實了吸收性色素並不是造成蝰蛇鱗片黑色外觀的主要原因。材料的折射率及其與周圍介質的關係才是決定性因子，能決定電磁輻射 (electromagnetic radiation) 是反射還是引導到材料中可被吸收之處。蝰蛇表皮材料主要由 α-及 β-角蛋白所組成，其折射率估計與鳥類的角蛋白相同（折射率 1.56），比金屬的折射率低。如同已知的蝴蝶翅膀結構，西非加蓬噝蝰表皮黑色鱗片的奈米構造可造成原本折射率在波長維度 (wavelength dimension) 上的偏移。因此表面結構會影響相應於光線吸收的反射率及透射率。(Spinner et al. 2013: 4)

在我們的測量中，經過金屬披覆處理的黑色蝰蛇鱗片仍能保持其黑色色彩，並比未處理的鱗片有更少的反射。考慮到金屬的高折射率，極黑外觀應不是由色素吸收光線所造成的效果。黑色色彩一定是由結構引起的折射率增加所導致。(Spinner et al. 2013: 4)

"SEM images from exuviae of *B. rhinoceros* showed that structuring of scale surfaces coincided with the colouration. Black areas featured a hierarchical micro- and nanostructured surface. They were covered with leaf-like microstructures consisting of several crests. Measured at the tip, the leaf-like structures had an average height of 30 +/- 4 μm (mean +/- s.d.) and an average density of 1900 +/- 100 mm^{-2}. These structures were covered by branched ridges at the nanometre scale. The ridges averaged a height of 600 +/- 10 nm, thickness of 60 +/- 10 nm and were after branching parallel with a distance of 330 +/- 50 nm to each other. Their orientation was perpendicular to the contour lines of the leaflike structures towards the apex and crests. Ridges were regularly connected with struts." (Spinner et al. 2013: 2-3)

"Incident light is reflected multiply and scattered by surface irregularities in the nano- and micrometre range (light trapping). In any case, one part of the incident (or previously by the structures scattered or reflected) light could be absorbed by dark pigments that are deposited within the uppermost layers of skin." (Spinner et al. 2013: 4)

"However, our data show that absorbing pigments are not the main reason for the black appearance of the snake scales. The refractive index of material and its relation to that of the surrounding medium is the decisive factor which defines whether electromagnetic radiation is reflected or led into the material where it can be absorbed. The refractive index of the snake's epidermal material mainly consisting of a- and b-keratin can be estimated as that of the keratin of birds (refractive index 1.56), which is lower than that of metal. As known from the structures on the wings of butterflies, the intrinsic refractive index of the epidermis of black scales of *B. rhinoceros* can be shifted by the nanostructures in wavelength dimension. Thereby surface structuring influences the rate of reflection and transmission which corresponds to the absorption." (Spinner et al. 2013: 4)

"In our measurements, metal coated black snake scales maintained their black colouration and became even less reflective than the untreated scales. Considering the high refractive index of metal, the ultrablack appearance might not be due to the effect of pigment absorption. The dark colouration must be rather caused by a structure-based increase of the refractivity." (Spinner et al. 2013: 4)

參考文獻清單與連結 (REFERENCE LIST)

Spinner, M., Alexander Kovalev, Stanislav N. Gorb, and Guido Westhoff. (2013). Snake velvet black: hierarchical micro- and nanostructure enhances dark colouration in *Bitis rhinoceros*. *Scientific Reports* 3: 1846. (https://www.nature.com/articles/srep01846)

延伸閱讀

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