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Abstract of Doctoral Thesis

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Cosmic-Ray Physics with the Pierre Auger Observatory

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Autoreferát dizertační práce

Radomír Šmída

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1 Thesis Overview

In contrast to photon astronomy, astroparticle physics has to deal in contrast to photon astronomy with charged messengers. Its attention is focused to the ultra-high energy cosmic rays (UHECRs) – cosmic rays with the energy above 10^{18} eV[1]. There are two main reasons, why UHECRs are extensively studied. First, these particles may propagate along almost linear trajectories through interstellar and intergalactic magnetic fields. Second, they could not travel more than a few tens of Mpc due to their interaction with microwave and infrared photons, if their energy is higher than 4×10^{19} eV. Therefore their sites of origin of UHECRs should be located in significantly restricted volume of the universe around our Galaxy and cosmic-ray arrival directions may even point few degrees away from their positions on the celestial sphere.

Because the flux of UHECRs is extremely low and the atmosphere is not transparent for them, they can be measured only indirectly. In the late thirties French physicist Pierre Auger with his colleagues discovered, that a primary cosmic ray initiates a huge shower of secondary particles [Aug39]. A bunch of millions or even billions produced secondary particles is called an extensive air shower. Vast majority of the secondary particles extincts during their propagation through the atmosphere, but a fraction of them can reach the ground and can be detected by a large net of sparse detectors as well-defined time coincidence signal. The second observation technique measures fluorescence light coming from the de-excitation of nitrogen molecules along the shower track. The best option is to use both detection techniques, because their combination provides significantly more information about the primary particle, which can not be achieved by using only one detection technique.

The largest observatory in the history is the Pierre Auger Observatory [Abr04]. Its construction started in 2003 and it was collecting data already during its building-up phase since January 2004. It is the first hybrid observatory, i.e. observatory combining together both surface and fluorescence detectors. Its 1 600 water Čerenkov stations cover an area of 3 000 km^2 (i.e. 30 times larger area than was the size of the previously largest experiment AGASA in Japan) in the western Argentina below Andes mountains. This area is overlooked by four fluorescence detector stations. Each station has six telescopes and they are operated during astronomical nights with the illuminated moon fraction smaller than 0.6 (i.e. one period of a fluorescence measurement consists typically of 16 days).

This doctoral thesis deals with cosmic rays at the highest energies and with the first results obtained at the Pierre Auger Observatory. Its first part describes the measurement and possible origin of cosmic rays. It starts with a brief review of the history of cosmic-ray observations and subsequently follows the description of

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[1] 1 eV $\simeq 1.602 \times 10^{-19}$ J

cosmic-ray detection. Also the acceleration and other models of cosmic-ray origin in the Universe together with the propagation of UHECRs from mysterious sources towards the Earth are discussed. We have focused particularly on a particle and antiparticle tracing at the highest energies. The propagation through novel model of the Galactic magnetic field and its interesting results, such as angular deflections for different magnetic-field components, can be found here.

The description of the Pierre Auger Observatory follows and its first results, such as cosmic-ray energy spectrum, upper limits on photon and neutrino fluxes, chemical composition and the analyses of observed cosmic-ray arrival directions are presented. Moreover, we summarize our study of space-time connection between bursting extragalactic or galactic gamma-ray sources observed by satellite experiments and cosmic rays measured by the Pierre Auger Observatory.

The other part of the thesis deals with detailed description of author's work on the fluorescence detector. We have studied performance of fluorescence telescopes during last years and the obtained results led to significant improvement of detector's performance and have been used in physics analyses. The influence of light background on the fluorescence measurement is discussed and the best conditions for the measurement of fluorescence detector are given. Further the background light exposure and its time evolution are discussed. The importance of this analysis has been essential for the protection of photomultipliers' sensitivity.

2 Ultra-High Energy Cosmic Rays

Ultra-high energy cosmic rays are unique particles because they should not be significantly deviated in either interstellar or intergalactic magnetic fields and moreover, they could not travel more than few tens of megaparsecs if their energy is higher than 4×10^{19} eV. Thus these particles are ideal for study of their origin and sources.

The limitation of their propagated distances is caused by the interaction with background radiation – cosmic microwave and infrared photons – on their journey through space. The most important is the Greisen-Zatsepin-Kuzmin effect [Gre66, Zat66], where a cosmic-ray proton interacts with a cosmic microwave photon. The proton loses through photopion production excited in such a collision typically 15% of its energy. Because the interaction is a stochastic process, there is still non-zero probability that the particle with given energy would survive travelling over a given distance. For example the probability, that protons with the energy of 6×10^{19} eV will arrive at the Earth from the source at the distance of 100 Mpc, is about 55%, but only 10% at the energy of 8×10^{19} eV [Cro05]. Heavier nuclei lose their energy even more rapidly due to photodisintegration. Generally, only protons and iron nuclei are expected to survive the propagation from extragalactic sources to the Earth.

