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THE USE OF A SYNCYTIUM MODEL OF THE CRYSTALLINE LENS OF THE HUMAN EYE TO STUDY THE LIGHT FLASHES SEEN BY ASTRONAUTS

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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. The crystalline lensis modelled as an ellipsoidal syncytium having a variable relative dielectric constant. The mathematical model proposed is given by a boundary value problem for a system of two coupled elliptic partial differential equations in two unknowns. We use a 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. In particular, we calculate the energy lost in the syncytium by a cosmic charged particle that goes through the syncytium and compare the results with those obtained using the Geant 3.21 simulation program. We study the interaction antimatter-syncytium. We use the Creme96 computer program to evaluate the cosmic ray fluxes encountered by the International Space Station.

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1 INTRODUCTION

In the next few years the average time spent on the International Space Station by human beings will substantially increase. For this reason the safety of human life in the space environment is crucial. There is a need to study the effects of cosmic rays particles on the human body and particularly on the functionality of the Central Nervous System (CNS).

The visual system has been chosen to "probe" the CNS because it is particularly sensitive to space environment. In missions Apollo 11 through 17, Skylab 4, Apollo-Soyuz, Mir, Iss, the astronauts, after some minutes of dark adaptation, observed brief flashes of white light (LF phenomenon) with the shape of thin or thick streaks, single or multiple dots, clouds, etc. (*1-3*).

The specific mechanism of the interaction between ionizing particles and the visual system remains uncertain. In order to evaluate the LF phenomenon it is necessary the simultaneous determination of time, nature, energy and trajectory of the particle passing through the cosmonaut eyes, as well as the cosmonaut LF perception time. Some previous experiments are described in (*4-6*).

A future experiment, named ALTEA (*7-10*), will be activated on the International Space Station in 2005. The ALTEA project is aimed at the study of the transient and long term effects of cosmic particles on the astronaut cerebral functions. It has been funded by the Italian Space Agency (ASI) and by the italian National Institute for Nuclear Physics (INFN) and "Highly recommended" by the European Space Agency (ESA). The experiment is an international and multidisciplinary collaboration.

The basic instrumentation is composed by a series of active particles telescopes, an ElectroEncephaloGrapher (EEG) and a visual stimulator, arranged in a helmet shaped device. This instrumentation is able to measure simultaneously the dynamics of the functional status of the visual system, the cortical electrophysiological activity, and the passage through the brain of those particles whose energy is included in a predetermined window. The three basic instruments can be used separately or in any combination, permitting several different experiments.

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, that is tissues where many cells are electrically coupled one to the other and to an extracellular medium. We note that multicellular syncytia are used to model important tissues such as, for example, the eye lens (*11-14*). We use the model of syncytial tissues presented in (*12*), (*14*) to suggest a mathematical explanation of the LF phenomenon. We note that the eye lens is only apart of the eye and that in the scientific literature more sophisticated models of the eye exist, see for example (*15*). Finally we have pointed out the sensitivity of the electrical behaviour of the proposed syncytium model respect to the direction of the particle passing through the astronaut visual system. In particular, we have calculated the energy lost in the syncytium by a cosmic charged particle going through the syncytium as a function of the direction of motion of the particle and we have compared the results obtained with the syncytium model with those obtained using the Geant 3.21 simulation program.

In section 2 we describe a mathematical model of a syncitial tissue that describes some electrical properties of the crystalline lens and a numerical method to approximate the solution of the model presented. In section 3 we describe the relative dielectric constant of the crystalline lens. In section 4 we show some numerical results obtained from the numerical solution of the model that could provide a qualitative explanation of the LF phenomenon. In section 5 we describe the interaction between antimatter and syncytium. In section 6 we show the cosmic ray fluxes within the Iss obtained using the Creme96 program. In section 7 we describe the Geant simulation of the phenomenon under scrutiny and compare the results obtained with Geant 3.21 with those obtained using the syncytium model. In section 8 we calculate the adsorbed and equivalent energy doses in the crystalline lens due to cosmic radiation. In section 9 some simple conclusions are drawn.

2 THE SYNCYTIUM MODEL AND THE FINITE DIFFERENCE APPROXIMATION

Let us introduce some notations. Let **R** be the set of real numbers, n be a positive integer and $\mathbf{R}^n$ be the n-dimensional real Euclidean space. Let $\underline{x} \in \mathbf{R}^n$ be a generic vector. Let **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 us consider an ellipsoid of rotation $D = \{ \underline{x} = (x, y, z)^t \in \mathbf{R}^3\text{: } \frac{x^2}{b^2} + \frac{y^2}{b^2} + \frac{z^2}{a^2} \leq 1 \}$ filled with a syncytial tissue. Let ∂D be the boundary of D. We choose the eccentricity of the ellipsoid $e = \sqrt{3}/2$. Then we have $b = a\sqrt{1-e^2}$. Let $\varepsilon_r(\underline{x})$ be the relative dielectric constant in $\underline{x} \in D$. Let us apply on a point $\underline{x}_I \in \partial D$ a time harmonic electric current having modulus proportional to I, direction $\underline{v}_I$ and frequency f. Let $R_i \geq 0$ be the resistivity of the intracellular medium, $R_e \geq 0$ be the resistivity of the extracellular medium, $Y_m = G_m + i\, 2\pi f C_m \in \mathbf{C}$ 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 cell 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 the same support D. Let $U^{(e)}(\underline{x})$, $U^{(i)}(\underline{x})$, $\underline{x} \in D$ be the electric potentials in the intracellular and extracellular compartments respectively, then we have (*12*):

