Cosmic ray ground level enhancements: Power of the pulse shape

O. Ogunjobi, R.D. Strauss

Center for Space Research, School for Physical and Chemical Sciences, North-West University, Potchefstroom, 2520 South Africa

E-mail: olakunle.ukzn@gmail.com

Abstract. Ground level enhancements (GLEs) of the cosmic-ray intensity have been observed seventy-one times over the past seven decades. GLEs are due to sudden increases in the intensity of solar energetic particles associated with large eruptive episodes. GLEs have been, controversially, divided into two distinct categories, gradual (classical) and impulsive events. Recent findings also argue that some GLEs are too impulsive to be accelerated in the eruptive episodes. Here we investigate this hypothesis by studying the time profiles of nine GLEs, which were observed with excellent data coverage of the associated solar eruptions. Results show that, when characterized solely on their time profile (i.e. pulse shape), GLEs do not separate into two distinct classes, but rather form a continuous distribution between these two extremes. Preliminary modelling results indicate that the interplanetary transport conditions may alter the GLE pulse shape in such a way as to obscure any source information by the time it reaches Earth. This implies that the shape of the GLE profile is, perhaps, a powerful indicator of propagation conditions between Sun and Earth.

1. Introduction

Ground level enhancements (GLEs) are sudden increases in the cosmic ray intensity as observed at Earth. Ground-based cosmic ray (CR) observations started with the observation of a GLE on 28 February 1942. Since then, GLEs have been observed seventy-one times by ground-based neutron monitors. This is possible due to large solar eruptive episodes that originate primarily from the western longitudes on the surface of the Sun. In other words, these GLEs are the result of solar eruptive episodes that produce atmospheric showers of secondary particles that can reach ground level, provided that the incoming particle energy is ≥ 500 MeV per unit charge, or rigidity ≥ 1 GV. Relativistic protons produced from these solar energetic particles (SEPs) events represent a direct sample of matter from some of the most energetic processes in the solar system, particularly, solar flares and coronal mass ejections (CMEs). Solar flare are enormous explosions which occur in the solar corona, while CMEs represent vast structures of plasma and magnetic fields that are expelled from the Sun into the heliosphere.

The relationship between flares and CMEs, and their role in accelerating particles to relativistic energies during major solar events remains an exigent scientific challenge. Previous studies e.g [1] classify SEPs, albeit controversially, into two distinct classes, impulsive and gradual events. Flares in the low solar corona are relatively short-lived and have a narrow range of solar longitudes (about one Earth radii, R_E) that are magnetically well-connected to

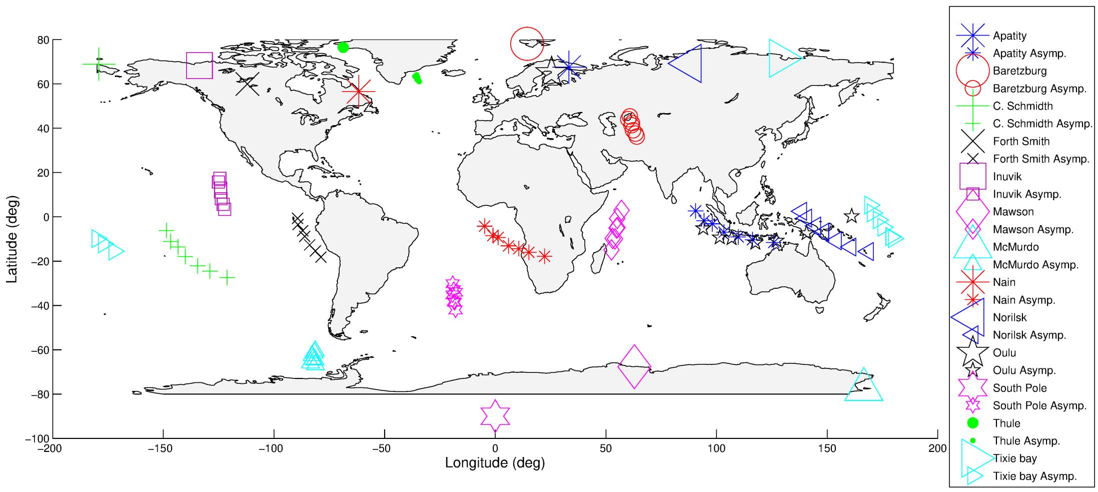

Figure 1. Geographical locations of the contributing neutron monitors with geomagnetic cut-off rigidity below 1 GV (large markers) and the corresponding asymptotic viewing directions (small markers).