Because the flux of cosmic rays decreases almost about three magnitudes per one magnitude in energy, and even faster above 4×10^{19} eV (see figure 2), cosmic rays can not be detected directly by satellite or balloon experiments at the energies above $\sim 10^{15}$ eV. An indirect observation is based on the detection of extensive air showers and the properties of primary particle are reconstructed from measured shower signal (particle density, arrival time etc.). The first UHECR was observed by J. Linsley [Lin61], who constructed an array of sparse detectors Volcano Ranch in the United States. Later on, other observatories have been operated. The most important of them were AGASA, consisting of scintillators covering an area of 100 km^2, and a fluorescence detector Fly's Eye with its successor HiRes that tracked light of developing showers in the night sky. The results these two only used observation techniques showed crucial discrepancy in the energy spectrum. It was not clear if there is a rapid decrease of cosmic-ray flux above the energy of 4×10^{19} eV, as it is expected for the astrophysical origin of UHECRs or if there is on the contrary hardening of the energy spectrum, as it was predicted for the decays of superheavy dark matter. The combination of both detection techniques and detection of larger number of observed events at the highest energies was necessary.

This challenge was picked up in early nineties and led to the idea of the Pierre Auger Observatory. Since start of its data taking in 2004 more than 1 million of cosmic rays have been observed till the end of year 2008. Significant fraction of them was observed independently by the surface and fluorescence detector. Such unique hybrid observations allow the energy calibration of reconstructed signals measured by the surface detector. The energy reconstruction of fluorescence detector data is almost independent on the models of hadronic interaction, while in the case of the surface detector reconstruction the models play significant role. However, for such purpose actual atmospheric conditions and the absolute calibration of fluorescence telescopes must be known. The unique correlation between the energy estimator of the surface detector and the energy measured by the fluorescence detector is shown in figure 1 [Abr08c]. There is still a fraction of the air shower energy that is not visible by the fluorescence detector (mostly high-energy muons and neutrinos) and this part is estimated with the help of the models of hadronic interactions. But the value of the invisible fraction is only few percents (about 4%) of the total energy of the primary cosmic ray. Due to this model-free calibration, the energy can be attributed to all events observed by surface detector.

One of the advantages of the surface detector is its almost 100% uptime, and thus it collects much more events at the highest energies than the fluorescence detector. Moreover, an aperture of the surface detector can be precisely calculated as the sum of the apertures of individual water Čerenkov stations, which is needed for the correct determination of the energy spectrum. The obtained surface-detector energy spectrum confirmed that the flux of UHECRs is significantly attenuated above the energy of 4×10^{19} eV as it has been predicted from the interaction with background photons [Abr08c] (see figure 2).

On the other hand the surface detector observes only a lateral distribution of the air shower and has higher energy threshold than the fluorescence detector. Even so, it can determine if the air shower was produced by a photon, neutrino or nucleus. Photons penetrate much deeper into the atmosphere than protons, and the latter ones get much deeper than heavier nuclei. This leads to the difference between the risetime of muonic and electromagnetic component of air showers measured by

