The unusual cosmic ray variations on July 2005 resulted from western and behind the limb solar activity

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Abstract – **One of the most interesting and unusual periods of the recent solar activity was July 2005. Despite the fact that this month was at the end of the 23rd solar cycle, it was a period of extreme activity. The main events of this occurred at the invisible side of the Sun and did not revealed significantly in the Earth or near the Earth consequences. However, cosmic ray variations testify high power of these events. A rather unusual Forbush effect was observed starting from July 16, 2005. It was characterized by very large cosmic ray anisotropy, the magnitude and direction of which are in accordance with a suggestion on a western powerful source. Usually in such a case when the main interplanetary disturbance is far on the west, the Forbush effect is absent or it is very small and short lasted. In July 2005 a rare exclusion was observed which may testify the giant (quite possible >=30%) decrease of 10 GV cosmic ray density to the west from the Sun-Earth line.**

In this work a description of the July 2005 situation as well as the results of the convection- diffusion treatment with space cosmic ray gradients is presented. Some general remarks concerning extreme western solar events and their impact on cosmic rays are also discussed.

Keywords – **Convection diffusion model, Forbush effects, Coronal Mass Ejections, Solar Flares**

I. INTRODUCTION

At the declining phase of the 23rd solar cycle, a number of extreme events characterized by rather peculiar properties have taken place, such as those of October-November 2003, January 2005, August-September 2005 and the recent ones of December 2006 [1], [2], [3]. Dynamic phenomena related to solar flares (SF) and coronal mass ejections (CMEs) dominated the heliosphere in a most profound way and resulted in large variations in cosmic ray (CR) intensity at least up to tens GeV energies. A number of attempts have been made in order to explore the relation between solar extreme phenomena and their impact on cosmic rays [4], [5], [6], [7], [3], [8]. It is commonly pointed out that solar extreme events influence cosmic rays in a dynamic way and different correlations can possibly be established between the cosmic ray variations and various characteristics of solar wind and interplanetary space [9]). On July 16, 2005 a deep decrease of the cosmic ray density (of about 8% for 10 GV particles) with a complicated shape and an intermediate large increase was recorded by neutron monitors during a non significant disturbance of the solar wind [10]. Right after the main phase of this Forbush effect (FE), a sharp enhancement of cosmic ray intensity starting from July 17, was registered only to be followed by a second decrease within less than 12 hours. The enhancement on July 17 was related neither to a ground level enhancement (GLE) nor to a geomagnetic effect. The analysis of this peculiar event shows that it could be connected with an internal structure of the disturbance similar to the event of March 1991 described by [11], but in our case it is not confirmed by solar wind data. Usually short - term cosmic ray variations are well correlated with solar wind changes near the Earth. During the events of July 2005 unusual CR variations were recorded and the most unusual fact was that these variations are not related with the changes in the solar wind.

In this work an extended analysis of these cosmic ray variations during the extreme events of July 2005 based mainly on the terms of anisotropy and space gradients of cosmic rays, is performed. The possibility to provide explanations on this kind of cosmic ray events is also being discussed.

II. DATA SELECTION

In this analysis the used data taken from the following web sites: http://sec.ts.astro.it/sec_ui.php on the solar and space conditions; http://www.ngdc.noaa.gov for solar flare data from and http://lasco-www.nrl.navy.mil for CME data.

In order to obtain variations in the flux and the first harmonic of anisotropy for 10 GV cosmic rays, data from as many stations as possible from the entire global network of neutron monitors (40 – 45 stations operating at present), with their own properties as coupling coefficients and yield functions, have been used. The calculation of the anisotropy components has been performed using the global survey method (GSM) (e.g. [3]).

III. SOLAR AND GEOMAGNETIC CONDITIONS

Solar activity: In the beginning of July, although several sunspot groups appeared on the face of the Sun, the main active region was the AR 786. It was the return of AR 775, a powerful active region (AR) from the previous rotation that caused long duration solar flares. Solar activity was dominated by AR 786 in the northern hemisphere, until it rotated over the west limb on July 14. In this period, this AR had produced 12 M-class and one X-class flares.

