

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

A. Papaioannou<sup>a</sup>, A. Belov<sup>b</sup>, H. Mavromichalaki<sup>a,\*</sup>, E. Eroshenko<sup>b</sup>, V. Oleneva<sup>b</sup>

<sup>a</sup> Nuclear and Particle Physics Section, Physics Department, Athens University, Panlpolis15771 Athens, Greece

<sup>b</sup> Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation by Pushkov, Russian Academy of Sciences, IZMIRAN, Russia

Received 11 January 2008; received in revised form 15 July 2008; accepted 5 September 2008

## Abstract

One of the most interesting and unusual periods of the recent solar activity was July 2005. Despite the fact that it was a late declining phase of the 23rd solar cycle, generally a time of solar quiescence, that period was marked by extreme activity. The main events occurred at the invisible side of the Sun and did not reveal significant consequences in the Earth or near the Earth. However, cosmic ray variations testify to the 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 western powerful source. Usually in such a case when the main interplanetary disturbance is far in the west, the Forbush effect is absent or it is very small and short lasting. In July 2005 a rare exclusion was observed which may testify to the giant decrease of 10 GV cosmic ray density (quite possible  $\geq 30\%$ , indicating an unusually high cosmic ray gradient) 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.

© 2008 COSPAR. Published by Elsevier Ltd. All rights reserved.

**Keywords:** Convection–diffusion model; Forbush effects; Coronal mass ejections; Solar flares

## 1. 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 (Eroshenko et al., 2004; Plainaki et al., 2007; Belov et al., 2005). 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 up to energies of at least tens GeV. A number of attempts have been made in order to explore the relation

between solar extreme phenomena and their impact on cosmic rays (Harrison, 1995; Hundhausen, 1999; Cane, 2000; Kudela and Brenkus, 2004; Belov et al., 2005; Mavromichalaki et al., 2007). 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 (Belov et al., 2001).

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 (Papaioannou et al., 2005). 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 h. The enhancement on July 17 was related neither

\* Corresponding author.

E-mail addresses: [atpapaio@phys.uoa.gr](mailto:atpapaio@phys.uoa.gr) (A. Papaioannou), [abelov@izmiran.ru](mailto:abelov@izmiran.ru) (A. Belov), [emavromi@phys.uoa.gr](mailto:emavromi@phys.uoa.gr) (H. Mavromichalaki), [erosh@izmiran.ru](mailto:erosh@izmiran.ru) (E. Eroshenko).

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 Hofer and Flueckiger (2000), 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 to 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.

## 2. Data selection

In this analysis the used data taken from the following web sites: [http://sec.ts.astro.it/sec\\_ui.php](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. Belov et al., 2005).

## 3. 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 western 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. On 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 14 two flares occurred: an M9.1 flare peaking at 07:25 UT and finally an X1.2 flare with long-duration starting 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.

*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 the Bz component of the interplanetary magnetic field (IMF) sharply turned southward and from 8 to 11 UT it was remained at a level <−5 nT. The geomagnetic activity then returned to the quiet – unsettled level, except for temporary active conditions recorded at several ground-based magnetometers on July 15 and 16. This weak geomagnetic activity may be a consequence of the partial halo CME observed 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

