Astrophys. Space Sci. Trans., 7, 439–443, 2011
www.astrophys-space-sci-trans.net/7/439/2011/
doi:10.5194/astra-7-439-2011

Astrophysics and Space Sciences Transactions

Solar activity and the associated ground level enhancements of solar cosmic rays during solar cycle 23

M. Andriopoulou[1], H. Mavromichalaki[1], P. Preka-Papadema[1], C. Plainaki[2,1], A. Belov[3], and E. Eroshenko[3]

[1]Physics Department, National and Kapodistrian University of Athens, 15771 Athens, Greece
[2]INAF-Istituto di Fisica dello Spazio Interplanetario, Roma, Italy
[3]Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation, Russian Academy of Science, Moscow, Russia

Received: 12 November 2010 – Revised: 7 April 2011 – Accepted: 12 April 2011 – Published: 7 October 2011

Abstract. The solar cycle 23 seems to be of great interest for the researchers due to many peculiarities. A study of the parameters of the sixteen ground level enhancements recorded during the approximately 12-year period of it (1996–2008) together with the associated solar activity, including the main properties of the solar flares, the coronal mass ejections and the radio bursts has been realized, in an effort to understand the connection of these events. All studied cases seem to be connected with very intense flares of long duration, having a mean importance value of $X5.9$ and a mean duration of 164.5 min, with either halo or partial halo coronal mass ejections with a mean linear velocity of 1876 km/sec, as well as with intense radio bursts. It is also noticed that the ground level enhancements of the 23rd solar cycle occurred after the onset time of the associated solar $X-$ray flares with a mean time delay of about 38 min, very useful result for their monitoring and prediction.

1 Introduction

Ground level enhancements (GLEs) of solar cosmic rays are the solar particle events that can be recorded from ground-based detectors as sharp increases of short duration in the cosmic ray intensity counting rates. These energetic particles recorded by the neutron monitors must have energies of at least 500 MeV in order to access the Earth's magnetosphere and to be recorded at the ground as secondary cosmic rays (Simpson, 2000).

Until today the acceleration mechanisms that take place during GLE events have not been fully understood. It is known that relativistic proton acceleration could take place either in processes involving magnetic reconnection (Cane et al., 2006) or at coronal or CME-driven shocks (Reames, 1999). Recent studies, however, suggest that there might be a strong possibility that solar flares and coronal mass ejections (CMEs) are manifestations of the same eruptive process (Lin et al., 2005).

Due to the fact that these relatively rare events (only seventy events have been recorded since their official registration in 1942) are very important for space weather studies (Mavromichalaki et al., 2007), many research works have been devoted to them, including the study of separate events mostly (Smart et al., 1971; Humble et al., 1991; Belov et al., 2005; Mavromichalaki et al., 2005; Vashenyuk et al., 2006; Plainaki et al., 2007, 2010) through the use of advanced modelling techniques that determine important characteristics, such as the primary cosmic ray spectrum and the pitch-angle distribution of the event. Recently, a number of works regarding the study of the main properties of many events has been presented, especially for those occurring during the last solar cycles (Storini et al., 2005; Andriopoulou et al., 2010; Belov et al., 2010; Firoz et al., 2010; Gopalswamy et al., 2010), since there were more available data in comparison with previous cycles. In these works many GLE parameters were calculated from the ground using data obtained from the worldwide network of neutron monitors as well as satellite data.

The main focus of this work is the determination of the solar phenomena related to the sixteen ground level enhancements of solar cycle 23 (May 1996–December 2008) in order to be able to have a better understanding about their properties. In particular, the characteristics of the related solar flares, the CMEs and the radio bursts have been analytically studied in an effort to understand their relationship with the GLEs.

Correspondence to: M. Andriopoulou (mariand@phys.uoa.gr)

Published by Copernicus Publications on behalf of the Arbeitsgemeinschaft Extraterrestrische Forschung e.V.

