Chapter 6

Laboratory experiments and theoretical research

CONTENT

Skobeltsyn Institute of Nuclear Physics of Lomonosov Moscow State University

6.1. TAIGA astrophysical observatory

(Skobeltsyn Institute of Nuclear Physics of Lomonosov Moscow State University)

For many years the SINP/MSU held in conjunction with the Irkutsk State University (ISU) research on cosmic rays on the basis of "Astrophysical complex MSU-ISU" in TUNKA valley, nearby Baikal lake in Siberia.

At the end of 2013 a number of Russian scientists (SINP/MSU, Irkutsk State University, Institute of Nuclear Research, Moscow Engineering Physical Institute, Joint Institute of Nuclear Research, etc.) and some European institutions (University of Hamburg, DESY, MPI (Munich), Torino University(Italy)) have established the collaboration TAIGA. The purpose of the collaboration is to conduct research in the field of gamma-astronomy of ultrahigh energies at a new level of sensitivity. It is currently completing construction of phase A: hybrid gamma-observatory TAIGA, an area of 1 km^2, on which collaboration will be critical to the world level. The next step is to expand the installation by 10 times.

The main direction of scientific research at this new facility – gamma-ray astronomy of super-high energies. For the gamma quanta energy range above 10^{13} eV (ultrahigh energy gamma astronomy), there are a number of fundamental questions that have no answers now. One such important issue is the question of the sources of Galactic cosmic rays at the energy of about 10^{15} eV. It should be noted that, to date, no gamma quanta with energy exceeding 10^{14} eV has been registered. An indication of the existence of gamma sources in this region of energies with sufficient luminosity for experimental detection is the discovery of high-energy neutrinos by the Ice-Cube telescope. Thus, research on ultrahigh-energy gamma astronomy will complement the research on high-energy neutrino astrophysics conducted in our country.

In the last few years, the first stage of the gamma observatory TAIGA (Tunka Advanced Instrument for cosmic ray physics and Gamma-ray Astronomy) began to be deployed at the Astrophysical Center in the Tunka Valley (50 km from Lake Baikal). The immediate goal is to build the first part of the observatory, which will consist of: 100 wide angle Cherenkov stations of the TAIGA-HiSCORE timing array, placed on an area of 1 km^2 and three IACTs with 4 m diameter dish by the end of 2019.

Such an installation will prove the effectiveness of the hybrid approach for gamma astronomy of ultrahigh energies and begin a serious scientific program. One of the TAIGA-HiSCORE station and IACT-1 are shown in Fig. 2.

Fig.2. *A HiSCORE station with IACT-1 in the background (TAIGA facility in the TUNKA valley, nearby Baikal lake).*

Adding IACTs (Imaging Atmospheric Cherenkov Telescope) to the TAIGA-HiSCORE wide-angle timing array allows a better separation between charged cosmic rays and gamma rays — by combining IACT image parameter information with information that can be better reconstructed by the timing array (core position, direction and energy of the air shower). Even for distances between the IACTs as large as ~600 m, one gets a high level of rejection of cosmic-ray showers (about 100:1 at ~100 TeV).

The expected integrated sensitivity of the facility with an area of 1 km^2 for 300 hours of observation of 100 TeVsource is approximately 2.5×10^{-13} TeV $cm^{-2}sec^{-1}$, compared to that of other projects. At present, TAIGA is still ahead of LHAASO in Tibet, the main competitor at highest energies. This timely lead will be hold for another~2 years until the LHAASO sensitivity will bypass that of TAIGA.

Note however that TAIGA's field of view covers sky regions which are not accessible to LHAASO, justifying the operation of a smaller array. CTA construction is still behind of both TAIGA and LHAASO.

Selected publications

N. Budnev et. ol. (TAIGA Collaboration), Journal of Physics: Conference Series ***718****, 052006 (2016).*

L. Kuzmichev et. ol. (TAIGA Collaboration), EPJ Web of Conf. ***145****, 01001 (2017).*

6.2. “SPHERE” experiment

(Skobeltsyn Institute of Nuclear Physics of Lomonosov Moscow State University)

Experiment SPHERE studies the energy spectrum and mass composition of the primary cosmic rays (PCR). The compact optical SPHERE-2 detector lifted over the snow-covered. Earth surface registers the reflected from the snow Cherenkov light (CL) of extensive air showers (EAS).

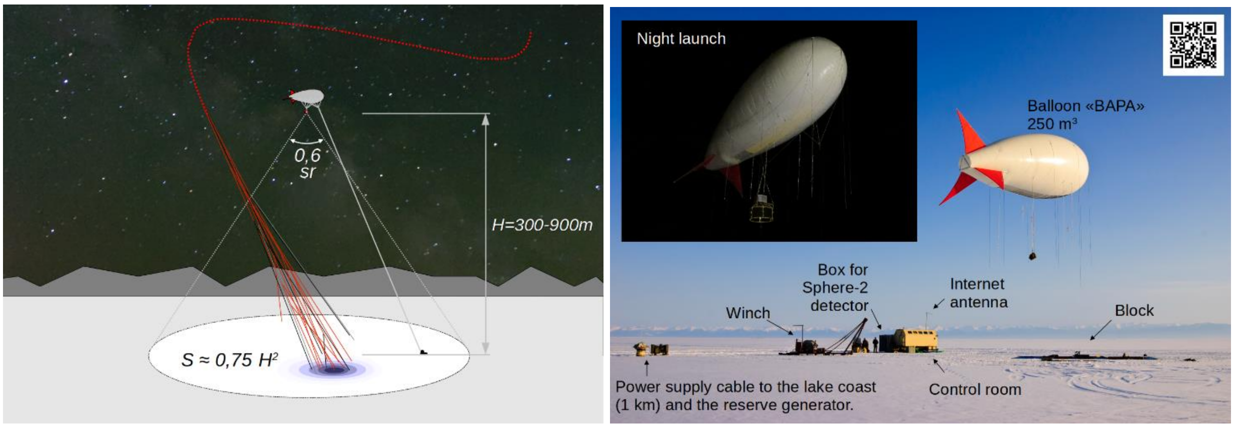
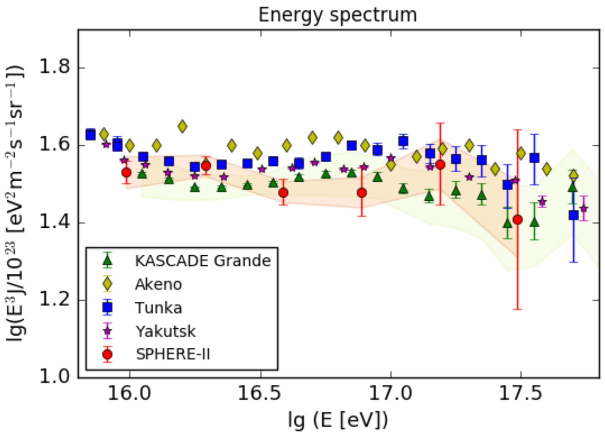


Fig.9. Scheme and photo of the experiment with SPHERE-2 detector on Lake Baikal.

The SPHERE-2 is the only existing detector that have registered a significant sample of EAS by means of the reflected CL method on event-by-event basis, at the same time reconstructing lateral distribution function (LDF) of all these events. The SPHERE-2 detector consistsof a spherical 1.5 m diameter mirror, a photomultiplier mosaic installed near the focal surface of the mirror, and an aperture diaphragm. The experiment was carried out in 2008-2013 on Lake Baikal. The SPHERE-2 detector was elevated to the altitudes from 200 to 900 m above lake level as Fig.9 shows. The exposition time was near 30 hours per year, totally about 1100 EAS events were detected. Full detailed MC simulation was performed by means of a dedicated highly modular code. A method for an event-by-event study of CR mass composition in the energy range 10-200 PeV using the LDF steepness was devised. Also it was shown that it is possible to improve the separation of the event classes by utilizing multivariate analysis methods. The Bayesian multivariate pattern recognition technique assuming a multidimensional Gaussian distribution of event features was used.

The all-nuclei cosmic ray spectrum reconstructed using the observations of the detector is shown on Fig.10. The total uncertainty of the spectrum including the systematical one was shown to be comparable with the uncertainty for the ground-based experiments.

The reflected Cherenkov light technique has a number of similarities and differences with other methods developed for EAS observation.



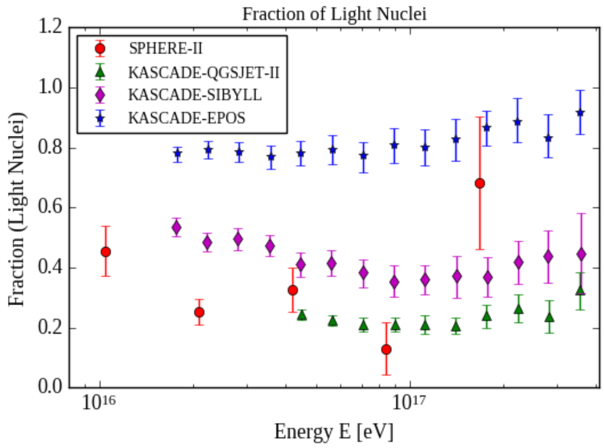


Fig.10. *Energy spectrum of PCR reconstructed for the 2011-2013 data of SPHERE experiment. Systematical uncertainty is shownby a colored area.*

Fig.11 *Light nuclear fraction reconstructed for the2013 run of the SPHERE experiment*

The fraction of light nuclei (protons and helium) in the 10–200 PeV energy range was estimated by means of an event-by-event approach using the LDF steepness parameter, see Fig.11.

A new experiment with a balloon-borne detector for registration of reflected CL and direct fluorescence light from EAS with energies $5\cdot10^{18}$–$5\cdot10^{19}$ eV in Antarctica is currently under development. The SPHERE-Antarctica project will significantly increase the exposure by at least 3–4 orders of duration comparedto the SPHERE-2 experiment.

