Geomagnetic Cyclotron Resonance in Living Cells

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ABSTRACT: Although considerable experimental evidence now exists to indicate that low-frequency magnetic fileds influence living cells, the mode of coupling remains a mystery. We propose a radical new model for electromagnetic interactions with cells, one resulting from a cyclotron resonance mechanism attached to ions moving through transmembrane channels. It is shown that the cyclotron resonance condition on such ions readily leads to a predicted ELF-coupling at geomagnetic levels. This model quantitatively explains the results reported by Blackman et al. (1984), identifying the focus of magnetic interaction in these experiments as K^+ charge carriers. The cyclotron resonance concept is consistent with recent indications showing that many membrane channels have helical configurations. This model is quite testable, can probably be applied to other circulating charge components within the cell and, most important, leads to the feasibility of direct resonant electromagnetic energy transfer to selected compartments of the cell.

INTRODUCTION

In view of the wide variety of experiments that have indicated some sort of coupling of low-level, low-frequency electromagnetic waves to living systems, it is remarkable that no single mechanism has been set forth to explain these observed phenomena. The great variety of signal shapes, model systems, and biological responses is shown in part in Table I. Discounting the signal shape (which, to a first approximation, may be irrelevant), one concludes that low-frequency periodic magnetic fields may lengthen (Marron et al., 1975) or shorten (Aarholt et al., 1981) the mitotic cycle, induce embryonic malformation (Delgado et al., 1982), and enhance mRNA transcription (Goodman et al., 1983), DNA synthesis (Liboff et al., 1984), and tumorigenic activity (Winters and Phillips, 1984). The clinical use of such fields, it is claimed, acts to repair non-unions in bone (Bassett et al., 1982), although there is at least one report to the contrary (Baker et al., 1984). A spate of recent epidemiological studies imply correlations between deaths from acute myelogenous leukemia (Milham, 1982; Wright et al., 1982; McDowell, 1983; Coleman et al 1983), other cancers (Wertheimer and Leeper, 1979, 1982), and an increase in human gestation time (Wertheimer, 1984), all with exposure to electromagnetic fields. This dizzying set of responses, even if only partially true, points to an underlying coupling mechanism which surely must reside at a very basic biophysical level. The cell membrane has been implicated (Chiabrera et al., 1984), by invoking mechanisms in which ionic currents are induced by Faraday's Law, $\nabla \times \vec{E} = -\delta\vec{B}/\delta t$. Presumably, the higher collision rate at cell surface receptors acts to enhance membrane transport, thereby producing the various types of observed cellular expression. Computer models and *in vivo* measurements (Pilla et al., 1983) have established that such eddy current densities might be as large as $0.1\text{-}1\ \mu A/cm^2$. However, attempts to test this hypothesis have failed. Despite the rather significant response reported by Liboff et al. (1984), the response itself remained constant over four orders of magnitude of $|d\vec{B}/dt|$, suggesting a mechanism other than a current-dependent enhancement of membrane transport. Sisken et al. (1984) similarly found no variation in response in a system that clearly showed a simple radial dependence on current density. An alternative model suggesting that eddy currents induced within the cell are responsible for the various observations is also untenable because these currents scale with the bounding radius (Liboff and Homer, 1983). Current densities $\simeq 10^{-11}\ A/cm^2$ result, too small to be meaningful.

CYCLOTRON RESONANCE MODEL

In the following, we propose a totally new model for the interaction of electromagnetic fields with living cells, one depending upon the well-established concept of cyclotron resonance. We suggest that, in regions of the cell where there may be reduced scattering, certain ionic species and perhaps even selected enzymes will tend to follow circular or helical well-defined orbits under the influence of static magnetic fields. It is likely that such regions of re-

only one ionic species is bound to have much longer relaxation times than, say, the cytoplasm or the extracellular environment. Unlike the helical motion of free particles in a magnetic field, we shall assume that channelized ions are already constrained to move along helical paths. A charge moving along such a path in the presence of a component B of the Earth's magnetic field normal to the plane of the path, will experience a radial force $qvB = mv^2/R$, where q and m are the respective charge and mass of the ion, v its velocity, and R the radius of curvature of the path. Because of this force, the particle will execute either a circular or a helical path (See Figure 1). The velocity can be simply expressed as the product of the frequency of rotation ν,