Table 1. Characteristics of the GLE events in solar cycle 23

GLE event	Station Abbrev.	I_{max} (%)	Flare GOES class.	Flare dur. (min)	CME linear speed (km/s)	CME acceler. (m/s2)	Radio emission types
GLE55:06/11/97	SOPO[1]	18.6	X9.4/2B	55	1556	−44.1	II/III/IV
GLE56: 02/05/98	OULU	6.6	X1.1/3B	136	938	−28.8	II/III/IV
GLE57: 06/05/98	OULU	4.2	X2.7/1N	67	1099	24.5	II/III/IV
GLE58: 24/08/98	KIEL	5.1	X1.0/3B	198	Data gap	–	II/III/IV
GLE59: 14/07/00	SOPO	59.4	X5.7/3B	103	1674	−96.1	II/III/IV
GLE60: 15/04/01	SOPO	236.7	X14.4/2B	136	1199	−35.9	II/III/IV
GLE61: 18/04/01	SOPO	26.0	C2.2/	-	2465	−9.5	II/III
GLE62: 04/11/01	OULU	8.2	X1.0/3B	457	1810	−63.4	II/III/IV
GLE63: 26/12/01	SOPO	12.6	M7.1/1B	135	1446	−39.9	II/III/IV
GLE64: 24/08/02	OULU	9.3	X3.1/1F	42	1913	43.7	II/III/IV
GLE65: 28/10/03	MCMD	46.9	X17.2/4B	269	1054	–	II/III/IV
					2459	−105.2	
GLE66: 29/10/03	SOPO	35.2	X10.0/2B	124	2029	−146.5	II/III/IV
GLE67: 02/11/03	SOPO	38.6	X8.3/2B	171	2598	−32.4	II/III/IV
GLE68: 17/01/05	OULU	3.5	X3.8/3B	192	2094	−118.8	II/III/IV
					2547	−159.1	
GLE69: 20/01/05	SOPO	5444.2	X7.1/2B	138	2500- 3242[2]	16.0[3]	II/III/IV
GLE70: 13/12/06	OULU	92.1	X3.4/4B	244	1774	−61.4	II/III/IV

[1]Explanation of abbreviation names: SOPO-South Pole, OULU-Oulu, KIEL-Kiel, MCMD- Mc Murdo
[2]According to two different estimations (Simnett et al., 2006; Gopalswamy et al., 2010)
[3]According to the SOHO/LASCO CME catalogue (http://cdaw.gsfc.nasa.gov/CME_list/)

2 Data selection

For this analysis cosmic ray intensity ground-based data from neutron monitor stations belonging to the worldwide network that were collected and processed from the IZMIRAN group (ftp://cr0.izmiran.rssi.ru/COSRAY!/FTP_GLE/) and from the recently created neutron monitor database (http://www.nmdb.eu/) were used. For the related solar phenomena we have used data for the coronal mass ejections (CMEs) from the SOHO/LASCO catalogue (http://cdaw.gsfc.nasa.gov/CME_list/) and solar flare data in the X-ray and H-alpha bands observed from the GOES satellites and collected from the NOAA database (ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_FLARES/) were also used. Finally, the radio signatures of the solar phenomena were also taken into account, using data from the NOAA database and the ARTEMIS IV radiospectrometer (http://www.cc.uoa.gr/~artemis/Artemis4_list.html). Each event was separately analyzed and the time relationships among the GLE events and the various solar phenomena were carefully examined. Additionally, the relationship of the parameters of the solar flares, the CMEs and the radio bursts was also studied.

3 Data analysis and results

During the solar cycle 23 sixteen ground level enhancements of various intensities were recorded by the ground-based neutron monitors, ranging from 4% up to 5442%. The event of 17 January 2005 (GLE68) was the smallest one and many scientists do not even consider it as a GLE event, since it was recorded from a very limited number of neutron monitors and with maximum amplitude reaching only 3.5%. The GLE occurrence covered a nine-year period and had an unusual time distribution in comparison to the previous cycles (Belov et al., 2010). For example, it is noticed that in October–November 2003 three GLE events occurred within one week, while 7 out of the 16 events appeared during the declining phase of the cycle (Andriopoulou et al., 2010). The time profiles of the five most intense GLEs of solar cycle 23, according to the Oulu recordings are shown in Fig. 1. Normalized cosmic-ray-intensity data have been used for this representation and for the whole GLE analysis in this paper, considering a background time period of 1 h prior to the onset time of each GLE. From this figure it is observed that GLE60, GLE69 and GLE70 were recorded as very sharp events, while GLE59 and GLE65 are featuring a wider time profile, something that is probably associated with how near the positions of the flares that are related to the GLE events are with respect to the foot point of the garden hose field line (Duldig et al., 1993). The time profiles in Fig. 1 would appear quite different if another station was used for this representation and especially if it was South Pole, McMurdo or Terre Adelie (Andriopoulou et al., 2010). This difference depends on the relative position of the asymptotic cones of acceptance of the different stations with respect to the source of anisotropy of an event (Plainaki et al., 2009).

