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A SYNCYTIUM MODEL FOR THE INTERPRETATION OF THE PHENOMENON OF ANOMALOUS LIGHT FLASHES OCCURING IN THE HUMAN EYE DURING SPACE MISSIONS

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Abstract

A syncytium model to study some electrical properties of the eye is proposed in the attempt to explain the phenomenon of anomalous Light Flashes (LF) perceived by astronauts in orbit. Recent experiments, placed on board the Russian Space Station MIR have investigated the possible causes and have attempted to explain the physical processes and their relation with Cosmic rays. We discuss a mathematical model of some electrical properties of the eye (i.e. the crystalline lens modelled as a spherical syncytium), that is a boundary value problem for a system of two coupled elliptic partial di erential equations in two unknowns. We usea numerical method to compute an approximate solution of this mathematical model and we show some numerical results that provide a possible (qualitative) explanation of the observed LF phenomenon.

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1 Introduction

We consider the study of some electrical properties of the eye (or more specifically of the crystalline lens) as an attempt to explain a phenomenon observed by astronauts during space missions, since the Apollo flights, consisting in the so-called anomalous Light Flashes (LF), [1], [2], [3]. Although the real nature of the Light Flashes' causes is still not clear, the most probable mechanism involves the passage of a cosmic charged particle through the astronaut visual system. Therefore, it is extremely important to simultaneously determine time, nature, energy and trajectory of the particle passing through the cosmonaut's eyes, as well as the astronaut's LF observation time. This kind of measurements was not optimally fulfilled by all the previous experiments in space.

The explanation of this phenomenon is considered an important issue also in view of the planned future missions, which require a long human permanence in space environment. A recent experiment, called SILEYE, has been performed on board the Russian Space Station MIR with the aim of studying the causes and processes related to the LF's and their relationship with Cosmic Rays. Two versions of the SILEYE apparatus, mainly consisting of computer-driven silicon detector telescopes have been built and placed on MIR and operated by different astronauts during dedicated measurement sessions.

The first version of the experiment, SILEYE-1, (see references in next section) was launched in 1995 and provided particles track and LF information. The data gathered indicate that heavy ion interactions with the eye could be the main cause of LF. To improve the quality and statistics of the measurements, a second version of the experimental apparatus, SILEYE-2, was placed on MIR in 1997 and started working in August 1998. This instrument provided energetic information, which allows nuclear identification that is ion classification in selected energy ranges.

In this paper we analyze a mathematical model able to describe some electrical properties of the eye. It is based on a mathematical model of syncytial tissues, where many cells are electrically coupled one to another and to an extracellular medium. We note that multicellular syncytia are used to model important tissues such as for example: eye lens [4], [5] and cardiac tissues [6], [7], [8]. We use the model of syncytial tissues presented in [5] to suggest a mathematical explanation of the LF phenomena. We note that the eye lens is only a part of the eye and that in the scientific literature more sophisticated models of the eye exist, see for example [9]. Finally we have pointed out the sensitivity of the electrical behaviour of the proposed syncytium model with respect to the direction of the particle passing through the astronaut visual system.

We introduce some notation. Let $\mathbf{R}$ be the set of real numbers, n be a positive integer and $\mathbf{R^n}$ be the n-dimensional real Euclidean space. Let $\mathbf{C}$ be the set of complex numbers. Let $z \in \mathbf{C}$, we denote with $Re(z)$ the real part of z and with $Im(z)$ the imaginary part of z. Let $\underline{x} \in \mathbf{R^n}$, we denote with $\|\underline{x}\|$ the Euclidean norm of $\underline{x}$. We use the usual notation for the physical units, that is: mm denotes millimeter, Kg denotes kilogram, MeV mega-electronVolt, A denotes Ampère, μV denotes micro-Volt, Ω denotes Ohm, Hz denotes Hertz, F denotes farad.

In section 2 we give a description of the SILEYE experiment. In section 3 we describe a mathematical model of some electrical properties of the eye and a numerical method to approximate the solution of the model presented. In section 3 we show some numerical results obtained from the implementation of the numerical method that could provide a qualitative explanation of the LF phenomenon. In section 4 some simple conclusions are drawn.

2 The SILEYE experiment

The objective of the SILEYE experiment is the study of some biophysical reactions of the human visual system subject to radiation in a space environment.