$$\nu = qB/2\pi m \qquad (1)$$

The functional dependence of ν on q/m is displayed in Fig. 2. It is instructive to inquire as to the values of resonance frequencies ν that correspond to the Earth's magnetic field. The total geomagnetic field varies from abou 0.70 gauss at the poles to 0.25 gauss at the geomagnetic equator, and averages $\simeq$ 0.5 gauss at mid-latitudes. Note that for such fields, frequencies in the range of 10-100 Hz correspond approximately to charge/mass ratios of 0.01 to 0.1 e/u, indicating that biologically important ions, heavier than protons but less massive than enzymes and proteins (see Table II), appear to have "natural" gyrofrequencies in the Earth's field that are in the ELF region. The happy circumstance that allows for these conditions to be established as a function of the Earth's magnetic field does not result in energy transfer from the local static field to the affected ions. On the other hand, if an additional oscillating electric or magnetic field is applied in resonance with ν, then energy transfer does indeed become

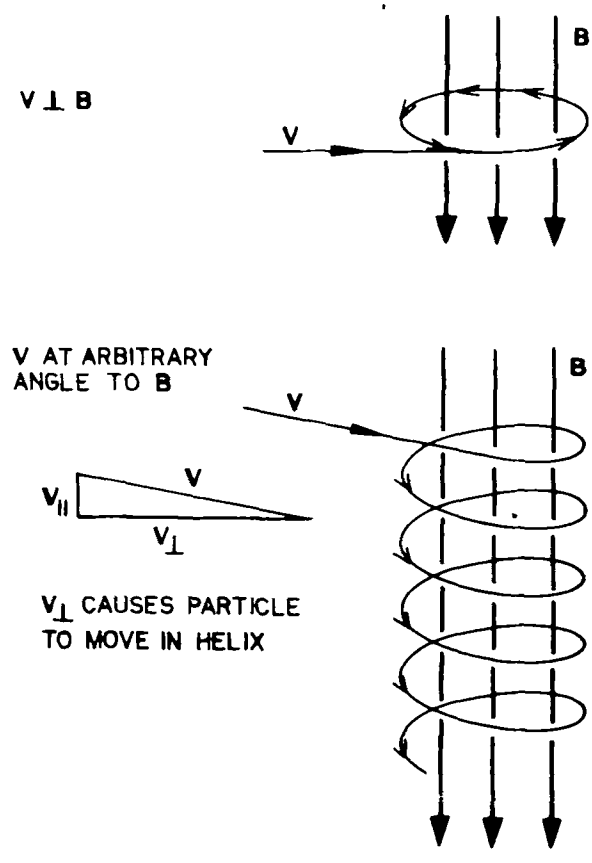

Figure 1. The angle between particle velocity and field direction determines type of path (in absence of any other field): a circle when v is normal to $\vec{B}$, a helix otherwise.

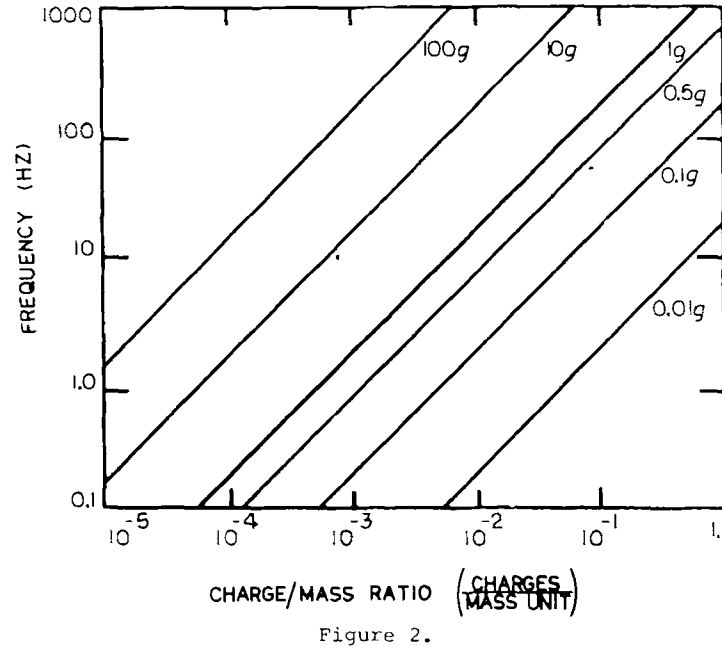

Figure 2.

