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Thunderstorm neutrons in near space: Analyses and numerical simulation

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[1] In this paper we perform a theoretical analysis of the direct passage of neutrons in the atmosphere from an altitude of about 5 km up to several hundred kilometers. We consider that these neutrons are generated during thunderstorms in what favor there is some experimental evidence. Two main mechanisms of the neutrons generation in thunderstorms appeared in the literature: the nuclear synthesis directly in the lightning channel and the photonuclear synthesis owing to production of gamma-rays by the runaway electrons. Both of them are discussed in the present work. For the qualitative analysis we considered the process of neutrons propagation in the atmosphere as consisting of three stages: initial neutron deceleration to thermal energies, then diffusion, and further free propagation. Absorption of neutrons was neglected. Also, in modeling the atmospheric matter only nitrogen and oxygen were considered as the main atmospheric components. With these conditions and taking into account the predicted parameters of the neutron generation source, it is shown that the estimated flux well corresponds to the known experimental results. On this basis the preferred mechanism of the neutron generation is indicated. For a more rigorous picture of the neutrons propagation, capable for description of the slowing down, thermalization, and diffusion processes, one has to perform a numerical calculation and for this we propose a computer simulation scheme based on the cellular automation method. The corresponding plain analysis of the neutrons passage confirms the estimation mentioned above. The proposed scheme can be used for modeling the real neutron source. On the basis of our results we discuss some characteristic features of the observed neutron fluxes. The obtained results are to be tested by the "Radioskaf" experiment based on the scientific device called "RAZREZ." One of the experiment objectives is detection of neutrons with different energies at altitudes of 200–400 km aiming to reveal the nature and characteristics of the neutron radiation source.

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1. Introduction

[2] The history of the thunderstorm neutrons studies takes its beginning from *Libby and Luken* [1973], where the suggestion on the possibility of neutron generation by processes associated with the acceleration of ions was put forward. A number of further experiments also favored this assumption. Among them there were on-ground experiments [*Shah et al.*, 1985; *Shyam and Kaushik*, 1999; *Bratolyubova-Tsulukidze et al.*, 2003] and space experiments performed onboard the microsatellite "Kolibri-2000," onboard the orbital space station "MIR" ("Ryabina-2" detector) and onboard ISS (Scorpion-1 detector) [*Bratolyubova-Tsulukidze et al.*, 2004]. The space experiments observed the background count growth as well as separate short bursts in the region of the geomagnetic equator. In the works of *Shah et al.* [1985] and *Shyam and Kaushik* [1999] it was assumed that the neutrons birth is due to nuclear reaction ^{2}H(^{2}H, n)^{3}He. Performed later by *Kuzhevsky* [2004], rough theoretical account of the neutron yield during a discharge directly in the lightning channel due to reaction ^{2}H(^{2}H, n)^{3}He gave the value of 10^9–10^{10} neutrons per stroke. However, this mechanism was criticized in the works of *Babich* [2006] and *Babich and Roussel-Dupré* [2007], where also another mechanism was proposed, according to which neutrons are generated over thunderstorm clouds in photonuclear reactions owing to production of runaway electrons. The corresponding estimations for the total neutron production per one upward atmospheric discharge gave the value

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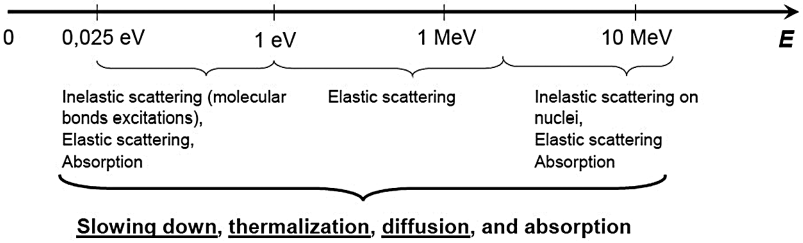


Figure 1. The schematic representation of neutron interactions depending on neutron energy *E*.

around 10^{15} for the altitude of 30 km [*Babich*, 2006]. Each of these models could be the key point in understanding of the correspondent phenomena: usual lightning in the first case and runaway electrons in the second. Thus study of thunderstorm neutrons is thought to be of extreme importance and interest. And the neutrons properties together with the question on the nature of the neutrons source are the natural problems that need to be investigated.

