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An extended features of the ground-level cosmic-ray event of 29 September 1989

M. A. El-Borie[1,2] **and S. S. Al-Thoyaib**[1]

[1]Physics Dept., Teachers College, Riyadh 11491, P.O. Box 4341, Kingdom of Saudi Arabia.
[2]Physics Dept., Faculty of Science, Alexandria University, Egypt.

Abstract. The cosmic-ray ground level enhancement on 29 September 1989 is the largest relativistic solar proton event since 1956's. Four representative pairs of neutron detector have been selected to compute the mean attenuation length for the solar protons (λ_S) produced in the considered event, over a wide range of particle rigidities. Each pair of detectors has a very similar of geomagnetic vertical cut-off rigidity and differs in terms of the altitude of the observing site. The computed values of λ_S have shown a strong correlation with the vertical geomagnetic cut-off rigidity for the observing site. Furthermore, we have studied the power spectra for the event. The time of the first maximum is dominated by the higher rigidity particles, while the lower rigidity flux reaches its maximum at the time of the second peak. In addition, at the time of the first maximum the spectrum of the event was hard and it soften throughout the remainder of the event.

1. Introduction

Ground level event (GLE) is a sharp increase in the counting rate of ground-base cosmic ray detectors which caused by the acceleration of charged particles from the Sun to energies sufficiently high and propagate along the heliomagnetic field to the Earth. The event of September 29, 1989 is the largest one ever observed since 1956. It was registered not only by neutron monitors (NMs) network and surface muon telescope (SMT) but also for the first time by the underground muon telescopes (UMT) (Humble et al., 1991; Duldig et al., 1993). The Socorro UMT (New Mexico, 82 meter water equivalent (mwe), higher cutoff rigidity) recorded no definite increase. In contrast, significant increases in muon intensity were observed by the vertical UGT at Embudo (New Mexico; 35 mwe) (Swinson and Shea, 1990), at Yakutsk (USSR; 7, 20, and 60 mwe) (Filippov et al., 1991), and also at Baksan underground scintillation telescope (USSR, it has a much high muon energy E ≥ 200 GeV) (Alekseev and Karpov, 1994), confirming the high energy nature of this event. These observations are consistent with an upper rigidity of ~ 30 GV for particles in the GLE (Lovell et al., 1998).

Several mechanisms, and strongly debated, were proposed to understand the acceleration of charged particles to energies sufficiently high during the GLE as well as, the propagation of these particles to the Earth. McCracken (1962) proposed a two-attenuation-length method for applying a pressure correction to the NM counting rate during a GLE. The computed mean value of the attenuation length (λ_S) for solar nucleons produced in the solar flare was given as; $\lambda_S = (100 \pm 5)$, g cm^{-2} (McCracken, 1962; Duggal, 1979). According to Ahluwalia and Xue (1993), they obtained a significantly larger value of λ_S than the consensus value.

In the present work, we examine the observation intensity/time profiles of GLE at multiple sites, in a wide energy range, to allow the determination the mean solar attenuation length (λ_S) in the Earth's atmosphere, as well as to examine the spectrum of the event.

2. Neutron monitors and solar observations

According to Shea et al., (1990), the flare believed responsible for the Sep. 29, 1989 event was located ~ 15° behind the west limb of the Sun (~ 105° West). The onset of an X-ray event started at 1047 UT and the maximum of the X-ray flare happened at 1133 UT (Class X9.8). The radio burst at 8800 MHz started at 1120 UT, reaching maximum emission at 1137 UT.

Since the considered GLE recorded at the mountain and sea level sites all over the Earth, we can use the Wilson et al. (1967) method to compute the attenuation length λ_S

Correspondence to: M.A. El-Borie

Table 1. Neutron Monitor Observations of 29 September 1989 GLE.