Selected publications

Podgrudkov D.A., Antonov R.A., Bonvech E.A., Chernov D.V., Finger Miroslav, Finger Michael, Dzhatdoev T.A., Cosmic ray study by means of reflected EAS Cherenkov light method with the SPHERE-2 detector. PoS(ICRC2017)537.

Chernov D.V., Antonov R.A., Bonvech E.A., Podgrudkov D.A., Roganova T.M., Dedenko L.G., Finger Mir., Detector for the ultrahigh energy cosmic rayscomposition study in Antarctica. Journal of Physics: Conference Series (798)1, 1-5, 2017.

Antonov R.A., Bonvech E.A., Chernov D.V., Podgrudkov D.A., Roganova T.M., The LED calibration system of the SPHERE-2 detector. Astroparticle Physics (77), 55-65, 2016.

Chernov D.V., Antonov R.A., Aulova T.V., Bonvech E.A., Galkin V.I., Dzhatdoev T.A., Podgrudkov D.A., Roganova T.M., Detection of reflected Cherenkov light from extensive air showers in the SPHERE experiment as a method of studying superhigh

6.3. “TUNKA” experiment

(Skobeltsyn Institute of Nuclear Physics of Lomonosov Moscow State University)

Since 1993, in the TUNKA valley (Republic of Buryatia), 50 km from lake Baikal, a large experimental center for research on the physics of cosmic rays and gamma astronomy has been developed. The first facility TUNKA-133 (Fig.12.), registers cosmic rays on Cherenkov light emitted in the atmosphere by charged particles of EAS. TUNKA-133 consists of 175 optical detectors located on an area of 3 km². Currently, it is the largest installation of this type in the world. When it was created, all the achievements of modern electronics (transmission of information on fiber-optic cables, ultra-fast ADC with a frequency of 200 MHz, reprogrammable logic matrices) were used, which qualitatively improved information about the recorded event.

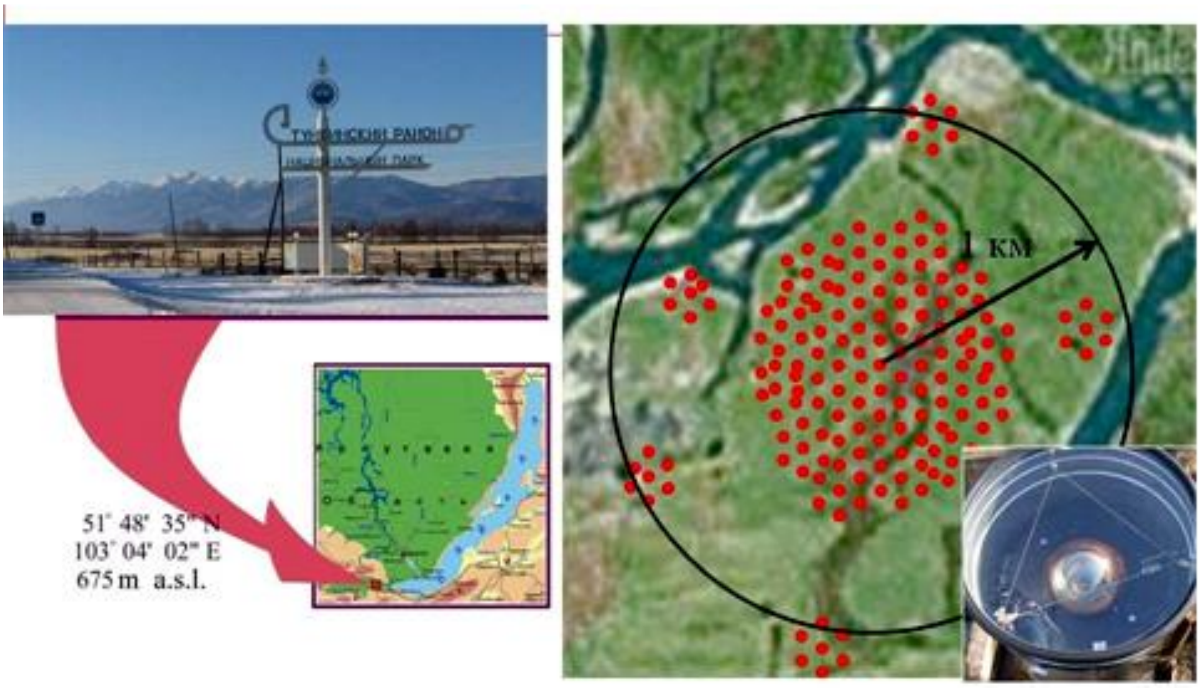


Fig. 12. TUNKA facility.

This facility was developedby cooperation of Russianresearchers (SINP MSU, NIIPP ISU, INR RAS, IZMIRAN) with scientists from Germany and Italy. Currently, in the field of astrophysics, the TUNKA-133 is the only Russian ground-based cosmic rays facility. The experimental facility of such a class as TUNKA-133provides possibility for the studiesof cosmic rays in the energy range from 10^{15}-10^{18} eV by a single method, including both the fracture in the spectrum at energy $3 \cdot 10^{15}$ eV and other features of the spectrum, possibly related to the transition from galactic to extragalactic cosmic rays, and to find out the origin of galactic rays of ultrahigh energies. One of the main results obtained by TUNKA-133 is the proof of a more complex dependence of cosmic ray intensity on energy than previously assumed. Two statistically secured features are observed in the spectrum. At the energy of $2 \cdot 10^{16}$ eV, the slope of the energy spectrum decreases by about 0.2 (Fig.13.), and at the energy of $3 \cdot 10^{17}$ eV, the value of the spectral slope indicator increases again by about 0.3. The same figure shows the spectrum obtained at TUNKA-25, the predecessor of TUNKA-133. The wraparound of the spectrum at the energy of $3 \cdot 10^{17}$ eV can be interpreted as the "second knee" in the energy spectrum associated with the transition from galactic to extragalactic cosmic rays. Also, the behavior of the spectrum of "heavy" and "light" nuclei indicates the transition to extragalactic cosmic rays. In the spectrum of heavy nuclei visible kink at the energy $8 \cdot 10^{16}$ eV exists. Apparently, this is the acceleration limit of galactic cosmic rays.

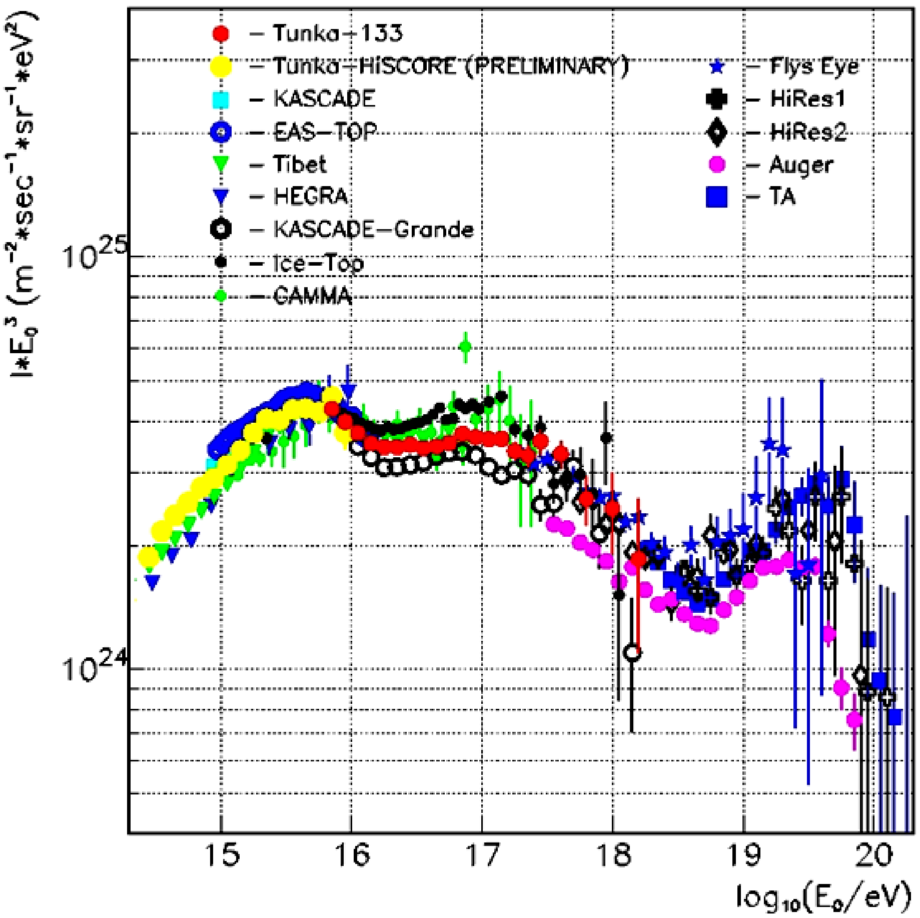


Fig.13. TUNKA-25 and TUNKA-133 and TAIGA-HISCORE.

Selected publications

*Prosin V.V., et al., (Tunka Collaboration) NIM A **756**, 94 (2014)*
Prosin et al., (TAIGA Collaboration) EPJ Web of Conferences 121, 03004 (2016)

6.4. Muon radiography

(Skobeltsyn Institute of Nuclear Physics of Lomonosov Moscow State University)

Cosmic rays, traditionally a source of information about processes in outer space, also make it possible to study the physical processes taking place on the Earth. The study of muon fluxes of cosmic origin formed the basis of a method of muon radiography (MR) —a method of nondestructive monitoring based on the "transmission" of an object by muon radiation and recording of radiation transmitted through this object. Analysis of the peculiarities of the passage of cosmic-muon fluxes through matter makes it possible to investigate the internal state of large natural and industrial objects on the Earth's surface and in its stratum, which are either an object of scientific or applied research or a source of potential danger to the surrounding infrastructure. The method of muon radiography makes it possible to obtain a two-dimensional or three-dimensional image of the objects under study.