[3] The theoretical account for the thunderstorm neutrons propagation in the atmosphere that we perform here is pursuing several aims. First of all it is to conduct a proof that, in principle, one of the known neutron generation mechanisms can lead to the proper neutron flux on the orbital altitudes (350–400 km). Either, that the neutrons produced via these mechanisms can be detected there. The comparison with experiment can be done using the satellite “Kolibri-2000” data [*Bratolyubova-Tsulukidze et al.*, 2004]. Simultaneously, it will be possible to disfavor one (or may be two) of the neutron generation mechanisms. In other words, consistency of the hole sketched picture may be verified. Another aim is to give a rough value of the count rate over the altitude for the planned experiment “Radioskaf” [*Drozdov et al.*, 2010], at the same time determining the necessary experiment configuration (the type of neutron detectors). As we do not need an accurate result, we will perform only an estimating analysis in our work, revealing the main physical processes. Of course, for the purposes of the experiment one will need a rather precision forecast of the neutron flux, what means need in elaboration of a numerical approach. In this regard we propose the idea on how the Cellular Automation (CA) method can be employed here.

2. Analysis and Modeling

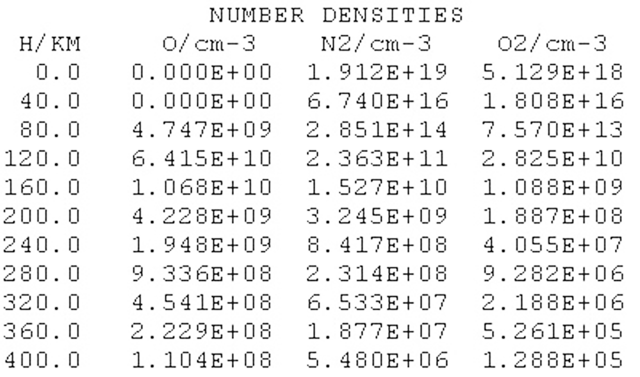
[4] To analyze the neutrons propagation in the atmosphere one should know the character of their interaction with background nuclei. A schematic representation of neutron interactions dependent on neutron energy is presented in Figure 1, where only the main processes are indicated for the given energy ranges. Once born with the energy of the order of several MeV, a neutron will move in the medium in a complicated trajectory undergoing collisions with environment nuclei. In this process, at first, neutrons penetrate into the air and also effectively loose their energy from the initial value down to almost thermal when the energy loss becomes slower. Having reached the thermal energy border, neutrons have further only propagation in the medium with no energy change. Thus, speaking in terms of neutron physics, one should expect that the bulk of neutrons produced in one event at the first stage will slow down, then thermalize and, during these stages and after on, diffuse. This picture, in nature, complements by the absorption. However, in the case of atmospheric composition (light nuclei) the corresponding cross section is reasonably small comparably to that of scattering and can be neglected in our considerations. The process of slowing down is the most efficient one among others and lasts a very short period of time (in comparison with the total time of neutron propagation to the altitudes of interest). Thus for obtaining the estimating results we can take the neutron initial energy value of the order of several MeV that is roughly the energy of a neutron born in the ^{2}H(^{2}H, n)^{3}He reaction and the upper energy bound in the photonuclear reaction. Since the thermalization stage also does not take long and also the corresponding energy does not differ much from the thermal it is of no significance for our purposes here and can be omitted in further considerations. The diffusion process would obviously take place if the matter was uniform. Since it is not, one has to clear up its range of applicability in the considered case (see the discussion hereafter).