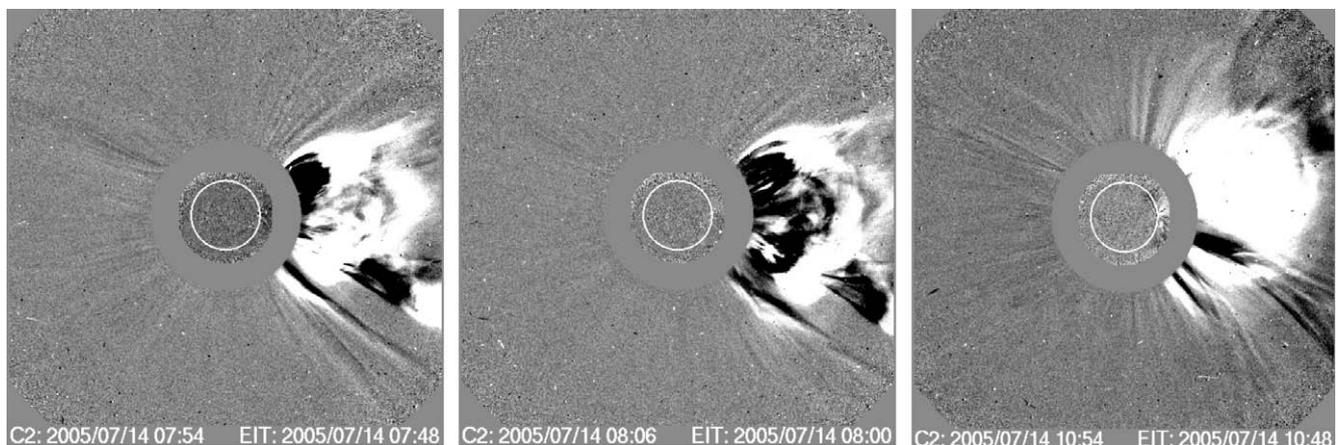


Fig. 1. The most significant CMEs on July 14, 2005 from AR786 as seen by LASCO C2.

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.

#### 4. 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 decreased by  $\sim 2\%$ . 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 middle 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). A disturbance in near Earth space at that time ( $V = 500$  km/s,  $H \sim 10$  nT,  $B_z$  was nearly  $-10$  nT) could not provide such a magnitude of the FE. Usually a Forbush decrease hardly reaches  $\sim 2\%$  under such modest parameters (Belov et al., 2001). 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).

##### 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). As can be seen in Fig. 3, the north–south anisotropy  $A_z$  increases significantly, up to  $\sim 4\%$  within the declining phase of the FE on July 16–17, and changes its direction from positive to negative in the middle 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  $\sim 10$ – $15$  nT, Dst =  $-74$ , Kp = 5+). We have analyzed all events in our database which occurred under Kp = 5+ (377 events during 45-years

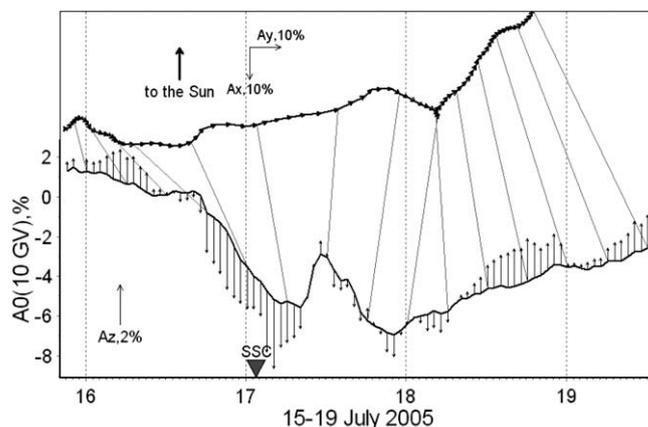


Fig. 3. The CR density ( $A_0$ ) temporal variations on July 15–19, 2005. The vector diagram presents the equatorial component ( $A_{xy}$ ) of CR anisotropy, while the vertical vectors along the density curve present the north–south component of anisotropy ( $A_z$ ). Thin lines connect the equal time moments on the density curve and vector diagram. Triangle (SSC) indicates the time of Sudden Storm Commencement (the time of shock arrival at the Earth).