On July 12 there was a long duration M1.5 flare starting at 12:47 UT associated with a bright partial halo CME directed to the NW. In the next day, July 13, two bright CMEs occurred in association with two long-duration flares. The second CME was first seen in LASCO C2 images at 14:30 UT and had an estimated speed of 1420 km/s. The event triggered a gradual increase of the proton and electron fluxes, which reached to the value of 134 pfu on July 14 (http://www.ngdc.noaa.gov). On July 14two flares occurred: an M9.1 flare peaked at 07:25 UT and finally an X1.2 flare with long duration started at 10:16 UT. The high energy proton fluxes rose above the NOAA event threshold and a full halo CME was first visible in LASCO C2 at 10:54 UT and arrived at the Earth on July 17, as it is shown in Fig. 1.

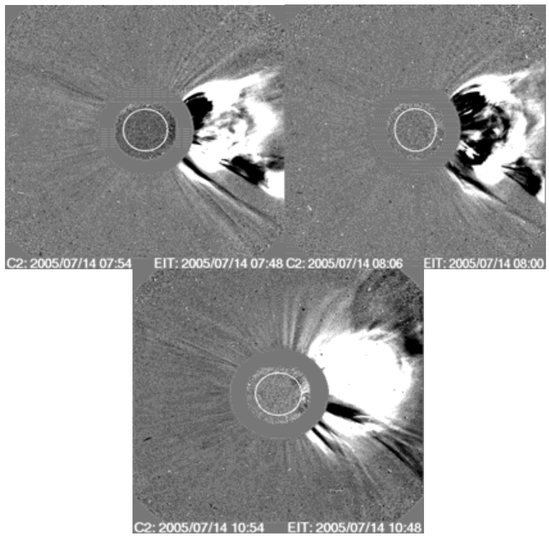

Fig. 1. The most significant CMEs on July 14, 2005 from AR 786 as seen by LASCO C2.

Geomagnetic activity. A minor geomagnetic storm occurred on July 13, probably due to the arrival of the partial halo CME from July 10 (C1.6 flare in AR 783). The solar wind speed was > 600 km/s (shock recorded at 04:24UT) and Bz component of the IMF (Interplanetary Magnetic Field) turned southward for a short period with a value of -5 nT. The geomagnetic activity then returned to the quiet - unsettled level, except of temporary active conditions recorded at some ground-based magnetometers on July 15 and 16. This weak geomagnetic activity may be a consequence of the partial halo CME originated on July 13 (~ M5.0 flare and the CMEs from early July 14, which erupted before the full halo CME related to the X1.2 flare. None of the blast waves were Earth directed, nevertheless, Earth's magnetic field was impacted by a weak shock that arrived at the Earth on July 17 at 1:23 UT. This caused mostly active conditions during July 17 (Dst=-74, Kp=5). Around 19:00 UT on July 17, the interplanetary magnetic field turned southward again to -10 nT. This immediately caused a major geomagnetic storm that persisted from late July 17 to around 12:00 UT of July 18.

IV. COSMIC RAY VARIATIONS

In the second decade of July 2005, heightened solar activity, especially in the western part of the solar disk, created a disturbed situation in the interplanetary space which was reflected in the CR behavior. The density of galactic cosmic rays started decreasing from July 10 after a series of relatively weak Forbush effects and by 16 July it had a decrease of ~2%. Most unusual events occurred on 16-17 July when the FD reached the value of 8% at high latitude neutron monitors within just a few hours. The CR intensity recovered rapidly up to almost the pre-event level, but in the mid of July 17 a sharp CR decrease started again and reached the same amplitude of 8% at many neutron monitor stations. Finally it followed the classical FE recovery, as it is shown in Fig. 2 (Papaioannou et al., 2005)[10]. A disturbance in near Earth space at that time (V=500 km/s, H~ 10 nT, Bz was nearly -10 nT) could not provide such a magnitude of the FE. Usually a Forbush decrease hardly reaches ~2% under such modest parameters (Belov et al., 2001)[9]. The observed CR density behavior and especially CR anisotropy with an unusually big equatorial sunwards component along the field line at this time may be caused by other reasons (Belov et al., 2003)[12].