TABLE I

Recent Experiments Indicating Cell--Field Interactions.

Experiment	Signal Shape	Cells Studied
Blackman et al. (1984)	sinusoidal	chick brain
Marron et al. (1975)	sinusoidal	slime mold
Aarholt et al. (1981)	rectangular	*E. coli*
Delgado et al. (1982)	rectangular	chick embryo
Goodman et al. (1983)	pulse train	dipteran
Liboff et al. (1984)	sinusoidal	human fibroblast
Winters & Phillips (1984)	sinusoidal	human tumor

feasible. This model therefore carries with it the implication that low-intensity electromagnetic fields can directly deliver energy to selected compartments of the living cell.

This idea is also consistent with the pre-existence of channels in the form of helical pathways through membrane-bound proteins. There is increasing evidence for the existence of channels having such configurations. One example of a likely helical channel is found in the structure of the light-driven proton pump, bacteriorhodopsin (Alberts et al., 1983), in which the polypeptide chain spans the membrane as seven twisted α-helices. Another is the acetylcholine receptor, a complex of five transmembrane subunits for which a helical structure has been proposed (Popot and Changeux, 1984). By far the most complete structural description along these lines has been made for the gramicidin A transmembrane channel. It is characterized as having a β-helical structure (Urry, 1971), with the carbonyl groups lining the pore interior oriented alternately skew anti-parallel to the channel axis (Jordan, 1984). It is also possible that a helical channel can be formed as an interstitial gap between adjacent lengths of a protein chain, so that the channel follows an α-helical geometry. Figure 3 illustrates the way any of these channels would tend to support cyclotron resonance. If there is a component of the local geomagnetic field, $B_{\parallel}$, parallel to the helix axis, then ions traversing this channel will also enjoy rotational motion normal to $B_{\parallel}$ at the gyrofrequency ν.

DISCUSSION

The final energy state reached by a membrane ion pump is in part limited by the drift velocity in the direction of the helical axis. We suggest that superposed periodic magnetic fields, such as those used in the experiments in Table I, will transfer kinetic energy to channel ions when the time-varying field is in proper resonance. This will increase ionic drift velocities through the membrane, allowing for more rapid charginf of such pumps. The first of the experiments listed in Table I is very suggestive of a cyclotron resonance mechansim.

Using a rather well-established system (Bawin and Adey, 1976), in which the effusion of calcium from freshly sliced chick brain tissue changes in a low-frequency oscillating field, Blackman et al. (1984) observed that the simultaneous application of the Earth's magnetic field markedly influences the results, the efflux occurring only for certain combinations of the static and the time-varying fields. Although somewhat similar to a nuclear resonance phenomenon, what Blackman and his group observed obviously was quite different--the frequencies of the applied field are far too small to excite nuclear mements. Thus, a larger Ca^{2+} efflux was observed for a combination of Earth's field and applied frequency of 0.38 gauss and 15 Hz, respectively. When these numbers were both doubled, to 0.76 and 30 Hz, the combination again gave rise to enhanced Ca^{2+} efflux. If we substitute these two sets of values for ν and B into Equation 1, the charge-to-mass ratio that results is .026 (in units of the ratio of electron charge e to atomic mass units u). This is precisely the charge-to-mass ratio for singly ionized potassium (see Table II). The cyclotron resonance model that we propose is therefore consistent with channelized potassium ions in resonance at 15 and 30 Hz in Blackman's experiment, in both cases extracting energy directly from the applied, time-varying field, and resulting in extra Ca^{2+} efflux.