On the surface of the Earth there is a large number of problem geological and industrial zones, the state of which poses a serious threat to the environment and social infrastructure and requires continuous monitoring. The proposed method makes it possible to detect regions of increased or lower density in the mass of the object under study by comparing the degree of absorption of cosmic muons by its various parts. The method can be used both for monitoring large natural objects — volcanoes (see Fig. 16), geological plates, etc., and for non-destructive testing of industrial facilities — mines and mining plants, nuclear reactors (see Fig.17), production and construction sites (tunnels, dams, blast furnaces, bridge supports, etc.), for monitoring fire-hazardous coal-dust dumps, for analyzing seismic processes, and as a promising addition to geophysical methods for mineral exploration.

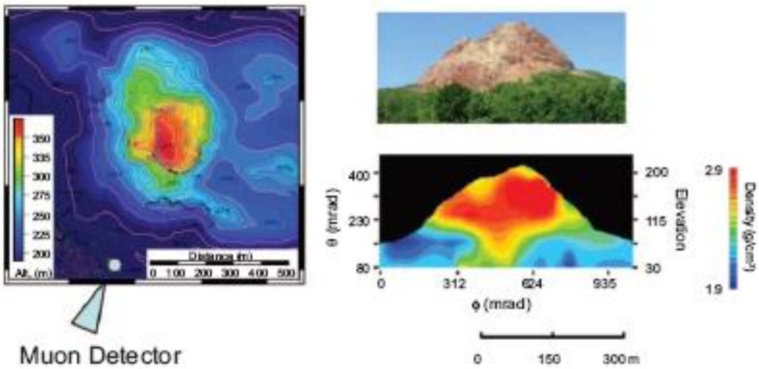


Fig.16. Radiographic image of the volcanic crater under the lava dome. On the left is a map of the lava dome and the position of the muon detector. To the right is the view of the volcano and the distribution of rock density in the vertical plane, obtained by the MR method.

Emulsion track detectors provide the best angular resolution (several milliradians) among all the detectors used in unilateral muon radiography. None of the currently known detectors of elementary particles can provide the spatial resolution that the nuclear emulsion gives: at a grain size of 0.3–1 micron, the deviation of the grains from the reconstructed particle trajectory on average does not exceed 0.8 microns, and under certain conditions can be 0.2 microns. Emulsion films, which are the basis of MR detectors, do not require power supply and an electronic reading system, which is an essential advantage in the difficult experimental conditions.

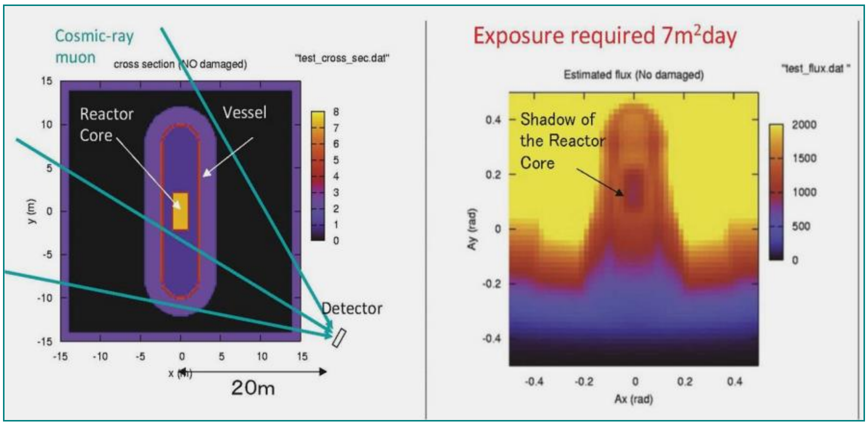


Fig. 17. Muon tomography of a nuclear reactor. To the left is the possible location of the detector during muon tomography and the trajectory of muons. On the right is an angular scan of the results of the muon tomography after exposure of 7 m2·day (the active zone of the reactor is visible, no damage was detected).

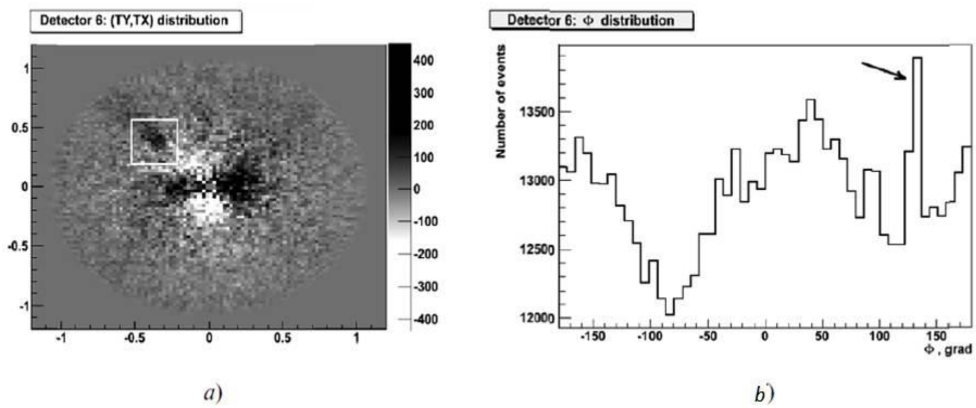


Fig.18. Visible signal from the elevator shaft and heterogeneities in the ground during an experiment in a research geophysical mine in Obninsk. a) the two-dimensional angular distribution of the muon flux at a depth of 30 m after subtracting the background averaged over the angle φ; b) the distribution of muon fluxes at a depth of 30 m along the azimuthal angle φ (the peak around 135^o corresponds to the diection of the elevator shaft, which is separated by a white square in Fig.18a).

The staff of SINP MSU and LPI conducted a number of test experiments with the goal of introducing the muon radiography method using nuclear emulsions as detectors. The processing of the emulsion data was carried out on the complexes of measuring equipment of SINP MSU and LPI, equipped with high precision optical tables and high-resolution digital video cameras for recording and digitizing optical images. The analysis of the results of test experiments has shown that the emulsion track method allows obtaining information on the structural features of the massive industrial and natural objects under investigation (Fig.18). Model calculations of inhomogeneities in the structure of objects and spatial distributions of muon fluxes, measured in test experiments, in general give good agreement.

Thus the work with the results of the analysis of experimental data and calculations on muon radiography provides the possibility and prospects for the development of the muon radiography method with use of emulsion track detectors in Russian institutes having facilities for scanning and processing emulsion data.In the SINP MSU urther work is being done for acquisition and development of the MR method, optimization of automatic scanners operation, for analysis ofexperimental data and model calculations for MP, here are planning new experiments that reveal the capabilities of this technique.

Selected publications

Aleksandrov A.B., Baklagin S.A., Galkin V.I., Grachev V.M., Vladimirov M.S., Zemskova S.G., Konovalova N.S., Managadze A.K., Polukhina N.G., Roganova T.M., Starkov N.I., Tyukov V.E., Chernyavsky M.M., Shchedrina T.V. Using Muon Radiography to Study the Structure of Massive Objects. Bulletin of the Russian Academy of Sciences: Physics, 2017. Vol. 81. № 4. PP. 500-502.Andrey Aleksandrov, Alexander Bagulya, Sergei Baklagin, Mikhail Chernyavsky, Vladimir Galkin, Victor Grachev, Nina Konovalova, Alexander Managadze, Natalya Polukhina, Tatiana Roganova, Nikolai Starkov, Tatiana Shchedrina, Valeri Tioukov, Mykhailo Vladymirov, Svetlana Zemskova. Experiments on muon radiography with emulsion track detectors. EPJ Web of Conferences. 2016. Vol. 125, P. 02022.Baklagin S.A., Grachev V.M., Konovalova N.S., Malovichko A.A., Managadze A.K., Polukhina N.G., Roganova T.M., Starkov N.I., Tyukov V.E., Shchedrina T.V. Large Industrial and Natural Objects Investigation by the Muon Radiography on the Basis of Track Detectors. International Journal of Innovative Research in Science, Engineering and Technology. 2016. Vol. 5. № 7. PP. 12229-12236.

6.5. Modelling of hadronic interactions

(Skobeltsyn Institute of Nuclear Physics of Lomonosov Moscow State University)

The recent results of the very precise measurements of the primary cosmic protons and helium nuclei energy spectra by AMS-02, PAMELA, CREAM, ATIC-2 and some other collaborations and some rather accurate estimates of these proton and helium nuclei energy spectra generated in SNR allow us to elaborate the new high accuracy original approximation of the primary nucleon energy spectra. As the accuracy of this approximation is rather high we can use it to test various models of hadronic interactions with the help of atmospheric muon energy spectra. The atmospheric vertical muon energy spectra have been calculated in terms of the EPOS LHC, QGSJET01, QGSJETII-03 and QGSJETII-04 models in the energy range of 10^2–10^5 GeV with help of the CORSIKA package and this new approximation of the primary nucleon spectrum. Results of calculations have been compared with the muon spectra observed by collaborations L3+Cosmic, LVD and MACRO. The analysis has shown that all models predict approximately two times lower intensity of the muon energy spectra. As these muons are products of decays of the most energetic π and K mesons in the atmosphere, we can conclude that production of these π and K mesons is approximately two times underestimated by the EPOS LHC, QGSJET01, QGSJETII-03 and QGSJETII-04 models. Figures 19 and 20, where calculated muon spectra and data are shown, illustrate clearly these results.