$$\nabla \cdot [\varepsilon_r(\underline{x}) \nabla U^{(e)}(\underline{x})] + R_e \alpha_m Y_m [U^{(i)}(\underline{x}) - U^{(e)}(\underline{x})] = 0, \qquad \underline{x} \in D, \qquad (1)$$

$$\nabla \cdot [\varepsilon_r(\underline{x}) \nabla U^{(i)}(\underline{x})] + R_i \alpha_m Y_m [U^{(e)}(\underline{x}) - U^{(i)}(\underline{x})] = IR_i \frac{\partial \delta}{\partial \underline{v}_I}(\underline{x} - \underline{x}_I), \quad \underline{x} \in \tag{2}$$

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

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

where ∇ denotes the gradient operator, $\cdot$ denotes the scalar product, $\delta(\underline{x})$ denotes the Dirac delta and $\underline{\hat{n}}(\underline{x})$ is the outward unit normal vector to ∂D in $\underline{x} \in \partial D$. Note that the boundary condition given in eq.(3) states that the electric current can flow from the extracellular medium through the outer membrane located on ∂D with admittance 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 $Y_s = G_s + i\, 2i\pi f C_s \in \mathbf{C}$, 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, this term represents the effect of the charged particles passing through the astronauts visual system and the costant I that appears in (2) is proportional to the charge of the particles, $\underline{v}_I$ represents the direction of motion of these particles. This mathematical model is similar to the model derived in (*14*), so that we omit its derivation and we suggest to look at (*12*), (*14*), for a detailed explanation of the elementary physics that explains the model.

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

In the numerical experience described here we have computed the solution of this linear system using the biconjugate gradient method. See (*16*), for a description of the method. The components of the vector solution of this linear system are an approximation of the functions $U^{(e)}(\underline{x})$, $U^{(i)}(\underline{x})$, on the previously described grid points.

The values of the parameters appearing in eqs. (1), (2), (3), (4) are shown in Table 1.

These values are taken from (*12*) and they are relative to the frog eye. This is a starting point. The study of the problem with parameters relative to the human eye will probably give results qualitatively similar to those obtained with the data of Table 1. However the values of the human eye parameters are not available to us at the moment. Moreover we have chosen $\underline{x}_I = (0,\ 0,\ 1.6)^t$ mm and $N_\rho = N_\theta = N_\varphi = 30$. In the next sections the values of the electric current, frequency and relative dielectric constant used in our work are shown.

Table 1: Electrical and morphological parameters of the crystalline lens of the frog eye.

a	1.6 mm
R_i	$6.25 \cdot 10^3$ Ωmm
R_e	$4.85 \cdot 10^5$ Ωmm
G_m	$4.38 \cdot 10^{-9}\ \Omega^{-1}\text{mm}^{-2}$
C_m	$0.79 \cdot 10^{-8}\ \text{Fmm}^{-2}$
G_s	$2.14 \cdot 10^{-6}\ \Omega^{-1}\text{mm}^{-2}$
C_s	$9.75 \cdot 10^{-8}\ \text{Fmm}^{-2}$
α_m	$6 \cdot 10^2\ \text{mm}^{-1}$

3 THE RELATIVE DIELECTRIC COSTANT

In the macroscopic approach the biological tissues are generally considered as media that interact with the electric field induced by the external environment in two different ways: (1) generating electric currents of conduction that increase with the conductivity of tissues; (2) producing polarization effects that depend on the local dielectric constant. For this reason, from an electromagnetic point of view, biological tissues can be considered as dielectric media able to store and dissipate the energy of the electromagnetic fields involved. According to electromagnetic theory the physical quantity that characterizes these mechanisms is the complex relative dielectric constant. The real part of this constant takes into account the temporary storage of energy in the medium, while the imaginary part, depending on the conductivity σ, is responsible for the dissipation of the electromagnetic energy.

In this work we assume the crystalline lens of the frog eye to be a perfect dielectric ($\sigma = 0$), so that the relative dielectric costant $\varepsilon_r(\underline{x})$ has not imaginary part and is the square of the refraction index. The crystalline has the shape of a thin biconvex lens, is constituted by a very transparent and very elastic substance and has a concentric shell structure. Since the crystalline lens has variable density, $\varepsilon_r(\underline{x})$ is variable too.

Applying the finite difference method, we obtain a series of ellipsoidal shells with constant eccentricity equal to e. Let ρ to be the distance from the centre of the ellipsoid D (origin of the coordinates system) calculated along a semiaxis. A shell is determined by a value of the variable ρ. Then we suppose $\varepsilon_r(\underline{x})$ to be costant whithin every shell and given by:

$$\varepsilon_r(\underline{x}) = \varepsilon_c - \frac{\rho}{a}(\varepsilon_c - \varepsilon_s), \tag{5}$$

where $\varepsilon_c = 1.98$ and $\varepsilon_s = 1.89$ are the values in the centre ($\rho = 0$) and on the boundary of the ellipsoid (determined by the shell having $\rho = a$) respectively. The variation of $\varepsilon_r(\underline{x})$ between the centre and the boundary of the ellipsoid is 4.76\%. Figure 1 shows the relative dielectric costant vs. ρ.

