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Chapter 16 Electromagnetic resonance and morphogenesis

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Abstract: Science has yet to resolve the mystery of a living being's selfassembly into intricate patterns of form and function. Tissue patterns in developing flower buds implicate physical resonance as a mechanism through which positional information can be generated in biological development. In resonance, a trapped waveform creates a spatial pattern of a physical property. A resonance pattern is mathematically defined and is characteristic of the specific mechanism that produced the resonance. Resonances can spontaneously emerge as intricate 3D vector fields with varying strength and direction of action at every point in the involved space. As physical force fields, vector resonances can supply individual cells with positional information and influence genetic expression and other cell activities via a variety of established physical mechanisms such as voltage gated membrane channels, thereby changing cell state at specific locations to create a pattern of form and function. Remarkably, the three dimensional architectures of developing plant flower buds show striking parallels with resonance patterns formed by electromagnetic energy.

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Introduction

Ubiquitous yet stunning mysteries can be found in the exquisite patterns created by living beings, especially in the plant realm. For example, Figure 1A shows a cross-section through the ovary of an *abutilon* flower, revealing eight ova (immature seeds) that evenly divide the unit circle with a spacing of 45° ($2\pi/8$). Strikingly, the spatial characteristics of the abutilon flower ovary are described in close relation to two nested 8-point star polygons (Figure 1B). Similarly, Figure 1E shows the cross section through the male flower bud of a squash plant revealing 15 pairs of developing pollen tubes evenly dividing the unit circle with a spacing of 24° ($2\pi/15$) and exhibiting a featureless zone prescribed by a 15-point star polygon (Figure 1F). What physical mechanism can account for the appearance of such architectures? To shed light on these questions, attention must first be turned to the process of morphogenesis to appreciate the context of mysteries science has yet to elucidate.



Figure 1. Parallels between plant primordia and star polygons. Panel A shows a cross-section through an immature abutilon flower ovary. Panel B shows the same image in relation to 8-point star polygons. Panel E shows a cross-section through an immature male flower bud of a squash. Panel F shows the acorn squash primordia in relation to a 15-point star polygon. Panels C and G show the $TM_{4,4,2}$ and $TM_{15,15,2}$ modes (notation defined on pg. 8 and 10), respectively, with electric field direction shown as a streamlined vector, electric field magnitude as a blue gradient, and magnetic field magnitude as a red gradient. Panels D and H show the relationship between the modes and star polygons. Scale bar in images shows 250 µm.

Morphogenesis describes the development of biological form from a small collective of selfsame cells. In morphogenesis, intricate, mathematically precise natural architectures develop from simple, symmetrical initial states that show no traces of the patterns to come. An example of pattern emergence is given in Figure 2, where the inner compartment of a primordial squash ovary initially shows no distinct structure (Figure 2A), yet at a certain point in development a characteristic pattern defined by three sets of two spiral-like structures appears (Figure 2B). The emergence of pattern from a simple initial state is referred to as *symmetry breaking*. Like breaking a mirror, the initially smooth, continuous surface or shape with a high degree of symmetry is transformed into one with less symmetry due to the appearance of new structures and forms.



Figure 2. Emergence of pattern and morphostasis in female squash flower ovary primordium. Panel A shows the early primordium, Panel B shows a slightly larger primordium at a time of early symmetry breaking, and Panel C and D shows progressively more developed cross-sections of the fruit that retains aspects of the original emergent pattern. Panel E shows a three-dimensional view of the primordial female squash flower with an ovary marked by '*'. Scale-bars in images show 250 µm.

With continued growth and development, the pattern may remain essentially the same in its general characteristics, but is composed of first hundreds, then tens of thousands, and then millions to billions of cells in the final mature form (Figure 2C and D exemplify this for the squash ovary and fruit). This conservation of an early pattern throughout development of an organism is known as *morphostasis* (Levin, 2009). The mechanisms responsible for the first symmetry-breaking in the biological collective are therefore of great importance as the final pattern of the mature organism is often a multicellular/multifunctional version of the initial pattern to appear in the primordial collective.