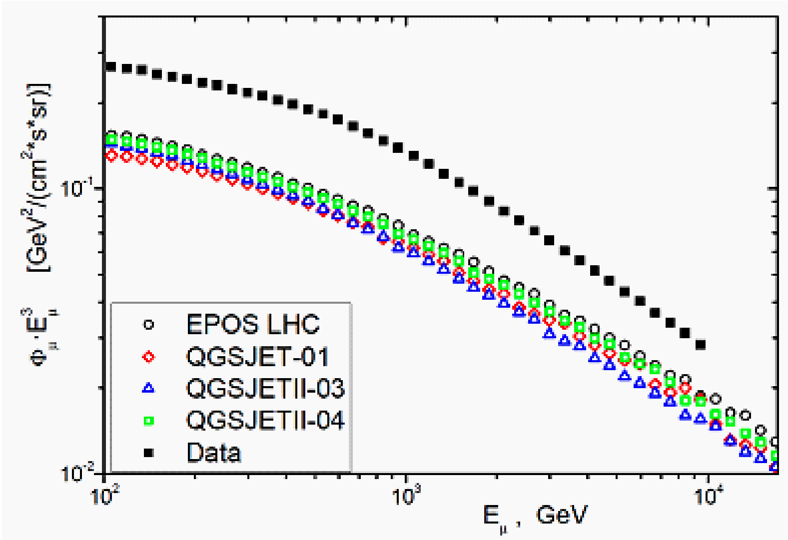


Fig.19. Calculated vertical atmospheric muon spectra and data.

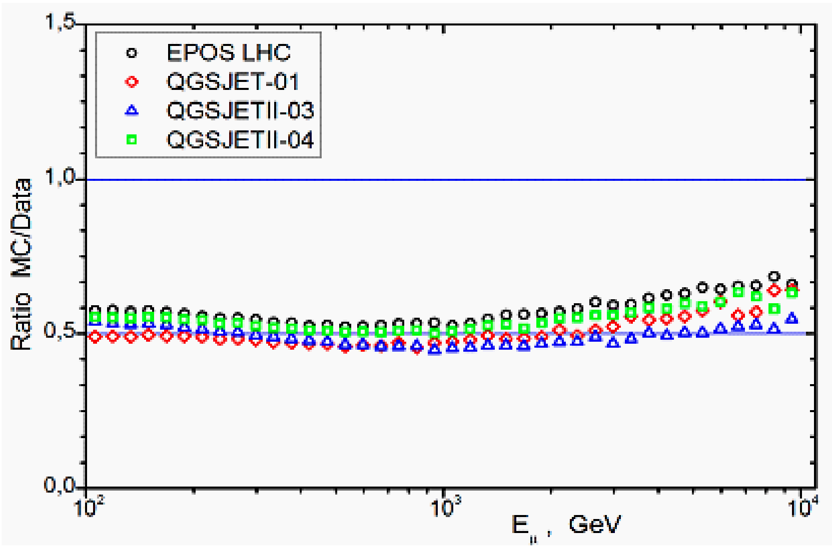


Fig.20. Ratio of calculated muon spectra to data.

These models may be used to simulate extensive air showers and some recommendations due to this testing should be elaborated. In order to solve many fundamental problems of cosmic-ray physics in the super high energy region it is necessary to determine the direction of arrival, nature, and energy of the primary cosmic radiation (PCR). The aim is to study interactions betweenPCRparticles and atomic nuclei in the atmosphere, searching for various possible manifestations of a new physics at energies far above those attained at the Large Hadron Collider, elucidating the acceleration mechanisms and sources of cosmic rays. The investigation method at the super high energy region consists in observations of signals in various detectors from secondary particles of extensive air showers. New formulas for estimating the energy of inclined extensive air showers on the basis of signals in detectors have been suggested. The detailed tables of such signals induced in scintillation detectors by photons, electrons, positrons, and muons have been calculated with help of the GEANT4 package. The parameters appearing in the proposed formulas were calculated by employing the CORSIKA package. It was shown that that calculated estimates of energy allow to decrease the intensity of cosmic ray observed at the Yakutsk array to the level which is comparable within errors with the intensity observed at the Telescope array. The mystery of the Extremely High Energy Cosmic Rays should be disclosed.

Selected publications

Dedenko L.G., Lukyashin A.V., Roganova T.M., Fedorova G.F. Calculating Vertical Atmospheric Muon Energy Spectra for Energies Ranging from 10^2 to 10^5 GeV. Bulletin of the Russian Academy of Sciences: Physics, 2017, V. 81, № 4, p. 496-499.

Dedenko L.G., Roganova T.M., Fedorova G.F. New Energy Estimates of Extensive Air ShowersUsing Signals Detected at Great Distances from the Shower Axis. MOSCOW UNIVERSITY PHYSICS BULLETIN, 2017, V.72, № 2, p. 187-190.

Anyutin N.V., Dedenko L.G., Roganova T.M., Fedorova G.F. New Estimates of Extensive-Air-Shower Energies on the Basis of Signalsin Scintillation Detectors. Physics of Atomic Nuclei, 2017, V. 80, № 2, p. 260-265.

Dedenko L.G., Lukyashin A.V., Roganova T.M., Fedorova G.F. Testing of the DPMJET and VENUS hadronic interaction models with help of the atmospheric muons. Journal of Physics: Conference Series, 2017, V. 798, p. 012045-012045+4.

6.6. TAIGA experiment

(Skobeltsyn Institute of Nuclear Physics of Lomonosov Moscow State University)

Currently, employees of SSD/SINP/MSU together with collaboration complete testing of the recording camera of the first atmospheric Cherenkov gamma-telescope with image analysis (Imaging Atmospheric Cherenkov Telescope) of TAIGA observatory (TUNKA Advanced Instrument for cosmic rays and Gamma Astronomy). The camera includes 560 PM’s and has a large enough viewing angle of 10° × 10° for Cherenkov telescopes. This viewing angle allows you to get "images" from the shawls with the axis position up to 500 m from the telescope.

The telescope itself, manufactured at JINR, is now already in the TUNKA valley and scientists and engineers of the Irkutsk University are doing everything possible to make the telescope work successfully during the cold Siberian winter. The recording camera will be sent to Irkutsk on November 8 and there is a reason to hope that the first "images" of the shawl will be received until the New year and it will be possible to begin tracking the source of gamma quanta in the Crab nebula.

By the beginning of the 2017-2018 winter season, the prototype of the observatory will consist of 60 wide-angle stations located on an area of 0.6 km^2 and one telescope. The expected integral sensitivity of the prototype at 200 hours of observation of the source(about 2 seasons of operation of the unit) in the range 30

– 200 TeV about 10-12 erg/(cm^2 sec), which approximately corresponds to the integral sensitivity of the HAWC unit in this energy range for 5 years of operation.

Selected publications

N.Budnev et al (TAIGA collaboration)// Journal of Instrumentation, Institute of Physics (United Kingdom), V 12, № 08, c. 08018-1-08018-17
N.Budnev et al (TAIGA collaboration) //NIM A, V 845, P. 330-333
Gress O, et all (TAIGA collaboration // NIM A, V 845, P. 367-372
Monkhoev R.D. et al (TAIGA Collaboration) // Journal of Instrumentation, Institute of Physics (United Kingdom), V 12, № 6, P. 06019

6.7. Cascade effects modelling for extragalactic gamma-ray propagation

(Skobeltsyn Institute of Nuclear Physics of Lomonosov Moscow State University)

The Universe is filled with extragalactic background light (EBL) and cosmic microwave background (CMB) photons. In the last 10 years EBL models became much more reliable and realistic, allowing for detailed study of extragalactic gamma-ray propagation processes. A vast majority of works in this area considered only two elementary processes: the absorption of primary gamma-rays on EBL photons and adiabatic losses (“the absorption-only model”). However, in the last years several indications have appeared that the absorption-only model is incomplete and must be modified in some way.

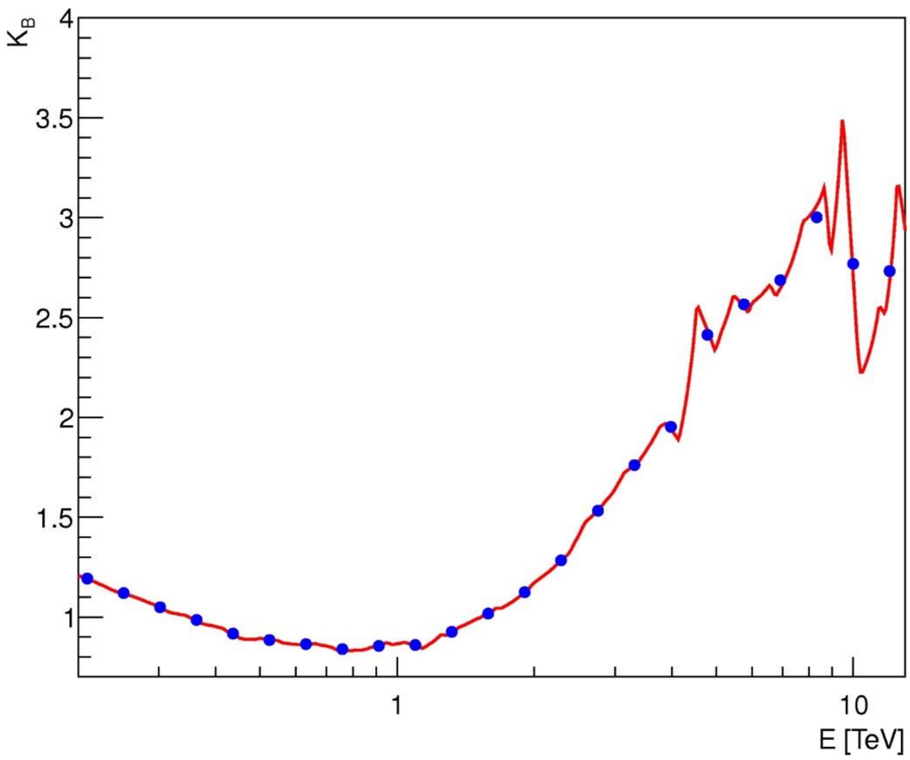


Fig. 24. Statistical significance corresponding to various hadronic cascade models.