Let l to be the index corresponding to a value of the ρ variable. Then l determines the values of the semiaxes of the l^{th}shell, a_l and b_l. In this way the distance between a point on shell and the origin is:

$$r_l = r_l(\theta) = \frac{a_l b_l \sqrt{1+\tan^2\vartheta}}{\sqrt{b_l^{\,2} + a_l^{\,2}\tan^2\vartheta}}, \qquad \theta \in [0, \pi]. \tag{6}$$

The variable that enters in the equations of the electric potentials is r_l. In the case of the spherical syncytium (*14*) we have $r_l = a_l$ when $\theta \in [0, \pi]$.

A theory describing the ocular lens as a radially nonuniform spherical syncytiym is proposed, solved and described as a simple equivalent circuit in *(13)*. In this paper the syncytium consists of a nucleus with one effective intracellular resistivity surrounded by a cortex with another resistivity.

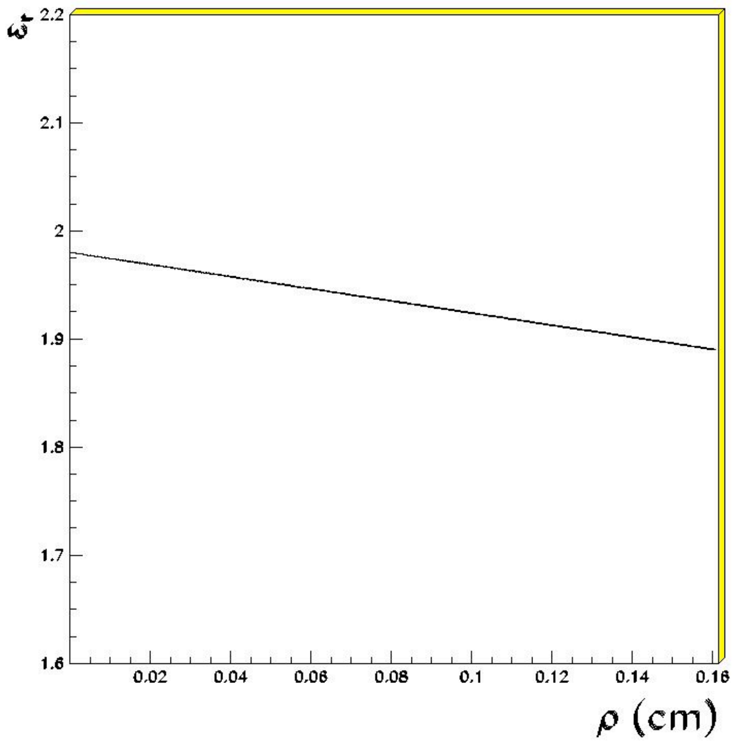

Figure 1: Relative dielectric costant of the eye vs. ρ.

4 THE ELECTRIC POTENTIAL AND THE ENERGY LOST IN THE SYNCYTIUM

We study the electric potentials of the syncytium with variable density as a function of the incidence direction of the cosmic charged particle. The incidence point $\underline{x}_I = (0, 0, z)^t \in \partial D$ is located on the North pole of the ellipsoidal syncytium.

Let α be the incidence angle on the crystalline lens measured respect to the positive z axis. When $\alpha = 90°$ the particle direction of motion is tangent to the ellipsoid and the interaction effect is minimum. When $\alpha = 180°$ the particle direction of motion is along the semiaxis of length a and the interaction effect is maximum.

Figure 2 shows the electrical behavior of the syncytium model respect to the choice of three different directions for the electric current when f = 3 Hz and I = 7 μA. This value of the electric current comes from the comparison with the Geant 3.21 simulation if we imagine that the incident cosmic particle is a proton (see section 7, Table 2). In Figure 2 we can see the shining effect when the electric potentials assume high values.

We have calculated the gradients of the electric potentials using the finite difference method in spherical coordinates. The energy lost by a cosmic charged particle in the intracellular and extracellular compartments of the syncytium is respectively:

$$\backslash\Delta E^{(i)} = \frac{\varepsilon_0}{2}\int_{V_e} \varepsilon_r\, |\nabla U^{(i)}|^2\, dV_e, \tag{7}$$

and

$$\Delta E^{(e)} = \frac{\varepsilon_0}{2}\int_{V_e} \varepsilon_r\, |\nabla U^{(e)}|^2 dV_e, \tag{8}$$

where $\varepsilon_0 = 8.854 \cdot 10^{-12}\ \frac{\mathrm{C}^2}{\mathrm{Nm}^2}$ (SI units) is the vacuum dielectric constant and V_e is the volume of the ellipsoid D.

The total energy lost in the syncytium is:

$$\Delta E^{(t)} = \Delta E^{(i)} + \Delta E^{(e)}. \tag{9}$$

Figure 3 shows the behavior of the energy lost in the intracellular compartment (I), in the extracellular compartment (E) and in the whole syncytium (T) vs. frequency of the electric current. We suppose $\varepsilon_r(\underline{x})$ to be constant in the range of frequencies considered. We have chosen $\alpha = 45°$ in order to have a mean trajectory of the cosmic particle in the syncytium.

