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Studying Forbush Effect in Geomagnetic Field of Earth

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ABSTRACT

The report discusses the dynamics of charged particle motion in a non-uniform magnetic field. Specifically, we examine the possible trajectories of cosmic rays in Earth's dipole magnetic field. The study demonstrates the potential chaotic dynamics of cosmic rays using the Lyapunov exponent and Fourier spectrum. Additionally, it presents modeling of Van Allen belt formation and analyzes the influence of cosmic ray energy on the geometry of these belts. Furthermore, an analysis was conducted on the impact of the May 10, 2024, magnetic storm on cosmic ray detection on Earth. As is known, during such storms, the Forbush effect is observed, which manifests as a decrease in the intensity of detected cosmic rays. Relevant laboratory records are provided, utilizing data from the Tbilisi Cosmic Ray Laboratory. The study also investigates the dependence of the Forbush effect's depth on the magnitude of geomagnetic field disturbances.

Key words: *Forbush effect, non-uniform magnetic field, cosmic rays*

Introduction

A non-uniform magnetic field is a field whose magnetic induction varies from point to point in space. An example of such field is the Earth's magnetic field, which in the first approximation can be considered as a dipole magnetic field. The field lines emerge from northern magnetic pole and enter the southern magnetic pole. In the case of a uniform magnetic field, the equation of motion can be solved analytically, but for a non-uniform magnetic field we must use numerical methods. The magnetic field produced by a magnetic dipole is known from the formula [1] [4]:

$$\vec{B} = \frac{\mu_0}{4\pi r^3}[3(\vec{m}\cdot\hat{r})\hat{r} - \vec{m}] \qquad (1)$$

$\vec{B}$ — magnetic field (T)

$\vec{m}$— magnetic dipole moment(for earth: $8.0 * 10^{22}$ ($A*m^2$))

$\hat{r}$— unit vector from dipole moment center to point in space

r — distance from dipole center(m)

μ_0— magnetic constant($1.256 *10^{-6}$ N/A^2)

Our goal is to investigate the trajectory of a particle moving in non-uniform magnetic field.Using the Lorenz force, we write the corresponding equation of motion and solve the system of differential equations using the Runge-Kutta numerical method(ODE-45):

$$\frac{d^2\vec{r}}{dt^2} = \frac{q}{m}\,\frac{\mu_0}{4\pi r^3}\frac{d\vec{r}}{dt}\times[3(\vec{m}\cdot\hat{r})\hat{r} - \vec{m}] \quad (2)$$

As charged particles we consider cosmic rays, which allows us to investigate and qualitatively evaluate the Forbush effect.

Results and disscusion

We obtained various trajectories for the motion of charged particles. The plots show coordinate system scaled by the Earth's radius. In this work, we chose alpha particles (He^{2+}) to model cosmic rays, since they constitute approximately 10% of the cosmic-ray flux. Alpha particles have charge q=2e and mass $m=4m_{p.}$

Additionally, the Lyapunov exponent was calculated for each trajectory to characterize the degree of chaotic behavior (Fig.1, Fig.2, Fig.3)

