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Scientific & Educational Centre NEVOD

A technique for identification of relativistic solar neutrons using a ground-based muon hodoscope

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

High-energy solar neutrons can be formed in various physical processes:

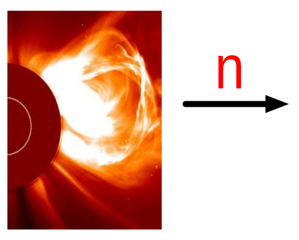
1) a pulsed neutron flux during powerful solar flares associated with generation of solar energetic protons (SEP);

2) a constant flux of neutrons is produced by interactions of PCR with the substance of the photosphere and the chromosphere (high-energy neutrons can appear as a result of *N-N* reactions).

In both cases, neutrons are produced in reactions of the charge-exchange type: $p + N \rightarrow n + N + \ldots$. The interplanetary magnetic field practically does not distort the trajectory of neutrons, and they propagate to the Earth in a straight line, like a ray of light. In the stratosphere of the Earth there are reactions of neutron interaction with the production of pions: $n + N \rightarrow \pi + N + N + \ldots$ and their decay, with the formation of muons: $\pi \rightarrow \mu + \nu$. At high energies, the trajectories of all three generations of particles ($n \rightarrow \pi \rightarrow \mu$) 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.

- **Flare processes on the Sun**

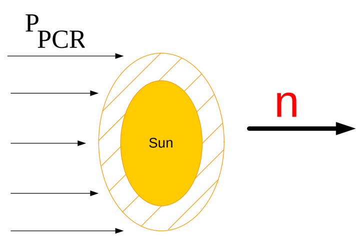
$$p_s + p_s \rightarrow n_s + \pi^+ + p_s$$



Duration of generation - minutes

- **The sun is the target for the protons of the PCR flux**

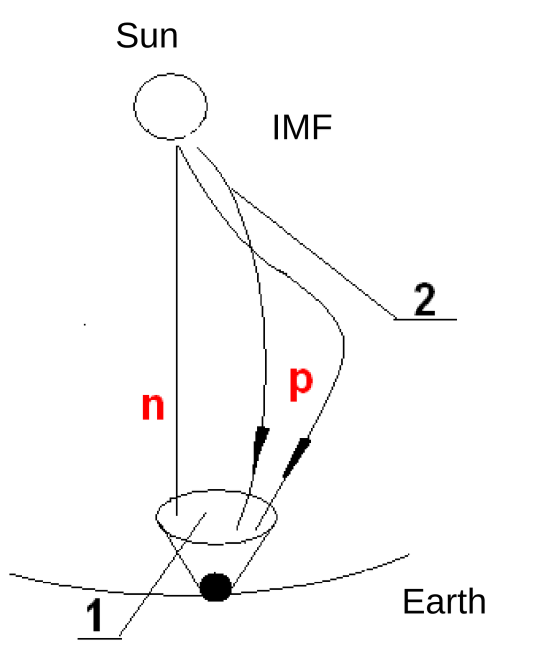
$$p^+_{PCR} + p_s \rightarrow n_s + N + \ldots$$



Duration of generation - continuous

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)

Atmospheric muons

$$n_s + N \rightarrow \pi^- + p + N$$

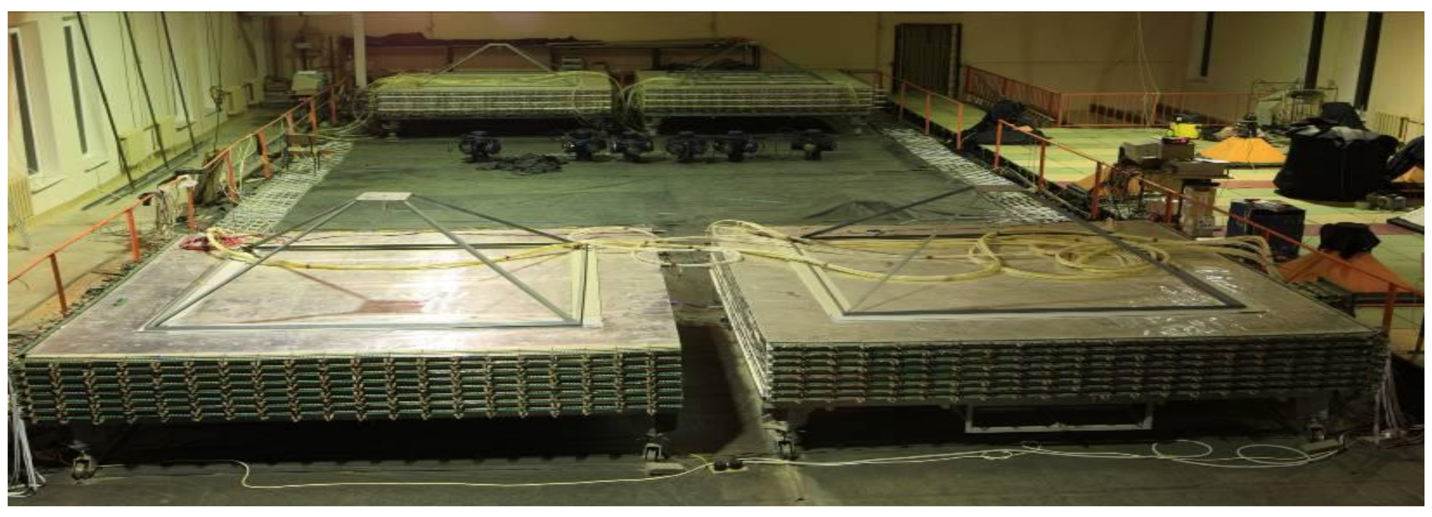
$$\pi^- \rightarrow \mu^- + \tilde{\nu}$$