In Figure 5 the most important result of this paper is shown, that is the energy lost in the syncytium vs. incidence angle α of the cosmic charged particle. These are symmetric curves respect to the line $\alpha = 90°$ because the system is symmetric with respect to the z axis. We can see that the energy lost reaches the maximum value when the incidence angle of the cosmic charged particles is 180°. The minimum value is reached for $\alpha = 90°$. Based on this fact we can suppose that the LF phenomenon occurs when cosmic charged particles pass through the astronaut visual system with a incidence angle of approximately 180°.

Figure 4 shows the behavior of the energy lost vs. intensity of the electric current when α = 45°.

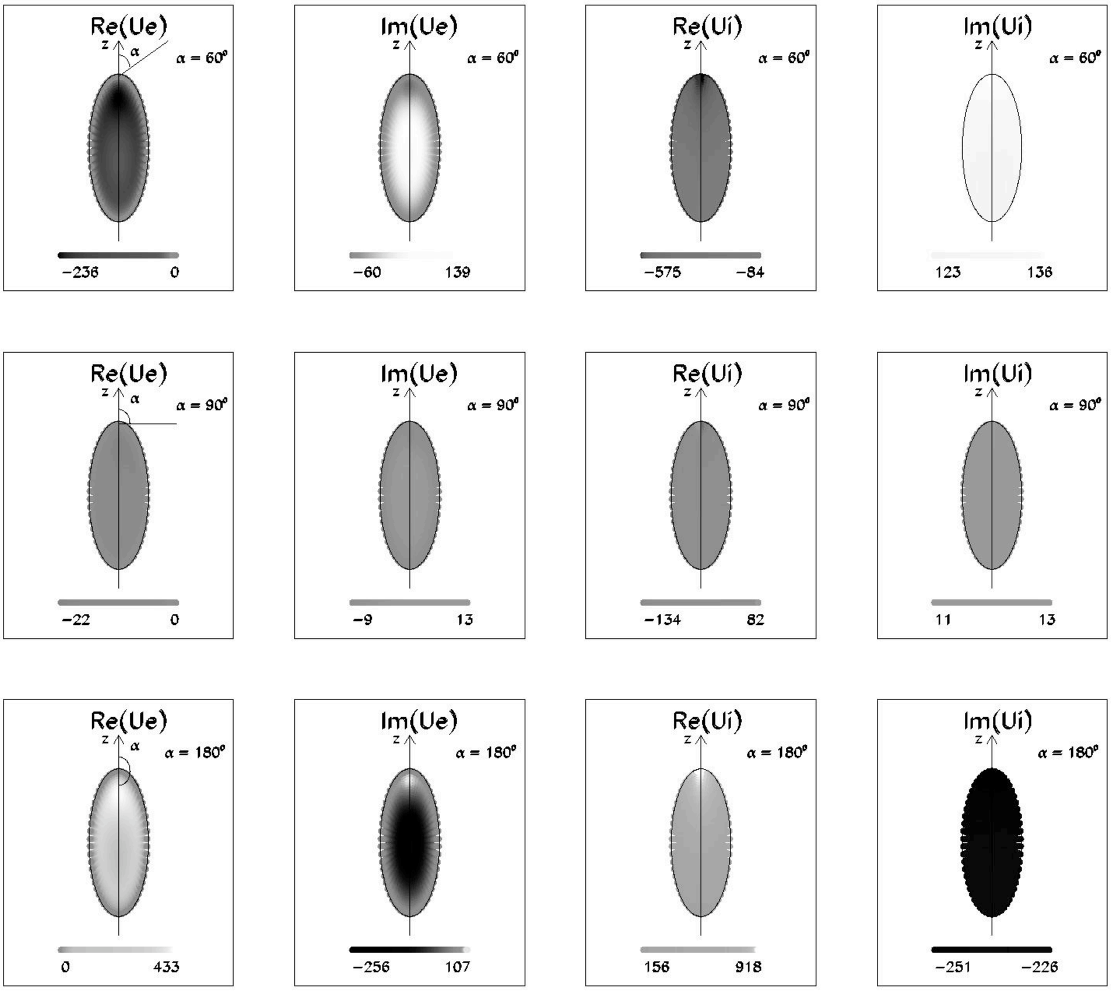

Figure 2: The electric potentials $U^{(e)}(\underline{x})$, $U^{(i)}(\underline{x})$, in the plane $x = 0$. We have chosen the directions $\alpha = 60°$, $90°$ and $180°$ the frequency $f = 3$ Hz and the electric current $I = 7$ μA. In order to do a comparison between the potentials corresponding to different incidence directions, in each column the values of the potentials are normalized to the absolute maximum and minimun values. In this way the resulting values are dimensionless and are represented on a grey scale between 0 (dark grey) and 1 (bright grey). The bars are drawn with the normalized values. Then in each column the same linear greyscale is used, but for figures on different columns different scales are used. But the numbers written below the bars are the real maximum and minimum values of the electric potentials and they are expressed in millivolts. We can see that when these values are high a shining effect exists.

