Biochemical Mechanisms for Magnetic Orientation in Animals

Physics 498 Biological Physics
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Magnetoreception in Animals

Magnetoreception exists in a wide variety of animals, including migratory birds, sea turtles, bees, fruit flies, mollusks, fish, salamanders, and bacteria.

First experiments were performed in the 1960s with homing pigeons and migratory birds.
Shore seeking response in salamanders

(John Phillips, Indiana U.)

~ 2 m

North

located in Indiana countryside; relocatable to laboratory

earth field white
rotated field light
earth field red light

fresh, 20° deep well water

Avian Magnetoreception

Migratory birds use the earth’s magnetic field to orient themselves during migration.

Have both a “map” of small variations in field intensity along migratory path and a “compass” to determine direction.

Captive birds are so eager to migrate that they will orient themselves in a cage in the direction they wish to fly.
Fig. 4.3. Orientation behavior of European Robins tested in magnetic fields of equal intensity, but with various declinations and inclinations. Symbols as in Fig. 4.2. (After W. Wiltschko and Wiltschko 1972)
Avian Compass is an Inclination Compass

Perception depends only on the inclination of the field lines, not the polarity

European robin

Birds must know the direction of “up” to differentiate North from South
Avian Compass is Light-Dependent

Migratory birds require light above a threshold wavelength to sense magnetic fields

- disoriented in darkness and in red or yellow light
- orient only under green or blue light

The physical mechanism for magnetoreception for birds is located in the right eye.

(Wiltschko 2005)
Visual Modulation Compass
Two Theories for Avian Magnetoreception

1. Use of Magnetite Particles
   small amounts of magnetic materials have been found in some bird species
does not explain:
   - why the compass is light-dependent
   - why the compass is inclination-only
   - why the compass works for only a narrow range of field strength
disagrees with experiments using pulsed magnetic field

2. Radical Pair Mechanism

birds may still use magnetite for a “magnetic map”
Magnetotactic Bacteria Suggest an Obvious Physics-Based Mechanism for Magnetotaxis

This is definitely one possible mechanism. Research at Frankfurt University (Gerda Fleissner et al) finally identified magnetic particles in birds’ beaks that are likely involved in magnetotaxis. However, it is generally assumed that an alternative magnetic sense exists that is based on a biochemical mechanism. Some evidence is provided below and the respective mechanism is subject of this lecture.
Two Theories for Avian Magnetoreception

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   disagrees with experiments using pulsed magnetic field

   birds may still use magnetite for a “magnetic map”

2. Radical Pair Mechanism
The Radical Pair Mechanism

\[ D^* + A \xrightarrow{\text{Light}} (\cdot D^+ + \cdot A^-)^S \]

\[ \xrightarrow{\text{Electron Transfer}} \]

\[ (\cdot D^+ + \cdot A^-)^S \xrightleftharpoons{\text{Singlet-Triplet Interconversion}} (\cdot D^+ + \cdot A^-)^T \]

Singlet Products

\[ H(B) = H_1(B) + H_2(B) \]

\[ H_j(B) = g\mu_B S_j \cdot (B + \sum_k a_{jk} I_{jk}) \]

(in both radicals)

Triplet Products
The Radical Pair Mechanism

Light

\[ \text{D}^* + \text{A} \rightarrow (\cdot \text{D}^* + \cdot \text{A}^-)^S \]

Electron Transfer

\[ \leftrightarrow \]

Singlet-Triplet Interconversion

\[ (\cdot \text{D}^* + \cdot \text{A}^-)^T \]

Singlet Products

\[ H(\vec{B}) = H_1(\vec{B}) + H_2(\vec{B}) \]

\[ H_j(\vec{B}) = g\mu_B \vec{S}_j \cdot (\vec{B} + \sum_k a_{jk} \vec{I}_{jk}) \]

(in both radicals)

\[ \vec{I}_j = \vec{B}_{\text{local}} \]

