A preliminary statistical analysis of the GLEs in solar cycles 22 and 23

M. Andriopoulou, C. Plainaki, H. Mavromichalaki, A. Belov, E. Eroshenko

***Abstract*— Registration of ground level enhancement events (GLEs) at ground based neutron monitors has started in the 1940s. Analytical studies of various GLEs have shown that each one of them constitutes a unique case, characterized by the specific solar and interplanetary conditions during the time period that it took place. However, possible similarities of the GLE characteristics between different event cases may be evidence for the existence of common physical mechanisms. Therefore realizing a statistical analysis of ground level enhancements is of great importance in order to reveal the inner relationship among these events. In this study the results of a preliminary statistical analysis of the ground level enhancements occurring during the solar cycles 22 and 23 (1986-2007) are presented, using data from both polar and middle latitude neutron monitors. A detailed comparison of the characteristics of these events is being held out in order to reveal possible similarities and differences among them. Special emphasis is finally given to the event recorded on April 15th, 2001 (GLE 60) as well as to the event of April 18th (GLE 61). The analysis of the various characteristics of these two events and their relation with the solar parameters reveals important information for the solar cosmic rays reaching the ground level. This statistical output can be also useful for GLE-modelling and other space weather applications.**

I. Introduction

Ground level enhancements (GLEs) are short and sharp increases in the counting rates of cosmic ray intensity. Despite the fact that GLEs taxonomically belong to the solar cosmic rays, which present a spectrum ranging from a few MeV up to a few GeV in general, the actual energies obtained are high enough (>500 MeV) for the particles to penetrate inside the Earth's atmosphere and finally be recorded by ground based neutron monitors. Their study is of particular importance, mainly due to their involvement in a vast range of scientific applications such as the prediction of dangerous particle fluxes that can cause serious damage to satellites and telecommunications [1], [2], the analysis of the interplanetary conditions [3] and predicting the occurrence of strong geomagnetic storms [4]. Several techniques that analysed and modelled some important GLE characteristics have been presented in the past, starting with [5] which was later advanced in [6], while [7], [8] [9] and [10] are also worth mentioned.

Thirty one ground level enhancements were recorded by the worldwide neutron monitor network during cycles 22 and 23. The sunspot number evolution together with the GLEs appearance rate inside these two cycles is presented in Fig. 1. The great event of the January 20, 2005 (GLE69), whose intensity was comparable to the event of the 23rd February 1956 (GLE5) and the event of the 29th September 1989 (GLE42) happened to be among them. The majority of the fifteen events which were recorded in the 22nd cycle occurred near the cycle's maximum phase. The following solar cycle 23 had quite a different behaviour. This is in agreement with [11] in which the distinction between even and odd solar cycles is being described. An absence of GLEs was noticed during the period from October 2000 to March 2001 which is possibly associated with the Gnevyshev gap [12], a time period during which a decline in solar atmospheric activity is observed [13]. Furthermore, an unexpected burst of solar activity during a period which was far from the maximum phase, October to November 2003, led to a series of ground level enhancements [14], [15], [16].

In this work the results of a preliminary statistical analysis for these ground level enhancements are presented. Also, some specific characteristics of the events of April 2001 (GLE60 and GLE61) are analysed and a comparison between the two events is being held out.

II. Description of the Analysis

An extended study of the eleven most intense events of the 22nd and 23rd solar cycles was realized in order to determine some of their special characteristics. The events that were examined are the event of 29 September 1989 (GLE42), the event of 19 October 1989 (GLE43), the event of 22 October 1989 (GLE44), the event of 24 October 1989 (GLE45) and the event of 15 June 1991 (GLE52) from solar cycle 22 and

M. Andriopoulou is with the Astronomy, Astrophysics and Mechanics Section, Department of Physics, National and Kapodistrian University of Athens, Greece, 15771 Athens Greece (e-mail: mariand012@gmail.com).

C. Plainaki, is with the Nuclear and Particle Physics Section, Department of Physics, National and Kapodistrian University of Athens, Greece and with the INAF-Istituto di Fisica dello Spazio Interplanetario, Via del Fosso del Cavaliere, 00133 Roma, Italy (e-mail: christina.plainaki@ifsi.roma.inaf.it).

H. Mavromichalaki is with the Nuclear and Particle Physics Section, Department of Physics, National and Kapodistrian University of Athens, Greece, 15771 Athens Greece (e-mail: emavromi@phys.uoa.gr).