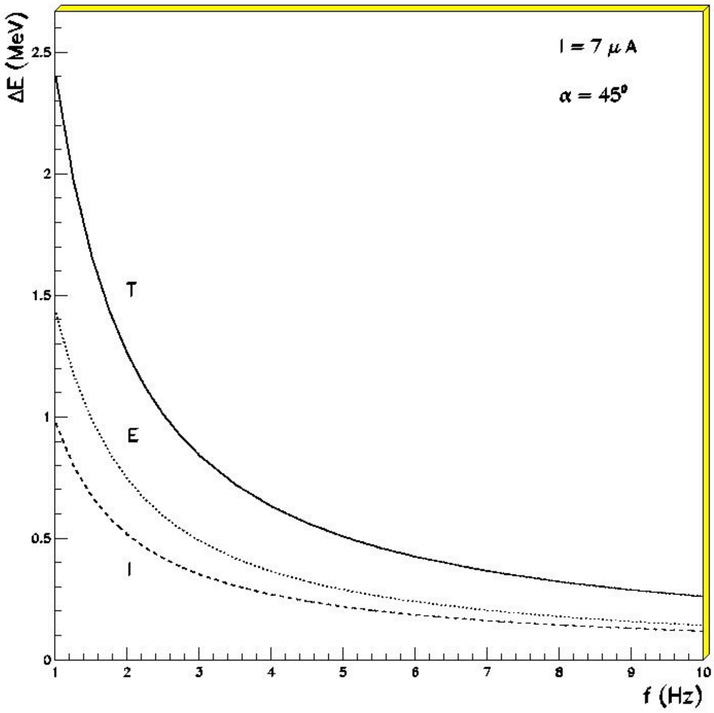

Figure 3: Energy lost in the syncytium vs. frequency.

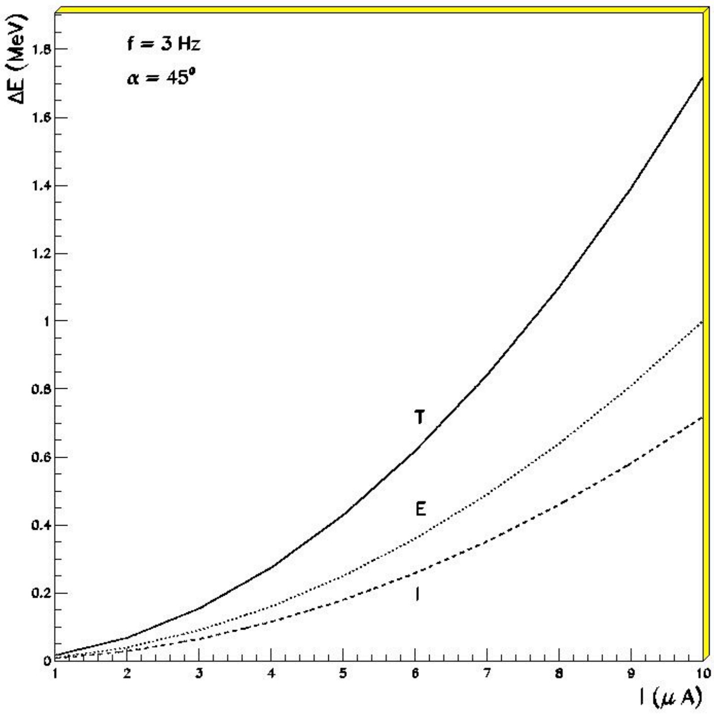

Figure 4: Energy lost in the syncytium vs. electric current.

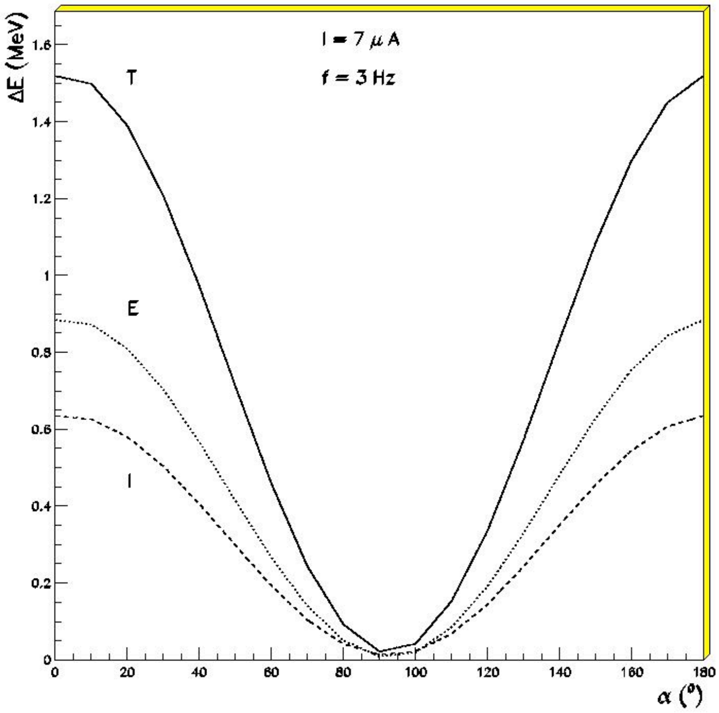

Figure 5: Energy lost in the syncytium vs. incidence angle of cosmic charged particle.