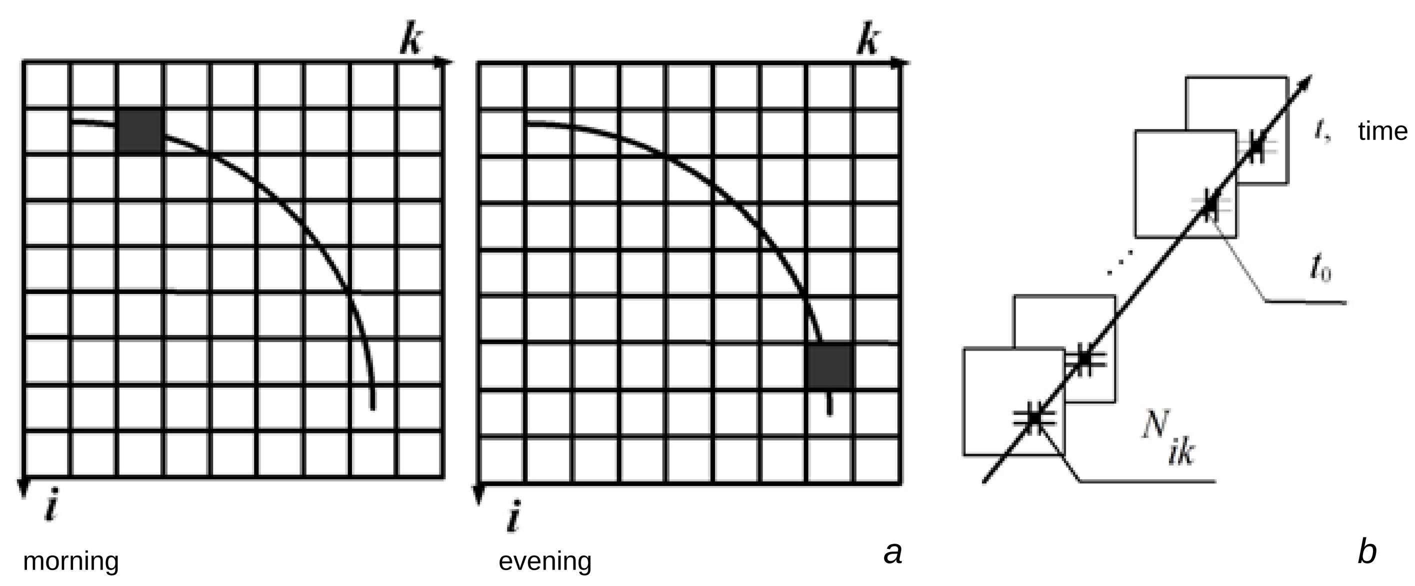
$$T_n^{min} \geq (dE/dx)_\mu \cdot \Delta x / cos\theta$$