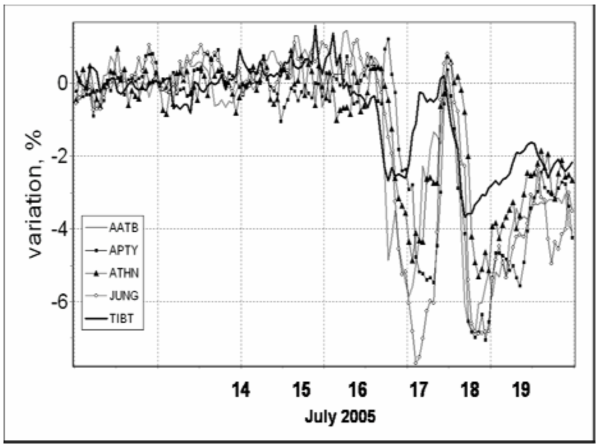

Fig. 2. Time profiles of the cosmic ray varisations observed on the Neutron Monitor stations: Alma-Ata B (aatb), Apatity (apty), Athens (athn), Jungfraugh (jung), Tibet (tibt). The curves are plotted in % relatively to the quiet period on July 14, 2005.

4.1 Cosmic Ray Anisotropy

The singularity of the events recorded on July 16-17, 2005 manifests itself in the size and temporal evolution of the CR density and anisotropy. The calculated equatorial component of the anisotropy A_{xy} is presented by a series of coupled vectors in Fig. 3. Thin lines connect the equal time points corresponding to the vector and CR density diagram. Vertical vectors along the density curve present the magnitude and direction of north-south anisotropy A_z (Chen and Bieber, 1993)[13]. As can be seen in Fig. 3, the north-south anisotropy A_z increases significantly, up to ~4% within the declining phase of the FE on July 16 to 17, and changes its direction from positive to negative in the mid of July 17. The equatorial component of anisotropy was abnormally big, A_{xy} increased up to >5%. All components of anisotropy reveal sharp and big changes on the background of more or less quiescent interplanetary and geomagnetic conditions (IMF~10-15 nT, Dst=-74, Kp=5+). We have analyzed all events in our database which occurred under Kp=5+ (377 events during 45-years of observation). The averaged magnitude of the Forbush effects (FE) over these events was found to be 1.57 %, the mean equatorial and the A_z components were correspondingly 1.44% and 1.55%. On this background the event on July, 16-17 looks outstanding as well as the number of other events (~10-15) recorded under similar geomagnetic conditions (Kp=5+).

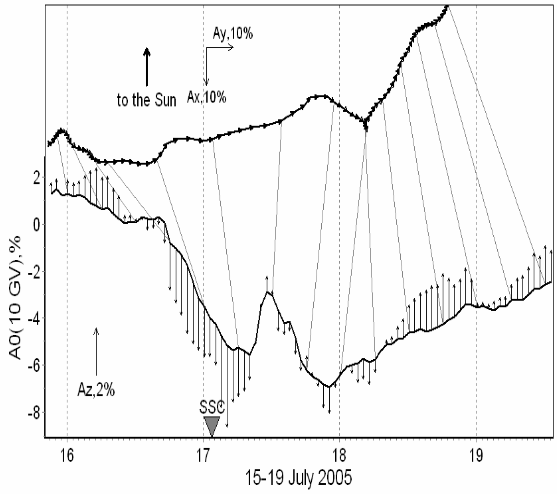

Fig. 3. The CR density (A0) temporal variations on July 15-19, 2005. The vector diagram presents the equatorial component (A_{xy}) of CR anisotropy, while the vertical vectors along the density curve present the north-south component of anisotropy (A_z). Thin lines connect the equal time moments on the density curve and vector diagram. Triangle (SSC) marks the time of Sudden Storm Commencement (the time of shock arrival at Earth).

