

Biological Optics, The DCU, and Scattering Physics

Research Session Notes

2025-11-20

1. Physical Mechanisms of Color

Mechanisms Overview

Based on *Hsiung et al. (2015)* and *Bagnara (2007)*, color is produced via:

1. **Pigments (Absorption):** Selective absorption (e.g., Carotenoids, Melanin). Rare for blue.
2. **Structural (Scattering):** Interaction of light with nanostructures.
 - **Incoherent:** Randomly distributed scatterers (e.g., Blue sky, Tyndall). *Note: Johnsen argues this is still coherent scattering by an incoherent ensemble.*
 - **Coherent:** Ordered structures producing interference.

Photonic Crystal Geometries

Based on *Umbers (2012)*:

Type	Structure	Appearance	Example
1D	Multilayer Reflectors	Iridescent (Angle-dependent)	Beetle shells, Fish platelets
2D	Diffraction Gratings	Iridescent	Bird feather barbules
3D	Inverse Opals / Lattices	Angle-Independent (Non-iridescent)	Weevil scales, <i>Parides</i> butterflies

Key Insight: Non-iridescent coherent blue can also be produced by **Quasi-Ordered Arrays** (short-range order, isotropic orientation), as seen in bird spongy keratin and tarantula hairs.

2. The Dermal Chromatophore Unit (DCU)

Definition

A functional vertical stacking of cells in the dermis that acts as a biological “pixel.” Defined formally by **Joseph Bagnara**.

- **Top Layer: Xanthophores** (Yellow Filter).
- **Middle Layer: Iridophores** (Blue/White Reflector).
- **Bottom Layer: Melanophores** (Light Absorber / Contrast Background).

The Interaction Model (Phase Shifts)

Evolution does not necessarily shift wavelength continuously. It often acts via **Subtractive Mixing**, creating discrete “Phase Shifts” in color space.

Green Phenotype = Blue Structural Scatter + Yellow Pigment Filter

Blue Phenotype = Blue Structural Scatter + No Filter

Evolutionary Implications

- **Continuous Evolution (Wasik et al.):** Changing nanostructure dimensions moves the peak λ_{max} (e.g., UV → Violet). Best modeled by **Brownian Motion**.
 - **Discontinuous Evolution (Bagnara):** Gaining/Losing the yellow filter causes instantaneous jumps between Blue and Green. Best modeled by **Discrete Markov Models (Mk)** or **Ornstein-Uhlenbeck (OU)** (stabilizing selection at specific optical optima).
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3. Experimental Protocol: Imaging the DCU

Goal: Correlate microscopic DCU architecture with macroscopic reflectance spectra (Ultris X50).

The “Digital DCU” Analysis

1. Image Acquisition (The Z-Stack Fix)

Do not use a single focal plane. The DCU has depth. * **Shot 1 (Surface):** Focus on Xanthophores (Yellow). * **Shot 2 (Deep):** Focus on Melanophores/Iridophores (Black/Reflective).

* *Sampling:* Take 3 snips per Ultris ROI to account for patchiness.

2. Quantification (Masking)

- **Yellow Filter Index (I_{yellow}):** Area fraction of yellow pigment (from Shot 1).
- **Melanophore Masking (I_{mask}):** Area fraction of melanin (from Shot 2).
- **Reflector Brightness:** Mean intensity of non-pigmented areas.

3. The Mathematical Model

Fit spectral data to the interaction equation:

$$S_{obs}(\lambda) \approx [(1 - I_{mask}) \cdot S_{irid}(\lambda)] \cdot (T_{yellow}(\lambda))^{I_{yellow}}$$

Study Designs

1. Intraspecific (Plasticity):

- Focus on **Melanophore State** (Expanded vs. Contracted).
- *Requirement:* Fixation (Ep/MSH/PFA) to standardize state.

2. Interspecific (Divergence):

- Focus on **Reflector Brightness** and **Pigment Presence**.
 - *Analysis:* PGLS to correct for phylogeny.
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4. Physics Deep Dive: The Sönke Johnsen Perspective

Scattering vs. Absorption

- **Absorption:** Photon energy matches a real state transition → Energy lost as heat.
- **Scattering:** Non-absorptive interaction. Photon energy does *not* match a transition → Virtual state → Re-emission of a “new” photon of identical energy.
 - *Analogy: “The Penny in the Well.”* A penny falls in (incident photon), hits the bottom (no shelf/state), and the system immediately throws a *new* penny back up (scattered photon).

The “Tyndall” Critique

Johnsen argues Prum’s dichotomy (Incoherent vs. Coherent) is semantically flawed. * “Tyndall Scattering” is historically outdated; it is just Mie scattering. * Rayleigh scattering is a **coherent** process (dipole oscillation). * The “Incoherent” nature of the blue sky is due to the **random distribution** of molecules, not the scattering mechanism itself.

5. Advanced Optics: Velocity & Refractive Index

The Sommerfeld Precursor

How light interacts with matter (The “Maternity Ward” Analogy).

1. **Signal Velocity (The Runner):** The wavefront. Moves at c . The electrons (babies) haven’t woken up yet.
2. **Phase Velocity (The Wake):** The steady-state wave. Speed determined by refractive index (n).
 - $n > 1$ (**Glass**): Electrons lag (Inertia) → Wave drags backward → $v_p < c$.
 - $0 < n < 1$ (**Gold/Plasma**): Electrons resonate (Spring-loaded) → Wave shifts forward → $v_p > c$.

The Paradox: Faster Than Light?

- **Gold** ($n = 0.25$): Phase velocity is $4c$.
- **Explanation:** The “Peaks” of the wave are geometric patterns (like the intersection of closing scissors). They race forward, but they **vanish** when they hit the “Front” (the Runner) because the amplitude there is zero.
- **Causality:** Information (Group/Signal Velocity) never exceeds c .

Beam Attenuation Coefficient (c)

The “Total Loss” of the directional beam.

$$c = a + b$$

* a (**Absorption**): Photon dies (Heating). * b (**Scattering**): Photon is deflected (Blurring).

* *Note:* Mathematically identical to the **Pure Death Model** in macroevolution (Exponential Decay).

6. Sci-Fi Connections: Cixin Liu

The Three Body Problem & Ball Lightning

Concept	Physics Principle	Usage in Fiction
Ball Lightning	Resonance	Macro-electrons tuned to the resonant frequency of specific matter (microchips, flesh) to destroy it selectively.
The Black Domain	Refractive Index	Modifying the vacuum (n) to lower the speed of light (c) to 16.7 km/s, trapping light via “Slow Fog.”
The Droplet	Strong Interaction	Material held together by the strong nuclear force (ignoring electromagnetic repulsion).

Concept	Physics Principle	Usage in Fiction
Sophons	Entanglement	Unfolded protons. <i>Scientific Error:</i> Liu uses entanglement for FTL communication (Signal Velocity $> c$), which violates the “Gold Paradox” rules.