This experiment is part of a wider international project, called RIM (Russian-Italian Missions), involving some Institutions of Russia, Italy, Sweden, Germany and USA. The Russian Space Corporation has granted dedicated session time on the MIR Space Station to perform the SILEYE experiment. We remind that the MIR Space Station orbited at an altitude of 400 kilometers with an inclination of 51.5 degrees.

The first version of the detector used in the SILEYE experiment, i.e. the SILEYE-1 detector [10], was placed on the Station MIR in October 1995. During two years of operation more than 50 LF's in 25 measurement sessions with 6 different astronauts were recorded. We note that each session takes 90minutes of time to complete, corresponding to the average duration of one orbit around the Earth. In the experiment a dark adaptation period of 15minutes precedes each session. Particles and LF frequencies have been derived averaging the results obtained at equal latitude in the South Atlantic Anomaly (SAA) over all eleven orbits, for three astronauts involved. SAA data have been treated separately. The results are shown in Figure 1, where we can observe a proportionality relation between particle flux and LF observation (the probability of a chance correlation is $p < 0.02$) except in the SAA region. In this plot we can notice a rather small growth of LF registration rate in the SAA, while it is known that the proton flux in the SAA increases several order of magnitudes in comparison with the equator. So that a possible conclusion is that protons are not the main LF source in orbit, and it seems more probable that heavy ions are the initiators.

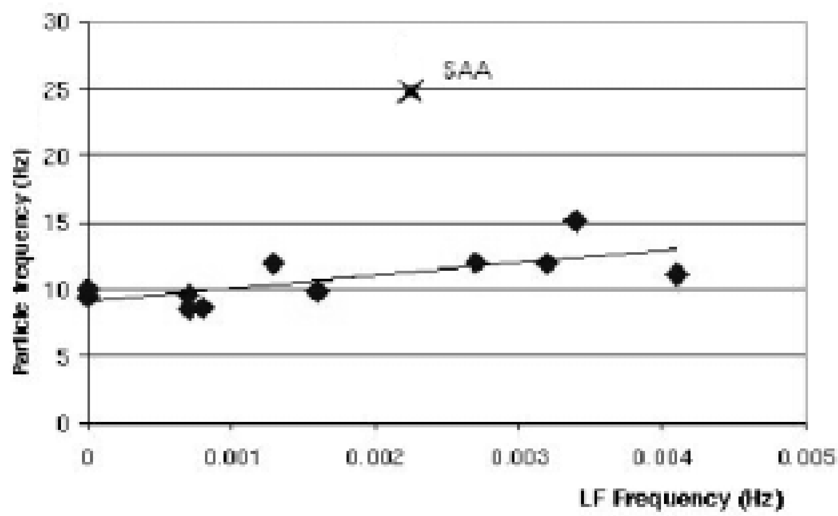

Figure 1: Particle flux as a function of observed Light Flashes. SAA observed flux is well above the fluxes relative to other latitudes.

The success of this mission has encouraged the upgrade of the SILEYE-1 apparatus to a new one, SILEYE-2. This detector has been developed in order to allow a more accurate analysis of the radiation flux (in particular for particles having a high atomic number Z) in the zone of the SAA and in the subpolar zones. The equipment of SILEYE-2 allows a simultaneous definition of the particle trajectory and its arrival time, an estimation of its energy and the recognition of its charge, [11], [12]: results of calibrations of this equipment carried out at accelerator test beams are described in [13]. The SILEYE-2 detector was placed on board the Space Station MIR in October 1997 and the acquisition sessions with different astronauts started in February 1998.

