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Two-detector recordings of GLE's at SANAE

P H STOKER[1]
[1]*Unit for Space Physics, NW University, Potchefstroom 2531, South Africa*
pieter.stoker@nwu.ac.za

Abstract: Ground level enhancements due to solar flare protons have been recorded at Sanae since 1971 by two neutron monitors with different sensitivities to primary protons in the rigidity range < 1 GV to ~5 GV. Spectral indexes can be determined from the enhancement ratios of the two detectors if their yield functions are known. The yield functions obtained from latitude surveys and primary cosmic ray proton spectrum had to be adjusted at lower rigidities to yield the same power spectral indexes as determined from enhancements recorded by the world wide network of ground based neutron monitors. Results obtained from recordings of the 6NM64 and 4NMD neutron monitors at Sanae IV during GLE's of the 23rd solar activity cycle are presented. A general feature appears to be that if the IMF was relatively quiet, the initial phase tends to show a harder proton spectrum than during maximum and the decay phase of a GLE.

Introduction

Since 1971, ground level enhancements from solar flare protons have been recorded at Sanae, Antarctica, by two neutron monitors with different sensitivities to primary protons in the low rigidity range [1]. Until 1994 the one detector at Sanae on the ice sheet was a standard 3NM64 until 1994, while the second was a neutron moderated detector (NMD) with 4 $B^{10}F_3$ tubes in paraffin wax cylinders but without lead. Since 1997, with Sanae IV on Vesleskarvet, the detectors are two 3NM64 and the 4NMD since 1997.

The rigidity spectrum of solar flare protons may be obtained from the relative enhancements in count rates of these two detectors if their yield functions are known. A yield function may be obtained from the response of a detector to changing cut-off rigidities during a latitude survey at the atmospheric depth of the neutron monitor station. Below the latitude knee at about 2 GV, the yield function falls off rapidly with decreasing rigidity and becomes experimentally uncertain.

The contribution of the low rigidity portion of a primary particle spectrum to the count rate of a detector depends on the steepness of the primary spectrum. Since the solar flare proton spectrum is generally much steeper (softer) than the galactic cosmic ray spectrum at 1 AU, the contribution to the count rate of a cosmic ray detector by flare particles below about 2 GV is more significant than that by primary galactic cosmic rays. It is therefore important that the rigidity dependence of the yield function below 2 GV is known when assessing the spectral index of solar proton flares from ground-based detector data. Lockwood, Webber and Hsieh [2] have deduced solar flare proton rigidity spectra from observations made by the network of cosmic ray neutron monitors between 1967 and 1972. Only those solar flare events were considered, during which satellite, rocket or balloon spectral recordings were also made.

We deduced yield functions of both detectors from the 1976 latitude surveys of Potgieter et al. [3] for rigidities P > 2 GV. For smaller rigidities a function was accepted so that GLE spectral indexes were obtained from relative enhancements in count rates similar to the indexes reviewed by Duggal [4] and from other publications. These yield functions for the 3NM64 at Sanae follow closely the Monte Carlo simulation of Debrunner et al. [5] (see [1]:342).

The spectral index of solar flare proton spectra

The enhancement in count rate observed by a detector relative to the galactic cosmic ray background count rate N_g is given by

$$\Delta N_f(P_c,t) = (1/N_g)\int_{P_c}^{P_m} S(P)\, j_f(P,t)\,dP$$

where P is the rigidity of the primary particles at the top of the atmosphere, $S(P)$ is the specific yield function (SYF) of the detector at the atmospheric depth of the station, P_c is the geomagnetic cutoff rigidity at the recording station, and P_m is a high rigidity cutoff in the solar flare differential proton spectrum, $j_f(P, t)$, defined by $j = P^{-\gamma}$ with γ the spectral index.

Response function for P > 2 GV: $N(P) = e^a (P+1)^{b+c\ln(P+1)}$, with a = 5.065 & 5.139, b = 0.3758 & 0.3406, c = – 0.1949 & – 0.1923, resp for 3NM64 & 4NMD, from the 1976 latitude surveys by [3].

From this function the yield functions of both detectors are (dN(P)/dP) / j(P), where j(P) is the primary galactic cosmic ray differential rigidity spectrum, which is equal to $\exp(A+B(\ln P)+C(\ln P)^2+D(\ln P)^3)$, with A = 7.082, B = –0.525, C = –0.5978, D = 0.0697, for the 1965 cosmic ray proton spectrum [6].

SYF for P < 2, (1) for 3NM64: $S_m(P) = \exp(d + e(\ln P) + f(\ln P)^2)$, with d = –9.994, e = 9.363, f = –3.643, to simulate the SYF of Lockwood et al. [2].

