Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research 57 (2016) 1314–1318

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

www.elsevier.com/locate/asr

Spectral index of solar cosmic-ray flux from the analysis of ground-level enhancements

R.A. Caballero-Lopez [a,*], H. Moraal [b]

[a] Ciencias Espaciales, Instituto de Geofísica, Universidad Nacional Autónoma de México, 04510 México D.F., Mexico
[b] Centre for Space Research, School for Physical and Chemical Sciences, North-West University, Potchefstroom 2520, South Africa

Received 1 June 2015; received in revised form 17 August 2015; accepted 24 August 2015
Available online 7 September 2015

Abstract

In this work we analyze the ground-level enhancement of the cosmic-ray intensity due to solar energetic particles as observed on 29 September 1989, by using two pairs of standard and lead-free neutron monitors. This enables one to separate spectral and anisotropy effects. This has been done previously by several authors for other events, but in this paper we make use of the large size and long duration of this event, as well as the fact that it is perhaps the best-observed one in the whole data base since 1942. It is shown that the method is more sensitive than the standard method that uses neutron monitors at different locations. The analysis provides a prototype for what can potentially be achieved by a new generation of mini neutron monitors.

Keywords: Ground-level enhancement; Anisotropy; Cosmic rays; Spectrum

1. Introduction

Ground-level enhancements are the most energetic solar particle events observed at Earth. In the 73 years since 1942, 71 of them were registered, mainly by neutron monitors. Many studies have been done using the available data (see, e.g., Shea and Smart, 1994; Miroshnichenko et al., 2000; McCracken et al., 2012).

Recently, Moraal and Caballero-Lopez (2014) analyzed GLE 42 of 29 September 1989 using all available data (from more than 50 neutron monitors), and inferred the spectral shape of the solar cosmic-ray spectrum during this event. These authors also compared the temporal profile of this GLE with GLE 69 of 20 January 2005.

A distinctive feature of a GLE relative to the intensity of galactic cosmic rays is its anisotropy, which depends on the nature of the source that produced the particles, and on the propagation characteristics. This anisotropy can mask the spectral shape of the intensity. Therefore, if one compares the increases observed by two neutron monitors, the anisotropy must first be subtracted before spectral information can be inferred. This procedure can be done by the fitting technique developed by Ruffolo et al. (2006), in which the axis of symmetry of the event is determined from a network of neutron monitors with the same spectral sensitivity, so that the differences are solely due to anisotropy effects.

The method does have its uncertainties and limited resolution. Therefore, alternative techniques have been employed where the anisotropy effect is less important for the determination of the spectral shape. For example, if one analyzes a GLE based on data from two very nearby stations at different altitudes they have different spectral sensitivity, but it is likely that their asymptotic cones are so near to one another that the anisotropy effect will be small. In this way De Koning (1994) analyzed three pairs

* Corresponding author.
E-mail addresses: rogelioc@geofisica.unam.mx (R.A. Caballero-Lopez), Harm.Moraal@nwu.ac.za (H. Moraal).

http://dx.doi.org/10.1016/j.asr.2015.08.019
0273-1177/

of nearby mountain–sea level stations to obtain the spectral power-law index for GLE 42.

Even this method has limited accuracy due to the fact that nearby detectors are still subject to different atmospheric and environmental conditions, which affects their spectral sensitivity, in particular their short-term fluctuations which causes a noisy signal.

A third method to separate the anisotropy effects from the spectral sensitivity is to employ the ratio of increase of two cosmic-ray detectors with different rigidity response functions, but in the same location, literally in the same building or enclosure. In the case of a pair of neutron monitors, this eliminates all pressure, temperature and other environmental uncertainties, and the need for their correction. Hence, the method is much more sensitive to small anisotropies. This is the case for lead-free neutron monitors (LFNM) alongside standard NM64 neutron monitors as at the South Pole and Sanae stations. The Sanae LFNM was installed in 1971. Several studies have used this approach, such as Stoker (1981), Bieber and Evenson (1991), Bieber et al. (2013) and Moraal and Caballero-Lopez (2014). The Moraal and Caballero-Lopez study was for GLE 42 on 29 September 1989, and its distinguishing feature was that it was so large (up to 300% increase), that it was long-lived, and perhaps the best-observed GLE in the entire data base. Hence it serves as the best example for a case of study to demonstrate the sensitivity of the method, and it provides a guideline for how to employ mini neutron monitors (Krüger et al., 2008; Krüger and Moraal, 2010; Aiemsa et al., 2015) with different spectral sensitivity in future for this analysis.