A. Belov is with the Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation (IZMIRAN), 142092, Troitsk, Moscow Region, Russia (e-mail: abelov@izmiran.rssi.ru).

E. Eroshenko is with the Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation (IZMIRAN), 142092, Troitsk, Moscow Region, Russia (e-mail: erosh@izmiran.rssi.ru).

the event of 14 July 2000 (GLE59), the event of 15 April 2001 (GLE60), the event of 28 October 2003 (GLE65), the event of 29 October 2003 (GLE66), the event of 20 January 2005 (GLE69) and finally the event of 13 December 2006 (GLE70) from solar cycle 23. Five-minute cosmic ray intensity data from about sixty neutron monitors in total have been used for this analysis which were provided by stations of the worldwide network of neutron monitors and finally all collected from the IZMIRAN group (ftp://cr0.izmiran.rssi.ru/COSRAY!/FTP_GLE/).

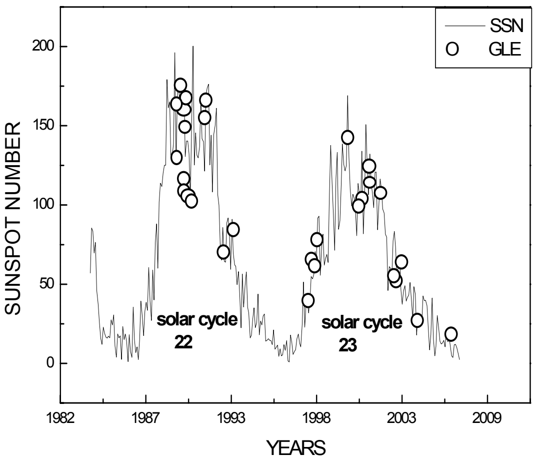


Fig. 1: Sunspot number and GLEs appearance rate occurring during the cycles 22 and 23.

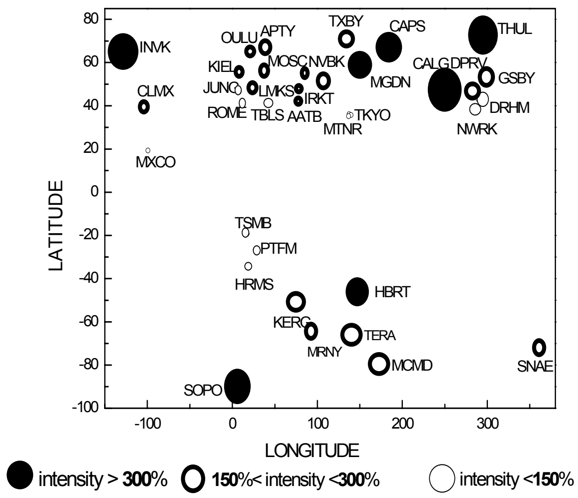


Fig. 2: The latitude-longitude distribution of the GLE42 in the NM stations used in this study. The different cycle sizes represent the different magnitudes of the cosmic ray intensity maximum.

The analysis of each ground level enhancement included the calculation of the onset time of each event for each station recorded the specific GLE, according to the 2σ criterion [14], the identification of the maximum intensity which was recorded by a specific station, the calculation of the time that the maximum flux was recorded as well as the calculation of the time-lag between the time of the maximum amplitude and the onset time. Furthermore, the longitudinal and the latitudinal distribution separately and the latitudinal-longitudinal one of each event maximum intensity was defined in order to determine preliminarily the specific geographical regions that usually observe a GLE.

As an example, some features of the event which was recorded on 29 September 1989 (GLE 42) are exhibited in Table I and Fig. 2. The abbreviation name, the rigidity R_c, according to the IGRF model [17], the onset time T_{on}, the maximum recorded intensity (%), the time that the maximum intensity was recorded T_{max} and the time-lag between the time of the maximum amplitude and the onset time T_{max}-T_{on} for