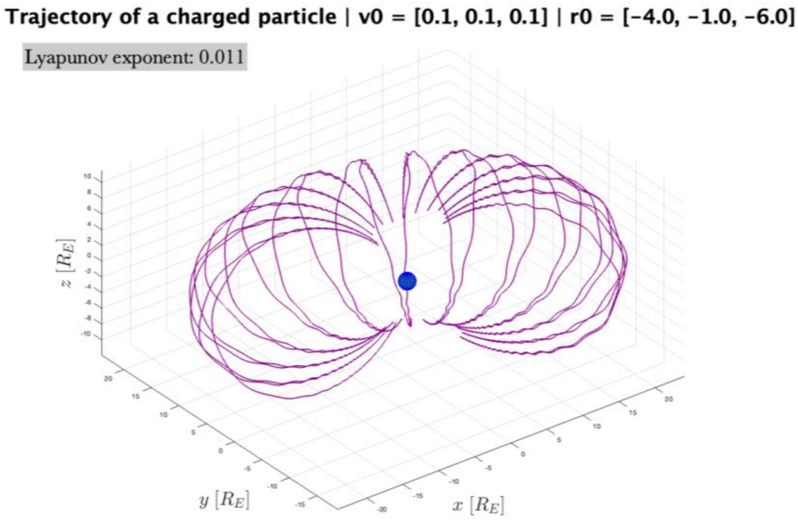

Fig. 1

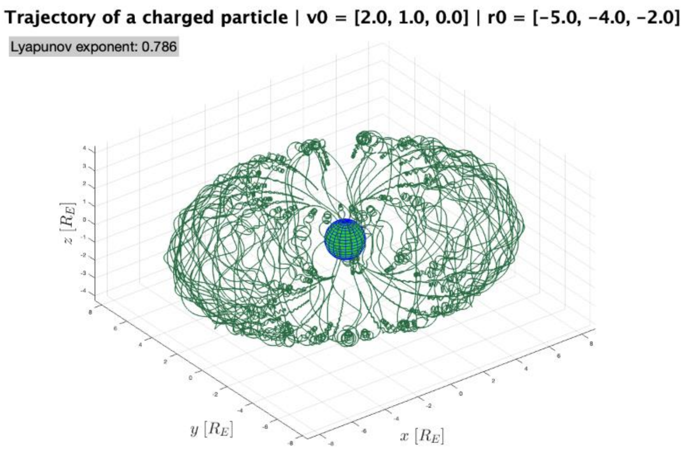

Fig. 2

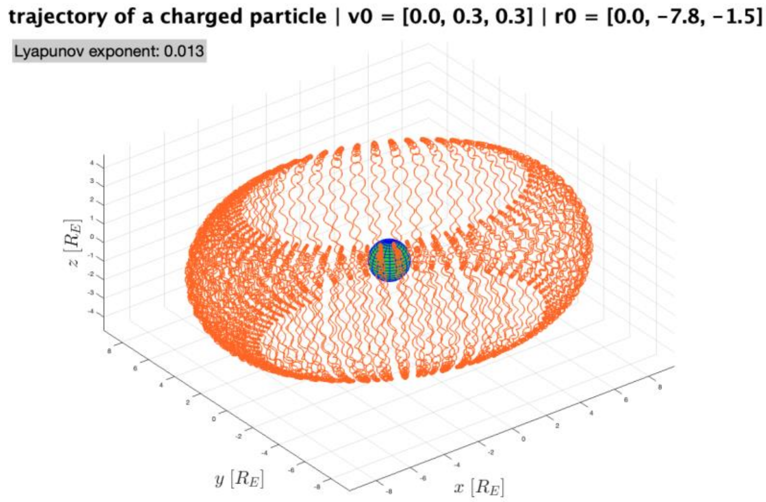

Fig. 3

Using this model, it is also possible to explain the Forbush effect. The Forbush effect is the reduction in cosmic-ray intensity observed on Earth during geomagnetic storms, caused by magnetic disturbances generated by solar eruptions.

In the model, we compare two cases: one with the normal geomagnetic field, and one with an enhanced field due to solar disturbances. The modeled particle moves in the Earth's dipole magnetic field under normal contidions (fig.5) and under enhanced field conditions (fig.4). When the magnetic field is doubled, the particle's trajectory changes significantly, it moves away from Earth and can no longer reach the same location.

This demonstrates that a strong magnetic field, such as that occurring during a Forbush event, hinders the arrival of cosmic rays at Earth- and this is precisely the Forbush effect.