The electromagnetic cascade model predicts four main signatures in blazar spectra (in the order of decreasing energy): 1) a high-energy cutoff; 2) an "ankle" at the intersection of the primary and cascade components; 3) a possible cutoff at a comparatively low energy ("the magnetic cutoff") as a result of the deflection of cascade electrons by the extragalactic magnetic field (EGMF); 4) a "second ankle" at the intersection of the primary and cascade components.

An astrophysical interpretation of the effect was suggested, that consists in the observation of blazars with relatively hard spectra in the energy region 10-300 *GeV* predominantly from directions to voids in the Large Scale Structure. This effect might be explained by the appearance of a cascade component, dominating the observable spectrum in the energy range E<1 *TeV*. In Fig.25. an approximation of the observable SED of blazar 1ES 1218+304 is shown, including the Fermi-LAT data in the energy range E<200 *GeV*. The notions are generally the same as in Fig.24; in addition green dashed curve denotes the spectrum with account for the EGMF influence (10^{-15}*Gs* at the coherence scale of 1 *Mpc*), red dashed curve — the sensitivity of Fermi-LAT (10 years of observation), cyan dashed curve — the sensitivity of atmospheric Cherenkov telescope array H.E.S.S. (100 hours of observation), blue and magenta dashed curves — the sensitivity of atmospheric Cherenkov telescope array CTA (100 and 1000 hours of observation, respectively).

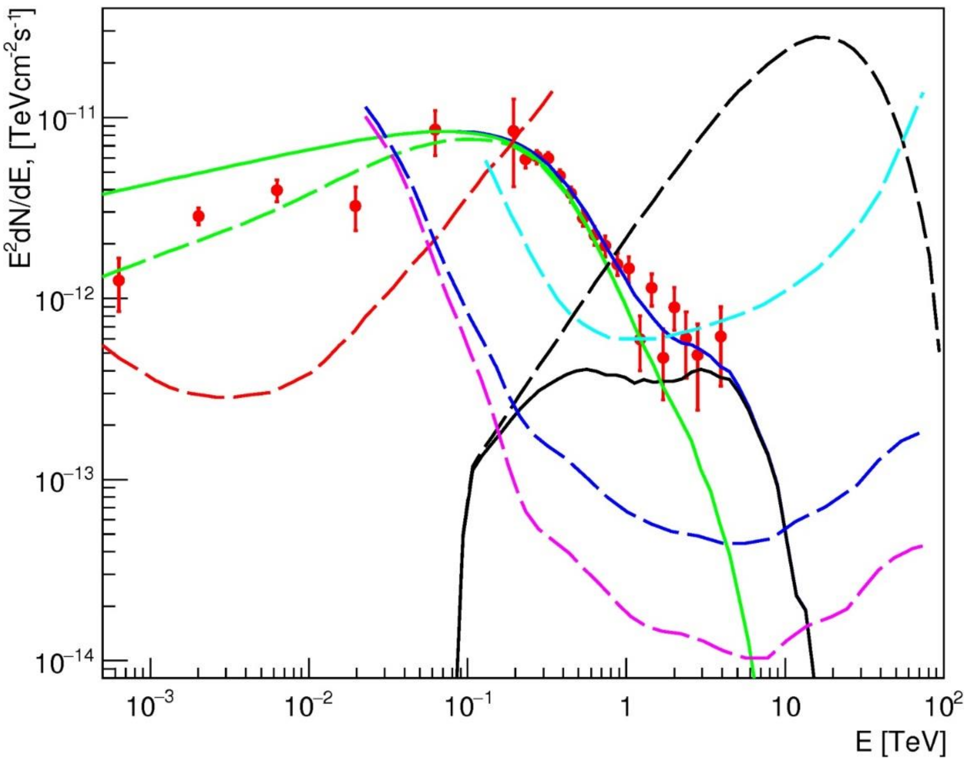


Fig.25. Approximation of observable SED of blazar 1ES 1218+304 (z= 0.182), demonstrating "the magnetic cutoff effect.

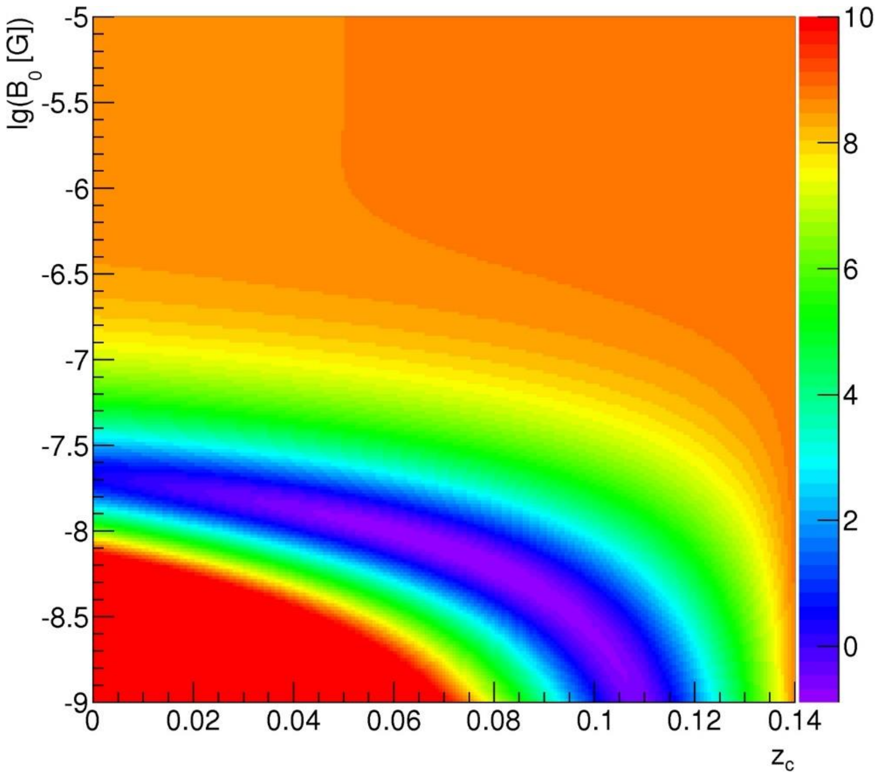


Fig. 26. Statistical significance corresponding to various hadronic cascade models.

Using some observational results it was shown that the emission model of blazar 1ES 0229+200 (*z*= 0.14) does not allow to obtain the observable intensity of gamma-rays in the framework of the "basic hadronic model", that assumes the production of all observable gamma-rays by cascades from primary protons of ultra-high energy on the way from the source to the observer (Fig.26.) where z_c is redshift of the cluster of galaxies in the model with structured EGMF, B_0 — magnetic field intensity in the center of the local structure around the blazar.

Selected publications

T. A. Dzhatdoev, E. V. Khalikov, A. P. Kircheva and A. A. Lyukshin.Electromagnetic cascade masquerade: a way to mimic gamma-axion-like particle mixing effects in blazar spectra, A&A, 2017, ***603****, A59*

S.A. Baklagin, T.A. Dzhatdoev, A.P. Kircheva et al. Cascades from Primary Gamma Rays and Nuclei as a Source of Background in Searches for Oscillations between Photons and Axion-like Particles, Phys. Part. Nucl., 2018, ***49****, 90*

T.A. Dzhatdoev, A.P. Kircheva, A.A. Lyukshin and E.V. Khalikov. Signatures of blazar spectra in the electromagnetic and hadronic intergalactic cascade models, Bull. Rus. Acad. Sci., 2017, ***81****, 443.*

6.8. OPERA experiment

(Skobeltsyn Institute of Nuclear Physics of Lomonosov Moscow State University)

In 2016-2017, the physical analysis of the OPERA neutrino experiment on searching for oscillations $\nu_\mu \rightarrow \nu_\tau$ was continued. The measurements of the emulsion material on the scanning complex of the SINP/MSU were carried out, and the features of the topology of the recorded events were studied. A total of 67 emulsion blocks (bricks) were scanned, the emulsion area of which was ~ 37 m^2. In the present in the OPERA experiment five candidate events with the creation of a lepton have been found by the collaboration, that proves the existence of oscillations along the channel. Parameter of oscillations for 5 candidates $\Delta m_{23}^2 = 2.44 \cdot 10^{-3} eV^2$ in the case of complete mixing ($\sin^2 2_{23}=1$).

The main results of the OPERA collaboration:

• The only background hypothesis (in the $\nu_\tau$search problem) was rejected at the level of statistical significance 5.1 σ.

• The search for oscillations by the channel.

• Restrictions have been imposed on the mixing of active neutrinos with sterile ones.

• Based on the analysis of muon spectrometer data, the ratio $R_\mu \equiv N_{\mu+}/N_{\mu-}$ for atmospheric muons is measured.

At the collaboration meeting it was decided to organize access to the database of neutrino events (i.e. to the information about all the characteristics of particle tracks corresponding to ~ 6700 neutrino interactions).

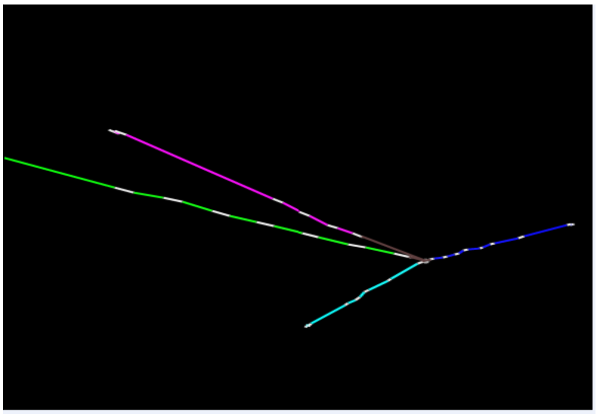


Fig.27. An example of found vertex.