Let us briefly describe the SILEYE-2 detector. It makes use of a silicon strip detector for the correlation of an LF occurrence and the passage of a ionizing particle. In the experiment the astronaut wears a helmet having on its side the detector box; the acquisition of the LF is controlled by a personal computer and it is made using a joystick connected to the same detector box. The times of LF seen by the astronaut are stored in a separate file for the correlation study. The helmet has a mask to shield the astronaut's eyes from light; and the system can perform various checks, such as for example the correct position of the detector, the dark adaptation of the observer and his reaction time. The main part of the detector is given by six silicon views, each view is a square ($60 \times 60\text{mm}^2$) wafer of silicon, divided in 16 strips, each 3.6mm wide. When a particle hits the strips the detector is able to determine the direction of the particle motion and its position in space. This system measures the particle trajectory with an angular accuracy of 3 degrees. Furthermore two passive absorbers are placed between the position-sensitive detectors. We note that the thickness of the absorbers determines the energy range for particles that can be detected. The absorbers (1mm iron each) in the SILEYE-2 detector allow to measure particle energy losses from 0.25MeV to more than 250MeV, and the minimum detection threshold can be changed and set from 0.25MeV up to 6MeV; this feature has been implemented to avoid saturation areas of the orbit where the particles rate is high such as for example in the SAA and in the subpolar areas. Indeed, the hardware threshold allows to exclude nuclei with $Z \leq 3$ from being monitored; they make more than 99% of all the particles crossing the detector in the SAA region. The system also performs controls on the device performances. All the physical parameters of the detector are software controlled.

The analysis of the data measured with the SILEYE-2 detector is in progress. A new project, called ALTEA [14] is under development. The purpose of the project ALTEA is the installation on board of the International Space Station of a larger telescope with the simultaneous use of electroencephalography and visual stimulation. This allows to directly correlate LF and particle crossing the head with brain activity.

3 The syncytium model and the finite difference approach

We study a simple mathematical model to describe some electrical properties of the eye. More precisely this mathematical model is found to be accurate to describe the electrical properties of the eye lens, see [5] for details, and a more complex model must be considered to take in account other organs of the eye, such as for example: retina, cornea and so on. However we limit our attention to this simple model since we believe that the electrical response of the eye lens and the electrical response of the other organs of the eye are correlated. The model considered is the basic model of syncytial tissues, that is tissues where roughly speaking we have many cells and the space outside the cells is filled with an extracellular medium. The space inside the cells is called intracellular compartment, the space in the tissue outside the cells is called extracellular compartment. The electrical properties of the syncytial tissues are determined by the fact that the intracellular medium and the extracellular medium have different electrical characteristics; moreover the cells are electrically coupled one to another by the extracellular medium.

Let us consider the domain $D = \{\underline{x} = (x_1, x_2, x_3)^t \in \mathbf{R^3}\colon \ \|\underline{x}\| \le a,\, a > 0\}$ filled by a syncytial tissue. Let ∂D be the boundary of D. Let us apply a time harmonic electric current on a point $\underline{x}_I \in \partial D$ having modulus proportional to I, direction $\underline{v}_I$ and frequency f. Let $R_i > 0$ be the resistivity of the intracellular medium, $R_e > 0$ be the resistivity of the extracellular medium, $Y_m \in \mathbf{C}$ be the specific admittance of the cell membrane, that is the membrane that separates the intracellular medium from the extracellular medium. We note that Y_m depends on f, but we suppose R_i, R_e, Y_m to be independent of the space variables $\underline{x} \in D$. Let $\alpha_m \in \mathbf{R}$ be the fraction of the volume occupied by the cells membrane per unit volume of tissue. As a consequence of the application of the electric current described above to the syncytium we have the generation of two different electric potentials: one in the intracellular compartment, the other in the extracellular compartment. These potentials can be seen as two complex functions having disjoint supports, however these functions can be extended over D obtaining two smooth functions. Let $U^{(i)}(\underline{x})$, $U^{(e)}(\underline{x})$, $\underline{x} \in D$ be the extension of the electric potential in the intracellular compartment and of the electric potential in the extracellular compartment respectively, then we have [5]:

$$\Delta U^{(e)}(\underline{x}) + R_e \alpha_m Y_m (U^{(i)}(\underline{x}) - U^{(e)}(\underline{x})) = 0, \quad \underline{x} \in D, \tag{1}$$

$$\Delta U^{(i)}(\underline{x}) + R_i \alpha_m Y_m (U^{(e)}(\underline{x}) - U^{(i)}(\underline{x})) = -I R_i \frac{\partial \delta}{\partial \underline{v}_I}(\underline{x} - \underline{x}_I), \quad \underline{x} \in D, \tag{2}$$

$$U^{(e)}(\underline{x}) = 0, \quad \underline{x} \in \partial D, \tag{3}$$

$$\frac{1}{R_i}\frac{\partial U^{(i)}}{\partial \hat{\underline{n}}}(\underline{x}) + Y_s U^{(i)}(\underline{x}) = 0, \quad \underline{x} \in \partial D, \tag{4}$$