It is well established that molecular signals and genetic expression play essential roles in both plant and animal development. Many years of research have focused on understanding development by inhibiting the expression of genes or the activities of their protein products. The result is an extensive list of correlations between various aspects of development and genetic expression. For example in plants, the activities of highly conserved gene families have been implicated in the formation of the four organ systems of the flower (*i.e.* the sepals, petals, stamens/anthers, and ovary/pistil) (Krizek et al., 2005). While the involvements of specific genetic expressions are well established in plant organogenesis, it remains largely unknown how genes are activated in certain spatial regions and how the distribution of functional biomolecules and cell types can form in dynamic spatial patterns. Ultimately, the processes involved in the symmetry-breaking of the early collective remain the greatest mysteries of morphogenesis in both plant and animal development.

For morphogenetic symmetry-breaking to happen, certain cells in certain spatial regions must suddenly change their genetic expression to become cells of a different differentiation state in those regions. The cells that are changing state in the collective must receive some kind of regionally specific signal telling them to change their activities. This regionally specific signal is referred to as *positional information*. The concept of positional information is essentially synonymous with the concept of a morphogenetic field (Gilbert, 2006; Gilbert et al., 2000). What is crucially missing from modern developmental biology is a comprehensive understanding of how positional information is supplied to the cells, or in other words, an elucidation of the physical nature of the morphogenetic field.

Various systems-focused answers have been proposed to account for the manifestation of long-range spatial organization in plant and animal development, and in reality a variety of different mechanisms may be simultaneously involved. Positional information has perhaps been most commonly considered in terms of Reaction-diffusion type mechanisms involving the emergence of a spatial pattern of a morphogenetic chemical (Koch et al., 1994; Meinhardt, 1996). Reaction-diffusion mechanisms were introduced by the renowned scientist Alan Turing (Turing, 1952) and have been developed further by a number of scientists including Koch et al., 1994 and Meinhardt, 1996. Reaction-diffusion mechanisms are important theories capable of describing chemical gradients forming in a developing organism, the shapes and colouring of sea-shells, development of reticulated vein networks, the spots and stripes on animal hides, and the appearance of divisions in the early stages of a developing embryo. In addition to reaction-diffusion type mechanisms, Beloussov has suggested that positional information be supplied by mechanical stress fields self-generated in a growing embryo (Beloussov, 2008; Beloussov et al., 2006). The alternative perspective presented herein sees a developing organ as a dynamic system self-trapping electromagnetic (EM) energy in a stable spatial pattern capable of supplying the cellular collective with rich positional information.

1. Dielectric resonators: Containers for light

It is well established, theoretically and experimentally, that a simple drop of water can act as a resonant cavity for light (Datsyuk, 2001; Hossein-Zadeh et al., 2006). In fact, water droplets are such good containers for light that, if doped with a light-producing material such as a *rhodamine* dye, they can even produce coherent laser light (Kiraz et al., 2007; Lin et al., 1992).

In a water-drop the situation is similar to that of the conventional laser, except instead of a resonant cavity created by mirrors, it is the air-water boundary of the spherical water-drop that reflects light back into the droplet (Datsyuk, 2001). When light traveling within a strong dielectric strikes the interface with a weak dielectric some transmission and reflection of the incident wave occurs that is dependent on the angle of incidence and the relative differences in dielectric strengths between the two materials. Therefore, if a beam of light is travelling within a spherical water-drop surrounded by air, the light can become trapped by consecutive internal reflections. If the light is of the right frequency to interfere constructively with itself along its path, an EM resonance is established in the water-drop. In order for the water-drop to behave as the resonant cavity of a laser, rhodamine dye molecules must be added to act as the optical gain medium.