[5] In that way, we will consider the neutrons propagation process consisting of at first slowing down, then diffusion and possibly a nondiffusive kind of motion afterward. The quantitative analysis of these processes is possible once the environment model is chosen. For the purposes of our work it is sufficient to make the simplest modeling of the atmosphere and to account for its nitrogen and oxygen components only. We also take the altitudinal dependence of these components concentrations according to the MSISE-90 model. The corresponding data can be generated online at http://ccmc.gsfc.nasa.gov/modelweb/ and the example of data set is given in Figure 2. Also we will consider the atmosphere to be of constant temperature and for definiteness we take it as for normal conditions. This is possible to do because the real temperature always holds the same order of magnitude in energetic scale in spite of its variations over the considered altitudes. The corresponding average thermal neutron energy is equal to the well known value of 0.024 eV.

[6] To account for the slowing down process we use the expression for the average slowing down length [*Beckurts and Wirtz*, 1964]:

$$\overline{R^2} = \frac{6\lambda^2}{\xi(3 - 2/A)} \ln\frac{E_0}{E}, \qquad (1)$$

where λ is the neutron free path, A is the mass number of the target particle, $\xi = 1 + \frac{(A-1)^2}{2A}\ln\frac{A-1}{A+1}$ is the average logarithmic loss, E_0 is the initial neutron energy and E is the final energy. At the ground level with the data from Figure 2



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                  NUMBER DENSITIES
 H/KM       O/cm-3      N2/cm-3      O2/cm-3
  0.0    0.000E+00   1.912E+19   5.129E+18
 40.0    0.000E+00   6.740E+16   1.808E+16
 80.0    4.747E+09   2.851E+14   7.570E+13
120.0    6.415E+10   2.363E+11   2.825E+10
160.0    1.068E+10   1.527E+10   1.088E+09
200.0    4.228E+09   3.245E+09   1.887E+08
240.0    1.948E+09   8.417E+08   4.055E+07
280.0    9.336E+08   2.314E+08   9.282E+06
320.0    4.541E+08   6.533E+07   2.188E+06
360.0    2.229E+08   1.877E+07   5.261E+05
400.0    1.104E+08   5.480E+06   1.288E+05
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Figure 2. The example of MSISE-90 data set generated for the altitudinal step 40 km.

these quantities take values: $\lambda \simeq 2 \cdot 10^3$ cm, $A = 14.6$ (the weighted average value over the concentration), $\xi = 0.131$. And if the energy changes from several MeV to the thermal we obtain the value of $R \simeq 10^3$ m. However, we must fit the presumption that neutrons are generated on altitudes from 3 to 30 km where the atmosphere density is lower. Moreover on the slowing down length scale the density can substantially change. Taking this into account it is possible to obtain the upper bound on the slowing down length $R \sim 8$ km within these altitudes. The corresponding time of the process can be deduced from the formula (1):

$$t = \frac{\lambda}{2\xi}\sqrt{\frac{m_n}{2}}\left(E^{-1/2} - E_0^{-1/2}\right), \tag{2}$$

where m_n is the neutron mass. And for the altitudes up to 30 km we have the upper estimation $t \sim 1$ c.

[7] Keeping in mind the value for the speed of thermal neutrons $v \simeq 2$ km/c we come to the conclusion that slowing down is a rapid and local process to be compared with the whole process of neutron propagation to orbital altitudes. With this conclusion, we can regard the further neutron propagation as the diffusion from point-like instantaneous source (here we also assume that the real sources produce rather short neutron pulses). The simplest equation, governing the evolution of thermal neutrons in uniform environment, is the well known diffusion equation. In the nonuniform matter the equation is slightly modified; however, its explicit form is optional for our purposes here. Nevertheless the question of its applicability and, in general, of the diffusion approximation validity is rather important for our considerations and thus let us focus on it briefly.