Station Name (NM)	Geographic Co-ordinates Lat. Deg.	Long. Deg.	Station Altitude (m)	Geomag. Cut-Off Rigidity R_o, GV	Mean Atten. Length λ_g, gcm^{-2}	Station Pressure p, gcm^{-2}	First Maximum Time (UT)	Amp. (%)	Second Maximum Time (UT)	Amp. (%)
Mt. Washington	44.3 N	71.3 W	1909	1.38	135.9	821.7	1215-1220	175	1345-1350	286
Durham	43.1 N	71.0 W	SL	1.41	140.9	1033.7	1210-1215	114.6	1335-1340	182
Jungfraujoch	46.5 N	7.98 E	3570	4.54	141.7	641.1	1215-1220	179.2	-	
Rome	41.9 N	12.5 E	60	6.2	145.4	1029.5	1210-1215	98.2	-	
Mt. Norikura	36.1 N	137.6 E	2770	11.39	145.7	734.4	1200-1205	32.3	-	
Tokyo	35.8 N	139.7 E	20	11.61	153.1	1034.3	1155-1200	27.9	-	
Mt. Wellington	42.9 S	147.4 E	725	1.89	139	946.6	1225-1230	342	1315-1320	344
Hobart	42.9 S	147.4 E	SL	1.88	138	1032.1	1215-1230	300	1315-1320	292

over a wide range of the proton rigidities. Four pairs of NMs have been selected; which are Mt. Washington / Durham (American stations), Jungfraujoch / Rome (European stations), Mt. Norikura / Tokyo (Japanese stations) and Mt. Wellington/Hobart (Australian stations). Table 1 gives the relevant parameters of these stations, the geographic coordinates, altitude from the sea level, geomagnetic vertical cutoff rigidity (R_0), the mean value of the attenuation lengths for galactic cosmic rays (λ_g), the station pressure (P), as well as the times and amplitudes of the first and second maxima (if found) for the GLE. Of the four neighboring stations, each has nearly identical asymptotic cones and is suited to the isotropic events. Wash/Dur form a typical high latitude pair in the western-northern hemisphere, Jung/Rom represent high location in the eastern-northern hemisphere, while Nori/Tok meet lower latitude in the far east-north hemisphere. Well/Hob are high latitude location in the far east-south hemisphere.

3. The GLE of 29 September 1989

The GLE of 29 Sep., 1989 has some unusual features. In general, at the flare site, some of the accelerated protons interacted with ions in the lower solar chromosphere and produced neutrons with high energy by the "knock-on" process. These high energy particles, coupled with the favorable geometry, permitted direct detection at the Earth (Chupp et al., 1987; Shea et al, 1991a; 1991b).

The intensity-time profiles as recorded at Durham, Rome, and Mt. Wellington for the considered event are given in Fig. 1. The plot is obtained from the 5-minutes averages of the data. The event obviously has a short rise time and an exponential decay. Alessio et al. (1991) reported that at 1149-1150 UT the intensity started to increase to the maximum level. We notice that the maximum increase is at 5-10 minutes earlier for NMs near the sea level than those of high altitudes (see Table 1). The higher altitude has larger increase in the observed flux. In particular, we find that the amplitude of the GLE observed on 29 Sept. 1989 for NM at Wash (altitude = 1909 m) is larger than that observed by NM at Dur. The difference was attributed to the absorption of nucleons by the atmospheric layer between the two station sites (Ahluwalia and Xue, 1993). Furthermore, two maximum peaks were observed in some stations $R_0 < 2$ GV (Wash, Dur, Well, and Hob), while others recorded only one. The second peak was not seen by muon telescopes, even those at the same sites as NMs which recorded two peaks (Lovell et al, 1998). Some NMs did not recover the pre-event intensity level throughout the considered period (e.g., Dur, Well, and Hob). It is clear that the time of the first maximum is dominated by the higher rigidity particles while the lower rigidity flux reaches its maximum at the time of the second peak. Subsequently the time of maximum, the CR intensity decreases exponentially. The short-term fluctuations occurring during the decay-phase of GLE of CR could be of some interest in connection with the particular features of its modulations in the interplanetary medium.

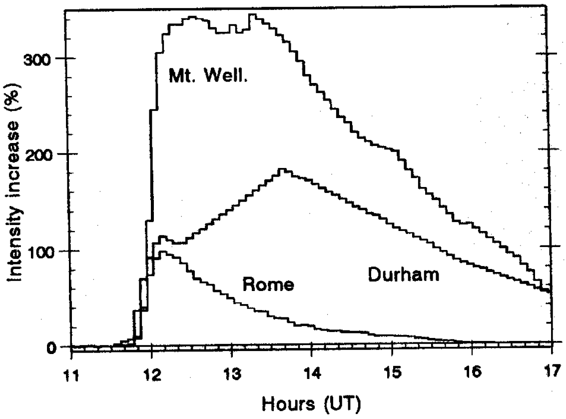

Fig. 1. 1989 September 29 GLE as observed by the Durham, Rome and Mt. Wellington neutron detectors.