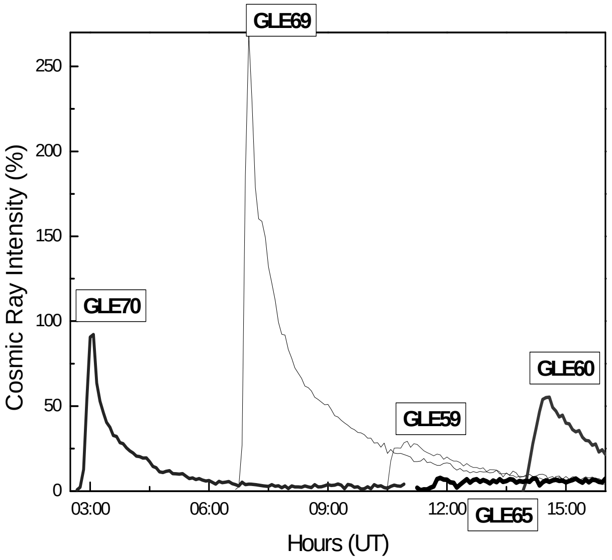

Fig. 1. Time profiles of the most intense GLEs of solar cycle 23, as recorded by Oulu neutron monitor station.

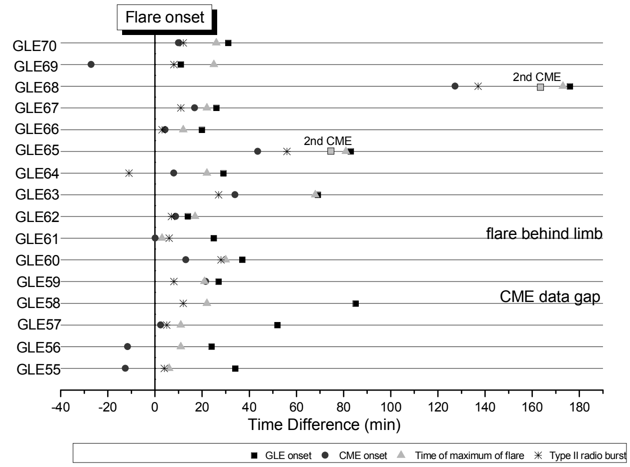

Fig. 2. Time connection of solar flares, GLEs, CMEs and type II radio bursts associated to the GLEs of solar cycle 23, considering the flare onset time as the time reference. Each horizontal line refers to a different GLE event, starting with GLE55 (06/11/1997) in the bottom, up to GLE70 (13/12/2006) in the top.

The list of the events and some characteristics of their related solar phenomena are presented in Table 1. In particular, the number and the date of the event, their maximum % recorded intensity and the neutron monitor that recorded it, the $X-$ray flare classification from GOES, the importance and the duration of the flares and the CME linear velocity and acceleration are given in Table 1. All the examined solar flares were very intense, having a mean importance value of X5.9 class, which is much greater in comparison to the mean flare value of the whole solar cycle that was C1.6 (Gopalswamy et al., 2010), and most of them covered a large area, with their mean value being 450 arcs^2, while their mean duration was 165.4 min. The flare that was related to the event of 18 April 2001 (GLE61) was excluded from this analysis, since it is estimated to have occurred behind the west limb and therefore it was almost entirely occulted. Observing the positions of the flares on the solar disk, it is shown that an 87% of them had a west origination, in accordance with Duldig et al. (1993), who stated that there is a strong tendency for solar active regions responsible for GLEs to be located at westward solar longitudes.

Moreover, all the events were related to very fast halo or partial halo CMEs with plane-of-the-sky speeds (POS; with linear fitting) that range from 938 up to more than 2500 km/s (maybe even reaching 3242 km/s according to the calculations of Gopalswamy et al. (2005) for the related CME of GLE69). Since the studied CMEs are very fast, the majority of them are decelerating. It was also found that all the events were associated to one CME apart from GLE65 and GLE68 that were associated with a double CME and a double type II radio burst.

