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Application of the NM-BANGLE model to GLE70

C. PLAINAKI [1], H. MAVROMICHALAKI [1], A. BELOV [2], E. EROSHENKO [2], V. YANKE [2]
[1] *Nuclear and Particle Physics Section, Physics Department, Athens University Pan/polis15771 Athens, Greece cplainak@phys.uoa.gr; emavromi@phys.uoa.gr*
[2] *Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation (IZMIRAN), 42092, Troitsk, Moscow Region, Russia , abelov@izmiran.ru;*
erosh@izmiran.ru

Abstract: A new significant ground level enhancement was recorded by the worldwide neutron monitor network during the minimum phase of the 23rd solar cycle, on 13 December, 2006. The event, also known as GLE70, started at ~ 2:48 UT, whereas the neutron monitor flux in most stations reached its maximum in ~3:00-3:10 UT. In northern Europe the event was registered with big amplitudes that in some cases reached ~ 70-90%, rendering this recent enhancement in one of the greatest ground level enhancements (GLEs) of the 23rd solar cycle. The low latitude neutron monitor station in Athens seems to have recorded some enhancement during the time period of the event providing possible evidence of the existence of high energy solar particles. In this work some preliminary results of a ground level neutron monitor data analysis for the event of 13 December, 2006, are presented. The application of the NM-BANGLE (Neutron Monitor Anisotropic GLE) model to GLE 70, using data from thirty four neutron monitor stations widely distributed around the globe, resulted in the determination of some GLE-parameters such as the rigidity spectrum and the location of the anisotropy source during different moments of the event. The morphology of this event seems to have similarities with GLE69 in January 2005. It seems that during the initial phase of the event the solar cosmic ray rigidity spectrum was quite hard whereas later its evolution was rather complicated. Moreover the very first energetic particles seem to have arrived in a narrow beam.

Introduction

Solar cosmic rays (SCR) can effectively be used for studying the processes of particle acceleration in the solar atmosphere and their propagation in interplanetary space. A solar flare can accelerate protons to sufficiently high energies for these particles to propagate along the interplanetary magnetic field (IMF) to the earth and be detected as a sharp increase in the counting rate of a ground based cosmic ray detector. Such events are known as ground level enhancements (GLEs).
Several techniques for modeling the dynamical behavior of GLEs throughout their evolving are presently available. Special methods for calculating the neutron monitor (NM) response during a solar proton event have been developed over many years (e.g.[1]) and they are described in [2]. Accurate representations of the Earth's magnetic field [3], [4] have significantly improved the GLE modeling, enabling the determination of viewing directions for ground level instruments. Recently, a new GLE model, based on the method of coupling coefficients [5], [6] as well as the determination of the asymptotic directions for each one of the neutron monitors, was proposed [7]. The so called NM-BANGLE (Neutron Monitor Anisotropic GLE) model has already been applied to the GLE69, leading to the determination of several descriptive GLE parameters.
Recently, a new anisotropic GLE was recorded by the worldwide neutron monitor network during the minimum phase of the 23rd solar cycle, on 13 December, 2006 (Fig. 1). In this work the NM-BANGLE model was applied to GLE70, using data from 33 NMs, covering a wide range of cutoff rigidities and asymptotic viewing directions.

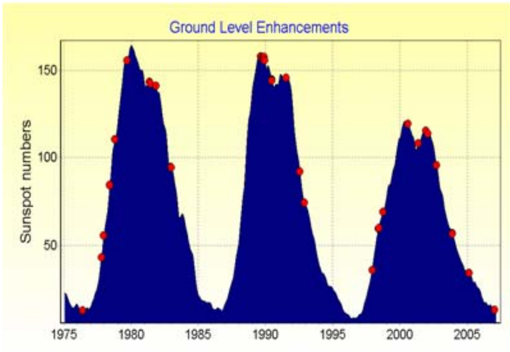

Figure 1: GLEs and sunspot number evolution over the last solar cycles

The NM-BANGLE Model

The NM-BANGLE model [7] is a new cosmic ray model which couples primary solar cosmic rays at the top of the Earth's atmosphere with the secondary ones detected at ground level by neutron monitors during GLEs. This model calculates the evolution of several GLE parameters such as the SCR spectrum and anisotropy as well as the particle flux distribution, revealing crucial information on the SCR particle propagation and distribution. As an input the NM-BANGLE model uses cosmic ray GLE data from NM stations widely distributed around the world. The total output of the NM-BANGLE model is a multidimensional GLE picture that gives an important contribution to understanding the physics of solar cosmic ray particles under extreme solar conditions.