The Tokyo and Mt. Norikura NMs recorded an 27.9 % and 32.3 % increase indicating that the solar particles up to at least 15 GeV must be present. The event commenced at Mt. Wellington and Hobart between 1150 and 1200 UT. The first increase persisted for about 50-55 minutes before a second rise. On the other hand, the American stations

(Wash and Dur) noticed the second rise after 85-90 minutes from the first one and with about 60 % excess in the relative increases.

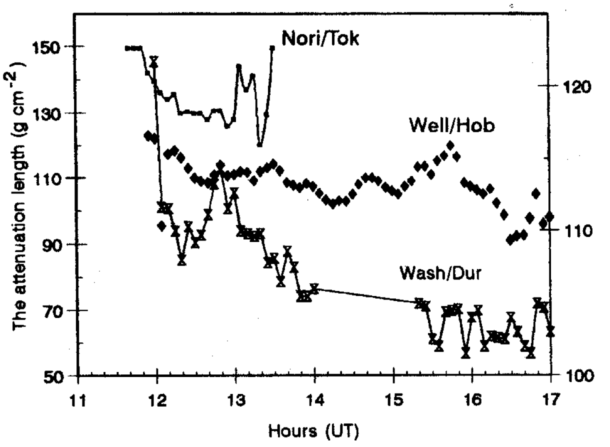

Fig. 2. Values of the solar attenuation length (λ_S) plotted versus the event time (every 5-minutes). The scale of the bottom curve (Wash/Dur) is in the right hand side.

4. The attenuation length for solar relativistic particles throughout the GLE

It is widely known that the attenuation lengths for the solar and galactic nucleons are different according to various interplanetary and atmospheric effects. Equation 1 describes the computation of the solar (basically nucleons) attenuation length (λ_S), at any time of the GLE, from the observed ratio of the fractional increases for a pair of stations. $\delta I_h(t)/\delta I_l(t)$ is the fractional increases of galactic intensity observed at higher and lower altitude locations at any time during the event records. Generally, the fractional increases are greater than unity. Δp is the pressure difference between the two detector sites.

$$\delta I_h(t) / \delta I_l(t) = \exp\,[\,\Delta p\,(\lambda_g - \lambda_S) / (\lambda_g\ \lambda_S)] \qquad (1)$$

Following the established technique described by Ahluwalia and Xue (1993), we calculated the values of λ_S every 5-minutes for the considered pairs of stations. These values are shown in Fig. 2. Note that, the scale of the Wash/Dur curve is in the right hand side. This curve has a break between 1400 UT and 1520 UT due to the missing NM data at Mt. Washington. We applied the Wilson et al (1967) equation from 1140 UT for Nor/Tok, 1155 UT for Well/Hob, and 1200 UT for Wash/Dur. Our conclusions can be listed as follows: (1) A remarkable great values of λ_S have been observed at the beginning of the onset-event of solar proton flux (15-20 minutes earlier the first maximum). Thereafter, the values of attenuation length decline strongly from 1150 to 1300 UT for Nor/Tok, and from 1250 UT to 1400 UT for Wash/Dur, and decrease smoothly between 1210 and 1500 UT for Well/Hob. After 1300 UT, the calculated values of λ_S for Nor/Tok exhibit larger fluctuations, this is due to that the flux of the solar proton at Mt. Norikura and Tokyo was closer to the normal state before the event. (2) High mean of λ_S during one-hour of the event, for the high cutoff rigidity stations may be explained the rapid response time for these detectors and the short-time duration of the event. (3) There is no definite change in the values of λ_S at the first and second maxima of the GLE. In contrast, a remarkable drop in the value of the solar attenuation length at 1205 UT for the two detectors pairs Well/Hob and Wash/Dur. (4) At the end of GLE until the background noise becomes appreciable (from 1520 UT for Wash/Dur and from 1600 UT for Well/Hob), the values of λ_S gradually approach the general value of attenuation length before the event (100 g cm^{-2}). (5) The mean value of λ_S, over the considered period for each detector pair, seems to depend upon the mean value of the vertical cutoff rigidity. Figure 3 shows a plot of the mean of the calculated values of λ_S versus the mean values of the four pair of neutron monitors. The best-fit line to the data is shown; the equation of the best-fit line and the regression coefficient, r, are also shown. The regression coefficient is 0.997. The following equation is given from the fit parameters;