5 INTERACTION ANTIMATTER-SYNCYTIUM

When we consider the interaction between antimatter and syncytium, the right hand side of eq.(2) must be changed because of the possible annihilation process. We can write:

$$\nabla \cdot [\varepsilon_r(\underline{x}) \nabla U^{(i)}(\underline{x})] + R_i \alpha_m Y_m [U^{(e)}(\underline{x}) - U^{(i)}(\underline{x})] = -IR_i \frac{\partial \delta}{\partial \underline{y}_I}(\underline{x} - \underline{x}_I) + k\, \delta(\underline{x} - \underline{x}_I), \qquad \underline{x} \in D, \quad (10)$$

with

$$k = 2\, m\, c^2\, g, \qquad (11)$$

where m is the mass of the antiparticle and g is a constant depending on the antiparticle expressed in V/N. This constant will be determined experimentally in space. It is linked to cross section of the annihilation process. When $g = 0$ we are considering matter; when $g = 1$ we suppose that all the antiparticles entering in the syncytium undergo the annihilation phenomenon. The true value of g is much smaller than 1 since the antiparticles that we consider are flying.

In order to study the antimatter effect in the syncytium, we have chosen the most favourable case ($g = 1$). We have seen that the effect of the annihilation process on the value of energy lost in the syncytium is negligible. In fact the source term $k\delta(\underline{x} - \underline{x}_I)$ in eq.(9) is much smaller than the other term when the current intensity I is of order of μA (see section 7, Table 2).

6 THE EVALUATION OF THE COSMIC RAY FLUXES

We used the Creme96 computer program to evaluate the cosmic ray fluxes within the International Space Station. Creme96 is a package of computer programs to create numerical models of the ionizing radiation environment in near Earth orbits and to evaluate the resulting radiation effects on electronic systems in spacecrafts and in high altitude flying aircrafts (*17-19*).

The differential fluxes, in minimum solar condition, are shown in Figure 6. There is a strong predominance of protons and alpha particles with respect to heavier nuclei and a great predominance of protons with respect to alpha particles when the kinetic energy is below 1 GeV/nucl. The maximum value for protons flux is near 10^2 MeV/nucl. The remaining particles have maximum values near 10^3 MeV/nucl.

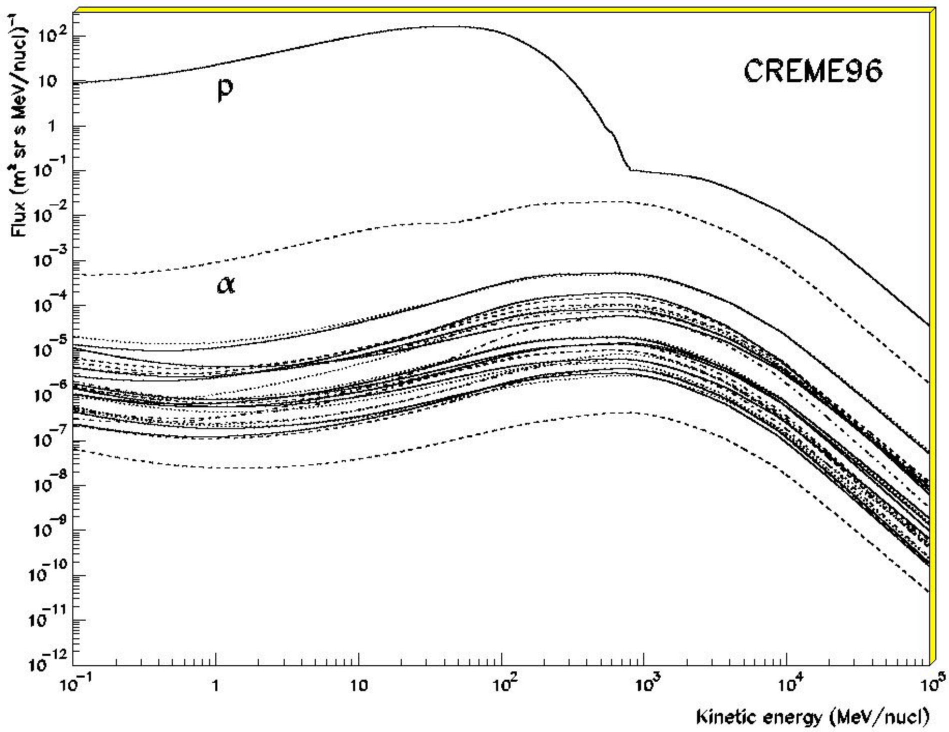

Figure 6: Cosmic ray differential fluxes vs. kinetic energy within the ISS.

7 THE GEANT SIMULATION

In order to control the reliability of the syncytium model, we have developed a simulation with the Geant 3.21 program.

The Geant 3.21 program simulates the passage of elementary particles through matter. This program originally designed for High Energy Physics experiments (HEP), today it has found applications also outside this domain in areas such as medical and biological sciences, radioprotection and astronautics.

The principal applications of Geant in HEP are:

(1) the transport of particles through an experimental setup for the simulation of the detector response;

(2) the graphical representation of the setup and of the particle trajectories.

These two functions are combined in the interactive version of Geant. This is very useful, since the direct observation of what is happening to a particle inside the detector makes the debugging easier and may reveal possible weakness of the setup.

The Geant 3.21 program system can be obtained from CERN, European Organization for Nuclear Research, in http://cernlib.web.cern.ch/cernlib/version.html and the program runs everywhere the CERN Program Library is installed.