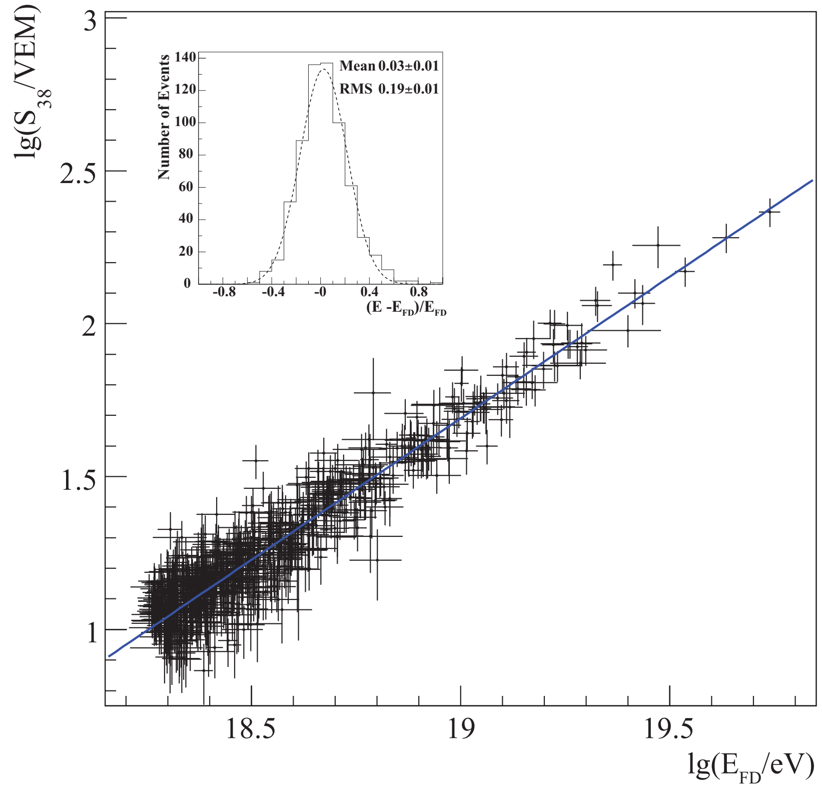


Figure 1: Correlation between energy estimator of surface detector (vertical axis) and energy measured by fluorescence detector (horizontal axis) for hybrid events. The full line is the best fit to measured data. The fractional differences between the two energy estimators are shown in the inset.

the surface detector. But the optimal parameter sensitive to cosmic-ray hadron composition is an air shower maximum, i.e. a slant depth where the number of produced secondary particles reaches its maximum. The air shower maxima can be directly observed only by the fluorescence detector.

The Pierre Auger Observatory provides new upper limits on the fraction of photons and also neutrinos [Abr09a, Abr09b]. Particularly, the upper limit on the photon fraction already ruled out some models of top-down mechanisms of UHECRs origin (i.e. decay of superheavy dark matter). The chemical composition seems to made a change from protons to heavier nuclei at the energy above 3×10^{18} eV, but no firm conclusion can be made at one magnitude higher energies because of the lack of data.

Before the Pierre Auger Observatory none anisotropy of UHECRs arrival directions have been observed. In the nineties few percent excess of CRs with energy around 10^{18} eV in the vicinity of the Galactic center was claimed to be observed by AGASA and also by the experiment SUGAR in Australia. No such anisotropy with significantly larger data set has been confirmed at the Pierre Auger Observatory. From this result an upper limit on the flux of neutrons coming from the Galactic center has been given. This limit on the production of neutrons restricts possible interaction processes in the proximity of our closest supermassive black hole.

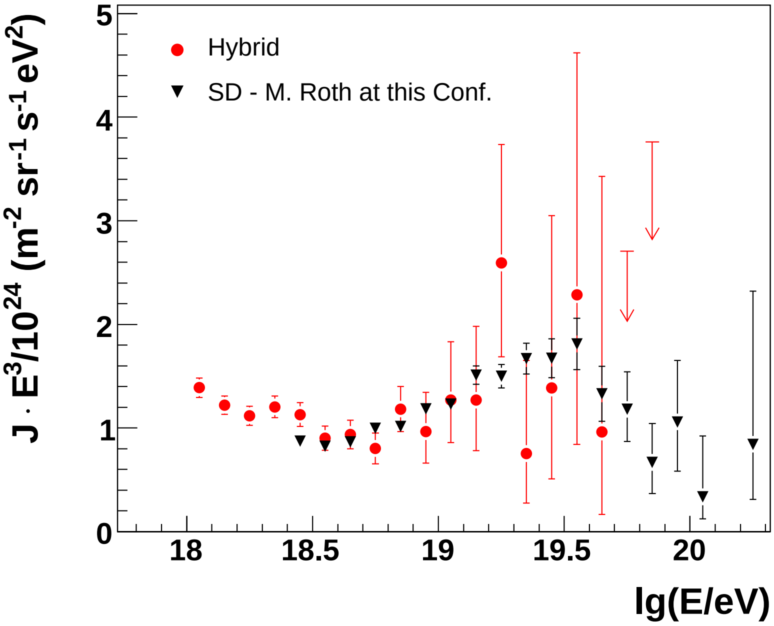
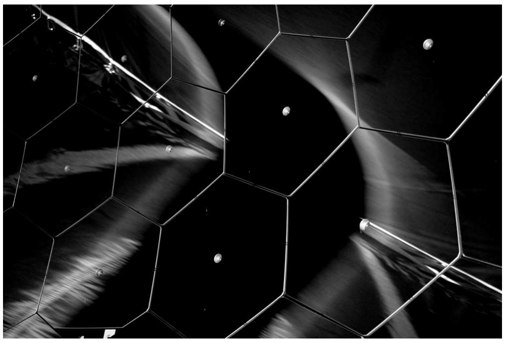


Figure 2: Hybrid energy spectrum shown in comparison with surface-detector spectrum (triangles) as presented by [Per07]. Only statistical uncertainties are given.