the observer. [1] and others also attribute particle acceleration to flare processes such as wave-particle interactions following magnetic reconnection. Conversely, CMEs develop more gradually at distances beyond about four R_E, which is much larger than the Sun, and should therefore have shock fronts that are widely extended in heliolatitude and longitude. So, it expected to associate the impulsive GLE events with acceleration in solar flares, and gradual GLE events in CME shock fronts. The classification of gradual versus impulsive events are mostly based only on the time profile (pulse shape) of the GLE event as observed by a number of neutron monitors.

Impulsive events, according to [1], are characterized by high ^{3}He/^{4}He ratios (>0.1), high Fe charge states (-20), high Fe/O ratios and low particle fluxes, while the composition of the gradual events is more characteristic of the composition of the solar wind or interplanetary medium. Hence, this supports the inference that impulsive SEP events contain particles that were accelerated in the corona, likely by solar flares, while the more gradual events originate more likely from the acceleration in the bow shocks of CMEs.

At energies of a few MeV per nucleon, space observation of impulsive and gradual events can be distinguished by compositional signatures. For GLEs, as observed primarily by ground-based neutron monitors, the signatures of the composition and ionization state are lost. However, GLEs observation with Earth's neutron monitors have the advantage of being sensitive to the arrival direction of the particles, which gives an indication of the anisotropy of the event. For vertical arrival at a neutron monitor, the particles must have come from a so-called asymptotic direction in space before they penetrated the geomagnetosphere [2]. This directional sensitivity explains why a given GLE can display an impulsive character on one set of neutron monitors, but only show up as gradual on others.

We show in Figure 1 the asymptotic cone of acceptance for all neutron monitors used in this study. The large symbols indicate the position of the neutron monitor, while the smaller symbols show the asymptotic position for rigidities of 1 - 5 GV. Note the highest rigidity point is closest to the station. Also, because only stations with a cut-off below 1 GV is used, all the monitors are located in the polar regions. For an anisotropic SEP event, the looking direction (asymptotic cone) will be different for different neutron monitor stations, and as such, they will measure different intensities.

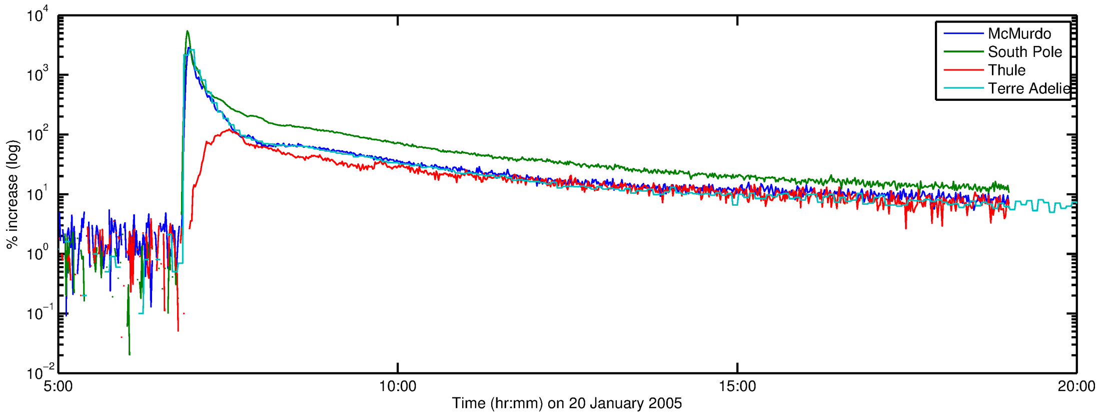

Figure 2. Time-intensity profile of GLE 69 showing both of impulsive and gradual characteristics.