Triplet Products
Formulas to Evaluate the Triplet Yield of the Radical Pair Reaction

\[
\Phi^T = \int_{0}^{\infty} k_T T(t) dt, \quad T(t) = \text{Tr}[Q^T \rho(t)]
\]

\[
\dot{\rho}(t) = -\frac{i}{\hbar} \left[ H, \rho(t) \right] - \frac{k_S}{2} \left[ Q^S, \rho(t) \right] + - \frac{k_T}{2} \left[ Q^T, \rho(t) \right]
\]

\[
\rho(t) = \frac{1}{N} e^{-iHt/\hbar} Q^S e^{iHt/\hbar} e^{-kt}
\]

\[
T(t) = \frac{1}{N} e^{-kt} \cdot \sum_{m=1}^{4N} \sum_{n=1}^{4N} Q^T_{mn} Q^S_{mn} \cos[(w_m - w_n)t]
\]

\[
\Phi^T = \frac{1}{N} \cdot \sum_{m=1}^{4N} \sum_{n=1}^{4N} Q^T_{mn} Q^S_{mn} \frac{k^2}{k^2 + (w_m - w_n)^2}
\]

reaction rate constant in triplet state
projection operator on triplets
projection operator on triplets
m-th eigenvalue of H
initial state
Spin-independent decay kinetics: \( k = k_S = k_T \)
Predicted and Observed Magnetic Field Dependence of Triplet Yield

\[ H(\vec{B}) = H_1(\vec{B}) + H_2(\vec{B}) \]

\[ H_j(\vec{B}) = g\mu_B \vec{S}_j \cdot (\vec{B} + \sum_k a_{jk} \vec{I}_{jk}) \]

\[ \rho(t) = -\frac{i}{\hbar} [H, \rho(t)]_+ - \frac{k_S}{2} [Q^S, \rho(t)]_+ - \frac{k_T}{2} [Q^T, \rho(t)]_+ \]

Field effect develops at \( B_{1/2} \approx \sum_{j,k} a_{jk} \)
Radical Pair Mechanism as a Compass

Light

\[ D^* + A \]

Electron Transfer

\[ (\cdot D^+ + \cdot A^-)_S \]

\[ (\cdot D^+ + \cdot A^-)_T \]

Singlet-Triplet Interconversion

\[ H(\vec{B}) = H_1(\vec{B}) + H_2(\vec{B}) \]

\[ H_j(\vec{B}) = g \mu_B \vec{S}_j \cdot (\vec{B} + \vec{A}_j \vec{I}_j) \]

(anisotropic hyperfine interaction does not yield a compass)

Note that the molecules are indeed anisotropic!
Magnetic Field Effect in Case of Anisotropic Hyperfine Coupling

$$H(\vec{B}) = H_1(\vec{B}) + H_2(\vec{B})$$

$$H_j(\vec{B}) = g\mu_B\vec{S}_j \cdot (\vec{B} + A_j\vec{I}_j)$$

$$A_1 = \begin{pmatrix} 10 \text{ G} & 0 & 0 \\ 0 & 10 \text{ G} & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \quad A_2 = \begin{pmatrix} 5 \text{ G} & 0 & 0 \\ 0 & 5 \text{ G} & 0 \\ 0 & 0 & 5 \text{ G} \end{pmatrix}$$

Should work in geo-magnetic field!
Applying Anisotropic Hyperfine Coupling to the Visual System


What a Bird Might See


FIGURE 7 Visual modulation patterns through the geomagnetic field (0.5 G) for a bird flying parallel to the horizon at Urbana-Champaign (geomagnetic field inclination of 68°) and looking toward N, NE, E, SE, S, SW, W, and NW. The patterns have been evaluated assuming radical-pair receptors with anisotropic hyperfine couplings arranged in the eye model depicted in Fig. 5.
Dependence on Strength of the Geomagnetic Field

FIGURE 8 Visual modulation patterns through magnetic fields of 0.1, 0.2, 0.5, 1.0, 2.0, and 5.0 G for a bird looking parallel to the magnetic field lines. Changes in the field strength induce changes in the contrast of the modulation pattern, e.g., the central disk feature that is clearly visible for 0.5 and 1.0 G field strengths becomes less visible for lower and higher magnetic fields. In addition, qualitative changes can be observed, such as the occurrence of a new ring feature for higher (5 G) magnetic fields.
Visual Modulation Compass

(from BBC)
Visual Modulation Compass

(from BBC)
But What is the Actual Photoreceptor?