TABLE I
ANALYSIS OF THE EVENT OF SEPTEMBER 29, 1989

Station (Abbrev.)	Rigidity* (GV)	Onset time T_{on} (UT)	Maximum Intensity (%)	T_{max} (UT)	T_{max}- T_{on} (min)
OULU	0.77	11:40	174.3	13:50	130
TERA	0.00	11:50	272.7	14:10	140
KERG	1.14	11:45	269.7	13:40	115
DPRV	1.25	11:45	233.4	12:15	30
CALG	1.09	11:40	403.6	12:55	75
DRHM	1.76	11:45	181.9	13:35	110
MRNY	0.00	11:50	217.7	13:30	100
TXBY	0.43	11:45	233.5	13:20	95
SNAE	0.75	11:40	214.6	14:05	145
MGDN	1.99	11:50	320.6	12:40	50
APTY	0.55	11:45	211.0	13:50	125
CAPS	0.52	11:50	354.5	12:50	60
MCMD	0.00	11:50	284.7	14:15	145
SOPO	0.05	11:50	365.4	13:25	95
THUL	0.00	11:45	374.4	13:05	80
HBRT	1.83	11:50	303.5	12:20	30
GSBY	0.74	11:45	248.4	12:20	35
INVK	0.14	11:45	372.8	13:30	105
LMKS	3.88	11:45	179.5	12:40	55
KIEL	2.36	11:45	170.8	13:00	75
MOSC	2.39	11:45	190.7	13:15	90
IRKT	3.49	11:45	209.8	12:20	35
NWRK	2.21	11:50	163.8	13:40	110
CLMX	2.93	11:45	187.2	12:15	30
BERN	4.42	11:50	116.4	12:25	35
ROME	6.30	11:45	98.3	12:10	25
MTNR	11.25	11:40	32.3	12:00	20
TKYO	11.40	11:45	27.9	11:55	10
TBLS	6.55	11:45	121.9	12:05	20
PTFM	6.85	11:50	104.8	12:05	15
HRMS	4.45	11:50	105.1	12:35	45
TSMB	9.06	11:45	61.4	12:05	20
AATA	6.45	11:45	150.9	12:05	20
AATB	6.45	11:45	151.2	12:05	20
MXCO	8.02	11:45	44.2	12:10	25
JUN2	4.59	11:50	143.7	12:30	40
JUNG	4.59	11:50	146.8	12:30	40

* The definition of Neutron Monitor Rigidities was based on the IGRF (International Geomagnetic Reference Field) model [17]

each station that was used in the study of GLE42 are presented in Table I. The latitudinal-longitudinal distribution of the cosmic ray maximum intensity recorded in each station for this event is presented in Fig. 2.

Finally, an effort was made in order to connect GLEs with solar and geomagnetic phenomena, like the solar flares (SF), the coronal mass ejections (CMEs) and the sudden storm commencements (SSCs).

For this purpose the event of April 15, 2001 (Easter GLE - GLE60) and the following event of April 18, 2001 (GLE61) were studied in detail. The Easter GLE, which is considered to be among the most important GLEs that were recorded during the cycles 22 and 23 (Fig. 3), occurred shortly after a great and very rare X14.4 X-ray flare (S20W85/2B) had reached its peak emission (13:50 UT) [18]. Initially, the spectrum was very hard, eventually it became softer and finally, approximately 50 minutes after the onset time of the event, the spectrum started becoming harder. An important anisotropy of the cosmic ray intensity was recorded between the north and the south hemisphere. This conclusion derived from the comparison of the time profiles of Thule (north hemisphere) and McMurdo (south hemisphere); the choice of these stations is explained in [19]. Also, an unusual difference between the time profiles of Oulu and Apatity stations was observed during GLE60. As Oulu and Apatity are two neutron monitor stations with very similar characteristics (Oulu: long. 25.47˚, lat.65.05˚, alt.15m, cut-off rigidity R_c 0.77GV and Apatity: long. 33.33˚, lat. 67.55˚, alt. 177m, R_c 0.55GV) it is expected to record approximately the same rates of cosmic ray intensity (%). However, this was not the case in GLE60. A similar behaviour was also noted for the events occurring on 14 July, 2000 and on 2 May, 1998 [20].