[8] The diffusion will take place unless the background density variations are not very large so that neutrons "feel" the density changing experiencing not very large variation of interactions with particles of the air over the characteristic length. This condition for the monoenergetic neutrons analytically can be written as:

$$\frac{\delta\lambda}{\lambda} = \frac{\delta n}{n} \ll 1, \tag{3}$$

where $\delta\lambda$ is the neutron free path variation due to the density changing δn. Having generated the data on the air density with the sufficiently small step one can see that this condition breaks for altitudes above approximately 50 km where the free path is of the order of 100 km. Some kilometers higher this boundary (about 5 km) when the density loses 1 order of magnitude the free path becomes 10^3 km accordingly. Hence in this region up to 400 km the neutrons motion can be regarded as almost free and accounted for with simple geometric considerations. The gap between the diffusion and "free-propagation" areas in approximately 5 km can be omitted due to its relative smallness.

[9] For the instantaneous and point source the diffusion equation in uniform matter has the solution:

$$N = \frac{Q}{2}(4\pi Dt)^{-3/2} e^{-r^2/4Dt}, t > 0, \tag{4}$$

where N is the neutrons number density, $D = ⅓v\lambda$ is the diffusion coefficient (v being neutron speed) and Q – the total number of neutrons produced in one burst. To quantify the neutrons passage to the required altitude we first advert to the maximal value for N at fixed r. The expression coming out,

$$N_{\max} = \frac{Q}{2}\left(\frac{2}{3}\pi e\right)^{-3/2}\frac{1}{r^3}, \tag{5}$$

does not contain related to matter parameter D and can be used for our estimations in the diffusion region. The solution (4) is itself valid as long as r satisfies $r^2 \leq 4Dt$, and the equation (5) is almost on the boundary of this condition, when $r^2 \simeq 6Dt$. The last relation may lead to a small for our purposes value of r which does not allow to cover the diffusion area up to 50 km thus leading to impossibility of the equation (5) usage. We return back to this condition and justify usage of the equation (5) after we have numerical simulations enabling to appreciate t. Summarizing the sketched approximate picture of neutrons propagation we obtain the estimation for the maximal neutron number density at 400 km altitude $N \sim 10^{-8}$ cm^{-3} for the height of neutron generation 30 km and number of the neutrons born $Q = 10^{15}$. This value coincide with the observed one in the "Kolibri-2000" experiment where the estimated neutron count rate was in the range $q \simeq 0.5 - 1.0$ s^{-1}, and the effective active square of the detector was 60 cm^{-2}. Indeed, with these numbers and the value of the microsatellite speed 8 km/s, each second one has the value of the detecting volume $V = 4.8 \cdot 10^7$ cm^3, so that $N = q \cdot 1\text{s}/V \sim 10^{-8}$ cm^{-3}.

[10] The obtained result favors the second mentioned mechanism of thunderstorm neutrons generation via photonuclear reactions. The numbers we used for the theoretical estimation are those predicted on the basis of this mechanism. At the same time the parameters of the first mechanism (altitude and number of neutrons in one stroke) can be adapted to fit the performed theoretical and experimental estimations by no means.

[11] We have demonstrated by our simple considerations that detection of thunderstorm neutrons with predicted properties indeed may take place. For most reliability the performed analyses should be supported by some another method which can be the numerical modeling. Simultaneously, this would be more accurate way of computation capable for obtaining the vivid results in the form of