where Δ denotes the Laplace operator, δ denotes the Dirac delta and $\hat{\underline{n}}(\underline{x})$ is the outward unit normal vector on ∂D in $\underline{x} \in \partial D$. Note that the boundary condition in eq.3 states that the electric current can flow from the extracellular medium through the outer membrane located on ∂D with impedance equal to zero, eq.4 states that the electric current can flow from the intracellular medium through the outer membrane located on ∂D with admittance $Y_s \in \mathbf{C}$, this admittance depends on f, but it is supposed to be constant with respect to the space variables $\underline{x} \in \partial D$. The term on the right hand side of eq.2 represents the application of the current on the tissue, in particular regarding the SILEYE experiment this term represents the charged particles passing through the astronaut visual system and I is proportional to the charge of the particles, $\underline{v}_I$ represents the direction of these particles. This mathematical model is similar to the one derived in [5], so that we omit its derivation and we suggest to look at [5] for a detailed explanation of the elementary physics at the basis of the model.

The boundary value problem eq.1, eq.2, eq.3, eq.4 has a unique solution pair $U^{(e)}(\underline{x})$, $U^{(i)}(\underline{x})$, $\underline{x} \in D$. However the solution can not be computed explicitely and an approximation method must be used to evaluate $U^{(e)}$, $U^{(i)}$ in D. In particular for the computation of an approximation of $U^{(e)}$, $U^{(i)}$ in D we have rewritten problem eq.1, eq.2, eq.3, eq.4 in spherical coordinates and the solution of the problem obtained is approximated using the finite difference method. Let $\rho \in [0, a]$, $\theta \in [0, \pi]$, $\phi \in [-\pi, \pi)$ be the spherical coordinates. Let N_ρ, N_θ, $N_\phi > 1$, be the number of points of the discretization grid used in the finite difference method along the coordinate ρ, θ, ϕ respectively, then from problem eq.1, eq.2, eq.3, eq.4 we obtain a linear system of $(2N_\rho - 1)(N_\theta - 1)N_\phi$ equations in $(2N_\rho - 1)(N_\theta - 1)N_\phi$ unknowns.

In the numerical experience described here we have computed an approximate solution of this linear system using the biconjugate gradient method, see [16] page 550 for a description of the method. The components of the solution vector of this linear system are an approximation of the functions $U^{(e)}$, $U^{(i)}$ on the previously described grid of points, that is something related to the electrical response of the eye to an external excitation given by an electrical current.

In Figure 2 we show some numerical results. These results are obtained with the following values of the parameters appearing in eq.1, eq.2, eq.3, eq.4: $a = 1.6\text{mm}$, $R_e = 6.25 \cdot 10^3\Omega\cdot\text{mm}$, $R_i = 4.85 \cdot 10^5\Omega\cdot\text{mm}$, $Y_m = G_m + i2\pi f C_m$, where $G_m = 4.38 \cdot 10^{-9}\Omega^{-1}\cdot\text{mm}^{-2}$, $C_m = 0.79 \cdot 10^{-8}\text{F}\cdot\text{mm}^{-2}$, $Y_s = G_s + i2\pi f C_s$, where $G_s = 2.14 \cdot 10^{-6}\Omega^{-1}\cdot\text{mm}^{-2}$, $C_m = 9.75 \cdot 10^{-8}\text{F}\cdot\text{mm}^{-2}$, $\alpha_m = 6 \cdot 10^2\text{mm}^{-1}$. These values are taken from [5] and they are relative to the frog eye: this is a starting point and the study of the parameters relative to the human eye is presently in progress. Moreover we have chosen $\underline{x}_I = (0\text{mm}, 0\text{mm}, 1.6\text{mm})^t$, $I = 10^{-9}\text{A}\cdot\text{mm}$, $f = 3\text{Hz}$, $N_\rho = N_\theta = N_\phi = 30$.