The concept of a water-drop resonator can be easily extended to developing plant organs (primordia), and in fact as is explored herein, there are substantial structural parallels between tissue patterns and EM resonant modes within leaf and flower primordia (Pietak, 2011a, b, 2012). At the time of first symmetry breaking, developing plant primordia are similar to a water-drop resonator as they are initially small (100 to 500 μ m radius), symmetrical (spherical, ellipsoidal, or nearly cylindrical), high water content (90-98%) structures surrounded by air or a porous, low water content rind of lower permittivity (Figure 2E). These early characteristics of plant primordia establish reasonable conditions for internal reflection of EM waves within the structure, and the consequential formation of resonant modes in a frequency range between 0.25 and 5 THz. Furthermore, the fact that plant and animal cells respond in various distinct ways to electric, magnetic, and EM fields is rather well established (Cifra et al., 2011a; Levin, 2003, 2009). However, unlike a water-drop resonator operating at optical frequencies, plant primordia would absorb internal EM at their resonant frequencies of 0.25-5 THz, leading to high damping of the EM resonance (low Q-values).

2. The spherical dielectric resonator

Modes within dielectric resonators are comprised of individual electric and magnetic field components. Each field type is a three-dimensional entity with a stable field pattern spanning the space of the resonator (Figure 3). In time, the space is alternatively filled by electric and magnetic field patterns turning over at the same frequency as the original EM wave. As two, distinct, three-dimensional spatial patterns, each with magnitude and direction at regions throughout the space, the EM resonant mode holds an incredible amount of positional information for any substrate capable of responding to it.



Figure 3. Three dimensional vector field representations of the electric (A and B) and magnetic (C and D) field components of the TM_{3,3,2} mode in a dielectric sphere. Panels A and C show a three dimensional vector field with respect to an isosurface of the field magnitude. Panel B shows the electric field in cross-section while panel D shows the magnetic field in long-section. Black shows areas of highest magnetic field strength and arrow sizes are scaled in proportion to field strengths.

Electromagnetic resonant modes come in transverse electric (TE) and transverse magnetic (TM) varieties. For TE modes on a sphere, the electric field has no component in the radial direction, with no further restrictions on the magnetic field aside from those required by Maxwell's Equations. In TM modes it is the opposite with no radial component of the magnetic field.

The mathematical equations describing electromagnetic resonance modes in a non-magnetic dielectric sphere are described by Yadav et al., 2004.

The boundary conditions determine the set of resonant frequencies for a spherical dielectric of a particular size and permittivity. For a spherical dielectric resonator, the tangential components of the electric and magnetic fields, and the normal component of the electric displacement field and magnetic flux density must be continuous across the boundary between the resonator and its surrounding environment. Applying these conditions for the various field equations of the resonator leads to the characteristic equations (Gastine et al., 1967):

For TM modes:

$$\frac{n}{ka} - \frac{J_{n-\frac{1}{2}}(ka)}{J_{n+\frac{1}{2}}(ka)} = \frac{n\varepsilon_r}{ka} - \sqrt{\varepsilon_r} \frac{H_{n-\frac{1}{2}}\left(\frac{ka}{\sqrt{\varepsilon_r}}\right)}{H_{n+\frac{1}{2}}\left(\frac{ka}{\sqrt{\varepsilon_r}}\right)}.$$
[1]

For TE modes:

$$\frac{J_{n-\frac{1}{2}}(k\,a)}{J_{n+\frac{1}{2}}(k\,a)} = \frac{1}{\sqrt{\varepsilon_r}} \frac{H_{n-\frac{1}{2}}\left(\frac{k\,a}{\sqrt{\varepsilon_r}}\right)}{H_{n+\frac{1}{2}}\left(\frac{k\,a}{\sqrt{\varepsilon_r}}\right)}.$$
[2]

Where $H_n(x)$ are Hankel functions of the first kind (*i.e.* $H_n(x) = J_n(x) + j Y(x)$). The radius of the sphere is represented by *a*. The parameters *k* and ε_r are the wavenumber and relative permittivity of the dielectric sphere material, respectively. Equations [1] and [2] assume the dielectric sphere is non-magnetic ($\mu_r = 1$) and surrounded by air with relative permittivity of 1.