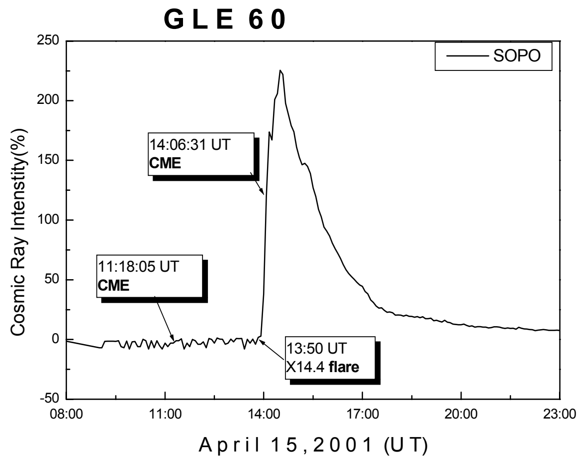
Three days after the GLE60, another ground level enhancement was recorded. This event on April 18, 2001 (GLE61) was very weak and seems to be connected with a great Halo CME which reached its maximum at 02:30:05 UT having a linear velocity 2465 km/sec. Also GLE61 had a less rapid evolvement in comparison to GLE60.

South Pole neutron monitor recorded a maximum intensity for each of these events, 225.4% for GLE60 and 24.1% for GLE61. The time profiles of the two events and the mapping of the most important solar flares (class-M and -X) and CMEs, which are possibly connected with these events, are presented in Fig. 3.

III. RESULTS - DISCUSSION

After an analytical study and a comparison among the eleven events that were examined in this work, some preliminary results of the statistical analysis are presented.

Firstly, using 5-minute data from Oulu neutron monitor station, the most important ground level enhancements and the distribution of total maximum are exhibited (Figs 4 and 5). Oulu station was selected because it is a sub-polar station (R_c: 0.77GV) which functioned during the whole period of cycles 22 and 23 (1986-2007) and has available data via the internet (http://cosmicrays.oulu.fi/). According to the recordings of Oulu, the most important events that were recorded during the last two solar cycles are in reverse order the event on 20 January 2005 (GLE69), the event on 29 September 1989 (GLE42), the event on 24 October 1989 (GLE45), the event on 13 December 2006 (GLE70) and finally the event on 15 April 2001 (GLE60). It is observed that GLE69, GLE70 and GLE60 have a sharp and rapid increase in the cosmic ray intensity (%), while GLE42 and GLE45 have more wide time profiles and a less rapid evolvement.



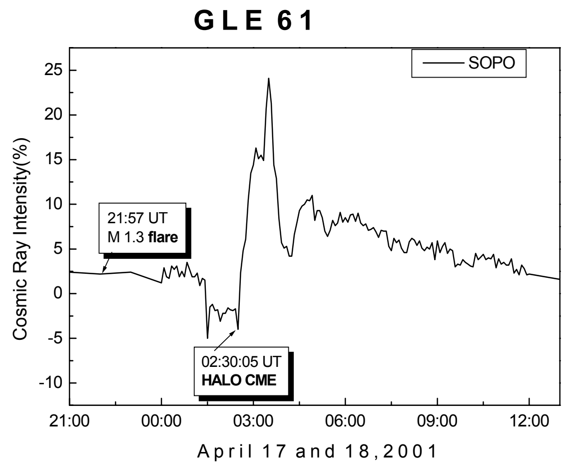


Fig. 3: Time profiles of the events of April 2001, as recorded by South Pole neutron monitor station

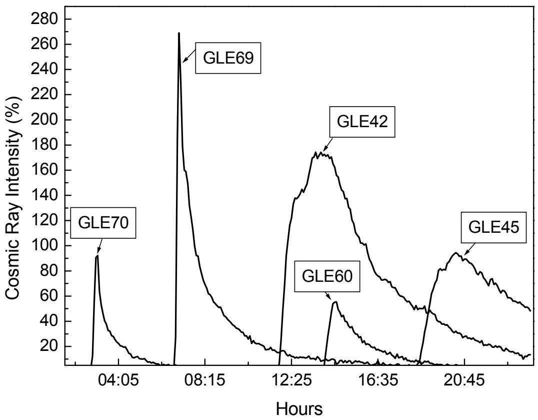


Fig. 4: The most important GLEs during solar cycles 22 and 23, as recorded by Oulu neutron monitor station