(2) for 4NMD: $S_n(P) = S_m(P).g.\exp(h / (P+1)^i)$, with g = 0.3067, h = 5.00, i = 1.0 in Stoker [1]. On account of the work of Vashenyuk et al., the constants were revised to g = 1.1142, h = 1.00, i = 0.90. This revised yield function for the 4NMD follows the function $S_n(P) = S_m(P).1.82 / \sqrt[6]{P}$ of Vashenyuk et al. [7].

Results

The enhancement of 6 November 1997

The solar flare was at the helio-longitude 63^0 west of the Sun–Earth line. The IMF was highly vari able in the vicinity of the Earth during the enhancement. However, the OMNIWeb Data Explorer satellite recorded a relatively quiet IMF the following day, implying that the initial transport of the solar flare particles to Earth was along fairly quiet magnetic field lines.

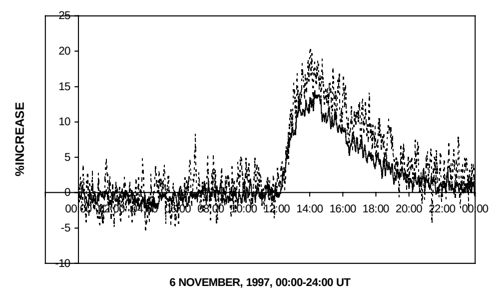

Figure 1:

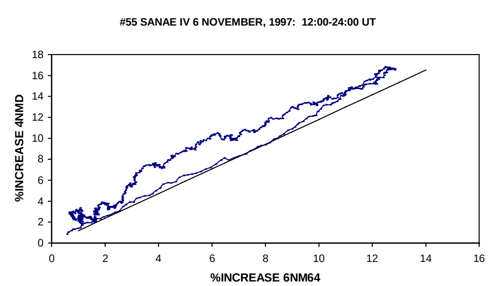

Figure 2:

Owing to the variability of the IMF in the vicinity of the Earth, 1-min detector count rates showed a larger than usual noise level. Figure 1 illustrates the 5-min averaged count rates of the 6NM64 and 4NMD monitors at SANAE IV for the 24 hours of 6 November 1997, normalized to the averaged count rates during the interval 11:00 to 12:00 UT. In Fig. 2 these filtered count rates of the 4NMD were plotted against those of the 6NM64 after a 12-point moving average filter was applied to the normalised 5-min averaged count rates of Fig. 1. It is apparent that the points of the decaying phase of the GLE lie above those of the rising phase. The straight line depicts a hard initial solar proton spectrum. After 12:58 UT the spectrum softened towards the GLE maximum and thereafter the proton spectrum softened stepwise, as indicated by the increasing gradient of a straight line drawn from the origin to the relevant point on the graph.

On 6 November 1997, a 1% increase was recorded at Hermanus (cutoff rigidity 4.58 GV), but at Potchefstroom (6.98 GV) no increase was detected. Accepting, therefore, a cutoff of 6 GV in a solar proton power spectrum, the initial gradient of 1.18 for the relative enhancements (see Fig. 2) suggests a hard spectrum with a power index of –2.3. At GLE maximum the gradient was 1.29, with a power index of –3.4. During the decaying phase the spectrum softened gradually. At 17:09 the gradient was 1.7, signifying a spectrum with an index of –7.2 until the end of the enhancement.

The enhancement of 14 July 2000

On 12 July 2000, a large sunspot group, # 9077, clearly developed a complex magnetic field that harboured energy for powerful solar flares. A pressure wave, the result of enhanced solar wind generated by the flare, arrived at Earth on 13 July, giving rise to a Forbush decrease in galactic cosmic rays. On 14 July a rapid increase in count rates was recorded by the 6NM64 monitor at Sanae IV, being 20 minutes from onset to maximum. The IMF was fairly steady after the Forbush decrease, but became highly variable shortly after the arrival of the solar flare protons.

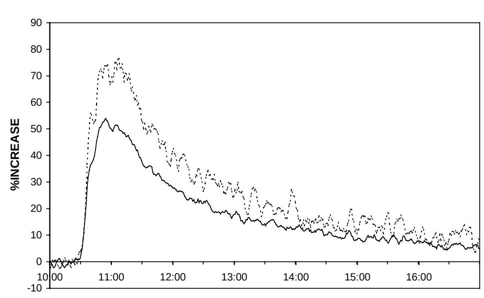

Figure 3:

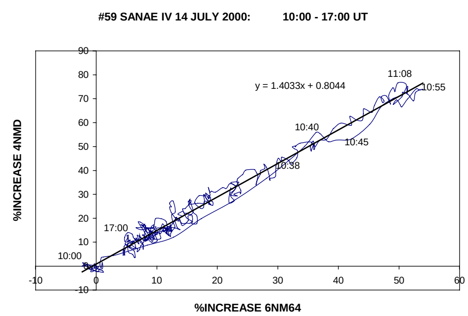

Figure 4:

The gradient of the linear regression line for the 1-min relative enhancement points of the decay phase in Figure 4 is 1.4. A 1% increase was observed by the neutron monitor at Hermanus, but no enhancement was seen at Potchefstroom, indicating a high rigidity cutoff at about 6 GV. The gradient of 1.4 suggests then a spectral power index of –4.5.