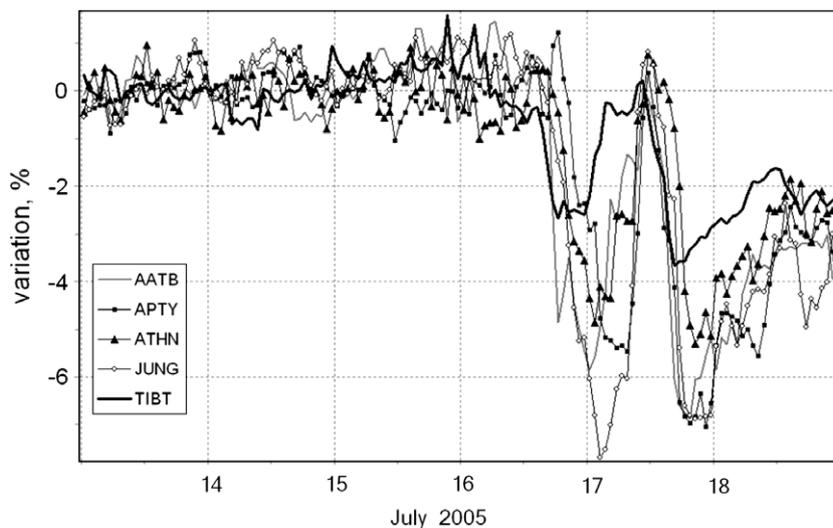


Fig. 2. Time profiles of the cosmic ray variations observed on the Neutron Monitor stations: Alma-Ata B (AATB), Apatity (APTY), Athens (ATHN), Jungfraugh (JUNG), Tibet (TIBT). The curves are plotted in % relatively to the quiet period on July 14, 2005.

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%. Relative to this background the event on July 16–17, looks outstanding as well as a number of other events ( $\sim 10$ – $15$ ) recorded under similar geomagnetic conditions ( $K_p = 5+$ ).

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 by 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  $< 1\%/h$ ) is located much above the averaged regression curve (correlation coefficient 0.61) 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 (correlation coefficient is 0.67) 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 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

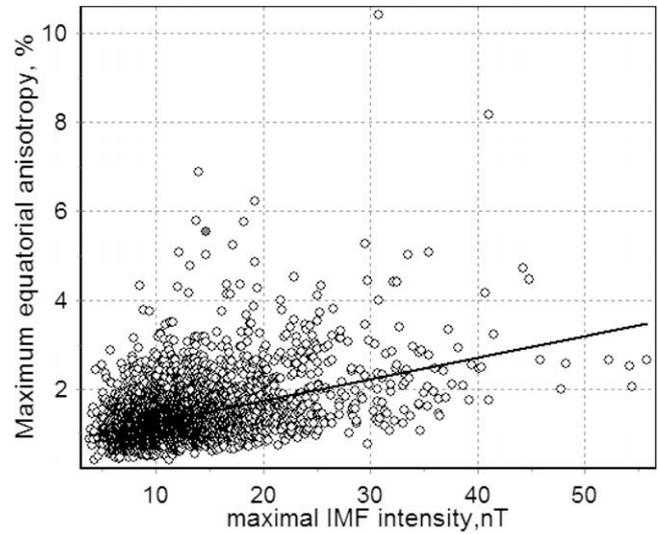


Fig. 5. Maximum equatorial anisotropy versus maximum IMF intensity (hourly values) by events over  $\sim 45$  years observation. The red point references to July, 17, 2005.

parameters of the interplanetary space near the Earth. Here it is necessary to recollect events which were observed at the western limb.

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 1:34 UT 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 ( $\sim 2280$  km/s), as it was observed by 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 on July 17. The big equatorial component of CR anisotropy at this time is an evidence of intensive inflow of particles 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 starting 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. The CR gradient and its components of the events in July 2005 were obtained from applying the con-

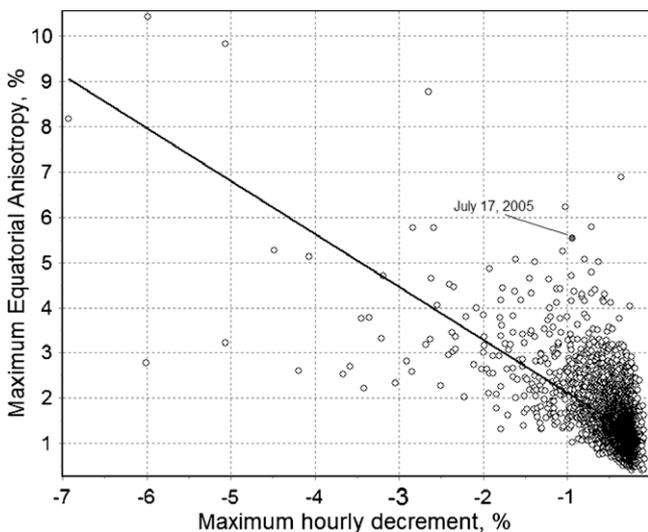


Fig. 4. Maximum equatorial component of CR anisotropy ( $A_{xy}$ ) versus maximum hourly decrement for FEs over 45-years of observation ( $\sim 6000$  events).