The anisotropy shows more singularity than the hourly rate of CR decrease (hourly decrement) during the main phase of FE. Such great anisotropy is usually being observed within the largest Forbush effects with high magnitude of decrease where the CR intensity goes down on 15-25% (for example, events in August 1972, February 1978, October 2003). The maximum equatorial anisotropy for about 6000 analyzed FEs plotted versus the maximum rate of CR decrease during those events is illustrated in Fig. 4. This statistical presentation shows that the point corresponding to July 17, 2005, with a relatively low decrease rate (decrement <1%/hour) is located much above the averaged regression curve because of the very high anisotropy in this event. In a vicinity of this point we have a group of events incorporated by attributes similar to the event on July 17, which is a basis for further study. Singularity of the anisotropy in this event is also emphasized by the dependence of the equatorial component on the magnitude of IMF which is presented in Fig. 5. According to the regression dependence with an IMF intensity of about 15 nT the maximum averaged equatorial anisotropy should be ranged within 0.5-2.6%, whereas, in our case, it was >5%. Again, we see a group of points around July 17 (not numerous) which appear to have the common properties. A great anisotropy was observed even before the arrival of the shock at the Earth.

All aforesaid testifies that it is difficult to explain the properties of the anisotropy and CR variation by local parameters of the interplanetary space near the Earth. Here it is necessary to recollect events which were observed at the western limb.

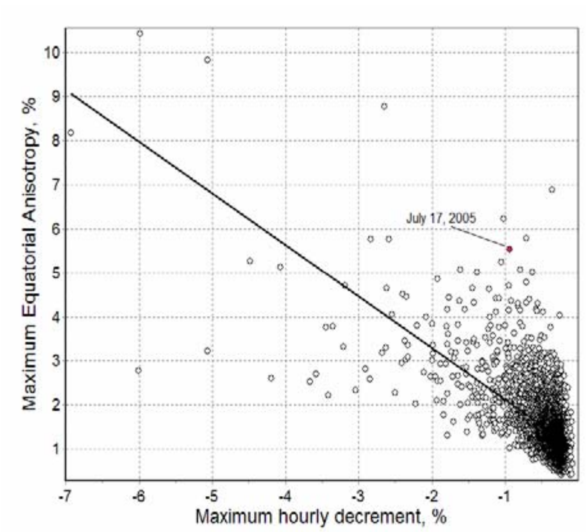

Fig. 4. Maximum equatorial component of CR anisotropy (Axy) versus maximum hourly decrement for FEs over 45-years of observation (~6000 events).

As it is known, powerful X-ray western (limb) flares on July 14 (M9.1 and X1.2) in the AR 10786 were followed by CMEs with a full asymmetric halo, and CME from X1.2 flare is profoundly affected by the CME event associated to the M9.1 X-ray flare. The shock which has arrived at Earth on July 17 at 1:34UT is apparently connected with these ejections. This assumption leads to the mean transit velocity of 1430 km/s that corresponds to the initial speed of CME (~2280 km/s), as by it was observed LASCO/EIT.

It is not improbable that such a disturbance might have caused a gigantic Forbush effect in the western part of the inner heliosphere, and Earth crossed its periphery area on the beginning of July 17. The big equatorial component of CR anisotropy at this time is an evidence of intensive inflow of particle flux from the eastern direction that provided fast recovery of the FD. On the other hand, LASCO/EIT observed also this day an asymmetric Full Halo Event started at 11:30 UT as a very strong brightening above the NW limb associated to a flare behind the limb from the same AR 786. By 11:54 UT, faint loop-like extensions can be seen all above the Sun's South Pole. The velocity of this "backside" event was 1300 km/s. Directly from this moment the new sharp decrease of CR intensity started on the background of very high anisotropy, and this coincidence in time seems to be not occasional but caused by a change in the conditions for particle propagation.