The anisotropy of cosmic-ray arrival directions is observed at the energies above $\sim 5 \times 10^{19}$ eV. This anisotropy was found due to the comparison of cosmic-ray arrival directions with the positions of close active galactic nuclei from the 12th edition of Veron-Cetty and Veron catalogue of the quasars and active galactic nuclei [Ver06]. The sum of areas of a given radius around AGN positions within chosen range of a redshift covers a fraction of the sky. The number of cosmic rays above a given energy inside this fraction of the sky were compared with the expectation for the isotropical distribution of cosmic rays. The prior was tested by an independent data. The largest excess of cosmic rays above 5.6×10^{19} eV was found within the distance of 3.1° from the positions of AGN with redshift less than 0.018 (i.e. the distance less than 75 Mpc). However, this result does not tell us that the closest AGN to sky's positions of measured UHECRs are the actual sources. Particularly if cosmic-ray composition and magnetic fields are not yet known. Nevertheless, it is promising step for the search of cosmic-ray sources and it will be extensively studied with the increasing number of observed events in a couple of years.

3 Astroparticle Astronomy



Arrival directions of neutral particles, such as photons, neutrons or neutrinos, point back to their sites of origin. Unfortunately none neutral ultra-high energy cosmic rays have been observed so far. From measurements it follows that less than 1% of primary particles are not hadrons – i.e. protons or heavier nuclei [Abr09a, Abr09b]. Primary cosmic rays as charged particles propagate through magnetic fields and their arrival directions do not point back to their sources. Although the magnetic deflection becomes less important at the highest energies, the flux of such energetic cosmic rays is extremely low. Moreover, our knowledge of a topology and strength of magnetic fields in intergalactic and also interstellar space are not sufficient to decide, which model of magnetic field should be used even in our own Galaxy. Moreover, the electric charge of measured cosmic rays is still unknown.

The study of the propagation of measured cosmic rays is a possible way for the simulation of a magnitude of magnetic deflections. We have studied cosmic-ray propagation through interstellar space in our Galaxy. The back- and also forward-tracing method were used. A particle is propagated from the Earth to the boundary of the Galactic magnetic field in the former method. The propagated particle with given energy has negative electric charge (i.e. opposite than primary cosmic-ray particle) and its direction of velocity vector points out from the Earth. In this case many arbitrary or measured directions can be traced over the whole sky. This method can be applied, if an energy losses and interactions can be neglected, and such conditions are satisfied in the case of cosmic-ray propagation through the Galaxy. More complicated procedure has to be applied in the forward-tracing method, where a particle starts at the boundary of the Galactic magnetic field and is propagated towards the Earth. The size of the Earth has to be large enough to be hitted by sufficient number of propagated particles. In our study a sphere of the radius of 25 pc was successfully used.

One complex model of the Galactic magnetic field was used in our study [Pro03]. This model differs from others due to the implementation of all three possible magnetic-field components – spiral, poloidal and toroidal. The first component is located in few hundred parsecs wide Galactic disk and may have either symmetric or axisymmetric configuration of logarithmic spiral arms. Its strength is about 4 μG at the Sun's position and increases in the direction of the Galactic center. The poloidal component is based on the observations of a vertical magnetic field component – very strong field in the Galactic center (few micro Gauss) and 0.2 μG field at the Sun. The vertical 1 μG field of the toroidal field is located above and below the disk at the height of 1 kpc. The magnetic field is assumed to be static and also Earth's motion is neglected.

It was found that the studied magnetic fields significantly deflect cosmic-ray trajectories even at the highest energies. Any possible connection between the

Table 1: Angular deflections in degrees of protons with the energy of 7×10^{19} eV averaged over the whole sky for bisymmetric (BSS), axisymmetric (ASS), poloidal (Pol) and toroidal (Tor) components of the Galactic magnetic field and their combinations. Angular deflections and their variances are in degrees.

GMF	H	σ_H^2	He	σ_{He}^2	C	σ_C^2	Fe	σ_{Fe}^2
BSS	2.0	0.3	4.0	1.1	12.6	12.4	55.5	180
ASS	2.9	4.6	5.6	12.6	16.3	68.7	63.0	180
Pol	1.7	1.4	3.4	5.4	10.2	46.4	43.5	180
Tor	1.4	3.3	2.5	6.3	6.1	19.1	19.1	180
BSS+Pol+Tor	3.1	2.9	6.2	9.2	18.3	91.9	75.0	180
ASS+Pol+Tor	2.9	4.2	5.7	12.3	17.7	87.3	80.1	180

arrival direction of UHECRs observed at the Pierre Auger Observatory and the positions of AGN located closer than 3.1° to cosmic-ray arrival directions is possible only if the primary particles are protons (see table 1). For any other nuclei the expected magnetic deflections are so large that their origin in those AGN is not possible. Moreover, heavy nuclei (such as iron) may be significantly deflected also by random turbulences in interstellar magnetic field and their propagation becomes more complicated.

