Magnetoreception exists in a wide variety of animals, including migratory birds, sea turtles, bees, fruit flies, mollusks, fish, salamanders, and bacteria.
The use of a magnetic compass by migratory birds was first demonstrated for European robins in 1966 in Frankfurt am Main (Germany).


Later, this sensory capability was demonstrated in 17 further species.

Magnetoreception in Animals
Navigating birds “cheat”, observation difficult, except for Dr. Doolittle
Avian Magnetoreception

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

Captive birds are so eager to migrate that they will orient themselves in a cage in the direction they wish to fly.

The mechanism underlying magnetoreception is still unknown!
Avian Compass - Observation

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)

Wiltschko and Wiltschko, Science 176: 62 (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
First Question: Where is the Compass?

It is actually difficult to locate animal magnetoreceptors:

• Magnetic fields pass freely through biological tissue, i.e., magnetoreceptors need not be in contact with the external environment and might be located anywhere within an animal’s body.

• Magnetoreceptors might also be tiny and dispersed throughout a large volume of tissue.

• The transduction process might involve a sequence of chemical reactions, i.e., no obvious organ or structure devoted to magnetoreception necessarily exists.

• Accessory structures such as lenses, which focus sensory stimuli on receptors and are often conspicuous, are unlikely to have evolved for magnetic field sensing because few biomaterials affect magnetic field lines.

Animal biologist, desperate, listened to theoreticians!
Two Theories for Avian Magnetoreception

1. Use of Magnetite Particles

*Magnetotactic bacteria* suggest an obvious physics based mechanism for magnetotaxis, and indeed magnetite has been found in birds, but it does not explain key observations.

![TEM image, T. St Pierre et al, Physics, UWA](image)

2. Radical Pair Mechanism

This *biochemical mechanism* was discovered in a physics laboratory while investigating a seemingly unrelated problem, so-called *fast triplets.*
How it all started in 1975: “Fast Triplets”

From this data one needed to find out what is what at which time!
How it all started in 1975: “Fast Triplets”

Singlet excited state

Singlet ground state

Triplet excited state

Electron Spin Entanglement

Fast triplet
How it all started in 1975: "Fast Triplets"

\[ 1\left( ^1D^* + ^1A \right) \]  
\[ \overset{\text{fast}}{\text{singlet excited state}} \]
\[ \overset{\text{slow}}{\text{triplet excited state}} \]
\[ 3\left( ^3D^* + ^1A \right) \]

Klaus is crazy!

ns laser light

10ns fast triplet

1\left( ^1D + ^1A \right)  
\overset{\text{slow}}{\text{singlet ground state}}
How it all started: “Fast Triplets”

Magnetic Field Dependence of the Geminate Recombination of Radical Ion Pairs in Polar Solvents

By


Max-Planck-Institut für biophysikalische Chemie, Göttingen, Germany

With 4 figures

(Received January 19, 1976)

What was done 35 years ago, i.e., 1975?

Evaluation of triplet probability through spectral expansion after block-diagonalizing the $3 \times 2^{19}$-dimensional spin Hamiltonian (in 1975!)
Predicted and Observed Magnetic Field Dependence of Triplet Yield

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

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

The radical pair mechanism explains avian magnetoreception

Light $\rightarrow$ D$^*$ + A

Electron Transfer

$(\cdot D^+ + \cdot A^-)^S$

Singlet-Triplet Interconversion

$(\cdot D^+ + \cdot A^-)^T$

Singlet Products

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

Triplet Products

$H_j(\vec{B}) = g\mu_B \vec{S}_j \cdot (\vec{B} + \sum_k a_{jk} \vec{l}_{jk})$ (in both radicals)

Zeeman - hyperfine interaction

Liouville equation!

\[
\dot{\rho}(t) = -\frac{i}{\hbar} [H, \rho(t)] - \frac{k_S}{2} [Q^S, \rho(t)] + \frac{k_T}{2} [Q^T, \rho(t)].
\]
The radical pair mechanism explains avian magnetoreception.

A less bold scientist would have thrown this work into a waste bin!
Magnetic Field Effect in Case of Anisotropic Hyperfine Coupling

\[ H(\vec{B}) = H_1(\vec{B}) + H_2(\vec{B}) \]
\[ H_j(\vec{B}) = g\mu_B \vec{S}_j \cdot (\vec{B} + \vec{A}_j \vec{I}_j) \]

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

Should work in geomagnetic field!