$$\lambda_S = (2.9 \pm 0.3)\, R_0 + (102.6 \pm 3), \text{ g cm}^{-2} \qquad (2)$$

Our results are broadly consistent with those reported by Ahluwalia and Xue (1993) and the mean attenuation length in the Earth's atmosphere for the protons produced in the solar flare is significantly larger than the known value (100 ± 5) g cm^{-2}.

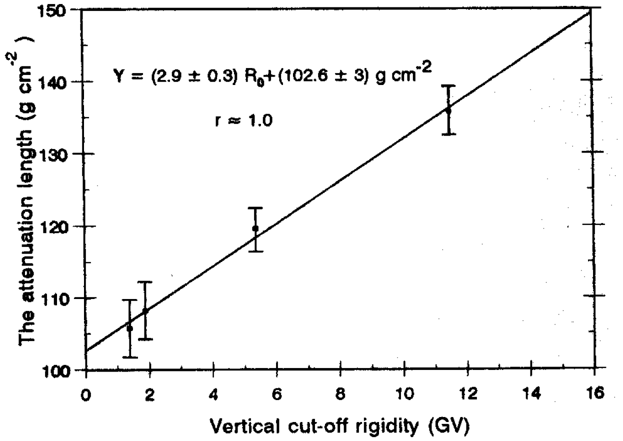

Fig. 3. The linear correlation between λ_S and R_0 for the four station pairs. The equation of best-fit line and the regression coefficient are expressed.

5. Power spectra of 29 September 1989 GLE

The rigidity spectrum and the time-profile of intensity distribution of solar particles causing GLE has various information about the dynamic structure of the interplanetary magnetic field in the heliosphere. Following the procedures described by El-Borie et al. (1997), we have performed a series of power spectra, using the observed ratio of the fractional increases detected every five minutes (starting from 1135 UT). Figure 4 shows the power densities for the increases ratio detected at Wash/Dur, Well/Hob, and Nori/Tok. Dash line represents the onset of the considered event. Due to differences in sensitivities at rigidities less than 2 GV, these two-pair of detectors recorded the GLE with different increases in counts rates relative to galactic cosmic ray background. It is clear that the spectrum is quite hard at the time of the first maximum peak (1155 UT to 1230 UT) and it smoothes throughout the remainder of the event.

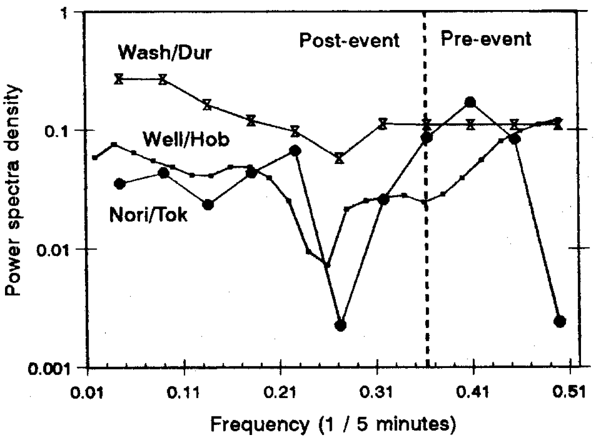

Fig. 4. Power spectra density of observed enhancements ratios at Wash/Dur, Well/Hob, and Nori/Tok. The onset-time of the event is displayed by dashed line.