This magnetic coupling mechanism may not be unique to the ion pump circulation in the membrane, but indeed might well apply to other processes within the cell. Any small constrained,

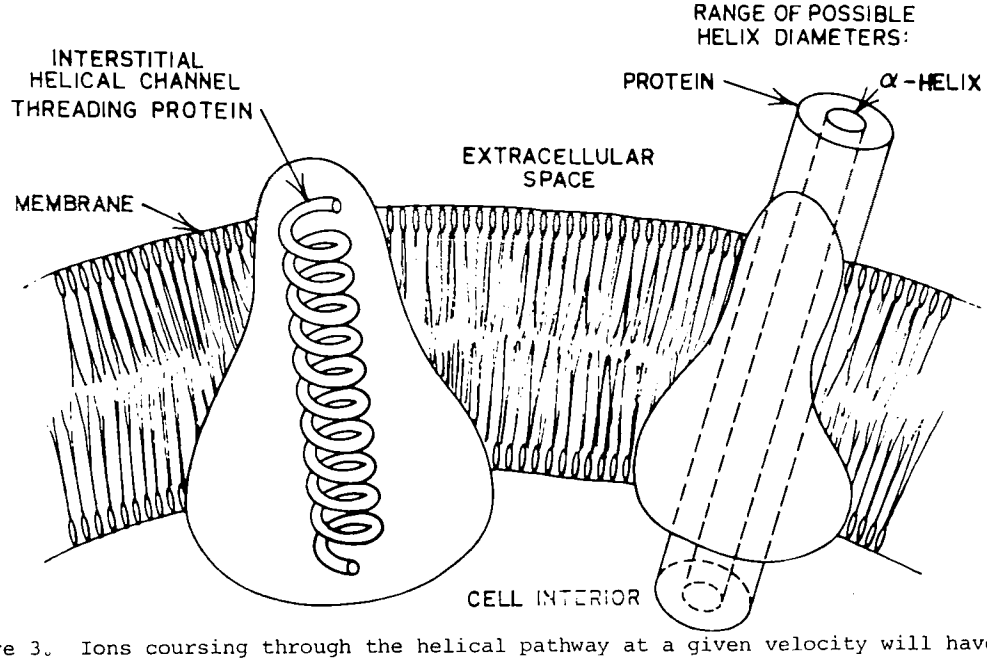

Figure 3. Ions coursing through the helical pathway at a given velocity will have a resonant frequency determined by the parallel component $B_{\parallel}$ of the local magneto-static field. The range of possible diameters for a helical channel as depicted must lie between that of the α-helix (~5 Å) and the protein diameter (~40 Å).

TABLE II

Calculated Cyclotron Resonances for Selected Free (unhydrated) Ions of Biological Interest, (Geomagnetic Field of 0.5 Gauss Assumed).

IONIC SPECIES	CHARGE/MASS RATIO (e/u)	CYCLOTRON RESONANCE FREQUENCY @ 0.5 g
H^+	0.99	760 Hz
Li^+	0.14	110
Mg^{2+}	0.082	61.5
Ca^{2+}	0.050	38.7
Na^+	0.043	33.3
Fe^{2+}	0.036	27.9
Zn^{2+}	0.031	23.4
K^+_{2+}	0.026	19.6
$Sr^{}$	0.023	17.3
Rb^+	0.012	9.0

circumscribed motion of charge will fit this model. As an example, consider the rotational motion of the topological enzyme, DNA gyrase, responsible for supercoiling of the DNA molecule in prokaryotes (Cozzarelli, 1980). It is difficult to estimate the residual charge on the relatively massive subunits that power this enzyme, but if the charge/mass ratio were as high as 10^{-4} e/u then a static field of $\approx$ 100 gauss would permit energy transfer to DNA gyrase, with potentially interesting consequences. One obvious test of this model would be to tweak the frequencies in the Ca-efflux and other experiments to bring the applied field into more precise resonance; hopefully the response will be magnified. It should be noted that the frequencies chosen by Blackman et al. were fortuitously close to resonance, given the ambient magnetic field present in their laboratory.

The beauty of the cyclotron resonance condition is its simplicity--not only because of its form but also because of the ease with which quantitative experiments can be designed around this condition. There are only three parameters--frequency, field strength, and charge-to-mass ratio--each of which can be separately varied for a given cell or membrane, or animal system. If cyclotron resonance does indeed occur at geomagnetic levels in biological systems, there is great potential, through corollary experiments, for a more detailed understanding of the cell.

We thank Carl Blackman for sharing his data with us, and stand indebted to Louis Homer for his kind advice and encouragement.

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