We have studied also a possible connection between gamma-ray bursts (GRBs) and UHECRs measured at the observatory. GRBs are the most energetic astronomical phenomena observed in the universe. Even if they are located mostly at large cosmological distances, they have enough power to produce a significant flux of particles at the highest energies and some of these particles may survive the propagation through photon background radiation. We have studied the scenario, where some neutral particles are produced at the GRBs observed by satellite experiments [Gre] and arrive within 100 days before or after gamma rays. We have compared the number of measured CRs within 5° and 30° cones around GBR's position, where the latter one can be taken as the background. No excess has been observed so far (see figure 3). The same analysis was adopted for the enormous burst of the Galactic source SGR 1806-20 on December 27th 2004. The distance of this source is 14.5 ± 1.4 kpc [Cor97] and neutrons have 20% (58%) probability to arrive to the Earth at the energy of 10^{18} eV ($10^{18.5}$ eV). Also for this prominent gamma-ray source no excess of CRs above 10^{18} eV has been observed [Anc07].

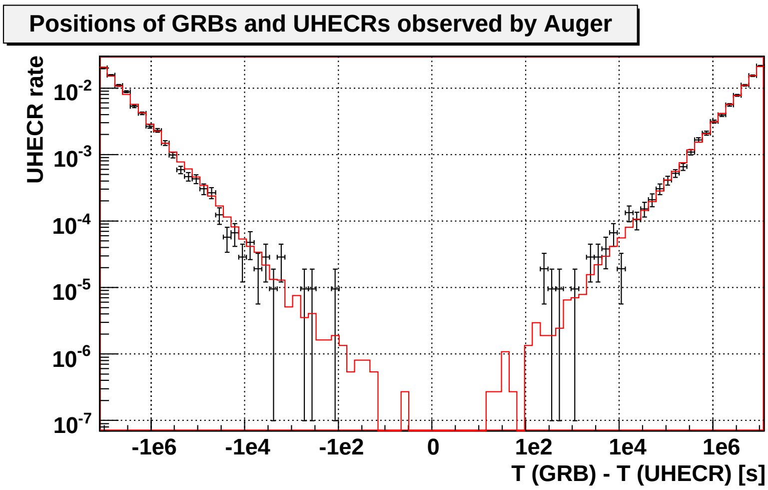


Figure 3: Rates of CR events as a function of the difference between the GRB time and the CR arrival time. Data falling within 30° of a GRB are indicated by red-lined histogram and within 5° by black points. For clarity, statistical errors are shown only for the 5°-distribution.

4 Performance of Fluorescence Detector

The fluorescence detector observes a faint flux of UV photons from a deexcitation of nitrogen molecules which are ionized by the secondary particles of an extensive air shower. Its telescopes track the shower development in the atmosphere. Such observation gives crucial advantages in the comparison with a mapping of lateral distribution of secondary particles on the ground by the surface detector. The deposited energy by primary cosmic-ray particle in the atmosphere is proportional to the flux of fluorescence photons. The shower maximum, which is sensitive to the type of a primary particle is reflected on the camera of the fluorescence telescope as points with the highest signal. The geometry of the air shower can be reconstructed from the timing information of triggered pixels.

One site of the fluorescence detector has six telescopes. Each telescope consists of an aperture with an UV transparent filter and a corrector ring, a segmented spherical mirror and a camera with 440 photomultipliers (see figure 4). The measured signal is digitized by a 10 MHz and further analyses.

The fluorescence detector can measure air showers only during a night with relatively low light background. Therefore, it is operated only during astronomical nights when the illuminated moon fraction is smaller than 60 %. Moreover, a telescope does not take data if the position of the moon is less than 5° from its field of view. Also other conditions has to be satisfied for successful performance of

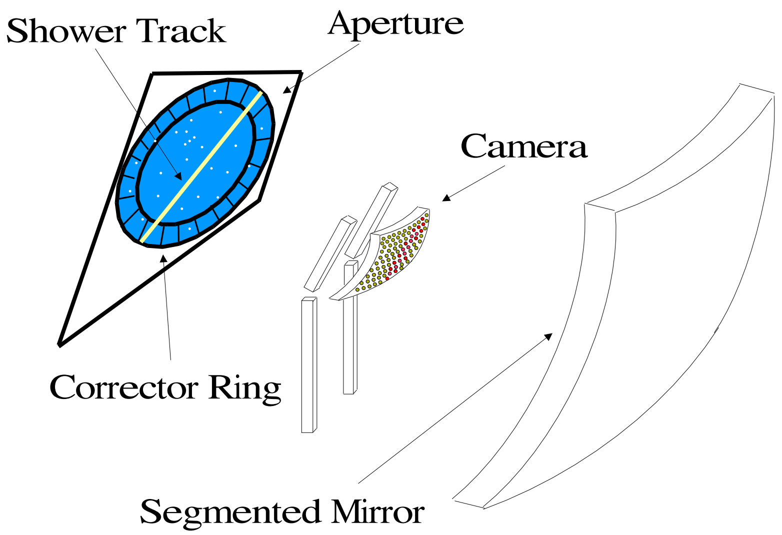


Figure 4: Schematic view of fluorescence telescope.