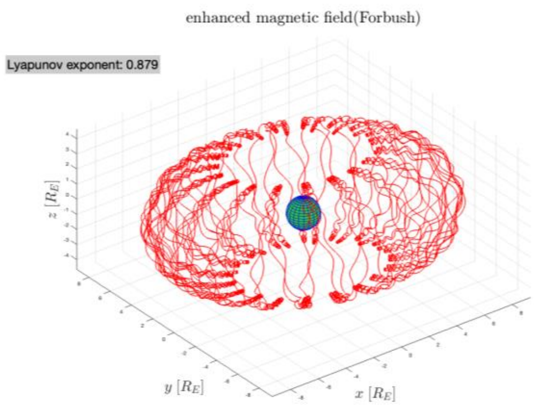

Fig. 4

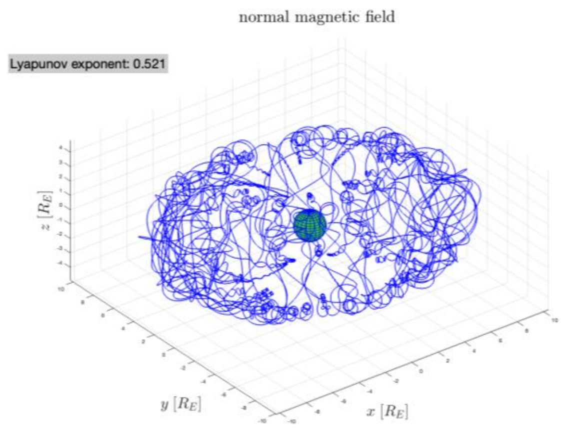

Fig. 5

We also used data from the Tbilisi Cosmic Ray Laboratory [5] to analyze the geomagnetic storm that occured between may 10-13, 2024. As can be seen in the yellow-highlighted region (fig.6), a sharp decrease in cosmic-ray intensity is recorded during the geomagnetic storm, which corresponds exactly to the forbush effect.