Figure 2 illustrates this directional sensitivity of the neutron monitor network on the very large GLE 69 of 20 January 2005. It was such that three neutron monitors (South Pole, Terre Adelie and McMurdo) saw an extremely impulsive increase, reaching the peak intensity in ~ 5 minutes, while Thule saw a much longer rise time of ~ 30 minutes. A third group of stations observed two consecutive peaks (not shown here). [3] interpreted this structure as indicating two injection/acceleration mechanisms, namely a fast, short-lived solar flare, and a slower, longer-lived bow shock of the CME. This was not consistent with the generally accepted idea that the slow rising-stations merely observed a filling-in effect from the directions that were viewed by the fast-rising ones. Earlier, [4] investigated all the impulsive GLEs over the entire time span, and demonstrated that these events typically extend to higher energies than the more gradual ones. The authors, [4], further noted that the fastest rising peak coincided well with high-energy gammas produced by particles slamming into the dense matter of the low corona while the rate of decrease shows an evidence of kink at ~ 1 hour. This is a natural explanation for the first, impulsive peak to recede below the second, gradual one at this time as presented in Figure 2.

Furthermore, the concept of impulsive versus gradual GLEs for large GLE 42 on 29 September 1989 was put in perspective by [5]. At the peak intensity the difference between impulsive and gradual is about a factor of 3, while for GLE 69 this difference is at least a factor of 30. This means that GLE 42 was much less anisotropic than GLE 69. The solar activity associated with GLE 69 was in the well-connected region at $\sim 65°$ W, while for GLE 42 it was invisible behind the western limb and could only be inferred indirectly at ~ 120 ° W. This longitude would have been so poorly connected that particles that might have been accelerated in the highly anisotropic first beam in the lower corona, could not have reached Earth. The combination of all available observations from ~ 40 neutron monitors show, however, that these variations are qualitatively different from the true impulsive and gradual peaks, and [3] ascribed them as due to fluctuations in the direction of the heliospheric magnetic field. It has been suggested in other studies e.g [5], that the knowledge of pulse shapes or time profile of GLEs is required to determine the fidelity of impulsive and gradual events, and how to interprete its physical meaning.

In this paper, the average pulse shapes of selected nine (9) GLEs were simultaneously determined. The maximum amplitude, the time-to-maximum, half decay time from the maximum intensity, and the heliolongitude of the asymptotic cone of acceptance of each of the 9 events were studied.

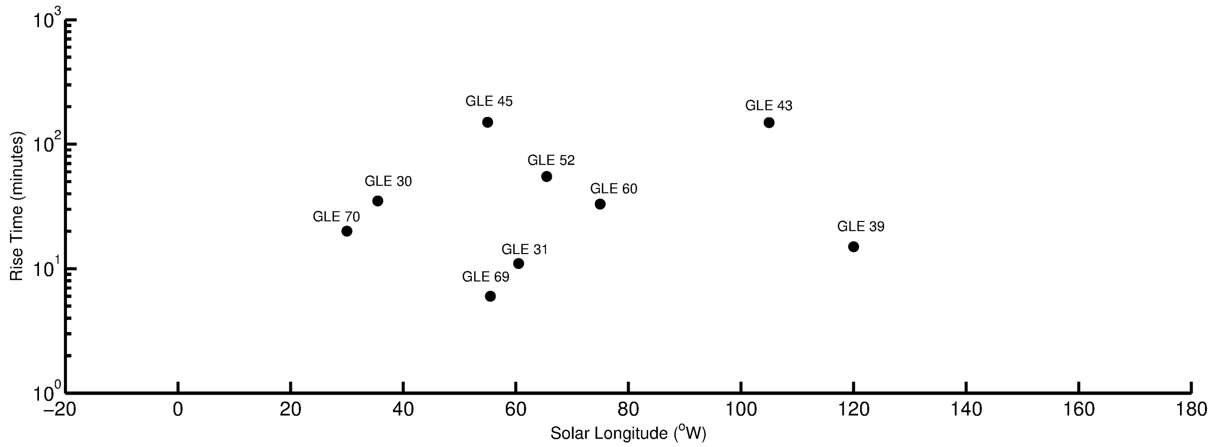

Figure 3. The relationship between the rise time of the selected 9 GLEs and the solar longitude of their associated solar events.

2. Observation and analysis of the time profile of selected 9 GLEs

The data base, which contains all available ground level neutron monitors observation, of all 71 GLEs since 1942 has been described by [6]. In this study, only 9 GLEs (30, 31, 39, 43, 45, 52, 70, 60 and 69) are used. These GLEs under study have amplitude much more than 10% and it is a subset of all available 71 GLEs. The peculiarities and differences between the intensities of secondary solar particles occurring between different neutron monitor stations during the selected 9 GLEs can be interpreted on the basis of their asymptotic directions of viewing. Here we used only the stations with cut-off rigidity below 1 GV in order to eliminate any energy/rigidity dependence. Also we study the time (pulse shapes) of the selected 9 GLEs simultaneously, to determine how to differentiate between impulsive and gradual ones, and how to, eventually, interpret its physical meaning. In doing this, it is important to see if the GLEs are magnetically well connected to Earth.