Observing the data of the related radio bursts it is concluded that for all the recorded GLE cases of solar cycle 23 there is always strong radio emission of type II, III and IV radio bursts related to each event. Only in the case of GLE61 there is an absence of the type IV radio burst, but this could be attributed to the fact that its related flare was behind the limb. The radio signature is usually recorded in the frequency range $200-800$ MHz and in some cases in the decimetre bands. Only for the case of the event of 14 July 2000 (GLE59), when the flare produced complex metric radio emissions, the recorded frequencies were at 120 MHz (Caroubalos et al., 2001).

Considering the flare onset as the reference time, the time differences of the GLE onset, the CME onset, the flare maximum time and the first type II radio burst onset with relation to the flare onset are depicted in Fig. 2. The results for the events GLE58 and GLE61 were uncertain, since in the first case there was a gap in the CME data and in the second case the flare was behind the limb. If we consider a time window of ± 20 min in the CME onset time of SOHO/LASCO calculations, it is derived from Fig. 2 that in nine out of the fourteen cases (GLE58 and GLE61 have been excluded), flares and CMEs were recorded simultaneously. For the cases of GLE63, GLE65 and GLE68 the flare begins before the CME, but the CME seems to be recorded during the rise phase of the flare. From our GLE onset calculations it is also derived that GLEs of solar cycle 23 were recorded at the ground with a time delay of at least 11 min after the flare onset and the mean time delay is 38 min. Finally, it is shown that almost every type II radio burst is recorded during the rise phase of the flare.

If we then combine the result stating that the majority of the flares and CMEs related to GLEs of solar cycle 23

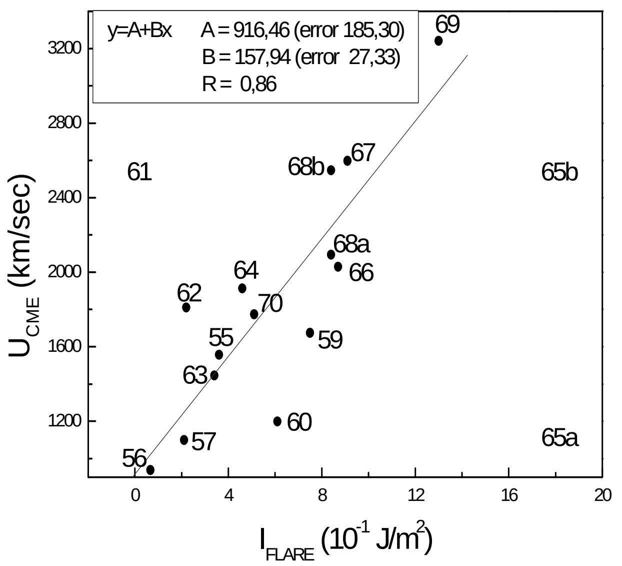

Fig. 3. Linear relationship of the flare integrated intensity with the CME linear velocity associated to the GLEs of solar cycle 23.

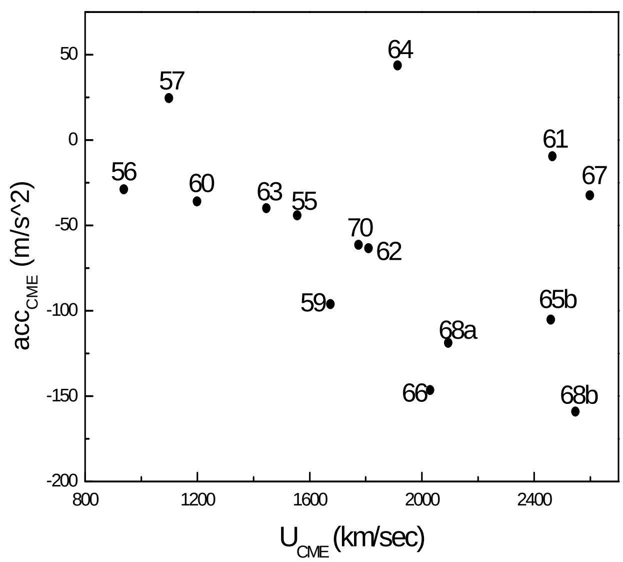

Fig. 4. Relation of the acceleration with respect to the linear velocity of the CMEs related to the GLEs of solar cycle 23. The numbers indicate the corresponding number of each GLE.

began almost simultaneously (Fig. 2) with the fact that we found a linear relationship between the integrated intensity of the flare and the CME linear velocity ($R = 0.86$, excluding GLE61 and GLE65) that is depicted in Fig. 3, we are also led to the conclusion that flares and CMEs could be manifestations of the same eruptive process, at least for the GLE related cases. This result also seems to be in agreement with Firoz et al. (2010), who studied the properties of 32 GLEs occurring during the period of January 1979 to July 2009 according to Oulu measurements and found that all the GLE cases were both solar flare and CME-associated.