The solutions to the characteristic equations are complex frequencies:

$$f = f_0 - j f'' \,. \tag{3}$$

The solutions (roots) of the characteristic equation can be indexed incrementally using the integer L. The real component of the complex frequency (f_o) represents the physical resonant frequency of the dielectric sphere. The imaginary component relates the radiative loss (*i.e.* leaking of EM energy) of the resonator in terms of the quality factor (Q_R) (Julien et al., 1986):

$$Q_R = \frac{f_0}{2 f''} \,. \tag{4}$$

The quality factor is the ratio of energy stored to the energy dissipated per oscillatory cycle, and indicates how well the material will resonate. In general, Q-factors less than 0.5 will not support resonances and Q-factors greater than 0.5 will. While equation [4] yields one component of the Qfactor, dielectrics also lose energy by dislocation and conduction of charge carriers under the influence of applied fields, transforming EM energy into heat. This phenomenon can be accounted for by representing the relative electric permittivity of a lossy dielectric by a complex number:

$$\varepsilon_r^* = \varepsilon_r + j \, \varepsilon_r^{\prime\prime} \,. \tag{5}$$

Note that the complex permittivity of water varies considerably with frequency. Over the range from 1 GHz to 7 THz the complex permittivity of water at 25 °C can be modeled using the equation (Vij et al., 2004):

$$\varepsilon_r^* = \varepsilon_{\infty} + \left(\sum_{q=1}^3 \frac{\varepsilon_q}{\left(1 + (j \ \omega \ \tau_q)^{\delta}\right)^{\beta}}\right) + \frac{\varepsilon_4}{1 + j \ \omega \ \tau_4 - \frac{\omega^2}{\omega_4^2}}, \tag{6}$$

with $\varepsilon_{\infty} = 2.2$, $\varepsilon_1 = 71.49$, $\varepsilon_2 = 2.80$, $\varepsilon_3 = 1.6$, $\varepsilon_4 = 0.92$, $\omega_4 = 5.26$ THz, $\tau_1 = 8.31$ ps, $\tau_2 = 1.0$ ps, $\tau_3 = 0.10$ ps, $\tau_4 = 0.025$ ps, $\beta_1 = 1.0$, $\beta_2 = 0.77$, $\beta_3 = 0.8$, $\delta_1 = 1.0$, $\delta_2 = 1.0$, $\delta_3 = 0.9$. The real component of equation [6] was used in the characteristic equations [1] and [2] to solve for resonant frequencies at specific permittivities of water-based dielectric sphere resonators in the range from 1 GHz to 7 THz.

The dielectric loss tangent, $\tan \delta$, reflects the dielectric loss component of the quality factor (Q_D):

$$\tan \delta = \frac{\varepsilon_r''}{\varepsilon_r} = \frac{1}{Q_D}.$$
[7]

The total quality factor (Q_T) of the non-ideal dielectric resonator can be written in terms of the radiative and dielectric loss Q-factors (Pozar, 1998; Sheen, 2008):

$$Q_T = \left(\frac{1}{Q_R} + \frac{1}{Q_D}\right)^{-1}.$$
[8]

Variations in the different parameters, n, m and L, yield distinct resonant mode patterns. For the dielectric resonator, n is related to the number of field maxima between the poles of the sphere. The number of field maxima in the *x*-*y* plane (the azimuthal or ϕ -maxima) are given directly by the m parameter.



Figure 4. Cross-sectional characteristics of EM resonant modes forming on a dielectric sphere. All panels show TM modes with electric component displayed as a streamlined vector field and magnetic fields superimposed as a grayscale gradient (field direction of magnetic fields is out of the page). The numbers in the lower right corner of each panel indicate the parameters n, m, and L, respectively of the mode index as defined on page 10.

The roots of the characteristic equations [1] and [2] are indexed by the integer *L*. A formal way to index the modes is to label them according to their TE or TM character and by the three mathematical indices yielding the designations: $\text{TE}_{n,m,l}$ and $\text{TM}_{n,m,l}$. The combined electric and magnetic field patterns of a sphere for TM modes with n = 1 to 3 and L = 1 to 3 are shown along the mid-plane cross-section in Figure 4.

