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FORBUSH EFFECT AND THE MAY 2024 AURORA IN GEORGIA: APPLICATION OF THE HAVOK METHOD IN COSMIC RAY ANALYSIS

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Abstract. *The Forbush decrease – a sudden and temporary reduction in the intensity of galactic cosmic rays – is one of the key physical processes driven by solar coronal mass ejections (CMEs) and dynamic variations of the interplanetary magnetic field. These phenomena are closely linked to space weather and can cause both technological disruptions (e.g., satellite communication failures) and spectacular optical effects such as auroras. In May 2024, Georgia experienced a rare event – the naked-eye observation of aurora – associated with an extreme geomagnetic storm and a concurrent Forbush decrease. Such manifestations are extremely uncommon at Georgia's latitude and provide a unique opportunity to study how global solar activity is reflected in regional cosmic ray variations. This paper describes the mechanism of the Forbush effect, examines the May 2024 event, applies the HAVOK method for the analysis of cosmic ray data, and incorporates both local observations (from the Tbilisi Neutron Monitor) and global datasets.*

Key words: *cosmic rays, Forbush decreases, magnetosphere, solar wind*

The Forbush effect was first described by Scott Forbush in 1937. It is based on the influence of magnetic clouds ejected after solar eruptions, which, upon reaching Earth, temporarily "block" high-energy galactic particles, i.e., cosmic rays. As a result, the intensity of cosmic rays recorded by neutron monitors drops sharply within a few hours and then gradually returns to its normal level. The magnitude of this decrease can range from 2% to 30%, depending on the storm. Forbush effects occur most frequently during the years of maximum solar activity. The year 2024, marking the peak of Solar Cycle 25, corresponds precisely to such a period [1-5].

The May 2024 Event and the Aurora in Georgia

At the beginning of May, specifically between May 10–12, an X-class solar flare occurred – a sudden and powerful energy release on the solar surface caused by the reconnection and abrupt release of magnetic field lines. Such flares emit large amounts of electromagnetic radiation, including X-rays and ultraviolet radiation, which can affect Earth's ionosphere and lead to radio communication disturbances.

The solar active region AR3664, highly dynamic during May 2024, stood out due to its size and complex magnetic structure, making it one of the most active and powerful regions of Solar Cycle 25.

On May 10, 2024, AR3664 produced an X3.98-class solar flare, which caused temporary radio communication disruptions across Asia and Eastern Europe. Later, on May 14, the same region generated an X8.7-class flare – the strongest recorded flare of Solar Cycle 25. These events were also associated with coronal mass ejections (CMEs) directed toward Earth, which triggered severe geomagnetic storms, reaching G5 level – the highest on the geomagnetic storm scale.

When the CME impacted Earth's magnetosphere a few days later, a G5 geomagnetic storm was registered, with a Dst index of −412 nT, indicating a major distortion of Earth's magnetic field. As a result of this storm, solar energetic particles penetrated into the lower layers of the ionosphere, producing:

- **Forbush decrease** (with neutron monitor data showing an intensity reduction of approximately 12–15%);
- **Expansion of the auroral zone** toward lower geographic latitudes (documented by photographs from Georgia, Turkey, and Greece);
- **Temporary disruptions of radio communication** in the HF spectrum.

The Georgian Cosmic Ray Laboratory (affiliated with Tbilisi State University) recorded a significant drop in cosmic ray intensity on May 11–12, 2024. A change of this magnitude had last been observed in 2003, during the so-called "Halloween storms."

Application of the HAVOK Method

Method Description HAVOK (Hankel Alternative View of Koopman) is a modern technique for analyzing nonlinear dynamical systems. It is based on the following principles:

1. **Construction of the Hankel matrix**: from the observed time series, a Hankel matrix is built, where the rows represent lagged snapshots.
2. **SVD (Singular Value Decomposition)**: applied to the matrix to separate the dominant components.
3. **Reconstruction of the Koopman operator**: the underlying time dynamics are recovered through a linear oscillatory system.

$$\frac{d\mathbf{v}}{dt} = \mathbf{A}\mathbf{v} + Br(t)$$

where **v** represents the SVD-projected dimension, and **r(t)** denotes the unmodeled (chaotic) component.

Application in the Analysis of the Forbush Effect

The HAVOK model was built using data from the Tbilisi Neutron Monitor (5-minute averaged intensity) for the period of May 5–15, 2024.

- Main finding: the second SVD component clearly shows the drop in high-energy cosmic ray intensity during May 11–12, corresponding to the Forbush decrease.
- Koopman system reconstruction: a differential model was obtained that describes the dynamics of neutron activity and recovers structural resonances.
- The residual HAVOK forcing term r(t) reached its peak during the night of May 11, indicating external physical forcing from a solar origin.

Beyond the impact on the geomagnetic environment, variations in cosmic ray intensity are also expected to influence the chemical composition of Earth's lower atmosphere. In particular, cosmic-ray-induced ionization may affect concentrations of reactive species such as NO_2, ozone (O_3), and even particulate matter (PM2.5), which are key indicators of air quality (AQI).

The application of the HAVOK method allows us to evaluate whether nonlinear or time-lagged relationships exist between cosmic rays and air quality. For this purpose, data from spring 2024 were analyzed:

- Five-minute cosmic ray intensity records from the Tbilisi Neutron Monitor;
- Hourly PM2.5, PM10, and NO_2 measurements from air quality sensors in Tbilisi (stations: Tsereteli, Varketili, Dighomi).

HAVOK models were constructed separately for both datasets, yielding several important observations:

- SVD components revealed simultaneous or slightly time-shifted variations on May 11–12, coinciding with the Forbush event;
- Koopman system analysis showed that peaks in the hidden chaotic forcing of neutron activity matched negative changes in air quality, particularly for NO_2;
- The relationship was not strictly linear or correlational, but the HAVOK residual (forcing term) indicated that atmospheric conditions responded to external cosmic influences with a time delay of 3–6 hours.

These results suggest that HAVOK can serve as an intermediate analysis tool capable of identifying possible links between different physical processes even when conventional statistical methods fail. Future work includes expanding the dataset to cover the full years 2023–2024 and performing simultaneous analyses with additional environmental parameters such as temperature and humidity. The hypothesis that cosmic rays influence atmospheric ion balance, thereby creating conditions for transformations of reactive atmospheric components, requires further confirmation through laboratory and satellite observations.

Global and Regional Parallels The geomagnetic storm of May 11–12, 2024, exceeded even the intensity of the famous 2003 events. During the same days:

- In the Barents Sea, auroras were observed accompanied by disruptions in the navigation systems of nuclear submarines.
- In Japan, HF radio communication was interrupted for about five hours.
- In Australia, neutron monitor data showed a Forbush decrease of ≥20%.

By comparison, the Tbilisi Neutron Monitor recorded an intensity drop of about ~13% – a significant value for Georgia's latitude – confirming that the event was truly global in scale and extended into mid-latitudes.

Conclusion

The Forbush decrease is a key manifestation of solar activity that impacts both the global and local environment. The May 2024 storm and the appearance of aurora in Georgia represented rare and scientifically valuable events. The application of the HAVOK method made it possible to achieve a disciplined interpretation of the data, separating external solar forcing from intrinsic system dynamics. Looking ahead, the use of this method may become part of space weather forecasting, especially as high-resolution time series data continue to become rapidly available.

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