Additionally, observing the relationship between the CME linear velocity and the acceleration, which is shown in Fig. 4, we can see that for most GLE cases, the higher the CME linear velocity is, the higher the CME deceleration becomes. From this figure GLE69 was excluded since its CME estimates had a significant uncertainty, ranging from 2500 – 3242 km/s (Gopalswamy et al., 2005; Simnett, 2006). A similar behaviour has been also observed from Andrews (2002) for CMEs that are associated with intense flares and it also seems to be the case for CMEs and flares that are related to GLEs. It is also noticed in this figure that GLE61, GLE64 and GLE67 seem to be separated from the other data points. Apart from this rather peculiar behaviour of these 3 events, their only common feature is that all of them are small solar cosmic ray events, with maximum amplitudes of 26%, 9.3% and 38.6%, respectively.

4 Conclusions

The most significant conclusions that came up from this analysis including all the events of solar cycle 23 are the following:

i. As it is known from the previous cycles, it is confirmed once again that every studied GLE case during the solar cycle 23 seems to be associated with a very intense solar activity. There is always an intense flare, a fast CME and strong radio emissions of type II, III and IV radio bursts related to the event, making it difficult to determine which the dominant acceleration mechanism in each GLE case is.

ii. The GLE-associated flares of solar cycle 23 were very intense with a mean importance value of X5.9. They had a relatively long duration with a mean value of 164.5 min and covered large areas in comparison to the mean values of all the flares of solar cycle 23, as Gopalswamy et al. (2010) have also showed. Additionally, it is interesting that all the flares related to GLEs were gradual events.

iii. In general, CMEs that are related to GLEs are halo or partial halo and fast events as it is also reported by Andriopoulou et al. (2010). There seems to be an analogy between the CME linear velocity and the deceleration increase with a correlation coefficient of 86% (Andrews, 2002). The CME of GLE69 was excluded from this analysis, due to uncertainties in the estimations of the CME velocity and acceleration.

iv. The fact that solar flares and CMEs started almost simultaneously in the majority of GLEs together with the fact that there is a linear relationship between the integrated intensity of the flare and the linear velocity of the CME, provides additional evidence that flares and CMEs could be manifestations of the same eruptive process, at least for the GLE-related cases.

Concluding we can say that it is obviously very difficult to make clear conclusions about the dominant acceleration mechanisms that are present during the GLE events. A more detailed analysis of each event separately needs to be done to this direction and furthermore future events occurring with the start of the new solar cycle 24, should be also studied in order to determine if the aforementioned results apply to them as well.

Acknowledgements. We thankfully acknowledge the colleagues from the neutron monitors and the solar observatories that kindly provided us with the data used in this work. We would also like to thank the Special Research Account of the University of Athens for supporting this research.

Edited by: B. Heber
Reviewed by: four anonymous referees

References

Andrews, M.: Characteristics of CMEs associated with big flares, in: Proc. 10th Europ. Solar Phys. Meet., ESA-SP506, 531-534, 2002.

Andriopoulou, M., Mavromichalaki, H., Plainaki, C., Belov, A., and Eroshenko, E.: Intense ground level enhancements of solar cosmic rays during the last solar cycles, Solar Phys., 269, 155–168, doi:10.1007/s11207-010-9678-1, 2011.

Belov, A., Eroshenko, E., Kryakunova, O., Kurt, V., and Yanke, V.: Ground level enhancements of solar cosmic rays during the last solar cycles, Geomagn. Aeronomy, 50, 21–33, 2010.

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

Cane, H. V., Mewaldt, R. A., Cohen, C. M. S., and von Rosenvinge, T. T.: Role of flares and shocks in determining solar energetic particle abundances, J. Geophys. Res., 111, A6, 2006.