4.2 Cosmic Ray Gradients

It is clear that CR anisotropy is responsible for the space gradient. A treatment of CR with the convection-diffusion model (CDM) to the events on July 2005 has been performed in order to obtain CR gradient and its components. The model proposed by Krymsky (1964)[14] was developed at several works [15], [16], [13]. Despite the fact that a lot of other models concerning cosmic rays appeared through the years, the convection-diffusion model still remains the most basic one and is valid to a degree sufficient for this analysis.
Using a simple approach by solving an inverse problem in Belov et al. (1987), the three components of the CR space gradient, g_x, g_y, g_z are given by the following equations:

$$g_x = \frac{1}{\rho}[-\sqrt{\kappa}(A_x - A_c) - \sin\psi\sqrt{1-\kappa}]$$

(1a)

$$g_y = \frac{1}{\rho}[-\sqrt{\kappa}A_y + \cos\psi\sqrt{1-\kappa}A_z] \quad (1b)$$

$$g_z = \frac{1}{\rho}[\sin\psi\sqrt{1-\kappa}(A_x - A_c) - \cos\psi\sqrt{1-\kappa}A_y - \sqrt{\kappa}A_z]$$

(1c)

Where Ax, Ay and Az are the three components of anisotropy in the coordinate system related to the IMF field line (OX and OY are in the ecliptic plane, herewith OX is directed along the IMF force line); ψ is the angle between IMF direction $\vec{H}$ and solar wind velocity $\vec{u}$; ρ is the particle's hyroradius in the total IMF; k is a degree of the IMF irregularity.
The calculated g_x, g_y have been used to obtain ecliptic component (G_E) of CR space gradient which is plotted in Fig.6 together with the IMF intensity (upper panel). Periods of strong IMF and large values of CR gradient are seen on the days 1-2, 9-12, 19-21 and 27-29 of July (on July 16-17 we see very large gradient, but not strong IMF). Usually the biggest CR gradient is observed together with the increasing of IMF intensity because of additional CR modulation produced

within the regions with strengthened IMF (Forbush effect). Besides, the strengthened field is able to separate regions of different CR density. In July the strongest IMF intensity (up to 25 nT) was on July 10 and the magnitude of G_E in this day exceeded the value of 50%/AU.

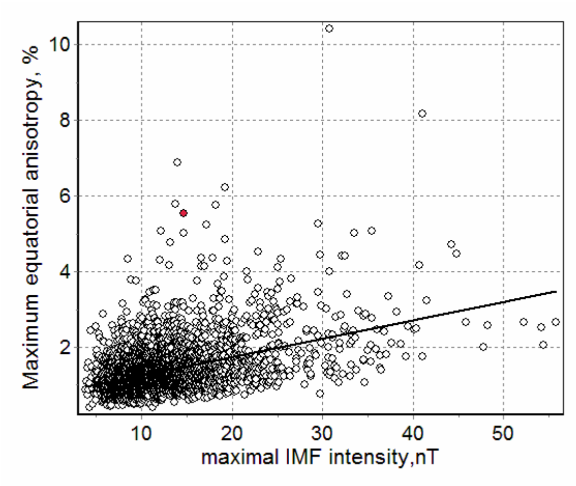

Fig. 5. Maximum equatorial anisotropy versus maximum IMF intensity (hourly values) by events over ~45 years observation. The red point references to July, 17, 2005.

However, the biggest gradient was not observed during this day, but on July 16-17. It exceeded 150%, when the IMF intensity was nearly 10 nT. There are many days in July with approximately the same or even higher IMF intensity, but the magnitude of G_E those days was many times less than that on 16-17 July. In the lower panel of this figure a relation between the IMF intensity (B) and the magnitude of G_E is presented. In general a good correlation between these two parameters is observed, but there are also some evidently outstanding points, all of them being related to 16-17 July. This is one more evidence of the unusual situation on July 16-17, when an anomalously large gradient of cosmic rays was produced not by disturbances of interplanetary space near Earth but by other, remote from the Earth, solar wind disturbances.