the telescopes, such as for example suitable weather conditions (no thunderstorm in the vicinity of the fluorescence building, no rain or snowing etc.).

Sometimes a failure of hardware, power cuts or some software error occur and they are not immediately noticed. Data measured during such period must be carefully studied and bad runs filtered out. The calculation of the uptime of fluorescence telescopes takes all such periods into account. Downtime is caused also by lidars, which regularly monitor the status of the atmosphere, if they are allowed to shoot into the field of view of the fluorescence telescope. Before such shooting the veto is send to fluorescence telescopes. We have found that veto time caused by the lidars was too high in the first half of 2007 (see figure 5). Its fraction was above 10% of fluorescence telescope's uptime in some cases. Since then the veto time is routinely checked and its fraction is less than 1%, which was found to be acceptable for the accumulation of a required data by the lidars.

The uptime fractions for all telescopes are shown in figure 6. As can be seen their values were around 12% during the last year. The most problematic periods were usually during the first year of telescope's measurement, when the apparatus was tunned. Another change happened during year 2007, when more strict limitations were applied for the measurement. This restriction led to significant decrease of sensitivity losses of photomultipliers at the cost of marginal losses of measured air showers. (More details are given in the next section.)

The precise knowledge of fluorescence detector's performance is necessary for the calculation of the aperture of each fluorescence telescope and subsequently for the calculation of the hybrid spectrum (see figure 2). The hybrid spectrum has lower number of events at high energies and therefore larger statistics uncertainty than surface detector spectrum, but it extends to lower energies and uses only its own energy reconstruction. Hence it can be used not only to extend the lower

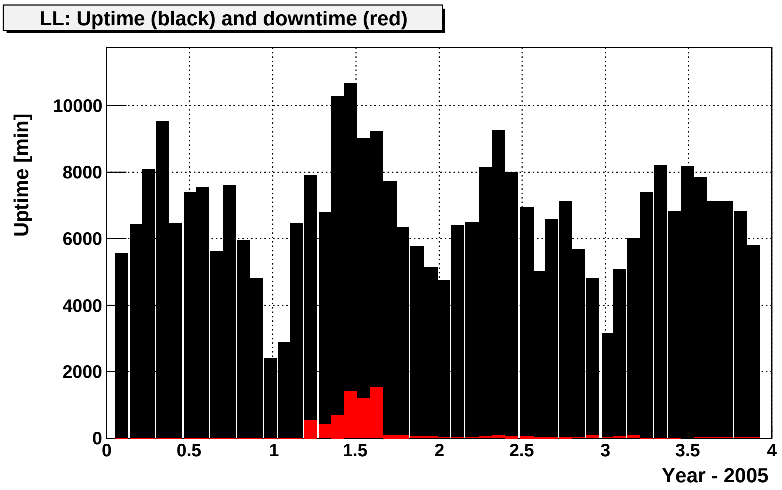


Figure 5: Uptime (black) and downtime (red) caused mainly by lidar's veto for one building of fluorescence detector. Seasonal variations of uptime are clearly visible.

energy part of the spectrum but also to crosscheck the results of the surface detector spectrum at higher energies.

5 Night-Sky Photon Background

Successful detection and reconstruction of cosmic-ray events by the fluorescence detector depends on the background light level. As it was described in [Kle03] there is a direct relation between the variance of the ADC signal and its average. Therefore the variance of measured signal is proportional to an incoming photon flux. Variances of ADC signal come every 6.5 ms from values recorded during 100 ns integration periods and are stored into a database every 30 seconds. We have studied the rate of observed hybrid events, their distances and energies as a function of night-sky background. As expected, scattered moonlight is the prominent source of ADC variances above maximal level allowed for FD measurement and the rate of measured events decreases with the illuminated size of the moon (see figure 7).