To determine the rise times of each event, the beginning of the event was taken as the earliest time for which a statistically significant increase could be visually inspected from the intensity-time profile. The time of maximum was generally easy to read off, but was sometimes complicated when the profile lingered around the maximum intensity, or when it even show multiple peaks. [9] hypothesised that multiple peaks found in some GLEs could be due to to two different injections or a probable swing in magnetic field direction.

Figure 3 displays the rise time of the events as function of heliolongitude. The distribution is centered on the heliolongitude that connects to Earth via the nominal Parker spiral magnetic field, corresponding to 60° W [7]. This corroborates the study by [8], which showed that the hardest spectra, at energies below the GLE cutoff, originated from the region around 60° W. Although [9] recently reported a weak correlation with longitude. No clear distribution is evident from Figure 3 and we are unable to confirm that the so-called “fast-risers” (i.e. GLEs with short rise times) are always magnetically connected to Earth.

Figure 4 shows the relationship between the rise and decay times (to 50% of the peak intensity) of all the GLEs. The full line on the plot is the best-fit linear regression. This shows that, on average, the decay time is about twice as long as the rise time. The main result of this analysis is that GLEs do not separate into two distinct categories of impulsive and gradual events. The rise times show a continuous range from 5 to 160 minutes. Effort is underway to interpret these results in terms of a particle transport model, with initial results presented in [10].

Irrespective of the step taken when determining the rise times in Figures 3 and 4, we note that

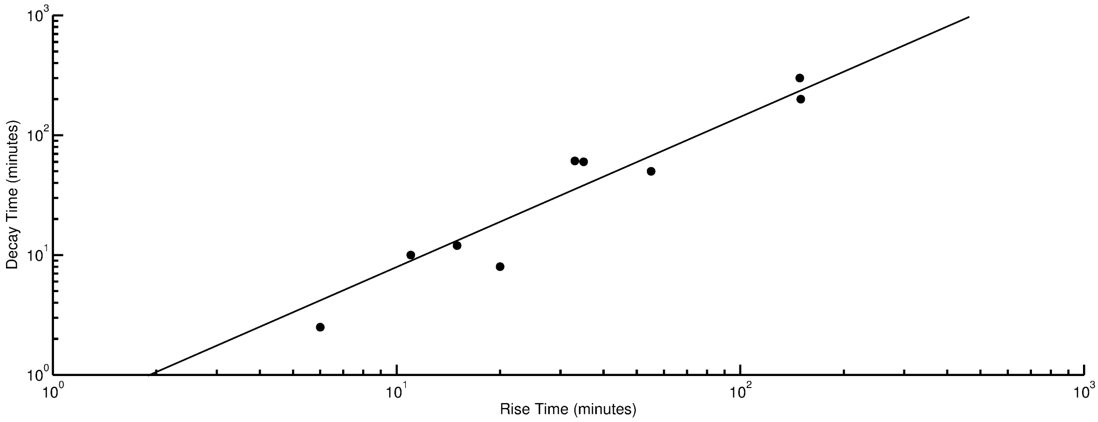

Figure 4. The relationship between the rise and decay time of the selected 9 GLEs. The thick line is the best-fit linear regression.

the beginning of the event may be difficult to be interpreted physically or in terms of modeling. This is due to the obvious anisotropic direction of propagation of the solar particle and due to the disparities in the counting rates recorded between different contributing neutron monitors. In order to correct this problem, we apply the measure of central tendency by averaging over viewing direction. This will provide us with cosmic ray fluxes which can better compared with model solutions.

Figure 5 shows the average time-profile recorded by all the contributing neutron monitors during each of the selected events. Note that the ninth GLEs (GLE 69) has been represented in Figure 2. The use of the average time-profile (in Figure 5), however, has eliminated some of the limitations such as the large uncertainty in the time-profile as measured by different stations. Based on the average, the selected events do not have strong anisotropic like distributions. They are, in fact, isotropic. These isotropic observations fulfil all the necessary assumptions of our ongoing transport model. Interpretations of the present observation in terms of the propagation of a gyro-tropic distribution of SEPs transport model is underway.