V. CONCLUSIONS

The solar activity burst in July 2005 was distinguished by the main events occurred near the western limb and at the invisible side of the Sun. Great disturbances of the solar wind comparable with those observed earlier in the last solar cycle – in 2000, 2001 and 2003 have not arrived to the Earth and there was no severe magnetic storm recorded at the Earth. On this background the CR variations look more interesting and unusual, especially on 16-17 July. A set of peculiarities in the behavior of CR density and anisotropy contradicts an explanation of this behavior by variations in parameters of near Earth interplanetary medium. The main reason of the large and unusual Forbush effect on July 16-17 has apparently to be searched near the western limb of the Sun where, starting from July 14, under interferential influence of several CMEs a giant and complicated decrease of galactic CR was created.

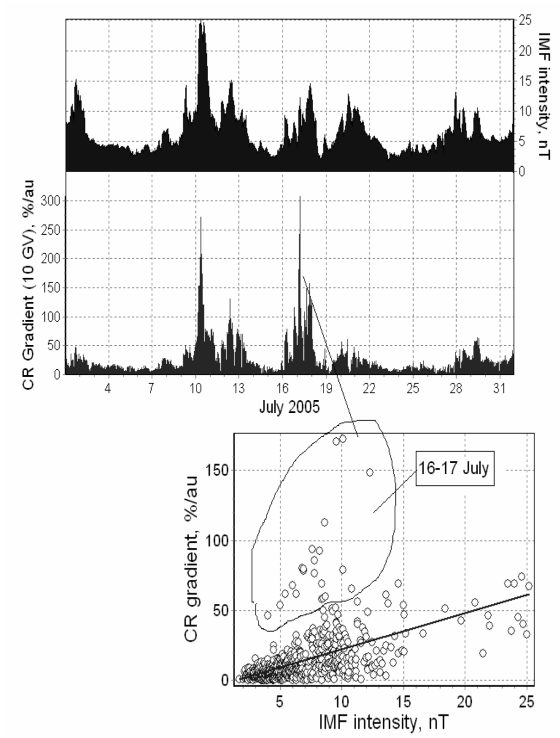

Fig.6. Hourly means of the IMF intensity (upper panel) and of the ecliptic component G_E of the CR gradient for 10 GV particles derived from data on CR anisotropy by means of the convective-diffusive model (middle panel) in July 2005. The CR gradient versus IMF intensity by events in July 2005 is given in the lower panel.

A discrepancy between the Forbush decrease magnitude and the parameters of near Earth disturbance of solar wind is being observed from time to time and such events have been studied earlier [17], [18], [12]. Usually such events are caused by remote ea stern solar sources. But in July 2005 we encountered with another type of inconsistency related to remote but western source. Such events differ from the events of eastern origin by greater anisotropy. They occur significantly rarer, however, as a retrospective analysis shows, they consist a definite sub-class of Forbush effects. Analysis of such events testifies that the CR variations are able to give us the information on sufficiently remote heliospheric phenomena. Such events are worthy the special attention and individual studying

ACKNOWLEDGMENT

The authors thank all collaborators providing continuous ground level monitoring of cosmic rays and researchers providing satellite data via internet. Thanks are due to all our colleagues from the neutron monitor stations, who kindly provided us with the data used in this analysis: Alma Ata, Apatity, Athens, Baksan, Barentsburg, Cape Schmidt, Fort Smith, Hermanus, Inuvik, Irkutsk-1,2,3, Jungfraujoch, Jungfraujoch-1, Kerguelen, Kingston, Kiel, Larc, Lomnicky Stit, Magadan, Mawson, McMurdo, Moscow, Nain, Norilsk, Novosibirsk, Oulu, Potchefstroom, Peawanuck, Rome, Sanae, San Tiago, Terre Adelie , Thule, Tsumeb, Tixie Bay and Yakutsk. This work was supported partly by Greek grant PYTHAGORAS II which is funded by European Social funds and National recourses and Russian Foundation for Basic Research (RFBR grants 07-02-00915, 07-02-13525, 06-02-39028 and Program BR of the Presidium RAS "Neutrino Physics". Thanks for stations see also in http://cr0.izmiran.rssi.ru/ThankYou/main.htm.