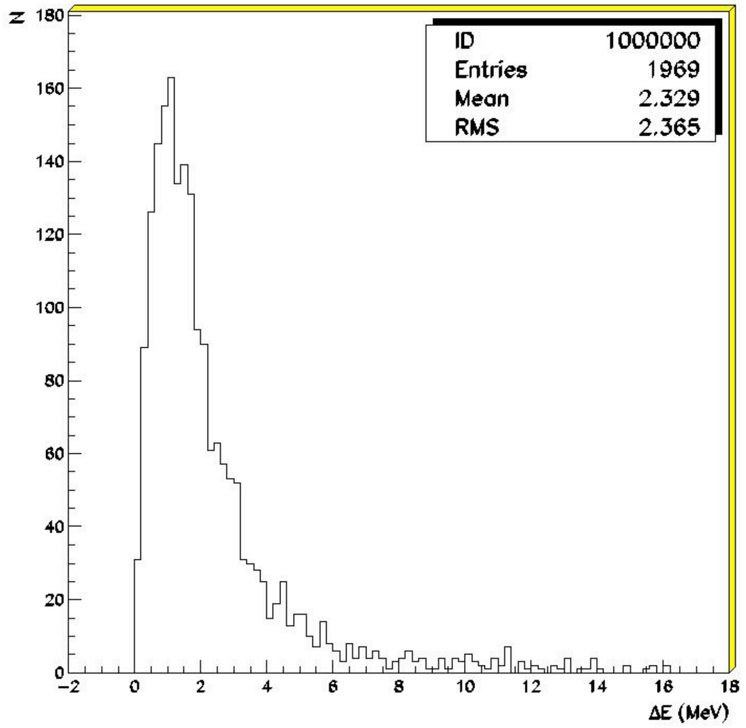

Figure 7: Events distribution vs. energy lost when a cosmic proton hits a sphere of water. The energy is expressed in MeV.

We remember that in (*6*) at least two causes of Light Flashes are hypothesized, one due to protons and the other due to heavy nuclei. For this reason we have developed a lot of simulations using the Geant 3.21 program.

In our simulation the incident particles are generated in a random way and isotropically on a big spherical surface with the crystalline lens in the centre. The lens is represented by a uniform sphere of water with the ray equal to *a* because the Geant 3.21 program can not simulate an ellipsoid. The energy of a particle is chosen in a random way within the cosmic ray spectrum obtained using the Creme96 program (Figure 6), so that events are distributed according to this spectrum. The direction of a particle is isotropically generated in a random way.

Figure 7 shows events distribution vs. energy lost for cosmic protons that hit a sphere of water obtained by using the Geant 3.21 program.

Table 2 shows the comparison between the Geant simulation and the syncytium model. We remember that the sphere has radius *a* and the ellipsoid has semiaxes *a* and *a*/2. In the first column we report the kind of particle considered in the Geant simulations. The second column shows the average energy lost in a sphere of water of radius *a* calculated by Geant. In the third column there is the electrical current that in a uniform spherical syncytium with $\varepsilon_r(\underline{x}) = 1$ yield a lost of energy (fourth column) almost equal to the one calculated by Geant. The fifth, sixth and seventh columns show the energy lost in the intracellular and extracellular compartments and in the whole ellipsoidal syncytium respectively having the parameters reported in Table 1 and the variable density described in section 3. In the last column we show the ratio between the energies lost in the spherical and ellipsoidal syncytia. We can see that the energy lost in an uniform spherical syncytium is almost three times greater then the energy lost in the ellipsoidal syncytium having variable relative dielectric constant described previously. This difference is due to the difference in volume and in the dielectric constant $\varepsilon_r(\underline{x})$.

The comparison between the Geant simulation and the syncytium model indicates the reliability of the latter in the study of some electrical properties of the eye.

Table 2: Comparison between the syncytium model and the Geant simulation. The energy is expressed in MeV. The electric current is expressed in μA. The values of the parameters are f = 3 Hz and α = 45°.

Particle	ΔE_G	I	ΔE_s	ΔE^I_e	ΔE^E_e	ΔE^T_e	$\Delta E_s/\Delta E^T_e$
p	2.329	7	2.329	0.351	0.490	0.841	2.77
α	1.833	6	1.909	0.258	0.360	0.618	3.09
$^{7}Li_3$	4.044	9	4.295	0.581	0.809	1.390	3.09
$^{10}B_5$	11.54	15	11.93	1.615	2.249	3.864	3.09
$^{12}C_6$	16.46	17	15.32	2.074	2.888	4.962	3.09
$^{14}N_7$	22.21	20	21.21	2.871	3.998	6.869	3.09
$^{16}O_8$	28.80	23	28.05	3.801	5.286	9.087	3.09
$^{56}Fe_{26}$	308.2	76	306.3	41.50	57.72	99.22	3.09

8 THE SPACE RADIATION EFFECTS

The health risk to astronauts from cosmic rays radiation determines the maximum lenght of space missions. As a consequence it is very important to evaluate the effects of charged particles on organs of the human body. It is necessary to have a set of dosimetric codes to convert the radiation environment within spacecrafts into radiation protection quantities, which can be used to evaluate astronaut risk when exposure limits have been established. These limits exist for Low Earth Orbit (LEO) only. For missions beyond the protection of the Earth's magnetic field, risk increases. In each case the shielding of spacecrafts is basic.

We studied the effects of cosmic radiation on an “eye” simulated by Geant 3.21 program.

We remember some definitions. The *absorbed dose* D_I is the quantity which measures the total energy absorbed per unit mass and is the fundamental parameter in radiological protection. Then we have:

$$D_I = \frac{\Delta E_G}{M_G}, \tag{12}$$

where M_G is the mass of the uniform sphere of water simulated by Geant. The unit of D_I is the Gray which is defined as 1 Gy = 1 J/kg.