Using the Oulu neutron monitor data, the maximum annual record of cosmic ray intensity during the period of the 22nd and 23rd solar cycles is presented in Fig. 5. It is interested that the year 1989 the maximum annual record was noted in the year 1989, is characterized by the maximum value. If the recordings of another station were used in the distribution of total maximum cosmic ray intensity, the picture could be probably different from Fig. 5. Especially, if the recordings from McMurdo, South Pole or Terre Adelie were used, the year 2005 would be the one with the maximum annual intensity and a great difference among the annual record of 2005 and the annual record of other years would have been observed. The reason of this difference is that these three stations recorded a maximum intensity greater than 2000% (McMurdo 2093%, South Pole 4809%, Terre Adelie 2650% using 5-minute data) for the event of 20th January 2005, which is possibly caused by the prompt component of the solar cosmic rays arriving at the Earth [21]. If the total cosmic ray intensity maximum for the years 2005 and 2006 is not taken into account, the distribution of the total maximum cosmic ray intensity has a similar evolvement with the sunspot number of cycles 22 and 23, as it is presented in Fig. 1.

Furthermore, using the observations of the latitudinal-longitudinal distribution of each event, some interesting results are given in Table II. This Table describes the specific geographical regions that usually record GLEs. To be more specific, there are two regions (regions # 1 and # 2) which in most cases record high rates of cosmic ray intensity and the maximum intensity is usually recorded by one of these regions. Regions #5 and #6 seem to record the lowest rates of intensity and there are many cases in which stations from these areas cannot record a GLE.

It should be underlined that the above geographical regions of Table II are defined only approximately due to the non-existence of neutron stations in specific regions and due to the lack of data in some GLE cases.

Also, if the possible relationship between GLEs and coronal mass ejections (CMEs) that has been noticed by Gopalswamy [22] is not taken into consideration and the assumption that only intense solar flares produce GLEs is made, it seems to be that the majority of X-ray solar flares of X-class connected with GLE production, originates from the west and south solar active regions. This result is in agreement with [23] where the greater possibility for a GLE being observed is connected with the western X-class associated flares. It is explained through the typical geometry of the ''garden hose'' field line that connects the Sun to the Earth.

Moreover a calculation of the average time-lag between the time of the maximum amplitude and the onset time for each event was performed. The calculation did not lead to certain results since there are some low and middle latitude stations that seem to have quite different time lags compared to polar stations. In the future, a more complete analysis on the basis of a bigger number of neuron monitors, widely distributed around the globe, is intended.

Finally, a calculation of the onset time variability for each observed GLE, among all neutron monitors that observed the event, was realized. It was found that all except one of the 11 GLEs had an onset time variability from 10 to 35 minutes. However, one should consider that this time-variability is not necessarily due to some different physical mechanisms in the particle penetration inside different geographical sites of the Earth's atmosphere, while it is partly related to the resolution of the data used in this analysis. In other words, as a first step in this statistical study, we used 5-min cosmic ray data, considering them more reliable in respect to the 1-min ones. Nevertheless, when it comes to the calculation of sensitive GLE parameters such as the onset time, maybe 1-min data would be a more wise choice, in case of course that these high-resolution data are reliable enough. Such an analysis is intended in the near future.

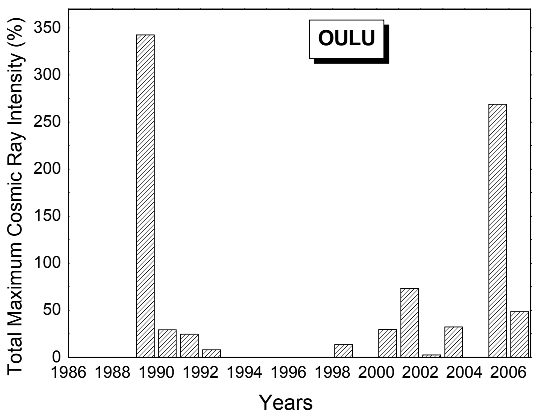


Fig. 5 Distribution of the total cosmic ray intensity maximum during solar cycles 22 and 23 as recorded in Oulu station.

The event of 29th October 2003 (GLE66) is an exception,

TABLE II
COSMIC RAY INTENSITY RATES OF GEOGRAPHICAL REGIONS

Region #	Longitude (˚)	Latitude (˚)	Counting rate
1	0 to 167	-90 to -43	high
2	150 to 300	43 to 77	high
3	-134 to -61	55 to 69	medium
4	25 to 34	65 to 68	medium
5	18 to 28	-35 to -19	low
6	7 to 105	40 to 61	low

having an onset time variability of 75 minutes. This event, of course, was a rather complicated one due to the magnetospheric event that was also recorded in the same day [14] and seems to have influenced the whole evolution of the GLE.