Cryptochrome


- Activated through 300-500 nm light
- Blue-light receptor transfers excitation to flavin (green)
- Flavin repairs DNA through radical pair reaction

- Evolved from highly homologous ancestor photolyase

- Cryptochromes are expressed in eyes
Hypocotyl Growth Inhibition Response of Sunflower seedlings
(from Roger Hangarter, U. Indiana, web site)

Effect of light is to shorten the hypocotyl. (stem between root and cotyledon.)
Cryptochrome and Arabidopsis

Cryptochrome mediates certain blue-light-dependent responses in plants, such as hypocotyl inhibition and anthocyanin accumulation.

seedling lacking cryptochrome has long hypocotyl
wild-type seedling has shorter hypocotyl
Plant cryptochrome undergoes a light-dependent redox reaction under steady state conditions.

Oxidized flavin (FAD)

Semiquinone flavin (FADH)

- 3min light
- 10min light
- 30min light
Cryptochrome Signaling and Electron Transfer

- back-transfer can only occur when the unpaired electrons on FADH and Trp are in a singlet state
- this back-transfer quenches signaling state
Magnetic Field Dependence of Radical Pair Mechanism for Cryptochrome 1 Photoactivation

Quantum Yield of Activation

\[ \dot{\rho}(t) = -\frac{i}{\hbar} [H, \rho(t)]_\pm - \frac{k_S}{2} [Q^S, \rho(t)]_\pm - \frac{k_T}{2} [Q^T, \rho(t)]_\pm \]

- $\dot{\rho}(t)$ is the rate of change of the density matrix.
- $H$ is the Hamiltonian.
- $[H, \rho(t)]_\pm$ represents the anticommutator of $H$ and $\rho(t)$.
- $k_S$ and $k_T$ are rate constants for different processes.
- $Q^S$ and $Q^T$ are operators.

Diagram: FADH and Tryptophan structures with parameters for quantum yield of activation.
Magnetic Field Dependence of Radical Pair Mechanism for Cryptochrome 1 Photoactivation

**Time Dependence of Product Formation**

\[
\dot{\rho}(t) = -\frac{i}{\hbar} [H, \rho(t)]_{-} - \frac{k_{S}}{2} [Q^{S}, \rho(t)]_{+} - \frac{k_{T}}{2} [Q^{T}, \rho(t)]_{+}
\]
Cryptochrome - dependent hypocotyl growth inhibition in plants is sensitive to the geomagnetic field.

Relative growth of Arabidopsis seedlings in local field and 10 X local field.

Relative growth of Arabidopsis seedlings in local field and 10 X local field.
Magnetic Field Dependence of Radical Pair Mechanism for Cryptochrome 1 Photoactivation

Orientation Dependence of Quantum Yield

Model 1

\[ \dot{\rho}(t) = -\frac{i}{\hbar} [H, \rho(t)]_\pm - \frac{k_S}{2} [Q^S, \rho(t)]_\pm - \frac{k_T}{2} [Q^T, \rho(t)]_\pm \]
Colocation of activity spots and cryptochrome expression in the garden warbler retina

Mouritsen et al., PNAS (2005)
Effect of Radio Frequency Fields on the Orientation Behavior of Robins

Biochemical Mechanisms for Magnetic Orientation in Animals

biochemical magnetic sensory mechanism

visual field

protein
Visual Modulation Compass

\[ \dot{\rho}(t) = -\frac{i}{\hbar} [H, \rho(t)]_\pm - \frac{k_S}{2} [Q^S, \rho(t)]_+ - \frac{k_T}{2} [Q^T, \rho(t)]_+ \]
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