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The technique of continuous registration of relativistic neutral particles from the Sun using a ground-based muon hodoscope

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The sun is a source of high-energy neutrons (> 1 GeV)

Neutral particles from the Sun can be formed in various physical processes a constant flux of neutral particles is produced by interactions of primary cosmic ray (PCR) with the substance of the photosphere and the chromosphere (high-energy neutrons can appear as a result of *N-N* reactions). The interplanetary magnetic field practically does not distort the trajectory of neutral particles, and they propagate to the Earth in a straight line, like a ray of light. In the Earth's atmosphere due to photonuclear reactions $\gamma+N\to\pi+N$ or recharge reactions $n+N\to\pi+N+N$ short-lived charged pions appear, which quickly decay to generate long-lived muons $\pi\to\mu+\nu$ reaching the ground level. At high energies, the trajectories of all three generations of particles ($n \to \pi \to \mu$) practically lie on one ray. The muons of "solar origin" from the PCR flux must be constantly observed during the daytime, while the light beam passes through the aperture of the apparatus. The limit of the lower limit of the energy of neutrons in recording such processes is due to the loss of energy of relativistic muons to ionization in the atmosphere: $T_n \geq (dE/dx)\cdot \Delta x / \cos(\theta)$ and is not less than 2 GeV. Value $\cos(\theta)$ takes into account the increase in the thickness of the atmosphere for the inclined trajectory of muons.