3. Electromagnetic resonance and plant tissue patterns

As can be quickly appreciated, the seemingly mysterious relationships between features of 8- and 15- point star polygons and abutilon ovary and male squash flower bud cross-sections are shared between the $TM_{4,4,2}$ and $TM_{15,15,2}$ resonant modes of the sphere (Figure 1). In these plant structures, note that ova formation in abutilon and pollen-tube formation in male squash flower buds both coincide with the locations of highest magnetic field strength in the $TM_{4,4,2}$ and $TM_{15,15,2}$ modes, respectively (Figure 1).

The tissue pattern in primordial squash ovaries from the female flower also show remarkable parallels with the TM_{333} mode of a spherical dielectric resonator (Figure 5). Similar to the abutilon ovary and squash male flower bud, cells in the female squash ovary in regions that correlate to highest electric field strength have changed into placental tissue cells, while the six places of high magnetic field strength are also the six places where ova form in the squash ovary (Figure 5). Also, the exterior tissue (endocarp) of the squash coincides with a region of both low electric and magnetic fields that is in correct proportion with the EM field patterns (Figure 5). In three dimensions, the electric field spirals form six consistent tubes all the way through the long axis of the egg-shaped model, which is the same pattern seen in the squash ovary. The remarkable parallels between the squash ovary and $TM_{3,3,3}$ mode also suggest an important involvement of the electric field direction as the reduced symmetry of the pattern correlates to the direction of flow paths that could be induced by the electric field. Regions where electric field lines intersect are correlated with the formation of the three main axes of the squash ovary cross-section pattern (Figure 5). Conversely, where electric fields diverge, the placental lines are separated by a gap and no main axis forms (Figure 5). Features of plant primordia at the time of first symmetry breaking allow resonant frequencies and loss factors to be estimated. The emergence of patterns in various flower buds has been observed for primordia sizes ranging from radii of 150 to 500 µm. At early stages of development, the water content of primordia is on the order of 95% by mass. Furthermore, the microwave-terahertz dielectric permittivity of high water content biological tissue has been shown to be well correlated to that of pure water (Nelson et al., 2005; Sipahioglu et al., 2003).



Figure 5. The squash ovary primordium (female flower) shows remarkable parallels to the $TM_{3,3,3}$ mode of a dielectric sphere and indicates an important role for electric field direction. Panel A shows the cross section through a squash ovary primordium with primordial ovum marked by '*', placental tissue line marked with 'p', interior tissue (endocarp) marked with 'm', and exterior tissue (exocarp) marked with 'x'. Panel B shows a cross-section through the $TM_{3,3,3}$ mode with electric component shown as a vector field and magnetic field as a superimposed gradient. Panel C shows streamlines of the electric field. Panel D compiles the rich information of the $TM_{3,3,3}$ mode showing convergent electric field streamlines as 'p', regions of highest magnetic field as '*', and interior and radial node regions as 'x' and 'm', respectively.

Mode	n	L	f _o (THz)	$\boldsymbol{\mathcal{E}_{\mathrm{r}}}$	Q_R	Q_D	Q_T
TM	3	3	1.57	4.3	6.4	1.95	1.50
TM	4	2	1.44	4.4	2.5	1.95	1.10
TM	15	2	4.13	3.4	107.6	1.60	1.58

Table 1. Summary of resonant frequencies, Q-values, and water permittivities for EM modes forming on a spherical plant primordium approximated as a watery dielectric sphere with a radius of 150 μ m. The parameters '*n*' and '*L*' represent components of the mode index (see page 10), f_0 is the resonant frequency, and ε_r represents the relative dielectric strength of the resonator. The parameters Q_R , Q_D , and Q_T represent the quality factor for radiative loss, dielectric loss and total loss, respectively (defined on pages 9 and 10).

Taking these factors into account and making use of equations [1] to [8], plant primordia are indicated to be far-IR resonators with the widest estimate of their operating frequencies marking a range between 0.25 and 5 THz. While modes typically have low total Q-factors in the range of 1 to 2, Q-factors above 0.5 are able to physically resonate. The mode Q-factors are dominated by the dielectric loss of water and are relatively independent of radiation losses. The resonant frequencies and Q-factors for specific resonant modes and sizes of a spherical developing plant primordium (approximated as a water-based dielectric sphere) are summarized in Table 1.