Magnetic Field Dependence of the Geminate Recombination of Radical Ion Pairs in Polar Solvents

Compass
But it is “only” an inclination compass!
And works in narrow field window!
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 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

Each triangle represents the orientation of one bird

(Wiltschko 2005)
Visual Modulation Compass
What a Bird Might See!
What a Bird Might See


**FIGURE 6** Visual modulation patterns through the geomagnetic field (0.5 G) for a bird looking into different directions at angles 0°, 30°, 60°, 90°, 120°, 150°, and 180° with the magnetic field vector. The patterns have been evaluated assuming radical-pair receptors with anisotropic hyperfine couplings arranged in the eye model depicted in Fig. 5. The schematic illustrations next to the modulation patterns indicate the corresponding direction into which a bird would be flying at Urbana-Champaign (geomagnetic field inclination of 68°).
What a Bird May See!
What a Bird May See!
What a Bird May See!
What a Bird May See!
What a Bird May See!
Dependence on Strength of the Geomagnetic Field

Strong argument against a magnetite-based compass!

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.

But What is the Actual Photoreceptor? It Is Cryptochrome!

- evolved from highly homologous ancestor photolyase


- activated through 300-500 nm light
- blue-light receptor transfers excitation to flavin (green)


- cryptochromes are expressed in eyes
Colocation of activity spots and cryptochrome expression in the garden warbler retina

Mouritsen et al., PNAS (2005)
Cryptochrome mediates light-dependent magnetosensitivity in *Drosophila*  

Robert J. Gegear¹, Amy Casselman¹, Scott Waddell¹ & Steven M. Reppert¹

Cryptochrome Signaling


Cryptochrome is observed in three states: FAD, FADH and FADH$^\cdot$

Magnetic Field Dependence 1 Affecting Photoactivation of Cryptochrome

Magnetic Field Dependence 1 Affecting Photoactivation of Cryptochrome

\[ \frac{d\rho}{dt} = -\frac{i}{\hbar} [H, \rho] - [K \rho + \rho K] \]

Magnetic Field Dependence for Cryptochrome 1

Photoactivation \( \frac{d\rho}{dt} = -\frac{i}{\hbar} [H, \rho] - [K \rho + \rho K] \)

Orientation Dependence of Quantum Yield

Dark Deactivation of Cryptochrome Involving Molecular Oxygen

\[ \frac{d\rho}{dt} = -\frac{i}{\hbar} [H, \rho] - [K \rho + \rho K] \]

I.A. Solov'yov and K. Schulten, Biophysical Journal 96, 4804-4313 (2009)
Dark Deactivation of Cryptochrome Actually Involving Superoxide, $\text{O}_2^-$

Superoxide at low conc. Toxic!
Humans prefer longevity over sense of direction.

$$\Delta E \xrightarrow{k_{\text{et}}}$$ magnetic field dependence $\text{non-signalling}$

$$25\%$$ $\xrightarrow{k_\text{b}}$ $\xrightarrow{k_\text{Ox}}$ $75\%$

$$\frac{d\rho}{dt} = -\frac{i}{\hbar} [H, \rho] - [K \rho + \rho K]$$

---

Orientation Dependence of Magnetic Field Effect on Dark Deactivation (Reaction Duration Time)

\[
\frac{d\rho}{dt} = -\frac{i}{\hbar} [H, \rho] - [K \rho + \rho K]
\]

stochastic Liouville Equation

Consider fixed field

\[ B_0 = 0.5 \text{ G} \]

(i) \( k_b = 10^6 \text{ s}^{-1} \)
(ii) \( k_b = 3 \times 10^6 \text{ s}^{-1} \)
(iii) \( k_b = 5 \times 10^6 \text{ s}^{-1} \)
(iv) \( k_b = 10^7 \text{ s}^{-1} \)

The angular dependence of the reaction duration time corresponds to an inclination compass. The maximal variation in \( \tau \) is 18 \%. 

I.A. Solov'yov and K. Schulten, Biophysical Journal 96, 4804-4313 (2009)
Locating and Orienting Cryptochrome in the Eye

\[
\frac{d\rho}{dt} = -\frac{i}{\hbar} [H, \rho] - [K \rho + \rho K]
\]

Liouville equation!
What a bird might see?
\[
\frac{d\rho}{dt} = -\frac{i}{\hbar} [H, \rho] - [K \rho + \rho K]
\]
\[ \frac{d\rho}{dt} = -\frac{i}{\hbar} [H, \rho] - [K \rho + \rho K] \]

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Papers on Quantum Biology of Magnetoreception


These papers suggest radio frequency radiation to probe biochemical compass mechanism. The magnetic field dependence of photoactivation of cryptochrome is shown. Application to plant cryptochrome is discussed. Investigates degree of cryptochrome orientation.