The solar corona is the target for the protons of the PCR flux

1) $p^+_{PCR} + p_{Sun} \to n_{Sun} + \pi^+ + p^+$

$n_{Sun} + N_{Earth} \to \pi^- + p^+ + N_{Earth}$

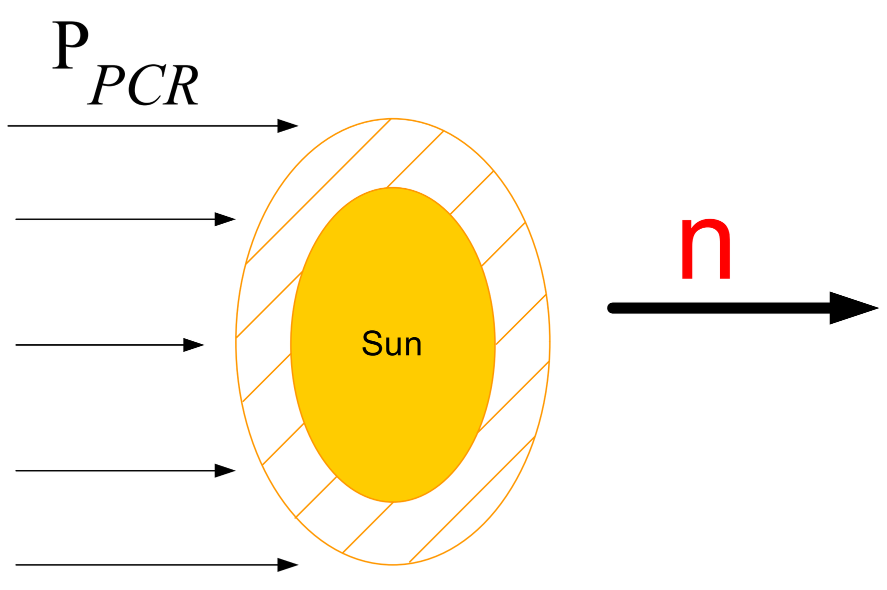
$\pi^- \to \mu^- + \tilde{\nu}$

2) $p^+_{PCR} + p_{Sun} \to \pi^0 + p^+ + p^+$

$\pi^0 \to \Upsilon + \Upsilon$

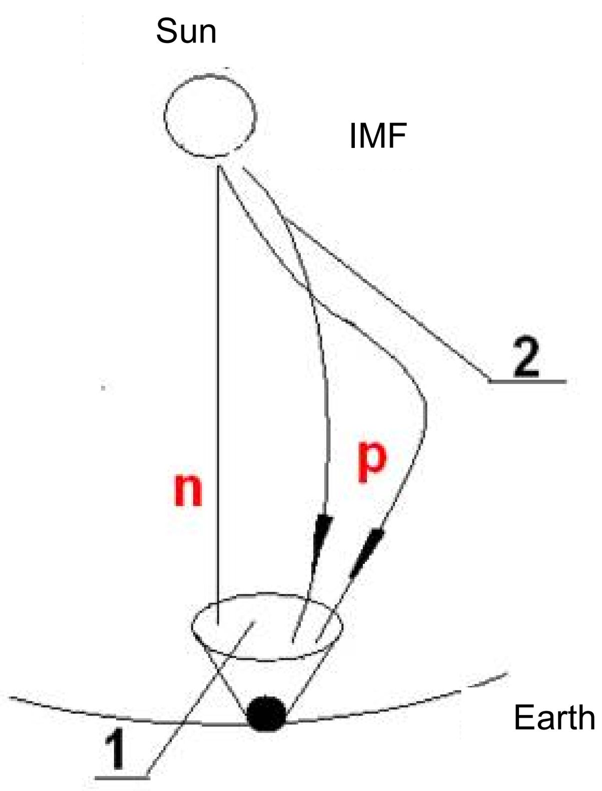
$\Upsilon + N_{Earth} \to \pi^+ + N_{Earth}$

$\pi^+ \to \mu^+ + \nu$



Secker et.al. Astphys. J. (1991)

Scheme of propagation of solar particles (n, p)



n – the beam divergence is less than 0.5 degree

1 – Hodoscope aperture

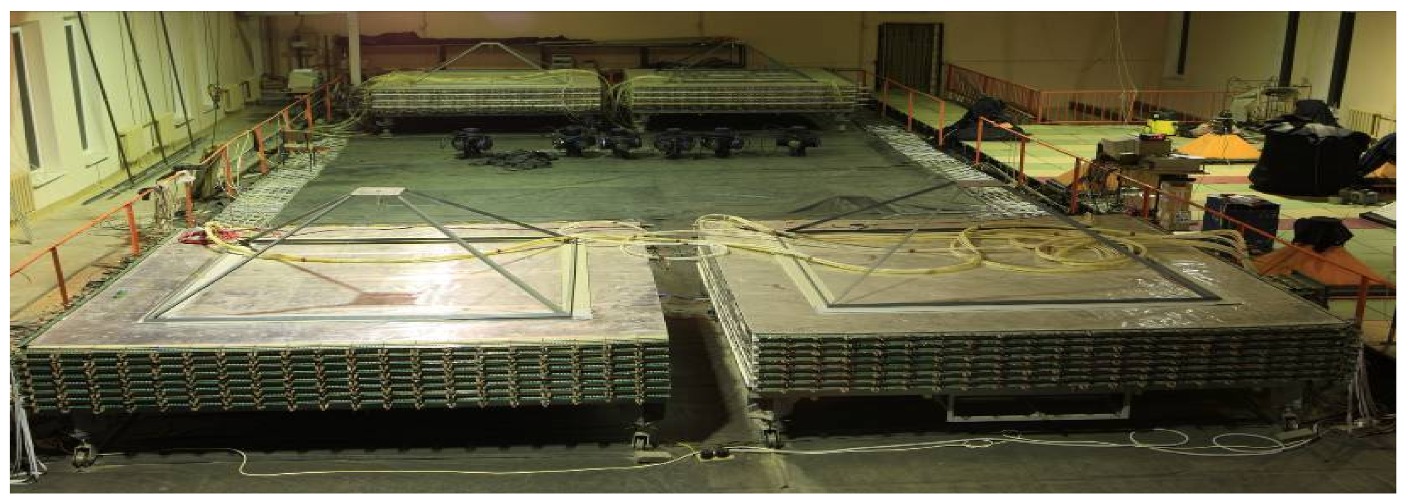
2 – Archimedes' spiral (IMF line)