4. Discussion

In developing plant primordia, cell orientation is correlated with the direction of the electric field of EM resonant modes. Cell orientation with the electric field is assumed as an electrically polarizable entity such as a cell will align with the direction of a static or dynamic electric field. Various kinds of tissue differentiation are correlated to respective areas of high electric or magnetic fields. Generally, reproductive tissue (ova or anther) formation is coincident with sites of highest magnetic field, whereas septa/placental lines form in regions of highest electric field. The above fieldtissue correlations assume the modes are TM in character, however, if modes are TE, the relations are opposite with cells aligning in magnetic fields and reproductive tissue forming at sites of highest electric field. Overall, the structural evidence and physical uniqueness of EM mode patterns indicates developing plant organs can support EM resonances, whereby the electric and magnetic field components guide symmetry-breaking and therefore resemble the first pattern to emerge in primordia. Rich in positional information, the EM resonant mode represents a possible physical manifestation of the morphogenetic field.

It is well established that electric and magnetic fields can influence cellular behaviour in development and regeneration. The direct effects of electric and magnetic fields on cell behaviour, including electric field induced cell orientation and directions of preferred growth, have been experimentally confirmed in plants and animals (Hinkle et al., 1981; Hush et al., 1991; Levin, 2009; Malho et al., 1992; Zhao et al., 1999). Weak electric fields and intercellular ion flows have also been observed to influence embryonic and stem cell differentiation states in plants and animals (Grattarola et al., 1985; Harrington et al., 1973; Levin, 2003, 2009). Biological voltage gradients and ion flow have also been associated with control of cell proliferation and controlled apoptosis via gated ion channels (Levin, 2009).



Figure 6. Comparison of cell life cycle characteristics and dielectrophoretic force fields of the first and second modes of spherical resonators. Panel A and C show the dielectrophoretic force field of the fundamental mode of a resonator in interphase and metaphase, respectively, with force direction shown as arrows and magnitude as a spectral colourmap with red indicating highest force strength and blue the lowest. Panel B and C show the configuration of a cell's cytoskeleton (red) and nuclear material (blue) during interphase and metaphase, respectively.

Dynamic electromagnetic fields may be capable of altering genetic expression of cells via gated calcium ion channels (Pall, 2013). Weak magnetic fields have been observed to induce changes in ion flux through cell membranes and altered cell growth characteristics (Blackman et al., 1994; Lednev, 1991). Furthermore, dielectrophoresis describes force exerted on a dielectric particle when it is in the vicinity of a non-uniform static or time-varying electric field (Pohl, 1978). Dielectrophoresis may alter the three-dimensional distribution of morphogenetic substances in relation to a static or dynamic electric field, leading to changes in cell differentiation state and other features such as proliferation rates.

A confirmation of the EM excitation source for the developing plant remains beyond the scope of this work. However, it is possible to speculate on various possibilities. The prospect of endogenous EM production by biological systems, in a range from 10^{11} to 10^{12} Hz (the same range expected for mode frequencies in developing plants, Table 1) was first developed by physicist Herbert Fröhlich in 1968 (Fröhlich, 1968a, b, 1975). More recently, quantum field theory (QFT) has been used to further elucidate the possibility of endogenous radiation in biological systems (Del Giudice et al., 1985; Del Giudice et al., 2010; Preparata, 1995). Recent explorations using normal mode analysis of simulated microtubule structures have determined microtubules to be a likely source of endogenous EM up to several hundred gigahertz (Cifra et al., 2011b; Deriu et al., 2010). Microtubule vibrations may be stimulated by hydrolysis of GTP, motor protein-microtubule interactions, and energy efflux from mitochondria (Cifra et al., 2011b). A number of experiments have directly detected non-thermal radiation in radio (Cifra et al., 2008; Pokorny et al., 2001), microwave (Gebbie et al., 1997), and visible-UV (Popp et al., 2002; Yan et al., 2005) frequencies from various organisms.