In Figures 2 we have pointed out the electrical behaviour of the syncytium model with respect to the direction of the current v_I. In particular we note that the results in the first two rows of Figure 2, are quite different from the results in the last row of Figure 2. This is a surprising result because in Figure 2 the direction v_I in the second row is closer to the direction v_I in the third row than to the direction v_I in the first row. In fact there exists a small set $\mathcal{V}_I$ of directions v_I close to $(0, 0, -1)^t$ such that the electrical behaviour of the model is quite different with respect to the electrical behaviour of the model for $v_I \notin \mathcal{V}_I$. This abrupt change of

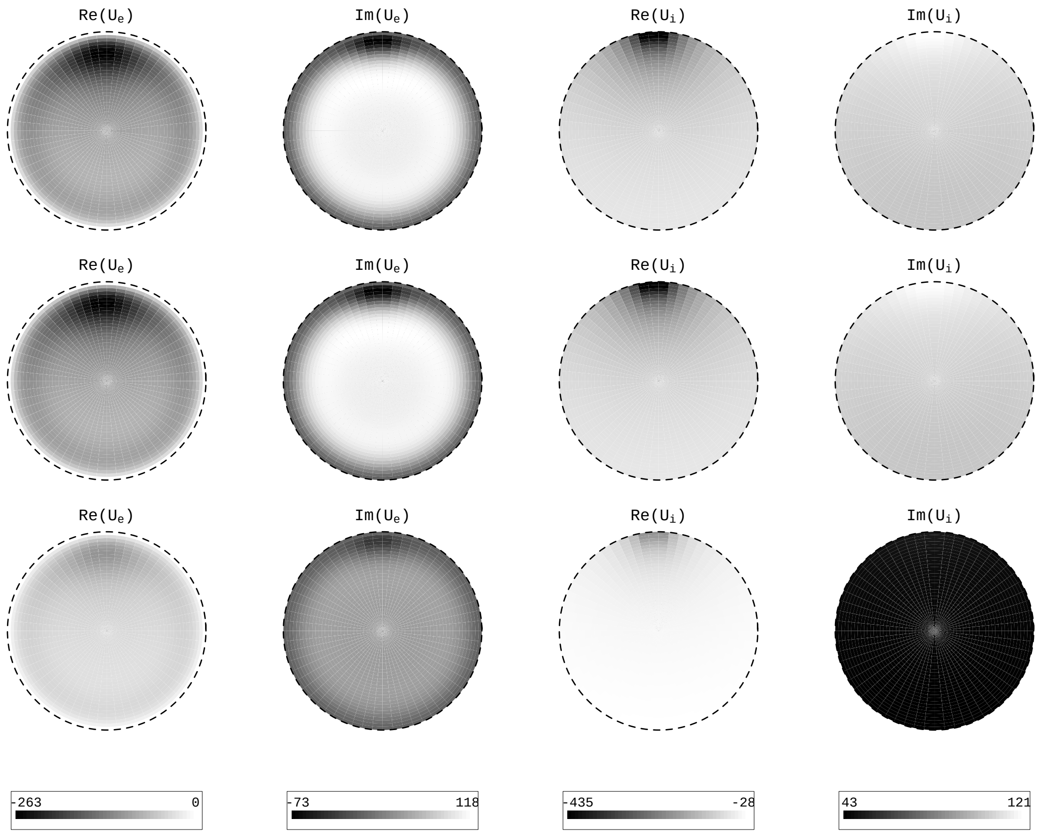

Figure 2: The electric potentials $U^{(i)}$, $U^{(e)}$, in μV, in the plane $x_1 = 0$. The direction of the current is $v_I = (1,0,0)^t$ in the first row, $v_I = (\cos(\frac{5}{6}\pi), 0, \sin(\frac{5}{6}\pi))^t$ in the second row and $v_I = (0,0,-1)^t$ in the third row. Note that in each column the same linear grey-scale is used, but for figures on different columns different scales are used.

behaviour can be put in relation with anomalous phenomena such as the observed LF phenomenon. We believe that the results shown in this section can be a first step in the interpretation of the LF, in fact we can suppose that the LF phenomenon occurs when cosmic charged particles pass through the astronaut visual system with a direction belonging to the corresponding set $\mathcal{V}_I$.

From numerical experience not reported in this paper we can conclude that for frequencies f ranging from 0Hz to 10Hz the electrical behaviour of the syncytium model with respect to the direction of the current $\underline{v}_I$ is similar to the one shown in Figure 2 obtained for $f = 3$Hz.

4 Conclusions

The modellization of the human visual system as a spherical syncytium is a very crude one. However the work presented here seems to suggest that it may be useful in studying qualitatively some unexpected phenomena such as the LF. This observation may deserve further investigation.

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