$\boxed{\text{Tn > 2 GeV/cos}\theta}$

Method for identifying relativistic solar neutrons during flares

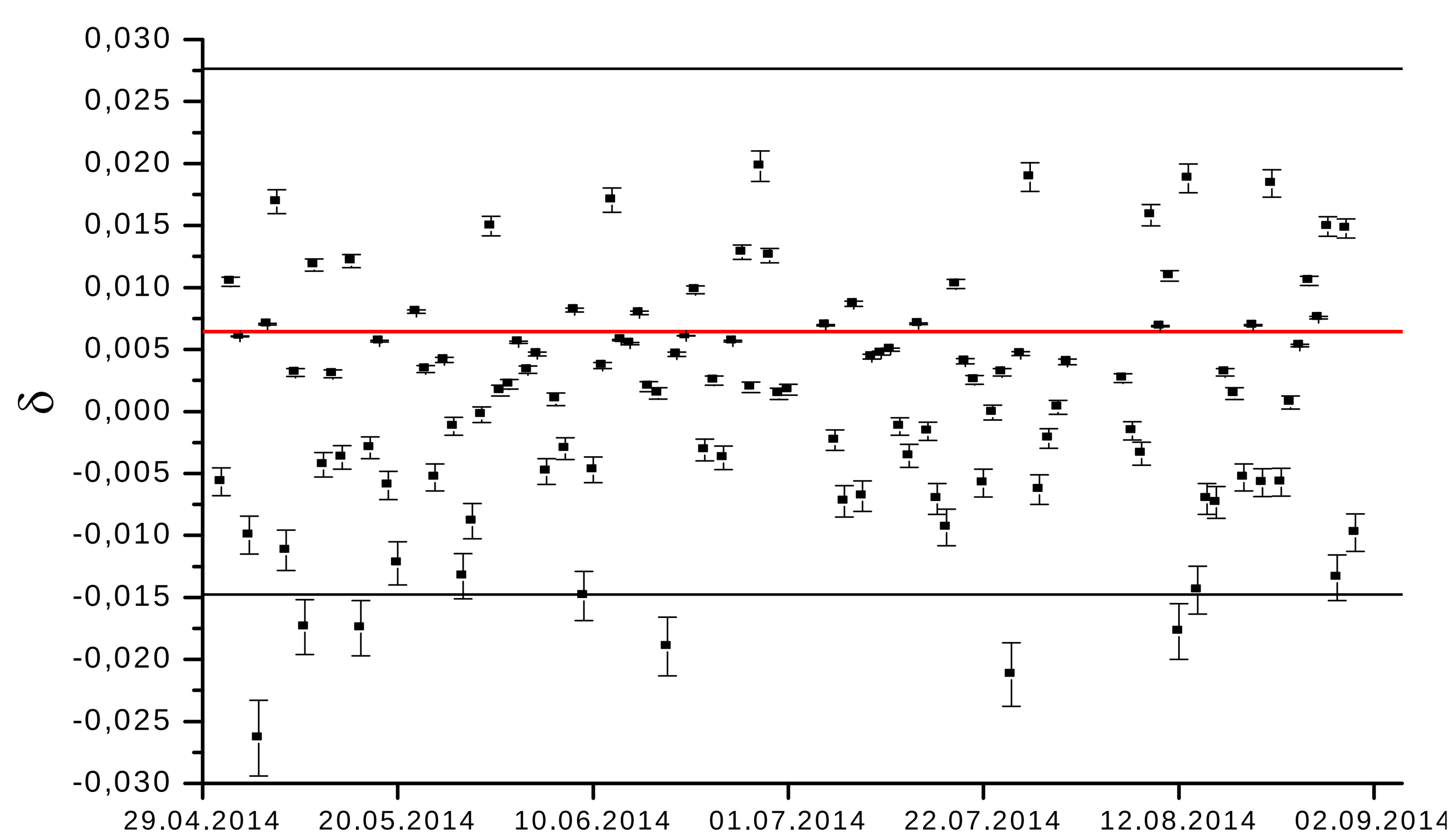
The muon hodoscope URAGAN consists of several independent mobile assemblies-supermodules (SM). Each SM provides high spatial and angular accuracy of detection of muons (1 cm and 0.8 °, respectively) in the range of zenith angles from 0 to 80 degrees. The effective area of one supermodule is about 11 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)). In order not to take into account the geometric factor, which depends on *ik*, as well as the angular dependence of the muon flux and meteorological effects, the data are converted into normalized quantities $n_{ik}(t)$ за счет исключения тренда $f_{ik}(t)$ для каждого элемента матрицы *ik*: $n_{ik}(t)=(N_{ik}(t)-f_{ik}(t))/\sigma_{ik}$. 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 procedure for leveling the quantities $N_{ik}(t)$ on time intervals from 10 minutes to one hour was performed by different methods, including: median smoothing, weighted mean, application of Chebyshev polynomials, etc. It turned out that simple linear smoothing gives the best result both in the minimum value of the scatter of individual points in the time series, and in the absence Systematic shift of the mean.





Method for identification of relativistic solar neutrons with constant interaction of GCR protons from the gas shell of the Sun

To search for "solar" muons, in the summer time 4 hours intervals are taken from the general exposition, relative to noon, when the effective thickness of the Earth's atmosphere in the direction of the hodoscope was minimal. The sample reduces the blurring of the beam of "solar" muons due to multiple scattering in the atmosphere. The procedure for processing data at a fixed value t_0 consists in the following: the date and time of day is used to determine the angular position of the Sun at the time t_0; then a time series of 1-minute values is formed, which includes a value in the middle of the interval, and a deviation is calculated from the background of a small time interval (t_0 ± 15) minute. This processing is successively repeated with a 1-minute offset for the entire time (+/- 2 hours from noon) for one day. As a result, the daily exposure of muons from the direction to the Sun was 240 values, according to which the average value was determined. In the absence of an additional muon flux, the mean value should be zero. A positive mean value means the existence of a directed flux of high-energy neutrons from the Sun.
The figure shows the first preliminary results of data analysis for 2014. The muon hodoscope URAGAN allows estimating the contribution of solar neutrons at the level of 0.5% of the PCR flux.



Conclusion

A technique for identifying direct solar neutrons with E≥ 2GeV by secondary atmospheric muons, which are registered by the terrestrial muon hodoscope URAGAN. There are statistics for the period 2007-2017, which allows us to verify the laws of the temporal behavior of neutron generation in the solar chromosphere for a long period of time. The first preliminary results of data analysis for 2014 are given. The muon hodoscope URAGAN allows estimating the contribution of solar neutrons at the level of 0.5% of the PCR flux.

Acknowledgements

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