A two-maxima structure in the enhancement was recorded (Figure 3). The first maximum at 10:55 UT recorded by the 6NM64 was larger than the second at 11:08 UT, while the 4NMD second maximum was larger than the first. This suggests a softening of the primary proton spectrum from 10:55 to 11:08 UT, since the 4NMD detector is more sensitive to primary particles of lower energy than the 6NM64.

In Figure 4, from the onset of the enhancements at 10:29 to 10:38 UT, the points lie below those of the decaying phase, indicating a hard initial proton spectrum, which softened from 10:38 to 10:40 UT, but which hardened again towards 10:45 UT, after which the spectrum softened again towards GLE maximum. This observation is supported by Pchelkin et al. [8], who found a remarkable softening of the proton spectrum from the interval 10:40–10:45 to 11:05–11:10 UT. They found for a proton spectrum, described by a power law in rigidity, an index that changed from –2.6 in the first interval to –4.9 in the second interval.

The spectral index of –4.5 we find for the decay phase is numerically smaller than the –5.8 found by Pchelkin et al. [8], and still smaller than the –8 to –9 estimate of Duldig [9]. Although the numerical values of the power indexes estimated by three different methods are different, the values indicate changes in the indexes always in the same directions.

The enhancement of 15 April 2001

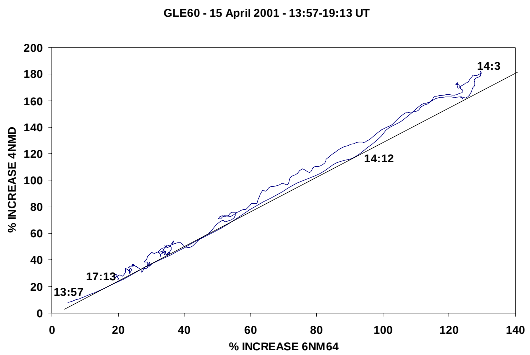

Figure 5:

The solar flare was at the helio-longitude 85^0 west of the Sun–Earth line. The IMF was fairly quite on 15 and 16 April. The initial increase from 13:57 until 14:12 UT was hard, with an enhancement ratio of 1.30. Then the spectrum softened and the subsequent increase to maximum was retraced by the decaying phase with a ratio of 1.40. The enhancement at Hermanus was 6%, at Potchefstroom ~1% and no enhancement at Tsumeb. With high rigidity cutoff ~ 8 GV, the spectral index was then –3.8 from onset to 14:12 UT and – 4.6 after 14:12 UT.

The enhancement of 13 December 2006

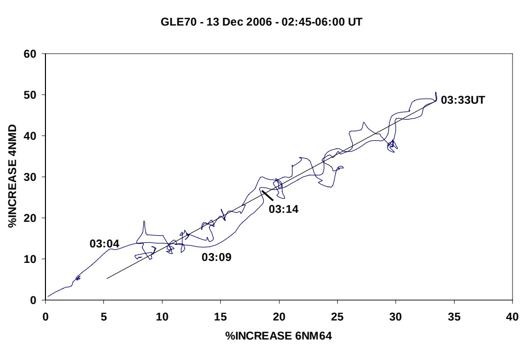

Figure 6:

The IMF at 1 AU was quiet on 13 December, but was fluctuating the following day. The initial enhancement from onset at 02:54 to 03:04 UT was very soft. The enhancement ratio was 2.3. Then the spectrum hardened and at 03:09 UT the enhancement ratio of 1.08 indicated a very hard spectrum. Thereafter the spectrum softened and from 03:14 to maximum at 03:33 UT and the subsequent decaying phase, the enhancement ratio was 1.45. With the maximum enhancement of ~2% at Hermanus and no enhancement at Potchefstroom above noise, high rigidity cutoff ~ 6 GV, the spectral index was –5.0.

Conclusions

A general feature of relativistic solar flare protons appears to be a hard spectrum initially, which softens before GLE maximum. The decaying phase tends to retrace the rising phase after softening. A fast rise to maximum is indicative of a good magnetic connection from the Sun to Earth. The initial hard phase is then also very anisotropic. The subsequent softening is indicative of isotropy in arrival directions of solar protons. Variability above statistical variation in the count rates should be due to variability in the IMF.

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