vection-diffusion model (CDM) to the CR density. The model proposed by Krymsky (1964) was derived in several studies (Forman and Gleeson, 1975; Belov, 1987; Chen and Bieber, 1993). 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 (1987), the three components of the CR space gradient,  $g_x, g_y, g_z$  are given by the following equations:

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

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

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

where  $A_x, A_y$  and  $A_z$  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);  $\psi$  is the angle between IMF direction  $\vec{H}$  and solar wind velocity  $\vec{u}$ ;  $\rho$  is the

particle's gyroradius in the total IMF;  $\kappa$  is a degree of the IMF irregularity.

The calculated  $g_x, g_y$  have been used to obtain the ecliptic component ( $G_E$ ) of the 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 a very large gradient, but not a 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. 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

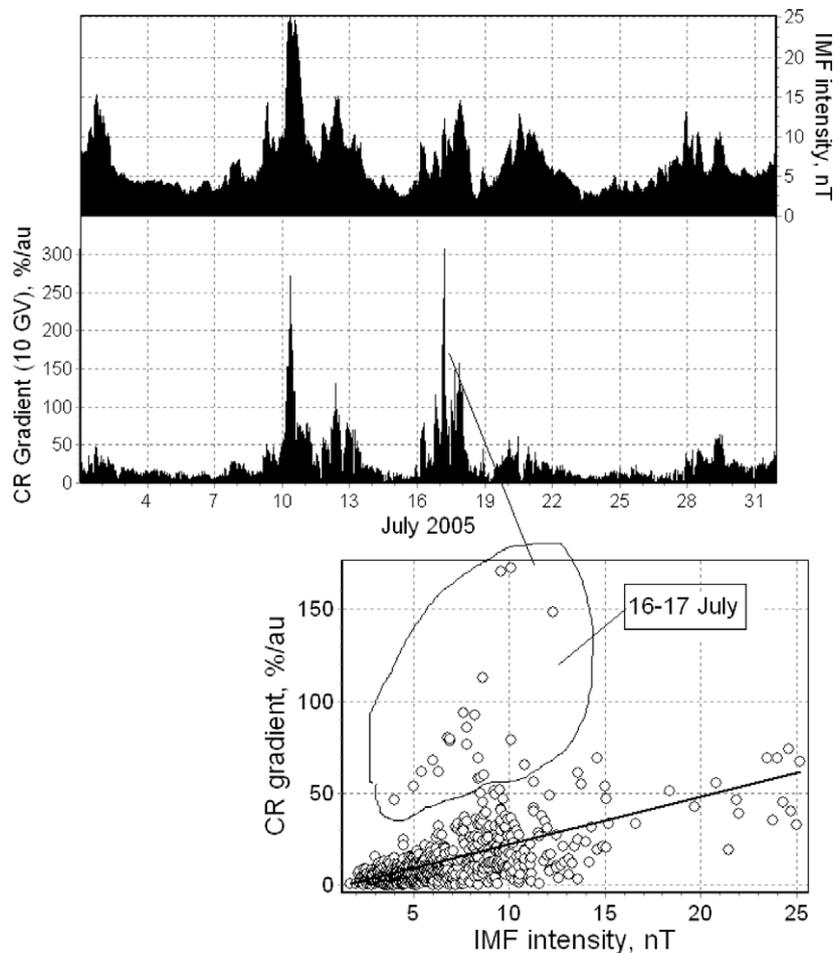


Fig. 6. Hourly means of the IMF intensity (upper panel) and of the ecliptic component  $G_E$  of the CR gradient for 10 GV particles derived from data on CR anisotropy by means of the convective-diffusive model (middle panel) in July 2005. The CR gradient versus IMF intensity by events in July 2005 is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

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. For the whole number of hours during July 2005 the correlation coefficient was found 0.52, while if the points regarded this event are excluded, it becomes to be much better taking the value of  $-0.79$ . 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.