The *absorbed dose* describes the physical effect of the incident radiation, but it gives no information on the rate of absorption and on the specific type of the radiation. These factors are very important when considering the biological effects of radiation, then D_I is an inadequate quantity. For example, an absorbed dose of α particles produces more damage than an equal dose of protons, and a given dose of protons produces more damage than a similar dose of electrons or γ-rays. In fact different particles deposit locally different energy per unit path lenght. Thus the particles with bigger ionizing power yield a greater local biological damage.

For considering this effect, to each radiation type is assigned a radiation weighting factor, w (*20*). The factors are independent from tissue type, are experimentally determined and have stochastic character. The quality factor of a radiation type is defined as the ratio between the biological damage produced by the absorption of 1 Gy of that type of radiation and the biological damage produced by 1 Gy of X or γ radiation.

Then the *equivalent dose*, H, is obtained multiplying the value of the *absorbed dose*, averaged over the entire tissue or organ, by the radiation weighting factor:

$$H = D_I \times w. \tag{13}$$

The *equivalent dose* expresses longterm risk (primarily cancer and leukemia) from low-level chronic exposure.

The unit of *equivalent dose* is the Sievert (Sv) which has the same dimensions as the Gray (J/kg), but now 1 Sv of α particles produces approximately the same effect as 1 Sv of X or γ rays, etc. Howewer the *equivalent dose* is not a quantity directly measurable while the *absorbed dose* is directly observable.

If more than one radiation type is present, the total biological effect suffered by a tissue or organ is:

$$H_{tot} = \sum_R D_R \, w_R, \tag{14}$$

where D_R is the average *absorbed dose* received by the organ from the radiation type R having a weighting factor equal to w_R.

Table 3 shows the *absorbed* and the *equivalent dose* in the crystalline lens (uniform sphere of water) relative to the average energy lost calculated by the Geant simulation. Then we obtain H_{tot} = 74.575 μSv.

Table 3: Absorbed and equivalent energy doses in the crystalline lens corresponding to the average energy lost calculated by Geant simulation. The energy is expressed in MeV. Absorbed and equivalent energy doses are expressed in μGy and in μSv respectively.

Particle	ΔE_G [MeV]	D [μGy]	w	H [μSv]
p	2.329	0.022	5	0.110
α	1.833	0.017	20	0.347
$^{7}Li_{3}$	4.044	0.038	20	0.766
$^{10}B_{5}$	11.54	0.109	20	2.186
$^{12}C_{6}$	16.46	0.156	20	3.118
$^{14}N_{7}$	22.21	0.210	20	4.207
$^{16}O_{8}$	28.80	0.273	20	5.456
$^{56}Fe_{26}$	308.2	2.919	20	58.385

Table 4 shows the *absorbed* and the *equivalent dose* in the crystalline lens relative to the average energy lost in one year calculated by the Geant simulation. Here q is the interactions number per second occurring in the lens and $\Delta E_G^s = \Delta E_G \times$ q is the mean energy lost in one second. Without protons we obtain H_{tot} = 96.4 mSv/yr.

Table 4: Absorbed and equivalent energy doses in the crystalline lens corresponding to the average energy lost in 1 year calculated by Geant simulation.

Particle	q	ΔE_G [MeV]	ΔE^s_G [eV]	D [mGy/yr]	H [mSv/yr]
p	1.508	2.329	3.51×10^{6}	1.048×10^{3}	5.24×10^{3}
α	3.79×10^{-3}	1.833	6950	2.08	41.6
$^{7}Li_{3}$	1.83×10^{-5}	4.044	74.0	2.21×10^{-2}	0.442
$^{10}B_{5}$	3.03×10^{-5}	11.54	349	10.45×10^{-2}	2.1
$^{12}C_{6}$	10.2×10^{-5}	16.46	1679	50.15×10^{-2}	10
$^{14}N_{7}$	2.71×10^{-5}	22.21	602	17.98×10^{-2}	3.6
$^{16}O_{8}$	9.76×10^{-5}	28.80	2811	83.97×10^{-2}	16.8
$^{56}Fe_{26}$	1.19×10^{-5}	308.2	3668	109.6×10^{-2}	21.9

In order to give an idea of character of the numbers of Table 4, we cite the dose limits as recommended by the International Commission on Radiological Protection (ICRP) (*20*). Two sets of limits are defined: one for individual exposed occupationally and one for the general public. For the lens of eye the limits are 150 mSv/yr (occupational) and 15 mSv/yr (general public). These are allowable doses in addition to the natural background dose. In radiotherapy the doses given to the tumour are typically around 100 to 200 Sv per treatment.

Examples of use of codes for calculating the dosimetric quantities for several near Earth environments can be found in (*21*).

Results of measurements of the absorbed and equivalent dose on board aircrafts, spacecrafts and space station Mir can be found in (*22*). A discussion of the planned radiation measurement on the International Space Station is given in (*23*).

9 CONCLUSIONS

The comparison with the results obtained with the Geant simulation program shows that the modellization of part of the human visual system with an ellipsoidal syncytium is promising. The work presented in this paper suggests that this model can be used in the qualitative study of some unexpected phenomena such as the Light Flashes observed by the astronauts.

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