REFERENCES

[1] Eroshenko, E., Belov, A., Mavromichalaki, H., Mariatos G., Oleneva, V., Plainaki, C., Yanke, V. Cosmic ray variations during the two great bursts of solar activity in the 23rd solar cycle. Solar Physics, 224, 345-358, 2004

[2] Plainaki C, Belov A., Eroshenko E., Mavromichalaki H., Yanke V. Modeling ground level enhancements: The event of 20 January 2005, J. Geophys. Res, 112, A04102, doi:10.1029/2006JA011926, 2007

[3] Belov A., Baisultanova L., Eroshenko E., Mavromichalaki H., Yanke V. Pchelkin V, Plainaki C., Mariatos G. Magnetospheric effects in cosmic rays during the unique magnetic storm on November 2003, J. Geophys. Res. 110, A09S20, doi:10.1029/2005JA011067, 2005

[4] Harrison, R.A The nature of solar-flares associated with coronal mass ejection, Astron. and Astrophys. 304, 585 - 594, 1995

[5] Hundhausen, A.J. Coronal mass Ejections, in K.T. Strong, J.L. Saba, B. H. Haisch and J.T. Schmelz, (eds.), The many faces of the Sun: A Summary of the results from NASA's Solar Maximum Mission, Springer, New York, 143, 1999

[6] Cane, H. V.: Coronal Mass Ejections and Forbush Decreases, Space Science Rev. 93, 55-77, 2000

[7] Kudela, K. and Brenkus R. Cosmic ray decreases and geomagnetic activity: List of events 1982-2002, J. Atm. and Solar-Terrestrial Physics, 66, 1121-1126, 2004

[8] Mavromichalaki H., Papaioannou A., Mariatos G., Papahliou M., Belov A., Eroshenko E., Yanke V. and Stassinopoulos E.G. Cosmic ray radiation effects on space environment associated to intense solar and geomagnetic activity, IEEE TNS, 54, 1089, 2007

[9] Belov A.V., E. A. Eroshenko, V.A. Oleneva, A.B., A.B. Struminsky, and V.G. Yanke: What determines the magnitude of Forbush decreases? JASR, 27, 625-630, 2001.

[10] Papaioannou A., Gerontidou M., Mariatos G., Mavromichalaki H., Plainaki C. Unusually extreme cosmic ray events in July 2005, 2-nd ESA SWW (14-18 November 2005) Holland http://esa-spaceweather.net/spweather/workshops/eswwII/

[11] Hofer M. and Flueckiger E. O. Cosmic Ray Spectral variations and anisotropy near Earth during the March 24, 1991 Forbush decrease, J. Geophys. Res., 105, 23085-23097, 2000

[12] Belov A. V., Butikofer R., Eroshenko E. A., Fluekiger E. O., Oleneva V. A., Yanke V.G. Interplanetary magnetic field disturbances with particularly large cosmic ray modulation efficiency, *Proc. 28-th ICRC*, 6, 3581-3585, 2003.

[13] Chen J. & Bieber W. J. Cosmic ray anisotropies and gradients in three dimensions, The Astrophys. Journal 405, 375-389, 1993

[14] Krymsky G.F. Diffusion mechanism of the diurnal cosmic ray variation, Geomagn. and Aeronomy, 4, 977-986, 1964 (in Russian)

[15] Forman, M. A. and Gleeson, L. J. : Cosmic Ray streaming and Anisotropies, Astrophys. and Space Sci., 32, 77-94, 1975

[16] Belov A. V. The First Harmonic of Cosmic Ray Anisotropy in the Convection-Diffusion Model, Proc. 20th ICRC, 4, 119-123, 1987

[17] Iucci, N., Parisi, M., Storini, M., Villoresi, G., Pinter, S. Longitudinal dependence of the interplanetary perturbation produced by energetic type 4 solar flares and of the associated cosmic ray modulation. 19th ICRC, 5, 234-237, 1985.

[18] Iucci, N., Pinter, S., Parisi, M., Storini, M. Villoresi, G. The longitudinal Asymmetry on the interplanetary perturbation producing Forbush decreases. Nuovo Cimento, 9C, 39-50, 1986.