A spectral index of power spectra of GLE may be estimated from the enhancements ratios recorded by the four-pair detectors. The power indexes, γ, derived from the ratios for a power law spectrum are 4.2 ± 0.25 for Wash/Dur, 4.5 ± 0.25 for Well/Hob, 5.5 ± 0.2 for Jun/Rom and 8.2 ± 0.33 for Nori/Tok. The spectral index derived from the observed ratios of the two Australian detectors for the initial phase of the event appeared to be the same as that found at American detectors, and there is a quite different in comparison with the Japanese detectors. Low pre-event enhancement ratios (corresponds to hard spectrum) are clearly observed. In contrast, the spectrum is soften after the event corresponding to high ratios every 5-minutes. The initial low ratios between each of the three-pairs of detectors suggested an earlier arrival of more energetic particles due to the time dispersion (Stoker et al., 1995). Furthermore, it is clearly seen that detectors of low rigidity particles recorded much softer particle spectrum during the GLE of 29 September 1989 than other considered monitors. This behavior is due to that the higher energy particles had a smaller mean free path and were more diffusive (Stoker et al., 1990; 1995).

6. Conclusions

The 29 September 1989 relativistic solar cosmic-ray event is the first occasion upon which all NMs, SMT, and some UMT observed solar particles. The time of the first maximum was dominated by the higher rigidity particles while the lower rigidity flux reached its maximum at the time of the second peak. The energy of particles in this event extended to at least 15 GeV. The mean computed attenuation length for the protons produced in the solar flare is significantly larger than (100 ± 5) g cm^{-2}. Our results indicated that higher rigidity particles were becoming relatively more numerous at the Earth as the GLE progressed. The post-event spectrum was softer than the initial spectrum of the main event and it more softer for detectors of low energy particles.

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References

Ahluwalia, H.S. and Xue, S.S., *Geophys. Res. Lett., 20*, 995, 1993.

Alessio, M., Allegri, L., Fargion, D., Improta, S., Iucci, N., Parisi, M., Villoresi, G., and Zangrilli, N.L., *Nuo. Cim., 14 C*, 1991.

Alekseev, E.N. and Karpov, S.N., *Geo. and Aero., 34*, 239, 1994.

Chupp, E.L., Forrest, D.L., Share, G.H., Kanbach, G., Debrunner, H., and Fluckiger, E., *Astrophys. J., 318*, 913, 1987.

Duggal, S.P., *Rev. Geophys. Space Phys., 17*, 1021, 1979.

Duldig, M.L., Cramp, J.L., Humble, J.E., Bieber, J.W., Evenson, P., Fenton, K.B., Fenton, A.G., and Bendoricchio, M.B.M., *Proceedings ASA, 10 (3)*, 211, 1993.

El-Borie, M.A., Duldig, M.L., and Humble, J.E., Proc. 25th Inter. Cosmic Ray Confer. (Durban), 1, 313, 1997.

Filippov, A.T., Krivoshapkin, P.A., and Transky, I.A. et al., *Izv. Acad. Sci. USSR, Ser. Phys., 55, 10*, 1893, 1991.

Humble, J.E., Duldig, M.L., Smart, D.F., and Shea, M.A., *Geophys. Res. Let., 18*, 737, 1991.

Lovell, J.L., Duldig, M.L., and Humble, J.E., *J. Geophys. Res., 103*, 23733, 1998.

McCracken, K.G., *J. Geophys. Res., 67*, 423, 1962.

Shea, M.A., Smart, D.F., and Gentile, L.C., *Proc. 21st Inter. Cosmic Ray Confer.(Adelaide), 7*, 1, 1990.

Shea, M.A., Smart, D.F., and Pyle, K.R., *Geophys. Res. Letters, 18*, 1655, 1991a.

Shea, M.A., Smart, D.F., Wilson, M.D., and Fluckiger, E.O., *Geophys. Res. Letters, 18*, 829, 1991b.

Stoker, P.H., *Proc. 21st Inter. Cosmic Ray Confer. (Adelaide), 12*, 205, 1990.

Stoker, P.H., Bieber, J.W., and Evenson, P., *24th Inter. Cosmic Ray Confer. (Rome), 4,* 224, 1995.

Swinson, D. B. and Shea, M.A., *Geophys. Res. Lett., 17*, 1073, 1990.

Wilson, B.G., Mathews, T., and Johnson, R.H., *Phys. Rev. Lett., 18*, 675, 1967.