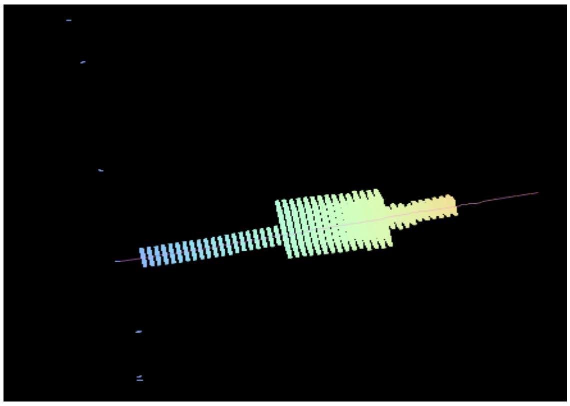


Fig.28. An example of tracing a track passing though all layers of an emulsion block (brick).

In 2017 the main efforts at SINP MSU were aimed at analyzing the interesting event that we detected while scanning the emulsion block 1006651. The event is shown in Fig. 29. On the sidebar, with a larger magnification, two peaks are shown, that is, there apparently was a short-lived particle that was born at point 1 (the neutrino interaction point) and disintegrated at point 2 with the creation of new particles.

Such a short-living particle can be a lepton (then this event can be one of the oscillatory ones) and a charmed meson (such events are considered by the OPERA collaboration as background ones).

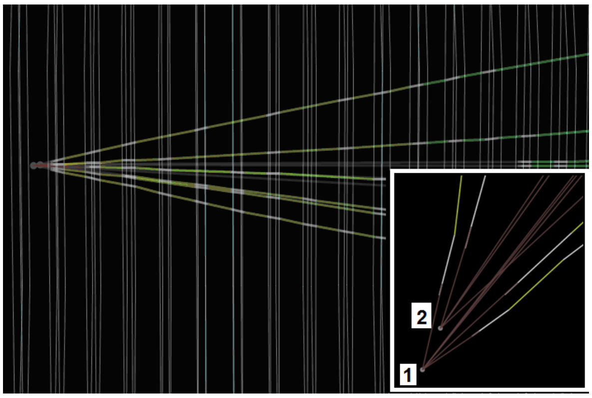


Fig.29. The event from emulsion block 1006651.

For event analysis its complete kinematic analysis is carried out. For that purpose in 2017 the bank of events was created for the interactions of the muon neutrino and the taon neutrino with a lead target using the modern neutrino interaction generator GENIE2.12.0. The scheme of carrying out of particles through elements of the emulsion block by means of program complex GEANT4.10.0 is debugged. Simulation of decays of taons or a charmed meson is performed using the PYTHIA6 software module. Currently the procedure of processing simulation results is being debugged for carrying out a multivariate analysis of the found two-vertex event and estimating the probability that the event is the interaction of appeared as a result of the oscillations.

Selected publications

Anokhina A., Dzatdoev T., Podgrudkov D., Roganova T.,et.al. (The NEWS Collaboration) NEWS: Nuclear Emulsions for WIMP Search, 2016. ArXiv e-prints 1604 04199.

Anokhina A., Dzatdoev T., Morgunova O., Roganova T., et.al. (The NEESSiE Collaboration). Search for Ste-rile Neutrinos in Muon Neutrino Disappearance Mode at FNAL, 2017. AarXiv.org/ hep-ph, V. 1503. № 07471,P. 1-19.

Anokhina A., Dzatdoev T., Morgunova O., Roganova T., et.al. (The NEESSiE Collaboration). Search for Ste-rile Neutrinos in Muon Neutrino Disappearance Mode,2017. European Physical Journal C, V. 77, P. 1-19.

Anokhina A., Dzatdoev T., Podgrudkov D., Roganova T., (OPERA Collaboration). Studyofcharged hadron multiplicities in charget-current neutrino-lead interactions in the OPERA detector. 2017. Arxiv e-prints.
№ 1706.07930,P.1-8
Acmete A.,Anokhina A., Chepurnov A., Dedenko L., Fedorova G.,Podgrudkov D., Roganova T., et al. The Active Muon Shield in the SHiP. Experiment. Journal of Instrumentation, 2017. V. 12. №5.P. P05011.

6.9. Effects of electromagnetic neutrino interaction and astrophysical applications

(Skobeltsyn Institute of Nuclear Physics of Lomonosov Moscow State University)

It was known that when moving in a medium, a massive neutrino can emit electromagnetic radiation due to a nonzero magnetic moment - the so-called spin neutrino light. In this current work, an analysis is made of the possibility of generating spin neutrino light in certain astrophysical media. It was shown that in the dense matter of neutron stars and short gamma-ray bursts there is a “window” in the set of parameters (matter density, electron fraction, neutrino energy) for which the radiation is allowed. The efficiency of generation is shown to be significant and thus one can expect that this type of radiation can be detectable from these objects.Within the framework of the standard scheme for description of spin-flavor neutrino oscillations, a rigorous derivation of the neutrino evolution equation in a magnetic field is given based on the matrix of neutrino magnetic moments defined in the mass basis. This approach enables to relate these fundamental neutrino parameters to the electromagnetic characteristics of physical neutrinos in the flavor basis and mixing parameters (mixing angle). Also, it explicitly takes into account the longitudinal component of the magnetic field, which, in this way, also affects the oscillations.

Selected publications

2017 Spin light of neutrino in astrophysical environments. Grigoriev A., Lokhov A., Studenikin A., Ternov A. Journal of Cosmology and Astroparticle Physics, издательство Institute of Physics (United Kingdom), 11, № 024, с. 1-23

2016 Neutrino spin-flavor oscillations derived from the mass basis. Fabbricatore R., Grigoriev A., Studenikin A. Journal of Physics: Conference Series, издательство Institute of Physics (United Kingdom), 718, с. 062058

6.10. Modelling of planets' magnetospheres

6.10.1. Development of universal paraboloid model of margetosphere

(Skobeltsyn Institute of Nuclear Physics of Lomonosov Moscow State University)

Planetary science covers the study of our Solar System and those around other stars. It is an interdisciplinary field of research that covers astronomy and geophysics, robotic and human exploration of other planets, as well as the search for extra-terrestrial life. Europe hosts one of the largest international communities of planetary scientists, with over 800 tenured academics and around 3000-4000 young researchers in more than 200 research groups/institutions, spread across nearly all European national states. The Europlanet 2020 Research Infrastructure (EPN2020-RI) is a pan-European project to support world-leading planetary research and build a bigger, stronger and more collaborative European planetary community. It is engaging a wide range of stakeholders (including policy makers, industry, amateur astronomers and the public) with the achievements, ambition and opportunities of European planetary research. EPN2020-RI is coordinated by the Open University, UK, and has 35 beneficiary institutions (including SINP /MSU) from 20 European countries (including Russia) and more than 160 participating individuals. The main contribution of the SSD/SINP/MSU team to the joint work, regulated by this agreement, consists in providing access to the *Universal Paraboloid Planetary Magnetosphere Model*, which can be used for the description of the magnetospheres of Mercury, Earth, Jupiter and Saturn's. The *Universal Paraboloid Planetary Magnetosphere Model*will be used mainly for the implementation of *PSWS (Planetary Space Weather Service)* and *VESPA (Virtual European Solar and Planetary Access)*, which are parts of EPN2020-RI.

Selected publications

T. J. Bradley, S. W.H. Cowley, G. Provan, G. J. Hunt, E. J. Bunce, S. J. Wharton, I. I. Alexeev, E. S. Belenkaya, V. V. Kalegaev, and M. K. Dougherty. Field-aligned currents in saturn's nightside magnetosphere: Subcorotation and planetary period oscillation components during northern spring. Journal of Geophysical Research: Space Physics, 123(4), 2018.

Luis Ballester Jose, Alexeev Igor, Collados Manuel, Downes Turlough, Robert F. Pfaff, Gilbert Holly, Khodachenko Maxim, Khomenko Elena, Ildar F. Shaikhislamov, Soler Roberto, Vazquez-Semadeni Enrique, and Zaqarashvili Teimuraz. Partially ionized plasmas in astrophysics. Space Science Reviews, 214(2):58–207, 2018.