The mainstream view of morphogenesis was established in 1952 by Alan Turing, who outlined how cellular collectives could generate bio-similar patterns of spots, stripes, and spirals using interrelated reaction-diffusion of chemicals in the cellular population (Turing, 1952). There are a number of issues that make chemically based reaction-diffusion mechanisms an unlikely explanation for the patterns in developing plants described herein. The main reason for this is because the phenomenon of chemical diffusion has fundamentally different physical properties, and therefore fundamentally different mathematical relations and stable patterns, than do electromagnetic (vector) resonances. Diffusion and reaction-diffusion are scalar processes exhibiting first-order changes in time, whereas electromagnetic resonances are *vector* properties demonstrating second-order changes in time. To date no reaction-diffusion mechanism has been identified that is capable of generating the three dimensional vector resonance patterns outlined in this paper. Furthermore, in a reaction-diffusion mechanism, the positional information would ultimately be generated by a spatial pattern of at least two chemical substances that change cell state in different ways and were patterned according to the two vector harmonic components representing the electric and magnetic fields of an EM resonance. To even form similar vector fields, there would need to be some presently unknown mechanism that acts as a vector property and can demonstrate vector curl. Finally, in plant patterns there are occasions when a similar pattern occurs but with a higher symmetry. On account of this rather common observation, the reaction-diffusion mechanism would need to have changes to the value of some parameters, such as a slower movement or reaction rate of a chemical, creating the appearance of the next harmonic in a resonance series. In other words, the reaction-diffusion mechanism would need to mimic a resonance mechanism, whereby a higher resonance frequency can generate a similar pattern but with higher symmetry. It is not clear how this would happen for a reaction-diffusion network.

The concept of a biological EM resonator can be extended to diverse size scales on the order of individual cells and whole planets. Popp and Cifra have independently explored the concept of single cells as EM resonators (Cifra, 2012; Popp et al., 2005). As suggested in Figure 6, the presence of an electromagnetic mode within the cell can account for patterns in cytoskeletal filaments and genetic material (nucleus, chromosomes) during various stages of the cell life-cycle (Cifra, 2012; Popp et al., 2005). On very large scales, it has been experimentally established that even our planet Earth can act as a cavity resonator (Balser et al., 1960). The Earth is an approximately spherical entity surrounded by an electrically conductive spherical ionosphere consisting of electrons and charged atoms and molecules, which behaves as a conductor surrounded by the vacuum of outer space. The spherical ionosphere acts like an EM resonant cavity surrounding the Earth. The Schumann resonances of Earth are experimentally verified low frequency resonances (beginning at \sim 7.8 Hz) excited by lightning discharges in the cavity formed by the Earth's surface and the ionosphere (Balser et al., 1960).

Experiments are required to determine if physiologically relevant endogenous electromagnetic resonances exist in plants and other organisms. Two core experimental strategies would involve i) attempts to directly detect EM produced by a developing plant in a range from 0.5 to 2 THz, beyond the scale expected from thermal background radiation, and ii) growing plants in the presence of an EM source emitting in the range of 0.5 to 3 THz in an attempt to alter or disrupt growth patterns in a manner consistent with the hypothesis of EM resonance and avoiding significant heating of the tissue in the process.

5. Conclusions

The spontaneous self-assembly of a living being into intricate patterns of functional form largely remains a mystery. While most current research seeks explanations in terms of genetic and molecular activities, a viable alternative view already exists. For living organisms have the capacity to behave as EM resonators, trapping within themselves EM fields in the form of spatial energy patterns. These patterned energy fields are called resonant modes and are a rich source of long-range information capable of guiding biological pattern formation from an early developmental stage. Focusing on plants, the so-called living crystals of the world, a comparison of tissue and EM resonant mode patterns reveals striking similarities. The concept of EM energy resonators is not limited to plants, but may extend to single cells, water droplets, other organisms, and whole planets.

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