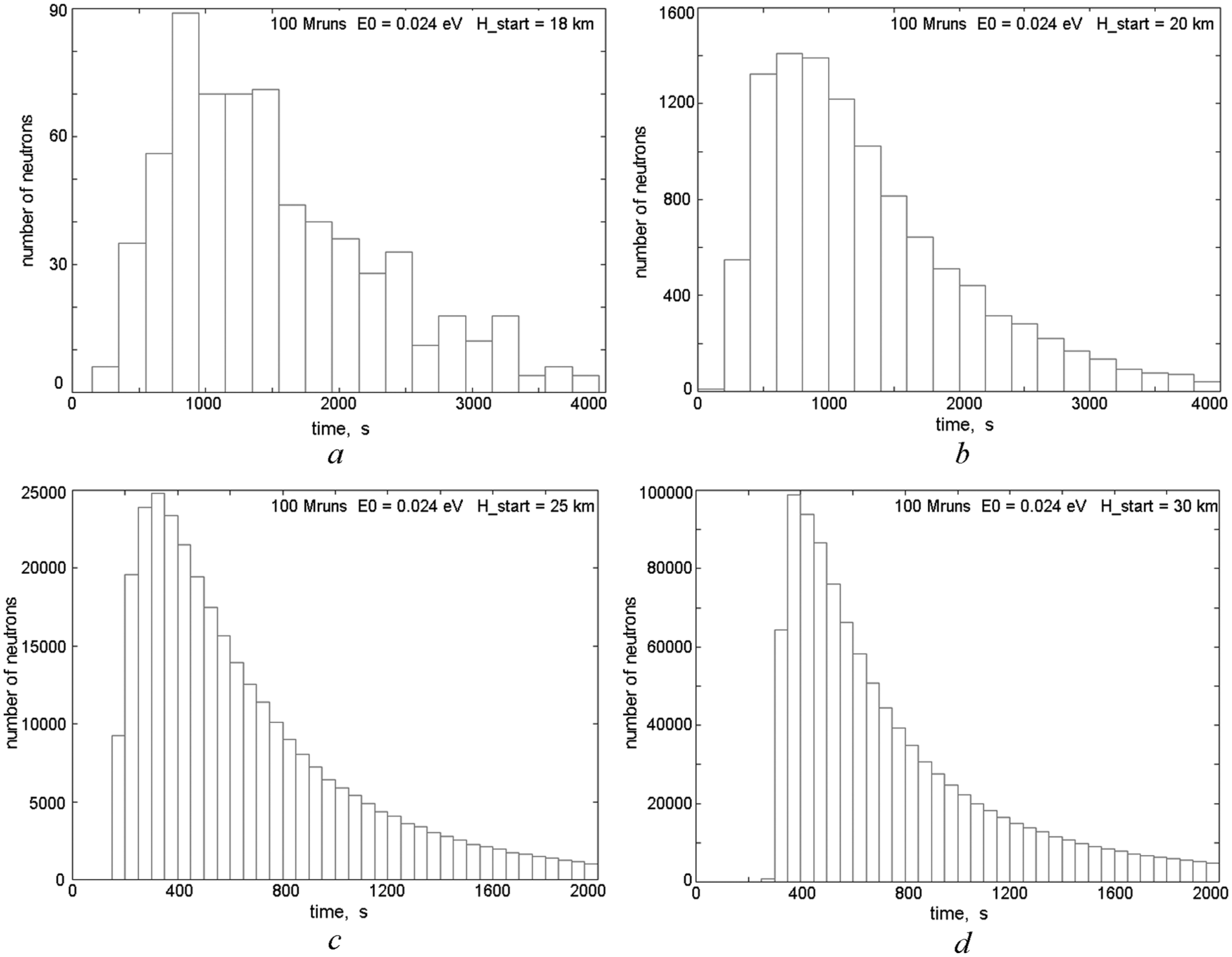

Figure 3. Time distributions of passage of thermal neutrons to the altitude 400 km for different generation altitudes: (a) 18 km, (b) 20 km, (c) 25 km, and (d) 30 km.

altitudinal diagrams. In principle it is the tool for working with a real experiment which can provide connection of the experimental data with theoretical models used to describe the neutron source. This possibility will be considered later below. Here so far we will restrict ourselves by description of the estimating modeling performed on the basis of the Monte Carlo package Geant4 (the information on the package is available at http://geant4.web.cern.ch).

[12] Conditions we chose for the Geant modeling were the following: the point-like instantaneous and isotropic source emitting 10^8 neutrons, 100×100 km^2 detection area (target) located exactly above the source, the layered model of the atmosphere consisting of nitrogen and oxygen (taken in accordance with the MSISE-90 data). Also in the calculation the neutron decay was not taken into account. As it is clear from the results of the modeling given in Figure 3, this simplification is not essential because most of the neutrons have enough time to reach the altitude. In Figure 3, presented are time distributions of passage of thermal neutrons to the altitude 400 km for several neutron source locations. It is seen from Figure 3a that for the low generation altitude the resulting neutron number at the target is substantially suppressed. The higher the generation point the larger amount of neutrons gets to the considered altitude and the corresponding distributions become smooth and diffusion-like.