Elena Belenkaya, Stanley Cowley, Igor Alexeev, Vladimir Kalegaev, Ivan Pensionerov, Marina Blokhina, David Parunakian, Open and partially closed models of the solar wind interaction with outer planet magnetospheres: The case of Saturn. Annales Geophysicae (35)6, 1293-1308, 2017

Hunt G.J., Cowley S.W.H, Provan G., Bunce E.J., Alexeev I.I., Belenkaya E.S., Kalegaev V.V., Dougherty M.K., Coates A.J., Field-aligned currents in Saturn's magnetosphere: Local time dependence of southern summer currents in the dawn sector between midnight and noon. Journal of Geophysical Research (121)8, 7785-7804, 2016

6.10.2. Simulation of Mercury's magnetosheath with a combined hybrid-paraboloid model

(Skobeltsyn Institute of Nuclear Physics of Lomonosov Moscow State University)

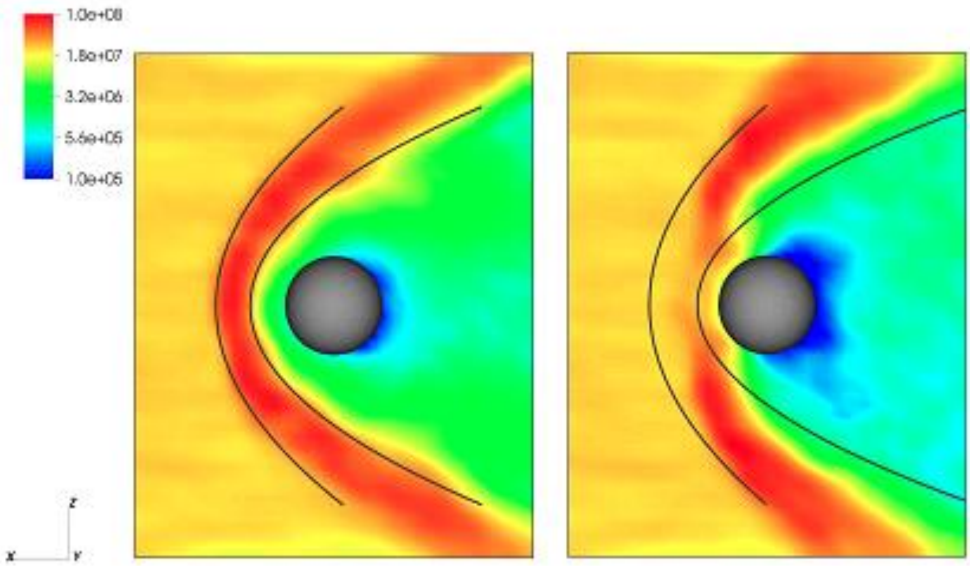


Fig. 46. Results of modelling of Mercury's magnetosphere for northward (left) and southward (right) directions of interplanetary magnetic field.

Selected publications

Igor Alexeev, David Parunakian, Sergey Dyadechkin, Elena Belenkaya, Maxim Khodachenko, Esa Kallio, Markku Alho, Calculation of the Initial Magnetic Field for Mercury's Magnetosphere Hybrid Model. Cosmic Research (English translation of Kosimicheskie Issledovaniya) (56)2, 108-114, 2018

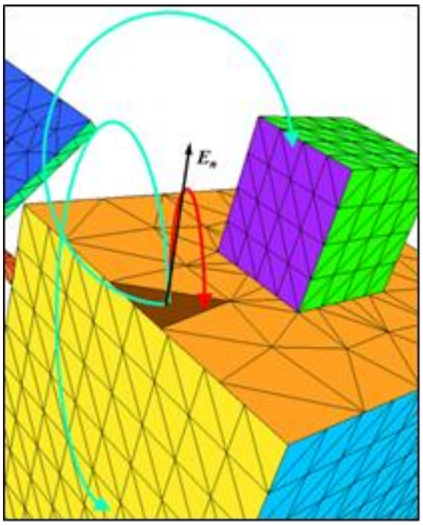
Parunakian David, Dyadechkin Sergey, Alexeev Igor, Belenkaya Elena, Khodachenko Maxim, Kallio Esa, and Alho Markku. Simulation of mercury's magnetosheath with a combined hybrid-paraboloid model. Journal of Geophysical Research: Space Physics, 122(7), 2017.

6.11. Space Environment Modeling and Space Materials

6.11.1. Modeling of spacecraft charging in geosynchronous orbit

(Skobeltsyn Institute of Nuclear Physics of Lomonosov Moscow State University)

Secondary emission (SE) electron currents near the differentially charged spacecraft, and dynamics of the spacecraft charging in hot magnetosphere plasma were investigated using the COULOMB-2 program complex developed in SSD/SINP/MSU.



Influence of the spacecraft electric field on secondary electron currents was analyzed in terms of computation of secondary electron trajectories. Modeling of the emitted electron trajectories in the electric field of the charged spacecraft having complex surface configuration enables to compute full electron current correctly, and use the value in the electric current balance equation solution for every spacecraft surface element.

Two manners of the computation above were proposed: electron recollection (ER) and SE suppression. ER is the emitted electron transfer from one surface element to another (blue lines in the figure), so the recollected electrons factors which are computed in COULOMB-2 by modeling of secondary electron trajectories in the spacecraft electric field are added into the current balance equation.

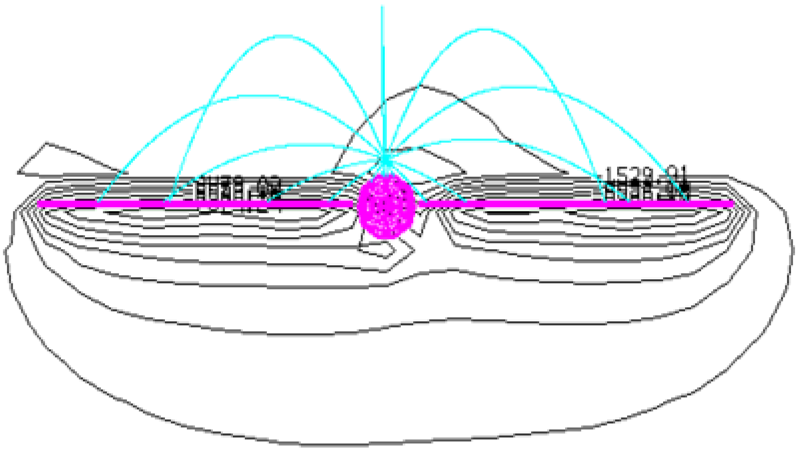


Fig.61. Secondary electron trajectories near the charged spacecraft.

SE suppression corresponds to the case of high local electric field values, so the probability of the emitted electron transfer to another surface elements is low. Criteria of the SE suppression model applicability is used in the COULOMB-2 procedure for the spacecraft charging modeling.

Modeling of spacecraft charging process (charging dynamics) was carried using the COULOMB-2 code out via numerical solution of differential equations describing time variations of the local electric charge on every spacecraft surface elements and of the spacecraft metal frame full charge. Primary currents of plasma particles are computed using Langmuir equations. Secondary emission currents caused by primary electron currents, and photoelectron emission current are computed using the ER factors and SE suppression model above.

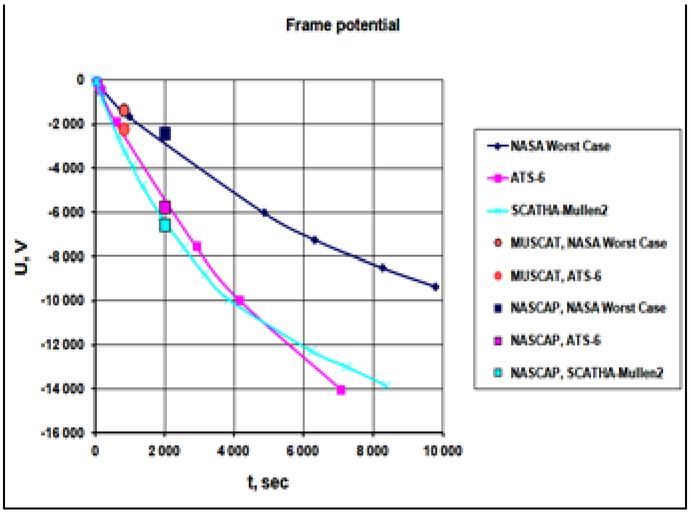


Fig.62. Electric potential of the spacecraft metal framein various charging cases.

Electric potentials of the spacecraft metal frame computed for typical sets of the hot plasma parameters (NASA Worst Case, ATS-6, and SCATHA-Mullen2). Typical charging time is ~ (3–5)x10^4 s.Comparison of the COULOMB-2 results with ones obtained using the NASCAP and MUSCAT codes gives the good agreement. Note that the discrepancy arises for various surface elements which have complicated shape, so the computation is very sensitive to the electric field and SE computation models.

Selected publications

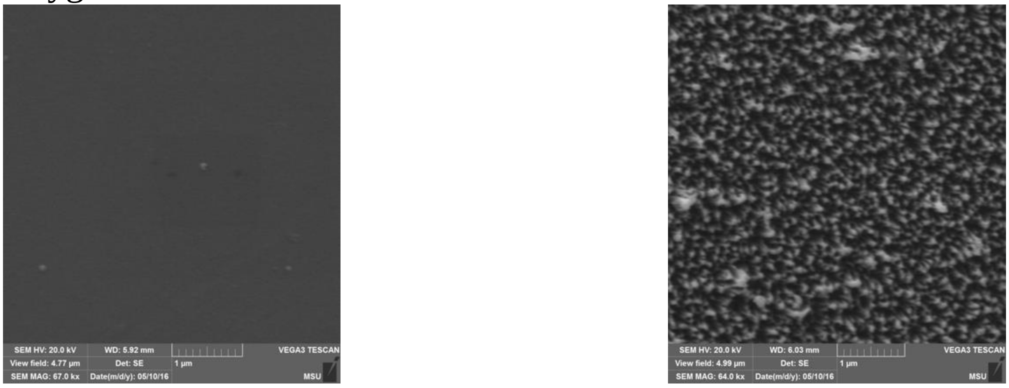
Novikov L. S., Makletsov A. A., Sinolits V. V. Comparison of Coulomb-2, NASCAP-2K, MUSCAT and SPIS codes for geosynchronous spacecraft charging // Adv. Sp. Research, vol. 57, No. 2, pp. 671-680, 2016.

Novikov L. S., Makletsov A. A., Sinolits V. V. Modeling of spacecraft charging dynamics using COULOMB-2 code // IEEE Transactions on Plasma Science, vol. 45, No. 8, pp. 1915–1918, 2017.

Novikov L. S., Makletsov A. A., Sinolits V. V. Analysis of recollection and transfer of electrons emitted from charged spacecraft surface using COULOMB-2 code // IEEE Transactions on Plasma Science, vol. 45, No. 8, pp. 1919–1922, 2017.