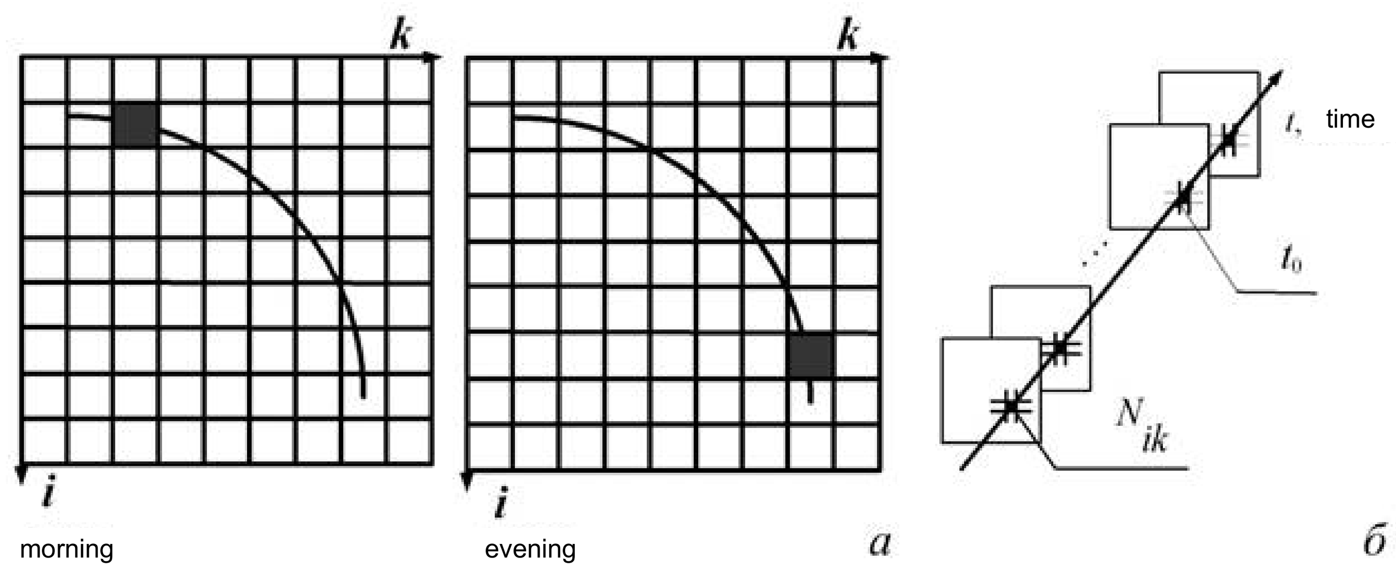
Method for identifying relativistic neutral particles from the Sun

In this work, search for neutral particles from the Sun using the muon hodoscope URAGAN. The muon hodoscope URAGAN consists of several independent mobile assemblies-supermodules (SM). Each SM provides high spatial and angular accuracy of detection of muons (1 cm and 0.8°, respectively) in the range of zenith angles from 0 to 80 degrees. The effective area of one supermodule is about 11 m^2. The threshold energy of the detected muons depends on the zenith angle and varies from 200 to 600 MeV. The altitude above sea level is 173 m, the threshold geomagnetic rigidity is 2.46 GV.

The muon hodoscope URAGAN continuously records the 1-minute intensity of the muon flux in the form of a sequence of matrices $N_{ik}(t)$. For any instant of time, each element of the matrix *ik* correspond to certain zenith and azimuth angles. During the line of sight of the Sun, the light ray describes a certain trajectory in the image-matrices (see Figure *a*, dark squares correspond to different moments of time (morning, evening)). Figure *b* shows an example of a sample of a time series $N_{ik}(t)$, for a fixed value of the cell number (i,k), which at the time t_0 corresponded to the direction of the sunlight beam.

The calculations use the data of the muon hodoscope URAGAN for the muon flux from three supermodules. Since neutral particles behave like a beam of light, to search for them from the data matrix URAGAN, a data cell of size 3° x 4° is selected, which at time t_0 corresponded to the direction of the solar light beam. Regarding the time t_0, a time series is selected with a 1-minute step and a duration of ± 30 minutes. The selected series is processed and the deviation (excess) of the muon flux at time t_0 relative to the background for this series is calculated. The deviation is calculated by the formula:

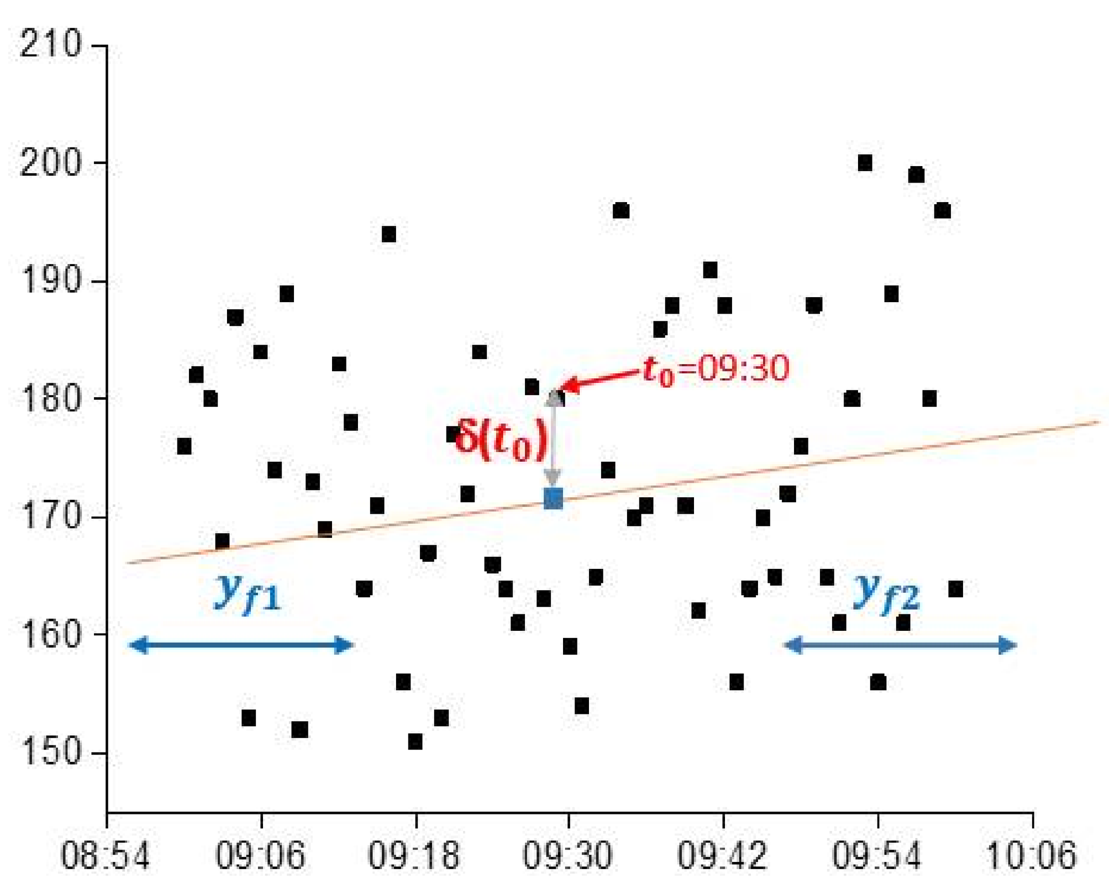


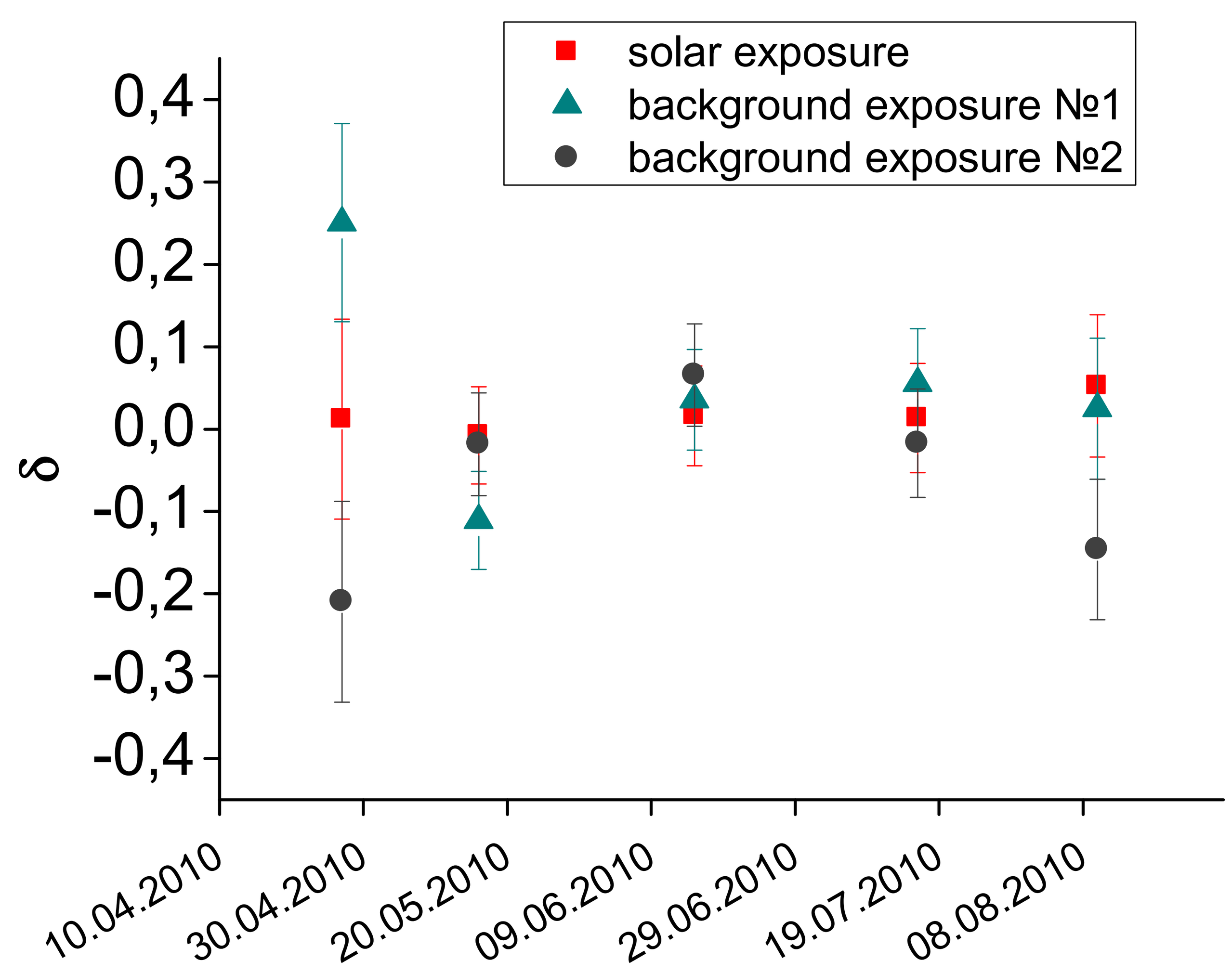


$$\delta\,(t_0) = (N_{sun}\,(t_0) - y_f) / \sigma_f,$$

where $N_{sun}(t_0)$ is the number of muons at time t_0; y_f is the background value calculated by approximation by a linear function; σ_f is the standard deviation of the background value. The time interval of ± 15 minutes relative to the time t_0 is not used in the calculation of the background value (see Figure). This results in two background values y_{f1} and y_{f2}, through which the linear dependence y_f is conducted. Figure shows the number of muons in the interval of ± 30 minutes relative to the time t_0, the time instant t_0 and two background values y_{f1} and y_{f2} are schematically shown.

The data of the muon hodoscope URAGAN for the period of 2010 is processed in a similar way. Solar exposure is obtained by processing data with an interval of ± 2.5 hours relative to 09:30 UTC. Two background exposures # 1, 2 are chosen with respect to solar exposition with a shift of ± 80 minutes. Background exposure # 1, 2 are processed similarly. Background exposure # 1 is selected at intervals of ± 2.5 hours relative to 08:10 UTC. Background exposition # 2 is selected with an interval of ± 2.5 hours relative to 10:50 UTC. Data analysis was performed in the range of ± 60 days relative to June 22 (day of the solar equinox).





Conclusion

A less expensive variant of research is the registration of generated long-lived relativistic particles far from the Sun - on the surface of the Earth. Since the flux of product particles is expected to be small due to the low intensity of the initial cosmic ray beam (with energies above 100-1000 GeV), it is safer to identify neutral particles (gamma quantum, neutron) during registration with a high angular resolution muon hogoscope URAGAN. The proposed data analysis technique is used for the first time to study the regularities of the production of relativistic particles in the central region of the heliosphere from the Earth's surface.

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