[13] For the case represented in Figure 3d, the volume, occupied by neutrons crossing the detection area during one second, is $V_{\mathrm{mod}} \simeq 2 \cdot 10^{19}$ cm^3 (since the neutrons velocity is about 2 km/s). Thus the detection volume of the "Kolibri-2000" detector contains $V/V_{\mathrm{mod}} \simeq 2.4 \cdot 10^{-12}$ times less neutrons. Furthermore, it is necessary to take into account that in the modulation 10^8 neutrons were generated instead of 10^{15} leading to the factor 10^7. Another factor of about 10 comes from the geometrical reasons due to the nonuniform neutron distribution over the detection area. Estimating from Figure 3d the count rate in the maximum as $N_{\mathrm{mod}} \simeq 2 \cdot 10^3$ s^{-1} we come to the same estimations for the neutron count rate, $q \simeq 10 \cdot 10^7 \cdot 2.4 \cdot 10^{-12} \cdot 4 \cdot 10^3$ s$^{-1} \approx 1$ s^{-1}, and maximal neutron number density, $N \sim 10^{-8}$ cm^{-3}.

[14] Recalling the diffusion condition for the equation (5), with the results of the simulation, we can estimate now the value for r at $N_{\max}$. The time of the maximum $N_{\max}$ in Figures 3a–3d changes from approximately 800 down to 175 s. Taking into account the slowing down length, which makes diffusion area some kilometers higher the source, and the "free-propagation" motion above 50 km, which takes around 160 s, this leads to values for $r = \sqrt{6Dt}$ in the

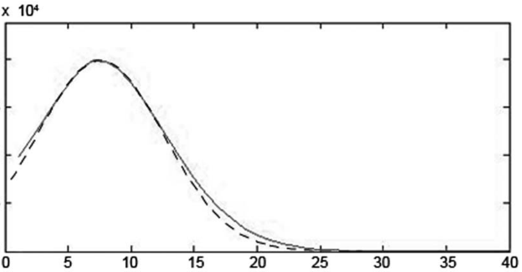

Figure 4. The plots for the neutron spatial distribution obtained by the CA method (solid line) and according to the exact solution of the diffusion equation (dashed line).

corresponding range from approximately 34 km to 44 km. In the estimation, the smallest values for D for the each case were used. The values for r are just enough to approve the use of the diffusion formula (5) on altitudes up to 50 km.

[15] If to speak about a real experiment on the detection of thunderstorm neutrons on orbital altitudes, here one note should be given. As it was mentioned above, ultimately, the collecting data should be confronted with the numerical predictions which should account for distribution of the sources on the Earth's surface and in time and also for the shape of the sources themselves (as they can be rather expanded according to the Babich model). Moreover, it is very desirable to establish the direct connection between lightnings and the neutron count rise in the detector and for this purpose the modeling of such real situations is needed. Thus the numerical method has to be rather fast, easy adopted for configuration changes of the problem (such as geometry, distribution of sources and motion of the detector). It is desired also that it would give the output in the suitable and graphic form. And Monte Carlo simulations do not help much here especially what is concerned configuration changes of the problem.

[16] The best known example that fits the required conditions is given by the CA method. Its main merits relevant to the problem are simplicity of algorithm and possibility for easy variation of the environment configuration. And the main problems are the absence of the specific CA model and lack of solid proof for the validity of any CA scheme (general disadvantage of the CA diffusion models). The last item means need in a justification of the correspondence of the chosen CA model to the real neutrons propagation process.