The photomultipliers on the cameras at the fluorescence telescopes are exposed to the night-sky background in the long term. Their sensitivity should decrease as a function of accumulated anode charges or as a function of the total ADC variances. However, it was found that the sensitivity shows larger loss than predicted for the measured ADC variances. Thus we have studied the influence of several observable parameters on telescope's behavior, such as the presence of the moon inside the

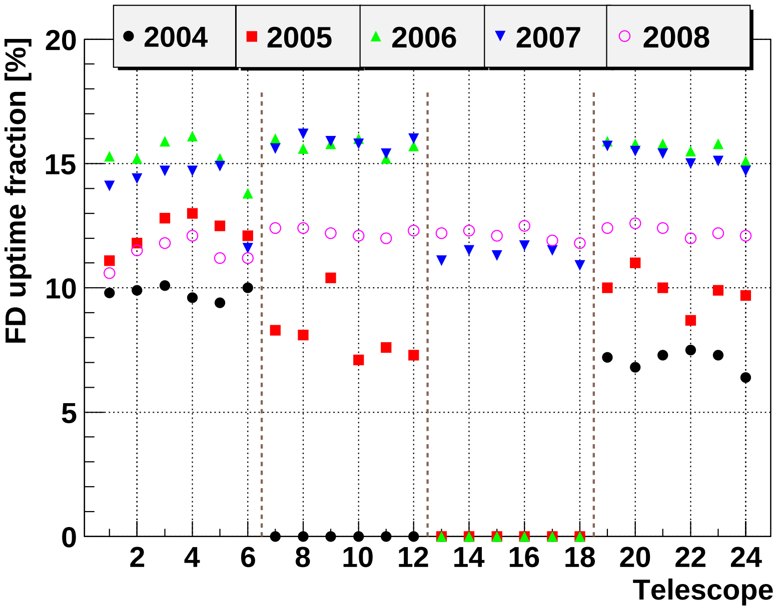


Figure 6: Yearly uptime for all 24 fluorescence telescopes.

field of view, the fraction of time measurement with extremely high level of the ADC variances, the fraction of accumulated ADC variances per time, etc. Also the maximum value of night-sky background for fluorescence telescope's measurement was extensively studied.

The sensitivity is a function of accumulated anode charge, which is proportional to the sum of the ADC variances. We have verified that the ADC variances below 100 (ADCcounts)^2 ($\sim$ photos/m^{-2} deg^{-2} μs^{-1}) are suitable for the fluorescence measurement [Abr09c] (see figure 7). The number of lost cosmic-ray events, particularly the most energetic ones, is negligible, but the accumulated ADC variances significantly decreases. Since the second half of year 2007, i.e. the routine implementation of a stopping of data taking if the ADC variances overreach the maximum allowed value of measurement, the ageing of PMTs seems to significantly slow down [Smi09b].

A clear elevation dependence of total ADC variances (see figure 8) was also found. It leads to almost 40% difference between the values on a top and a bottom rows of a camera. This difference should be seen in calibration data, but it was not. That's why we will study the elevation dependence and also time evolution of night-sky background further with new data coming during following years.

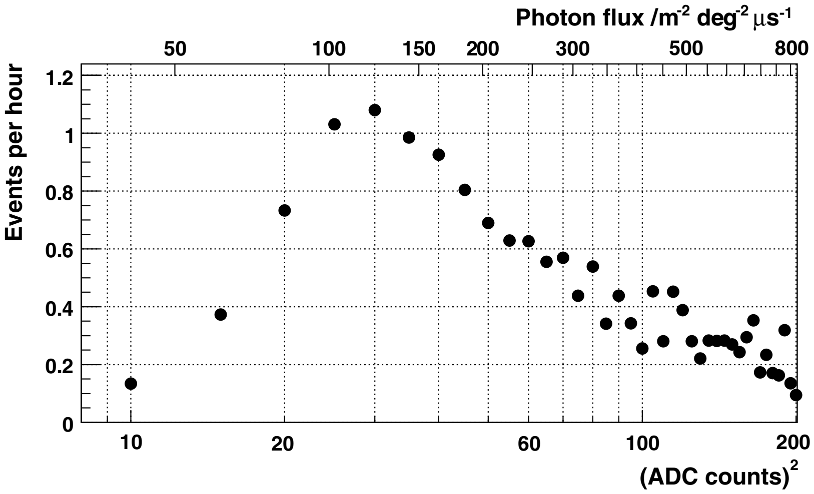


Figure 7: Event rate for observed air showers as a function of background light given in (ADC counts)^2 (lower x axis) and photon flux (upper x axis).