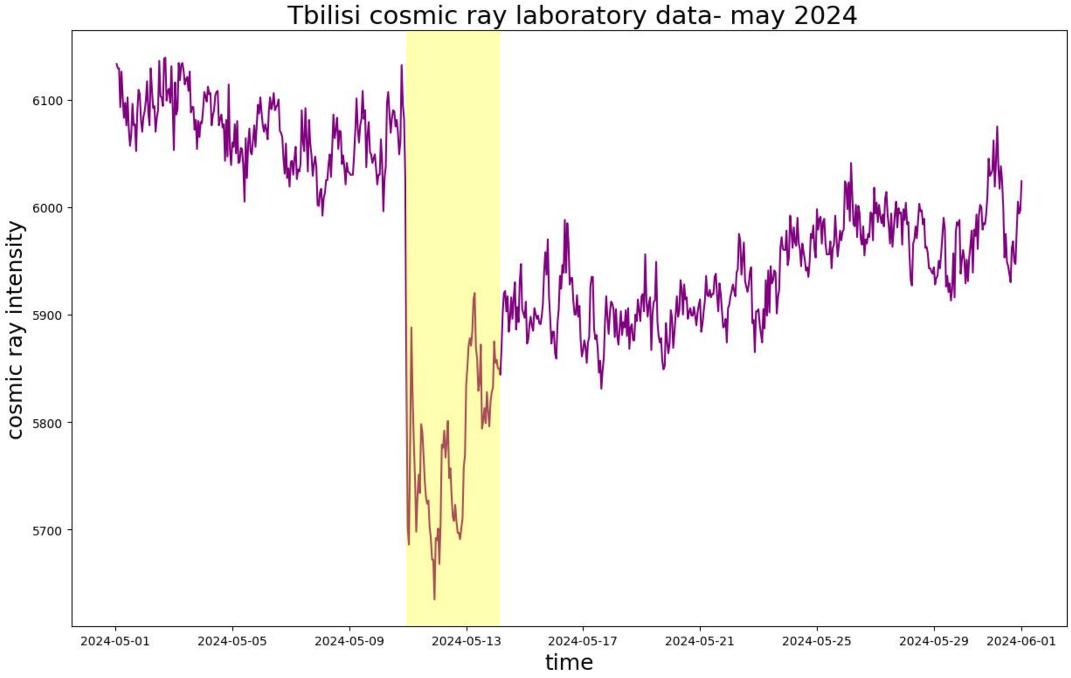

Fig. 6

Conclusion

In this work, we modeled the motion of charged particles in the Earth's non-uniform magnetic field and analyzed the impact of geomagnetic disturbances on their trajectories. Using alpha particles (He^{2+}) to represent cosmic rays, our simulations demonstrated that under normal geomagnetic conditions, charged particles can reach the Earth, whereas under enhanced magnetic field conditions such as those caused by solar eruptions, the trajectories are significantly altered, preventing particles from reaching the same locations.
The results clearly illustrate the physical mechanism behind the Forbush effect: strong geomagnetic fields generated during solar events reduce the flux of cosmic rays arriving at Earth. This modeling is supported by observational data from the Tbilisi Cosmic Ray Laboratory, which recorded a sharp decrease in cosmic-ray intensity during the geomagnetic storm of May 10-13, 2024.
Overall, this study highlights how numerical simulations of particle motion in the Earth's magnetosphere can effectively reproduce observed cosmic-ray modulation events, providing a valuable tool for understanding space weather effects on the near-Earth environment. The approach also allows for quantitative analysis of chaotic particle dynamics and can be extended to study other magnetospheric phenomena, such as the formation and structure of the Van Allen radiation belts.

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დედამიწის გეომაგნიტურ ველში ფორბუშის ეფექტის შესწავლა

მ. ასლამაზიშვილი, ო. ხარშილაძე, ა. ღურჭუმელია, გ. თაყაძე

რეზიუმე

მოხსენებაში განხილულია დამუხტული ნაწილაკების მოძრაობის დინამიკა არაერთგვაროვან მაგნიტურ ველში. კერძოდ, ვიხილავთ კოსმოსური სხივების შესაძლო ტრაექტორიებს დედამიწის დიპოლურ მაგნიტურ ველში. ნაშრომში ნაჩვენებია კოსმოსური სხივების შესაძლო ქაოსური დინამიკა ლიაპუნოვის მაჩვენებლისა და ფურიე სპექტრის საშუალებით. ასევე წარმოდგენილია ვან-ალენის სარტყლების ფორმირების მოდელირება და განხილულია კოსმოსური სხივების ენერგიის გავლენა ამ სარტყლების გეომეტრიაზე. ასევე ჩატარდა 2024 წლის 10 მაისის მაგნიტური ქარიშხლის გავლენის ანალიზი დედამიწის კოსმოსური სხივების დეტექტირებაზე. როგორც ცნობილია, ასეთი ქარიშხლების პერიოდში შეიმჩნევა ფორბუშის ეფექტი, რაც მდგომარეობს დედამიწაზე დეტექტირებული კოსმოსური სხივების ინტენსივობის შემცირებაში. მოყვანილი გვაქვს შესაბამისი ლაბორატორიული ჩანაწერები, სადაც გამოყენებულია თბილისის კოსმოსური სხივების ლაბორატორიის მონაცემები. გამოკვლეულია ფორბუშის ეფექტის სიღრმის დამოკიდებულება გეომაგნიტური ველის შეშფოთების სიდიდეზე.

საკვანძო სიტყვები: ფორბუშის ეფექტი, არაერთგვაროვანი მაგნიტური ველი, კოსმოსური სხივები

Изучение эффекта Форбуша в геомагнитном поле Земли

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Резюме

В работе рассматривается динамика движения заряженных частиц в неоднородном магнитном поле. В частности, изучаются возможные траектории космических лучей в дипольном магнитном поле Земли. В работе показана возможная хаотическая динамика космических лучей с использованием показателя Ляпунова и анализа Фурье. Также представлено моделирование формирования поясов Ван Аллена и обсуждается влияние энергии космических лучей на геометрию этих поясов. Кроме того, проведен анализ влияния магнитной бури 10 мая 2024 года на регистрацию космических лучей на Земле. Как известно, в периоды таких бурь наблюдается эффект Форбуша, заключающийся в уменьшении интенсивности космических лучей, зарегистрированных на Земле. Приведены соответствующие лабораторные записи, использующие данные Тбилисской лаборатории космических лучей. Исследуется зависимость глубины эффекта Форбуша от величины возмущения геомагнитного поля.

Ключевые слова: эффект Форбуша, неоднородное магнитное поле, космические лучи