[17] For the needs of the experiment "Radioskaf," we elaborated the CA scheme modeling neutrons transport in matter. The experiment is planned to conduct at the Moscow Sate University [*Drozdov et al.*, 2010]. The goals of the experiment are to prove the idea of neutron generation in thunderstorms, to explore main neutron fluxes features and to throw the light on the neutrons nature. The intention is to detect slow and thermal neutrons at altitudes of 200–400 km to obtain spectrum and altitudinal profile of the neutron flux. The proposed CA scheme is based on simple empiric considerations of neutrons motion where the neutron interaction with matter is represented through the probability of its transition to neighbor cells or to the same cell of the atmosphere partition.

[18] It is most convenient to introduce our scheme in the simplest one-dimensional and uniform case. Let us take that neutrons freely move within each cell and interact with medium only at the interface between cells deviating to the left or right cell after that (with respect to the dimensional axis). Further, we put the parameter P_{int} which characterizes probability of neutron interaction with medium (thus dependant on the density), parameters P_{int}^R and P_{int}^L which are the probabilities of the neutron motion to the left and right after the interaction, and parameters $P_R(i,t)$, $P_L(i,t)$ for the probabilities to find a neutron in a cell i moving to the right and left, respectively. The time is also partitioned in steps each one corresponding to the neutron free flight over the cell distance. The current number of neutrons in a cell can be found according to the relation $N(i,t) = Q(\mathrm{P}_R(i,t) + P_L(i,t))$. At the each time step the automation is performed following the rules:

$$
\begin{aligned}
P_R(i,t) &= (P_R(i-1,t-1) + P_L(i-1,t-1))P_{\text{int}}P_{\text{int}}^R, \\
P_L(i,t) &= (P_L(i+1,t-1) + P_R(i,t-1))P_{\text{int}}P_{\text{int}}^L.
\end{aligned}
\tag{6}
$$

Results of the modeling at some step i corresponding to source position at some distance from the origin of coordinates are plotted in Figure 4 by the solid line. For comparison, the curve, correspondent to exact solution of the one-dimensional diffusion equation for the same set of parameters, is also plotted by the dashed line. From Figure 4, a rather good conformity is seen between two curves. The apparent divergence of the curves arising with distance from the source point can be explained by the fact that the diffusion equation is valid only for those neutrons experiencing a lot of interactions, and thus gives incorrect value for their number in the sufficiently far region. On the contrary, the CA, in principle, accounts for the all neutrons at each position.

[19] The case of the CA for nonuniform medium basically follows the picture given above but differs from it by introducing the position-dependant probability $P_{\text{int}}(i)$. And also, the presented scheme can be used for modeling of the three-dimensional picture of the neutrons distribution in the atmosphere. On this way we obtained the same estimation for the maximal neutron number density at 400 km altitude as by means of our previous considerations.

3. Conclusions

[20] Completing our brief report we would like to pay attention to some observations that can be done on the basis of the obtained results. In the work of *Drozdov et al.* [2010] a peculiarity is indicated consisting in the lack of the neutron bursts over the American near-equatorial thunderstorm system while over the other main near-equatorial thunderstorm systems (Asian, Pacific and African) they were detected. It is a kind of small obstacle for the nowadays conventional view on the origin of the neutrons. A possible explanation of the phenomenon could be the following. The theoretical analysis performed by us shows that the neutron passage in the atmosphere to the given altitude is crucially dependant on the altitude of the neutron source (it is most clearly seen from the Geant4 modeling results presented). Thus the observed lack of neutrons can be explained by possible difference in source altitudes for these regions. Another

explanation can be given if to reformulate this feature in terms of the medium properties, especially its composition. A small fraction of the hydrogen containing substances, being good neutron moderators, could result in impossibility for the neutrons to come to the required altitudes. The simplest example is given by the water, whose sufficiently small amount at the place of generation would be enough. Thus we conclude that the moisture could play an important role for the process of neutron propagation in the atmosphere and, in principle, could also affect results of on-ground thunderstorm neutrons measurement experiments.

[21] **Acknowledgments.** Wolfgang Baumjohann thanks the reviewers for their assistance in evaluating this paper.

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