3. Summary

The main result of the paper is that there is no clear distinction of GLEs in impulsive and gradual classes, but rather a continuous range between these extremes. On average, the decay time is about twice as long as the rise time for the 9 selected GLE events, with a good linear correlation between these two quantities.

Acknowledgments

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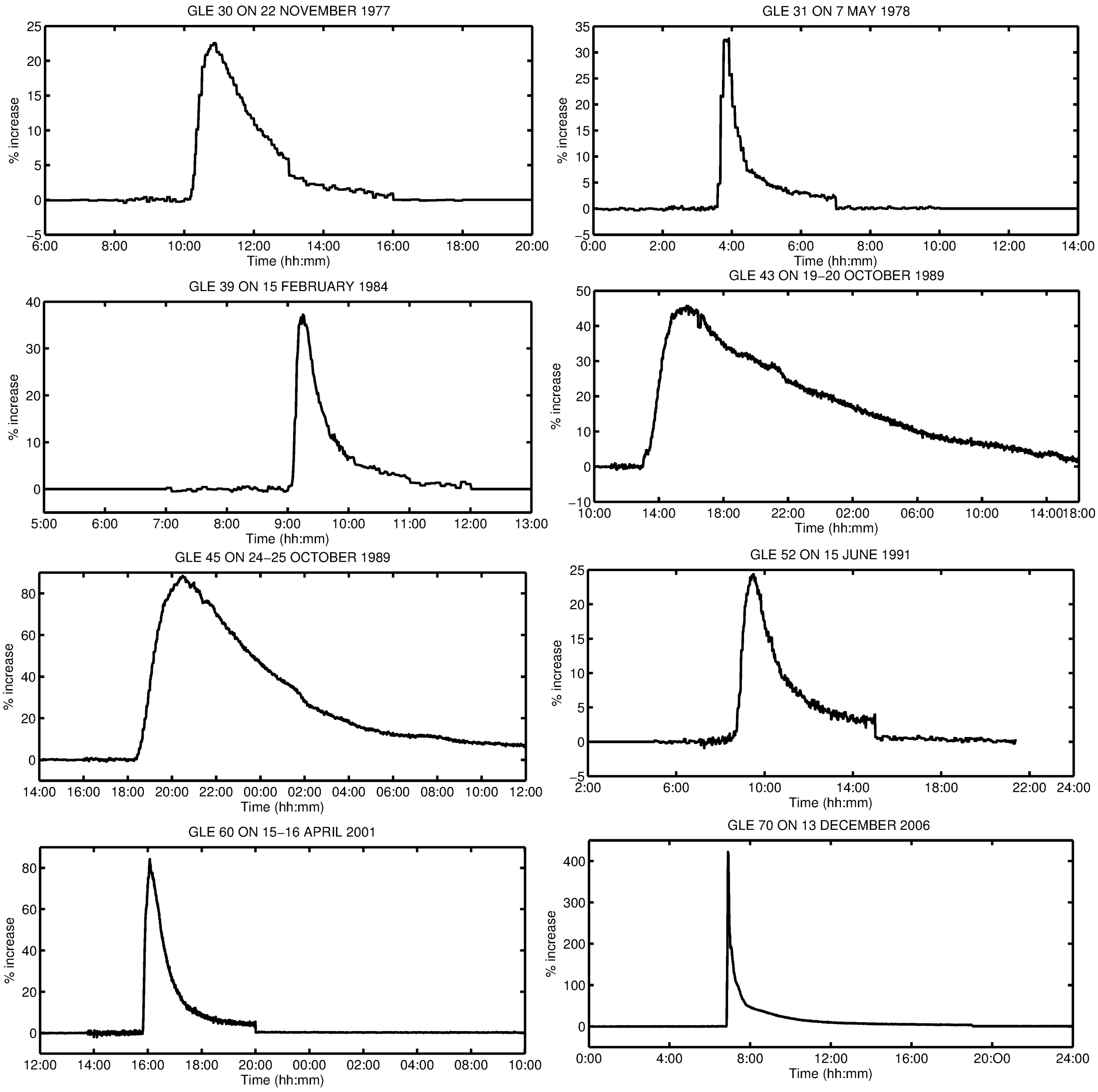

Figure 5. Average time-profile recorded by all the contributing neutron monitors during each event.

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