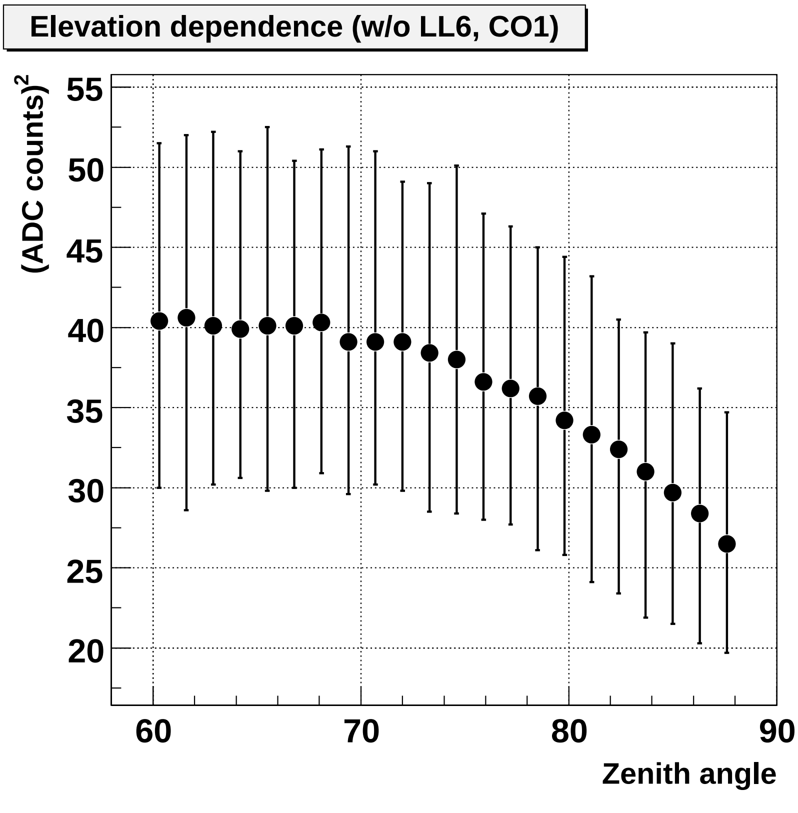
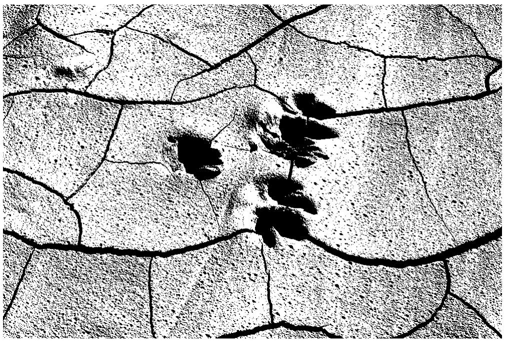


Figure 8: Elevation dependence of ADC variances averaged over whole measurement period of 22 fluorescence telescopes not affected by light pollution of city of Malargüe. Points show medians and lines indicate the 90th percentiles of values measured by studied photomultipliers.

6 Conclusions



The presented work was focused on the most energetic cosmic rays which have been intensively studied by the Pierre Auger Observatory during last years. Author has participated in the construction of the observatory and also in the measurement during his several stays in Argentina. His contribution to the experiment includes also data analysis and theoretical works, which were described in the doctoral thesis.

The main attention has been given to the performance of the fluorescence telescopes. Uptimes and downtimes of individual telescopes were calculated and these values have been successfully used to check the measurements and the identification of hardware difficulties. Particularly, the interference between lidars and fluorescence telescopes was detected and promptly solved. The uptime fraction is currently well above 10% per year even after restrictions applied in the physical analysis (e.g. the calculation of hybrid spectra).

The determination of night-sky brightness suitable to fluorescence observations led to the introduction of the highest level of night-sky brightness above which the fluorescence observation is not allowed. In this way the level of accumulated anode charges on the photomultipliers has been significantly reduced. The current results indicate the reduction of the losses of photomultiplier sensitivity since the introduction of this restriction. Moreover, the difference of about 40% was found between the illumination of photomultipliers located at the bottom and the top of a camera.

The propagation of cosmic rays through the Galactic magnetic field have been studied and the predictions for expected angular deflections are presented. The obtained results have significant consequences for any comparison of cosmic-ray arrival directions and the positions of possible astronomical sources. Our calculations show that the angular deflection less than 3° is possible only for protons.

Furthermore the data observed by the Pierre Auger Observatory were used to search for eventual signals coming from gamma-ray sources. This study was relevant particularly for the giant flare from the magnetar SGR 1806-20 located in our Galaxy. No clear signal from gamma-ray bursts as well as for the magnetar has been identified up to now.

The results were already published and presented at conferences ([Pro03], [Boh06], [Anc07], [Boh08], [Smi09], [Smi09b], [Tho09] and partially in [Abr08c] and [Abr09c]). These results are also used in several publications of the Pierre Auger Collaboration under preparation. Full list of author's publication and presentations is available at website address http://www-hep2.fzu.cz/∼smida/publication.html.

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