Caroubalos, C. E., Alissandrakis, A., Hillaris, A., Nindos, A., Tsitsipis, P., Moussas, X., Bougeret, J.-L., Bouratzis, K., Dumas, G., Kanellakis, G., Kontogeorgos, A., Maroulis, D., Patavalis, N., Perche, C., Polygiannakis, J., and Preka-Papadema, P.: ARTEMIS IV radio observations of the 14 July 2000 large solar event, Solar Phys., 204, 167–179, 2001.

Duldig, M. L., Cramp, J. L., Humble, J. E., Smart, D. F., Shea, M. A., Bieber, J. W., Evenson, P., Fenton, K. B., Fenton, A. G., and Bendoricchio, M. B. M.: The Ground Level Enhancements of 1989 September and October 22, in: Proc. Astron. Soc. Australia, 10, 211–217, 1993.

Firoz, K. A., Cho, K.-S., Hwang, J., Phani Kumar, D. V., Lee, J. J., Oh, S. Y., Kaushik, S. C., Subhash, C., Kudela, K., Rybanský, M., and Dorman, L.: Characteristics of ground-level enhancement-associated solar flares, coronal mass ejections, and solar energetic particles, J. Geophys. Res., 115, A9105, 2010.

Gopalswamy, N., Xie, H., Yashiro, S., and Usoskin, I.: Coronal Mass Ejections and Ground Level Enhancements, Proc. 29th ICRC, 1, 169–172, 2005.

Gopalswamy, N., Xie, H., Yashiro, S., and Usoskin, I.: Ground level enhancements of Solar Cycle 23, Indian J. Radio Space Phys., 39, 240–248, 2010.

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

Lin, J., Ko, Y.-K., Sui, L., Raymond, J. C., Stenborg, G. A., Jiang, Y., Zhao, S., and Mancuso, S.: Direct Observations of the Magnetic Reconnection Site of an Eruption on 2003 November 18, Astrophys. J., 622, 1251–1264, 2005.

Mavromichalaki, H., Gerontidou, M., Mariatos, G., Plainaki, C., Papaioannou, A., Sarlanis, C., Souvatzoglou, G., Belov, A., Eroshenko, E., Yanke, V., and Tsitomeneas, S.: Space Weather forecasting at the new Athens Center: The recent extreme events of January 2005, IEEE TNS, 52, 6, 2307–2312, 2005.

Mavromichalaki, H., Plainaki, C., Gerontidou, M., Sarlanis, C., Souvatzoglou, G., Mariatos, G., Belov, A., Eroshenko, E., Klepach, E., and Yanke, V.: GLEs as a Warning Tool for Radiation Effects on Electronics and Systems: A new Alert System based on Real-Time Neutron Monitors, IEEE TNS, 54, 1083–1088, 2007.

Plainaki, C., Belov, A., Eroshenko, E., Mavromichalaki, H., and Yanke, V.: Modeling ground level enhancements: Event of 20 January 2005, J. Geophys. Res., 112, A4, 2007.

Plainaki, C., Mavromichalaki, H., Belov, A., Eroshenko, E., and Yanke, V.: Neutron monitor asymptotic directions of viewing during the event of 13 December 2006, Adv. Space Res., 43, 518–522, 2009.

Plainaki, C., Mavromichalaki, H., Belov, A., Eroshenko, E., Andriopoulou, M., and Yanke, V.: A new version of the NMBANGLE Model applied to the GLE60, Solar Phys., 264, 239–254, 2010.

Reames, D. V.: Particle acceleration at the Sun and in the heliosphere, Space Sci. Rev., 90, 413–491, 1999.

Simnett, G. M.: The timing of relativistic proton acceleration in the 20 January 2005, Astronom. Astrophys., 445, 715–724, 2006.

Simpson, J. A.: The cosmic ray nucleonic component: The invention and scientific uses of the neutron monitor, Space Sci. Rev. 93, 11-32, 2000

Smart, D. F., Shea, M. A., and Taskanen, P. J.: A Determination of the Spectra Spatial Anisotropy and Propagation Characteristics of the Relativistic Solar Cosmic-Ray Flux on November 18, 1968, in: Proc. 12th ICRC, 2, 483–488, 1971.

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

Vashenyuk, E. V., Balabin, Y. V., Gvozdevsky, B. B., and Karpov, S. N.: Relativistic solar protons in the event of January 20, 2005: Model studies, Geomagn. Aeronomy, 46, 424–429, 2006.