## 5. Conclusions

The solar activity burst in July 2005 stands out due to the origin of the main events 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 the 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.

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 (Iucci et al., 1985, 1986; Belov et al., 2003). Usually such events are caused by remote eastern solar sources. But in July 2005 we encountered with another type of inconsistency related to a 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.

## Acknowledgements

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, Jungfrauoch, Jungfrauoch-1, Kerguelen, Kingston, Kiel, Larc, Lomnický Stit, Magadan, Mawson, McMurdo, Moscow, Nain, Norilsk, Novosibirsk, Oulu, Potchefstroom, Peawanuck, Rome, Sanae, San Tiago, Terre Adélie, 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

- Belov, A.V. The First Harmonic of Cosmic Ray Anisotropy in the Convection-Diffusion Model. *Proceedings of 20th ICRC*. 4, 119–123, 1987.
- Belov, A.V., Eroshenko, E.A., Oleneva, V.A., Struminsky, A.B., Yanke, V.G. What determines the magnitude of Forbush decreases? *JASR* 27, 625–630, 2001.
- Belov, A.V., Butikofer, R., Eroshenko, E.A., Flueckiger, E.O., Oleneva, V.A., Yanke, V.G. Interplanetary magnetic field disturbances with particularly large cosmic ray modulation efficiency. *Proceedings of 28th ICRC*. 6, 3581–3585, 2003.
- 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.
- Cane, H.V. Coronal mass ejections and forbush decreases. *Space Sci. Rev.* 93, 55–77, 2000.
- Chen, J., Bieber, W.J. Cosmic ray anisotropies and gradients in three dimensions. *Astrophys. J.* 405, 375–389, 1993.
- 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 Phys.* 224, 345–358, 2004.
- Forman, M.A., Gleeson, L.J. Cosmic ray streaming and anisotropies. *Astrophys. Space Sci.* 32, 77–94, 1975.
- Harrison, R.A. The nature of solar-flares associated with coronal mass ejection. *Astronaut. Astrophys.* 304, 585–594, 1995.
- Hofer, M., 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.
- Hundhausen, A.J. Coronal mass ejections, in: Strong, K.T., Saba, J.L., Haisch, B.H., Schmelz, J.T. (Eds.), *The many faces of the Sun: a Summary of the results from NASA’s solar maximum mission*, vol. 143. Springer, New York, 1999.
- Iucci, N., Parisi, M., Storini, M., Villorosi, G., Pinter, S. Longitudinal dependence of the interplanetary perturbation produced by energetic type 4 solar flares and of the associated cosmic ray modulation. *Proceedings of 19th ICRC*. 5, 234–237, 1985.
- Iucci, N., Pinter, S., Parisi, M., Storini, M., Villorosi, G. The longitudinal asymmetry on the interplanetary perturbation producing Forbush decreases. *Nuovo Cimento* 9C, 39–50, 1986.
- Krymsky, G.F. Diffusion mechanism of the diurnal cosmic ray variation. *Geomagn. Aeronomy* 4, 977–986, in Russian, 1964.
- Kudela, K., Brenkus, R. Cosmic ray decreases and geomagnetic activity: list of events 1982–2002. *J. Atm. Solar Terrestrial Phys.* 66, 1121–1126, 2004.
- Mavromichalaki, H., Papaioannou, A., Mariatos, G., Papahliou, M., Belov, A., Eroshenko, E., Yanke, V., Stassinopoulos, E.G. Cosmic ray radiation effects on space environment associated to intense solar and geomagnetic activity. *IEEE TNS* 54, 1089–1096, 2007.

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. Available from <<http://esa-spaceweather.net/spweather/workshops/eswwII/>>.

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.