IV. CONCLUSIONS

The statistical analysis of GLEs is summarized by the exhibition of the most important conclusions that have been derived from this work.

i. X-ray flares of high intensity are not necessarily the ones that can produce the most important GLEs. It is noted that there are also great solar flares that are not anyhow connected to a recorded by neutron monitors GLE; this is the case for the Mega flare 3B/X28.0 which was recorded on 4 November 2003 and it did not give a GLE event [15]. Also, on the basis of the analysis of the eleven most intense events, it is derived that the majority of the X-ray solar flares of class-X that are possibly connected with a GLE production come from west and south active solar regions.

ii. From the analysis of the longitudinal and latitudinal distribution of the eleven events it is derived that there are two geographical regions, region # 1: long. 0˚ to 167˚, lat. -90˚ to -43˚ and region 2: long. 150˚ to 300˚, lat. 43˚ to 77˚, approximately, which seem to record the highest rates of cosmic ray intensity. The maximum intensity (%) of each event usually occurs in these areas. On the other hand, stations from regions # 5 and # 6 seem to record very low rates and in many cases do not record GLEs.

iii. At each GLE observed, an onset time variability among all neutron monitors recorded the event of at least 10 minutes was noted. There are some events which presented remarkably anisotropic onset times, like the events GLE43, GLE69 and of course the event GLE66 which was a rather complicated event.

The above are only preliminary results of the statistical study of the GLEs. The work is to be continued to all solar cycles where cosmic ray data are avilable and more characteristics of the GLEs are to be examined, on the basis of a more complete analysis. This study will be very useful to the Space Weather applications.

ACKNOWLEDGMENTS

We thank our colleagues from neutron monitor stations who kindly provided us with the data used in this analysis: Alma Ata, Apatity, Baksan, Barentsburg, Bern, Calgary, Capeshcmidt, Climax, Deep River, Durham, Erevan, Fortsmith, Goose Bay, Hermanus, Hobart, Inuvik, Irkutsk, Jungfraujoch, Kerguelen, Kiel, Kiev, Kingston, Larc, Lomnicky Stit, Magadan, Mawson, McMurdo, Mexico City, Mirny, Morioka, Moscow, Mt Norikura, Mt Washington, Mt Wellington, Nain, Newark, Norilsk, Novosibirsk, Olc, Oulu, Peawanuck, Potchefstroom, Rome, Sanae, South Pole, Terre Adelie, Tbilisi, Thule, Tibet, Tixie Bay, Tokyo, Tsumeb, Yakutsk.

The authors of the University of Athens thank the Special Research Account of the Athens University for supporting this research. M. Andriopoulou expresses her gratitude to the local organizing committee for supporting her to participate to the ECRS 2008.

The research leading to these results has received funding from the European Community's Seventh Framework Programme ([FP7/2007-2013]) NMDB under grant agreement n° 213007.

REFERENCES

[1] H. Mavromichalaki, C. Plainaki, M. Gerontidou, C. Sarlanis, G. Souvatzoglou, G. Mariatos, A. Belov, E. Eroshenko, E. Klepach, V. Yanke: GLEs as a Warning Tool for Radiation Effects on Electronics and Systems: A New Alert System Based on Real-Time Neutron Monitors, *IEEE Trans. on Nuclear Science, 54,4, 2007,1082-1088.*

[2] L. Dorman, L. A. Pustil'nik, A. Sternlieb and G. Zukerman: Using ground level cosmic ray observation for automatically generating predictions of hazardous energetic particle levels, *Adv. Space Res., 31, 2003, 847-852.*

[3] E. O. Flückiger, R. Buetikofer, L. Desorgher, and M.R. Moser: The Role of GLEs in Space Weather, *36th COSPAR Scientific Assembly, Beijing ,* 2006, *3042.*

[4] R. Wang and J. Wang: Investigation of the cosmic ray ground level enhancements during solar cycle 23, *Adv. Space Res*., 38, 3, 2006, 489-492.

[5] D. F. Smart, M. A. Shea and P. J. Taskanen: A Determination of the Spectra, Spatial Anisotropy and Propagation Characteristics of the Relativistic Solar Cosmic-Ray Flux on November 18, 1968, *Proc. 12th Int. Cosmic Ray Conf.,* Tasmania, Australia, 1971.