According to the NM-BANGLE model, possible time variation of the total neutron counting rate, observed at cut-off rigidity R_c, at level h in the atmosphere at some moment can be determined by [8],[9],[7]:

$$\frac{\Delta N(R_c,h,t,t_0)}{N_0(R_c,h,t_0)}=\frac{\int_{R_c}^{R_u} W(R,h,t_0)\frac{\Delta I(\Omega,R,t)}{D_0(R)}(t,R)dR}{\int_{R_C}^{R_u} W(R,h,t_0)dR} \quad (1)$$

where $W(R,h,t_0)$ is the coupling function between secondary and primary cosmic rays arriving at the top of the atmosphere, and $\Delta I(\Omega,R,t)$ is the differential rigidity spectrum of solar cosmic rays at the top of the atmosphere and $D_0(R)$ is the background of the galactic cosmic ray variation, recorded at ground level. The rigidity dependent coupling functions can be calculated after parameterization of the results of [10] using an altitude dependent Dorman function [11] and a special power-law form in the low kinetic energy range [12].

Five-minute GLE data from several NM stations, widely distributed around the Earth, can be incorporated to fit the main equation (1), applying the Levenberg-Marquardt non-linear optimization algorithm[13], [14]. For the evaluation of the asymptotic directions and the cut-off rigidities for each NM location the NM-BANGLE model uses the Tsyganenko89 model [4].

Description of GLE70

December 2006 falls on the minimum of the 23rd cycle of solar activity. However, several solar events taking place in that time period lead to the conclusion that the situation in the near Earth interplanetary space cannot be considered as quiet. Moreover, on 7 December, a Forbush Decrease (FD) was registered by the neutron monitors of the worldwide network. In Athens the amplitude of the FD reached ~ 5%, on 15 December (Fig. 2).

On 13 December, 2006, sunspot 930, located at S06W26, unleashed a big X3.4/4 B solar flare, with onset at 2:14 UT and maximum at 2:40 UT. This flare produced energetic solar cosmic rays that were guided toward the Earth by the interplanetary magnetic field and caused increase in the count rates of the ground based cosmic ray detectors. On 13 December, 2006 the worldwide network of NMs recorded one of the biggest ground level enhancements of the last decade, classified as GLE70, starting at ~ 2:48 UT (Fig. 3). Although the event appeared on the minimum phase of the 23rd solar cycle (Fig.1), it manifested the extreme solar conditions taking place at that certain period. The maximum cosmic ray variation (~92%),recorded in Oulu NM at ~3:05 UT, classifies this event as the third biggest GLE of the 23rd cycle of solar activity, leaving behind only the enhancements of 15 April, 2001 and 20 January, 2005. The fact that the maximum enhancement was not registered at subpolar stations

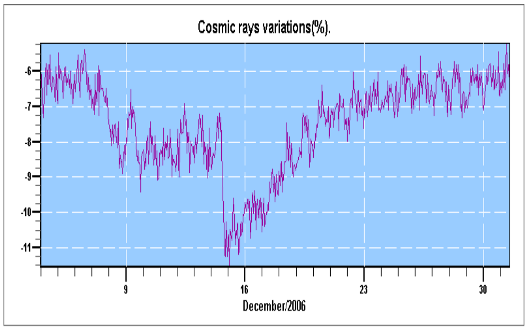

Figure 2: Forbush decrease recorded at Athens neutron monitor station in December 2006

as usual, but on lower latitudes leads to the conclusion that the source of anisotropy must have been located near the ecliptic plane. Mid and high latitude stations registered the GLE70 with different amplitudes, giving evidence of strong anisotropy, especially during the initial phase. Nevertheless the north-south anisotropy was small. Slow and pronounced beginning of the event renders difficult the accurate definition of the onset time, which can be placed in the time interval 2:45-2:52 UT.

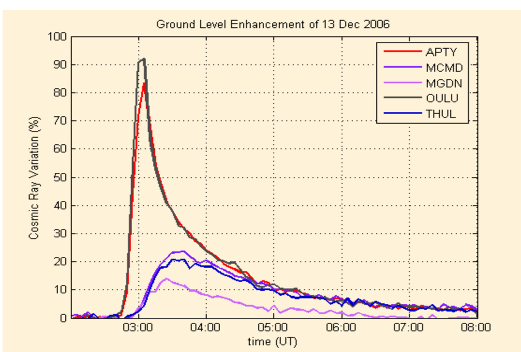

Figure 3: GLE70 as it was recorded by NM stations of the worldwide network

On 13 December, the interplanetary situation was moderately disturbed near Earth hence no big interplanetary disturbance was on the way of accelerated particles. During the first six hours of the day, Kp index had the value of 3, whereas from 06:00 UT to 21:00 UT it fell to zero. Periods of minor storms had occurred one day before (12 December, from 03:00 UT to 6:00 UT and from 18:00 UT to 21:00UT). The IMF had normal intensity (~4.4 nT). Several days prior to the event, the IMF did not undergo big variations. This is one of factors that provided big GLE, as the Earth's force field line root was close to flare location. On 13 December, solar wind velocity was enhanced (~ 600 km/s), due to the eastern ejecta taking place earlier. The coronal mass ejection (CME) associated with GLE70 created severe geomagnetic storm (with Kp up to 8+) on December 15.