6.11.2. Combined impact of 500 keV protons and atomic oxygen on polyimide films
(Skobeltsyn Institute of Nuclear Physics of Lomonosov Moscow State University)

For space conditions, laboratory investigation of combined impact of 500 keV protons with fluences of 10^{15}–10^{16} cm^{-2} and atomic oxygen with fluences of (0.8–3.5)x10^{20} cm^{-2}on polyimide (PL) films were made. The results of the experiments have shown that prior proton irradiation leads to increase in the erosion yield of the polyimide samples by 10–15%, i.e. to a certain decrease in their durability to atomic oxygen erosion.



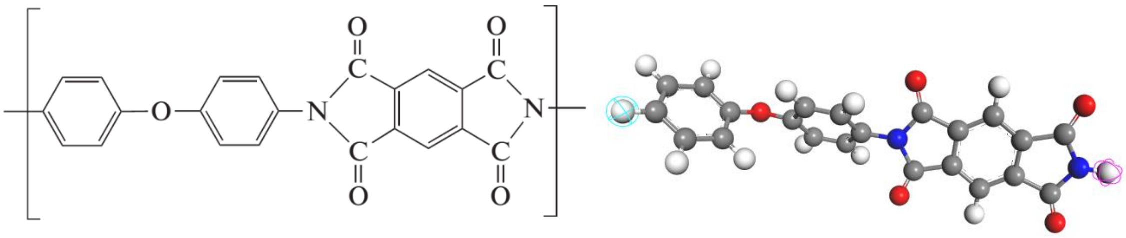
a b

Fig. 63. SEM images of the surface of PI specimens before (a) and after (b) oxygen exposure and proton irradiation with fluence 2.5x1015 cm^{-2}.

Proton irradiation at given fluences also causes a significant reduction of spectral transmittance in the visible range. This effect can be explained by carbonization of near-surface layers of carbon-rich polymers. Changes in spectral transmittance of specimens after oxygen plasma exposure were caused by two mechanisms: carpet-like relief leading to increase of light scattering, and removal of colored layer from the film surface. In the case of the full removal of damaged layer, for specimens which were non-irradiated or irradiated with relatively small proton fluences, oxygen exposure decreases the transmittance whereas samples irradiated with higher proton fluences the transmittance recovery was observed. Raman spectra of specimens after 500 keV proton irradiation indicate not only C–N and C=O bond breaking but the formation of graphitic nanoclusters. High-resolution C1s, O1s and N1s XPS spectra of pristine and irradiated samples show the gradual rise of aromatic C–C bonds and the corresponding decrease of C–O–C, C=O and C–N bonds. Comparison of the surface composition obtained on the base of XPS analysis and deconvoluted C1s, O1s and N1s peaks after proton and oxygen irradiation demonstrates the significant difference in mechanisms of 500 keV protons and atomic oxygen interaction with polyimide materials.

Fig. 64. Smoothed Raman spectra of the pristine (PI1) and proton irradiated specimens (PI2–PI5) with fluences of (1.0; 2.5; 5.0; 7.5)x1015 cm^{-2}*, respectively.*

Mathematical modeling of some processes occurring in polyimide under the influence of atomic oxygen was produced.



a b

Fig.65. PMDA-ODA chemical structure (a) and a computer model of PI monomer (b).

Selected publication

Novikov L. S., Voronina E.N., Chernik V.N., Zhilyakov L.A., Chirskaya N.P. Combined impact of 500 keV protons and oxygen plasma on polyimide films. Nuclear Instruments and Methods in Physics Research, Section B: Beam Interactions with Materials and Atoms, vol. 410, p. 60-67, 2017.

Novikov L. S., Voronina E.N., Chernik V.N., Vernigorov K.B., Yablokova M.Yu. Atomic oxygen influence on polymer nanocomposites with different fillers. Journal of Spacecraft and Rockets, vol.53, No 6, p. 1012-1018, 2016.

6.11.3. Modeling of the risk of single event upsets from cosmic particles for memory with error correction

(Skobeltsyn Institute of Nuclear Physics of Lomonosov Moscow State University)

Memory microchips onboard spacecraft are exposed to the risk of single event upsets (SEU), i.e. changing of the state of 1 memory bit, caused by the hit of energetic particle of space origin, or secondary particles, generated by the primary particles in the spacecraft materials. The main risk comes from the fluxes of energetic protons and ions from powerful solar flares, and the protons of radiation belts.

At the same time, there exists a technology of error checking and correction (ECC), which allows to detect and correct errors in 1 or more bits in a memory block by storing for each data block additional “control” bits. This technology is sufficiently standard for the ground-based devices, and is also used in space. The simple variant of technology allows to correct error in 1 bit and detect errors in 2 bits in memory block (Hamming code).

With the use of this technology onboard spacecraft, for the parameter of the memory sensitivity to SEUs one should consider not the error frequency itself, but the probability of error, which could not be detected or corrected using ECC, i.e. occurring of >1, >2 and so on errors in at least one memory block during the given time.

We have obtained formulas for computing such probability, and performed model computations of the probability of occurring of >1 and >2 errors in at least one memory block onboard spacecraft during the powerful solar flare and the flight in Earth’s radiation belts for certain operative memory microchips.

Fig. 66. a) Integral fluxes, b) number of errors in memory from protons (solid line), ions (dashed) and summarized (bold) from powerful solar flare, and from protons of Earth's radiation belts (dash-dotted). The dots show the proton fluences in solar event of 19–22 October 1989 measured by GOES-6.

Table 1. Frequency of SEUs and the probability of occurring of >1 and >2 errors in at least one memory block during the powerful solar flare; and during 1 month from protons of Earth's radiation belts in the orbit with the height 1400 km.

Shielding		Errors/ day	P(>1)	P(>2) g/cm^2
g/cm^2	mm Al			
Powerful solar flare, 1 day				
0.54	2	10000	0.2	0.54
1	3.7	4500	0.05	1
1.5	5.5	3000	0.02	1.5
Earth's radiation belt protons, 1 month				
<2	<7.4	250	0.005	<2

It was shown, that behind the shielding, equivalent to several mm Al, the technology of error correction can provide considerable level of protection from SEUs in operative memory even when using commercial SDRAM microchips.

Selected publication

Podzolko M. V., Modeling of the risk of single event upsets from cosmic particles for memory with error correction, Moscow University Physics Bulletin, v. 72, No. 6, 2017.

6.11.4. Empirical model of long-time variations of galactic cosmic ray particle fluxes

(Skobeltsyn Institute of Nuclear Physics of Lomonosov Moscow State University)

Fluxes of galactic cosmic ray (GCR) particles are essential components of Space radiation, affecting the spacecraft equipment and spaceship crews. For the purpose of predicting GCR fluxes for current and future space missions in SSD/SINP/MSU empirical models of temporal and spatial distribution of GCR fluxes are being developed. The current version of the model is based on the extensive set of data of measurements of interplanetary energetic particle fluxes onboard spacecraft and stratospheric balloons from 1970s till 2017. The model describes fluxes of GCR particles with charge z from 1 to 28 and energy from 80 MeV/nucleon up to 100

GeV/nucleon in the interplanetary space as a function of solar activity (averaged sunspot number) and the heliocentric distance. Computations of GCR fluxes for the next solar cycles 25–26 have been made with this model using the forecasts of sunspot number, assuming a possible long-term decrease in solar activity.

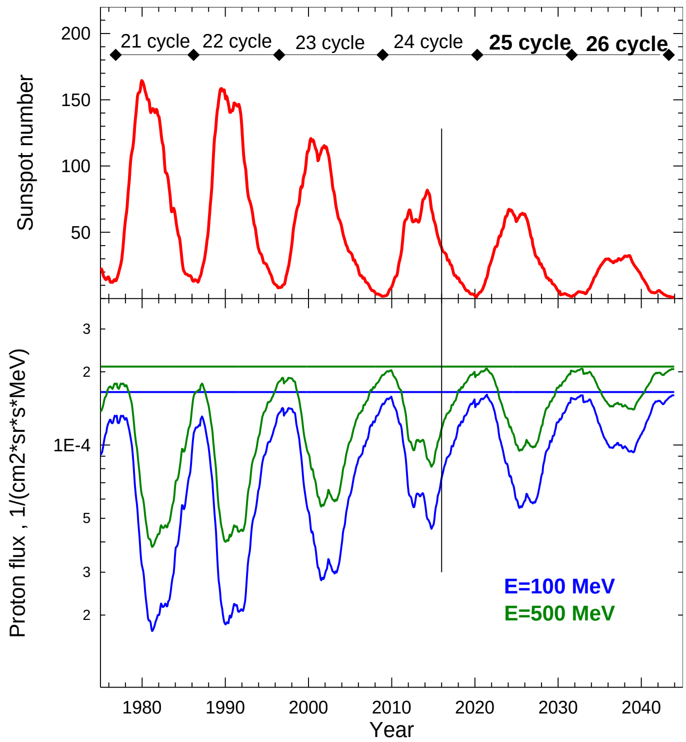


Fig. 67. The sunspot numbers (the top panel) and the GCR fluxes for proton energy E = 100 and 500 MeV (the bottom panel) versus time in the Earth's orbit. Predicted values are to the right of the vertical line. Horizontal lines are the proton fluxes (at a given energy) for the hypothetical case when W = 0.

Selected publications

Kuznetsov N.V., Popova H., Panasyuk M.I., Empirical model of long-time variations of galactic cosmic ray particle fluxes, Journal of Geophysical Research: Space Physics, 2017, 122(2), 1463-1472.

Popova E.P., Kuznetsov N.V., Panasyuk M.I., Predicting GCR Fluxes for Future Space Missions, Bulletin of the Russian Academy of Sciences: Physics, 2017, 81(2), 173-176.

Kuznetsov N.V., Popova H., Panasyuk M.I., Podzolko M.V., Empirical model of galactic cosmic ray particle fluxes based on the experimental data in solar cycles 21–24, Proceedings of Science, № 35th International Cosmic Ray Conference, 2017, PoS (ICRC2017)001.