The basic data set, as observed by the pairs of neutron monitors at South Pole and at Sanae, is shown in Fig. 1. The overall characteristics are: (1) The South Pole increases are larger than those at Sanae, which is due to the fact that South Pole is at 2820 m altitude, while Sanae is at 856 m.

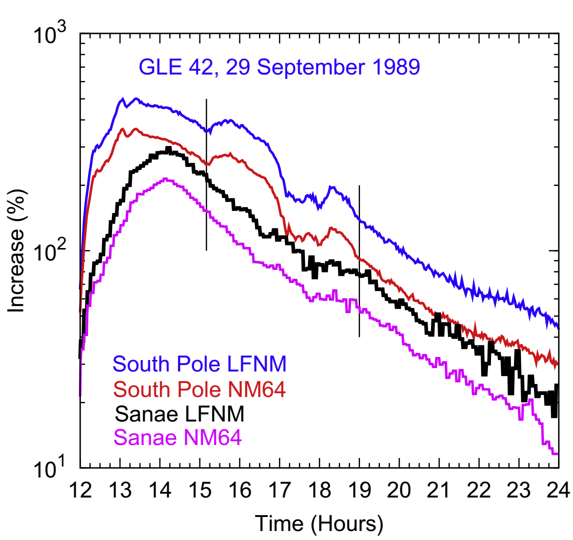

Fig. 1. Fractional increases observed at South Pole and Sanae stations during GLE 42 of 29 September 1989.

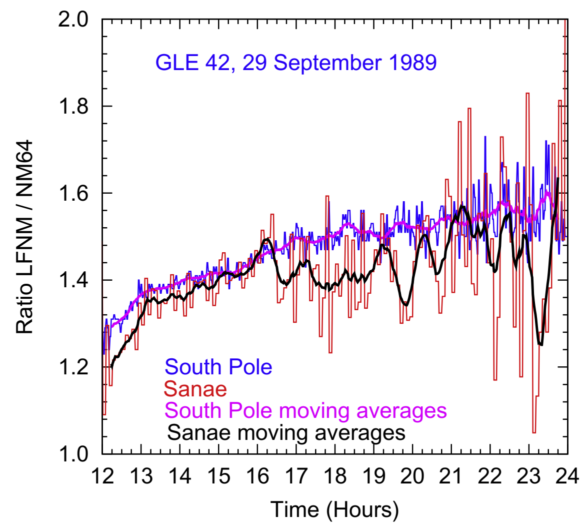

Fig. 2. Ratio of the fractional increases observed with LFNMs with respect to NM64s at South Pole and Sanae stations during GLE 42 of 29 September 1989.

(2) The LFNMs show a larger increase than the NM64 NMs, because they are more sensitive to lower energy particles (see, e.g., Fig. 20 of Moraal and Caballero-Lopez, 2014). (3) The statistical fluctuations (noisiness of the lines) reflects the counting rates of the individual counters. The large excursions on the South Pole detectors, which are absent at Sanae are analyzed in this paper. Fig. 2 shows the ratios of these pairs of detectors. It shows that, despite significant statistical fluctuations, from about 16:20 onwards the ratio of the Sanae detectors is persistently lower than for South Pole. The Sanae ratio also contains significant fluctuations that are absent at South Pole. We interpret this in terms of small anisotropy effects.

2. Counting rate and anisotropy analysis

Following the standard procedure of many previous papers (e.g., Shea and Smart, 1982; Humble et al., 1991; Duldig et al., 1993), the counting rate of a detector due to solar energetic particles arriving at the top of the atmosphere, can be written as:

$$N_s(P_c, x, t, \vec{a}) = \int_{P_c}^{\infty} S(P, x)F(t)A(\vec{a}, P)j_s(P, t)dP, \quad (1)$$

where:

$\vec{a}$ is the unit vector from which particles arrive at the detector, $F(t)$ is the temporal injection profile of solar particles, $j_s(P, t)$ is the primary spectrum (as function of rigidity, P, and time) and $A(\vec{a}, P)$ is the angular dependence of solar flux arriving at Earth (anisotropy), which is a function of the central angle, α, between the axis of symmetry of the arriving particle distribution and the asymptotic cone of acceptance for each neutron monitor. We note that α can be function of P due to different amounts of geomagnetic bending.