[6] M. A. Shea and D.F. Smart: Possible evidence for a rigidity-dependent release of relativistic protons from the solar corona, *Space Science Rev.,*32, 1-2, 1982, 251-271.

[7] J. E. Humble, M. L. Duldig, M. A. Shea and D. F. Smart: Detection of 0.5-15 GeV solar protons on 29 September 1989 at Australian stations, *Geophys. Res. Lett.,* 18, 1991, 737-740.

[8] J. L. Cramp, M. L. Duldig, E. O. Flückiger, J. E. Humble, M.A. Shea and D. F. Smart: The October 22, 1989, solar cosmic ray enhancement:

An analysis of the anisotropy and spectral characteristics, *J. Geophys. Res.,* 102, A11, 1997, 24237-24248.

[9] A. Belov, E. Eroshenko, H. Mavromichalaki, C. Plainaki and V. Yanke: Solar Cosmic Rays during the extremely high ground level enhancement on 23 February 1956, *Ann. Geophys.,* 23, 2005, 2281- 2291.

[10] C. Plainaki, A. Belov, E. Eroshenko, H. Mavromichalaki and V. Yanke: Modelling ground level enhancements: Event of 20 January 2005, *J. Geophys. Res.*, 112, A4, 2004.

[11] H. Mavromichalaki, E. Marmatsouri, A. Vassilaki: Solar-cycle phenomena in cosmic-ray intensity. Differences between even and odd cycles, *Earth, Moon, and Planets*, 42, 1988, 233-244.

[12] M. Storini, K. Kudela, E. G. Cordaro and S. Massetti: Ground- level enhancements during solar cycle 23: results from SVIRCO, LOMNICKY STIT and LARC neutron monitors, *Adv. Space Res.,* 35, 3, 2005, 416- 420.

[13] M. Storini, G.A. Bazilevskaya, E.O. Fluckiger, M.B. Krainev, V.S. Makhmutov and A.I. Sladkova.: The Gnevyshev gap: A review for space weather, *Adv. Space Res.,* 31, 4, 2003, 895- 900.

[14] C. Plainaki, A. Belov, E. Eroshenko, V. Kurt, H. Mavromichalaki and V. Yanke: Unexpected burst of solar activity recorded by neutron monitors during October- November 2003, *Adv. Space Res.* 35, 2005, 691-696.

[15] W. Uddin, R. Chandra and S.S. Ali: Extremely Energetic 4B/X17.2 Flare and Associated Phenomena, *J. Astrophys. and Astron.* 27, 2 & 3, 2006, 267-276.

[16] E. Eroshenko, A. Belov, H. Mavromichalaki, G. Mariatos, V., Oleneva, C. Plainaki and V. Yanke: Cosmic- Ray Variations During the Two Greatest Bursts of Solar Activity in the 23rd Solar Cycle, *Solar Physics,* 224, 1-2, 2004, 345- 358.

[17] M. A. Shea and D. F. Smart: Vertical cutoff rigidities for cosmic ray stations since 1955, *Proc. Intern. Cosmic Ray Conf. 2001,* 4063.

[18] J. Poirier and C. D' Andrea: Ground level muons in coincidence with the solar flares of April 15, 2001, *arXiv: astro-ph/0211490v1*, Hamburg, (IUPAP), 2002, p. 3383.

[19] M. A. Pomerantz and S. P. Duggal: North-South Anisotropies in the Cosmic Radiation, *J. Geophys. Res,* 77, 1972, 263-265.

[20] E. V. Vashenyuk, B. B. Gvozdevsky and V.V. Phelkin: The ground-level enhancement of 14 July 2000: Explaining the difference between near-by neutron monitors at Apatity and Oulu, Proc. 27th Intern. Cosmic Ray Conf. . 07-15 August, 2001.

[21] E. V. Vashenyuk, Y. V. Balabin and B. B. Gvozdevsky: Relativistic solar cosmic ray dynamics in large ground level events, *Proc. 21st European Cosmic Ray Symposium*, Košice, 2008.

[22] N. Gopalswamy: Solar Sources of GLE events of Cycle 23, *Proceedings of FORGES 2008*, Erevan, Armenia, 2008

[23] M. L. Duldig: Cosmic ray transient variations observed from the Earth, *Astronomical Society of Australia, Proceedings*, 11, 2, 1994, 110- 125.