Results of the model application to GLE70 - Discussion

Five-minute data from 33 NM stations, widely distributed around the Earth, were incorporated to fit the main equation (1), assuming the existence of an anisotropic primary SCR flux of the form:

$$\Delta I(\Omega, R, t) = \Delta D(R, t) \cdot \Psi(\Omega, R, t) \qquad \textbf{(2)}$$

where $\Psi(\Omega, R, t)$ is the anisotropy function reflecting the angular dependence of the flux for particles with rigidity R coming from asymptotic direction Ω, and $\Delta D(R,t) = R^{\gamma}$ is the differential SCR rigidity spectrum.

Application of the NM-BANGLE model to GLE70 showed that during the initial phase of the event the rigidity spectrum was very hard (γ ~-2.9 at 2:45-250 UT) indicating the existence of very energetic solar particles, whereas later its evolution was rather complicated.

The asymptotic viewing directions of several NMs together with the contour areas of the equal fluxes of particles with rigidity bigger than 1 GV, during different phases of the GLE70, are presented in Fig.4. It is clearly seen that during the initial phases of the event, while the anisotropy is big, the highest particle fluxes are concentrated inside a narrow area. In the time-interval 2:55 UT-3:00 UT the asymptotic cones of the neutron monitor at Oulu fall inside this narrow area, hence the event is recorded with the maximum amplitude. Therefore, during the first time intervals of the event, the anisotropy in the direction of the particle arrival had a narrow beam-like form, centered above specific locations. This beam spread with time allowing the recording of big enhancement from more and more NMs. Similar situation existed during GLE69, in January 2005, when the very first solar particles were sensed only by the most favourably located NMs [7].

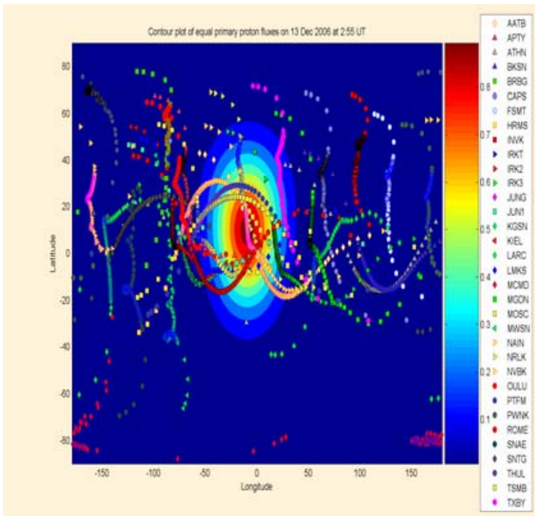

Figure 4: Contour areas of equal fluxes of particles with rigidity >1 GV together with asymptotic viewing directions of NMs, at 2:55-3:00UT

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References

[1] Duldig, M.L., J.L. Cramp, J.E. Humble, D.F. Smart, M.A. Shea, J. W. Bieber, P. Evenson, K.B. Fenton, A.G. Fenton and M.B.M Bendoricchio, The Ground-level enhancement of 1989 September 29 and October 22, *Proc. NASA 10,* 1993.

[2] Cramp, J.L., 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. Geoph. Res., 102, A11,* 24237, 1997.

[3] Tsyganenko, N.A, Global quantitative models of the geomagnetic field in the cislunar magnetosphere for different disturbance levels, *Planet. Space Sci., 35,* 134, 1987..

[4] Tsyganenko, N.A., A magnetospheric magnetic field model with the warped tail current sheet, *Planet. Space Sci., 37,1989.*

[5] Dorman, L. I., *Variatsii Kosmicheskix Luchej*, Gostexizdat, Moscow, English translation (limited edition): *Cosmic Ray Variations*, Technical liaison office, Wright-Patterson Air Force Base, Ohio, 1957.

[6]Dorman, L.I., Cosmic Rays in the Earth's atmosphere and underground, Kluwer Academic Publishers, The Netherlands, 2004.

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

[8] Dorman, L. I., Progress in Elementary Particle and Cosmic Ray Physics, J. G. Wilson and S.A. Wouthuysen (ed), North-Holland Publ. Co., Amsterdam, 1963.

[9] Belov, A., E. Eroshenko, H. Mavromichalaki, C. Plainaki and V. Yanke,, Solar cosmic rays during the extremely high ground level enhancement of February 23, 1956, Anal. Geophys. 23, 1, 2005.

[10] Dorman, L.I. and V. Yanke, The Coupling Functions of NM-64 Neutron Supermonitor, *Proc. Int. Conf. Cosmic Rays 17th, 4*, 326, 1981.

[11] Clem J. and L. I. Dorman (2000), Neutron monitor response functions. *Space Sci. Rev., 93, 1,* 335, 2000.

[12] Belov, A. V. and A.B. Struminsky, Neutron monitor sensitivity to primary protons below 3 GeV derived from data of ground level events, *Proc. Int. Conf. Cosmic Rays 25th,* 1, 201, 1997.

[13] Levenberg, K., A Method for the Solution of Certain Problems in Least Squares, *Quart. Appl. Math., 2,* 164, 1944.

[14] Marquardt, D.W., An algorithm for least-squares estimation of non linear parameters, *SIAM J. Appl. Math., 11,* 431, 1963.