SPECTRA OF SOLAR PROTON GROUND LEVEL EVENTS USING NEUTRON MONITOR AND NEUTRON MODERATED DETECTOR RECORDINGS

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ABSTRACT

Recordings on relativistic solar flare protons observed at Sanae, Antarctic, show that the percentage increase in counting rates of the neutron moderated detector (4NMD) is larger than the percentage increase in counting rates of the 3NM64 neutron monitor. These relative increases are described by solar proton differential spectra $j_s(P) = AP^{-\beta}$. The power β is determined for each event and the hardnesses of the temporal variations of β, found for the GLE's of 7 May, 1978 and 22 November, 1977, are related to the results of Debrunner et al. (1980).

1. Introduction. Neutron monitors record at ground level solar protons of energies $\gtrsim$ 0.5 GeV, while satellite data generally covers the energy range below 0.5 GeV. Debrunner et al. (1984) combined the two sets of observations for the solar proton events on 7 May, 1978 and 22 November, 1977, and deduced for various phases the solar proton energy spectra from 50 MeV to about 10 GeV.

These two events and several other solar proton events were recorded during the present solar cycle at Sanae with a cutoff rigidity of 0.86 GV in Antarctica. When looking at an event from only a single position on Earth, a particular spectral function has to be assumed in order to deduce the spectrum of solar protons entering the atmosphere. Since rigidity is the appropriate parameter for the combined effect of protons, α-particles and heavier particles for earth bound recordings, a rigidity dependent spectral function was considered. A power law rigidity spectrum $j = AP^{-\beta}$ appears to fit the spectra given by Debrunner et al. (1984) in the rigidity range ~ 0.5 GV - 10 GV better than the exponential rigidity spectrum $j = A\exp(-P/P_o)$.

The neutron moderated detector 4NMD and super neutron monitor 3NM64 record at Sanae primary cosmic rays with different rigidity dependent sensitivities. In order to derive solar proton spectra for ground level events from these recordings, the specific yield functions of these two detectors have to be obtained accurately for rigidities $\lesssim$ 1 GV. Solar proton ground level events recorded at Sanae during the present solar activity cycle are analyzed accordingly in this paper.

2. Method. A specific yield function was computed for each detector from $S(P) = n(P,t)/j(P,t)$. The primary differential rigidity spectrum $j(P,t)$ was obtained from the 1965 cosmic ray proton and helium particle spectra compiled by Webber (1973), while the differential response functions $n(P,t)$ were deduced from a least square fitting (Van der Walt, 1983) of the Dorman function $N(P) = N_o(1-\exp(-\alpha P^{-k}))$ to the data of the 1976 sea level survey (Potgieter et al., 1980). The differential response functions for the NMD

and NM64 thus obtained were applied to reproduce correctly the relative counting rates recorded for the 15 February, 1978 Forbush decrease (Stoker and Louw, 1983).

If $j_s(P,t)$ represents the primary solar proton differential spectrum, the enhanced counting rate due to a solar proton GLE is given by

$$\Delta N_s(P,t) = \int_{P_c}^{\infty} S(P) j_s(P,t) dP$$

with $j_s(P) = AP^{-\beta}$. The ratio of the enhanced counting rates recorded by the two detectors then becomes

$$\frac{\Delta N_s^{NMD}}{\Delta N_s^{NM64}} = \frac{\int_{P_c}^{\infty} S^{NMD} P^{-\beta} dP}{\int_{P_c}^{\infty} S^{NM64} P^{-\beta} dP}$$

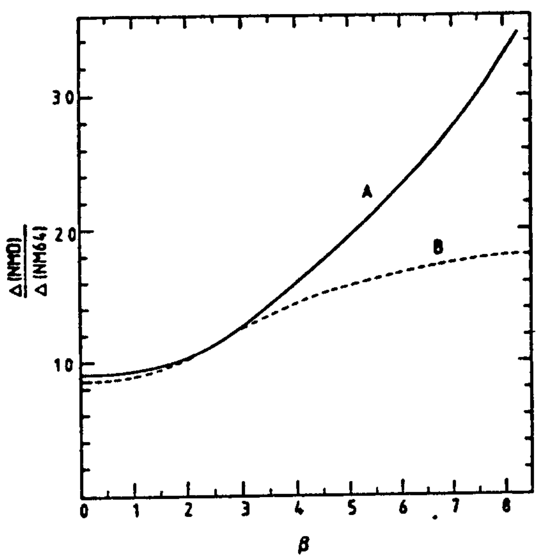


Figure 1

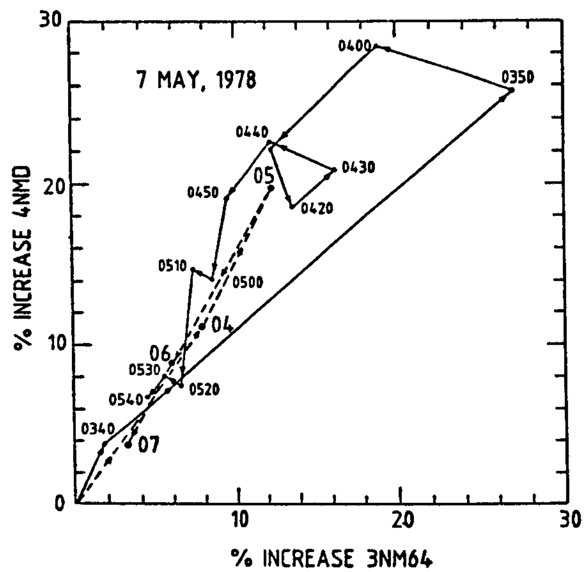


Figure 2

In Figure 1 the calculated ratio of enhanced counting rates is shown as a function of the power β, with P_c = 0.86 GV. The constants of the Dorman function used in calculating S(P) are N_o = 151.67, α = exp 2.13 and k = 0.894 for the 3NM64, while for the 4NMD the values are N_o = 157.68, α = exp 1.99 and exp 2.06, k = 0.898 and 0.940 respectively for the solid and broken lines A and B in the Figure. For both of these two sets of constants the Dorman functions lie within the statistical regression limits determined from fittings to latitude survey data for the NMD. The ratio of enhanced counting rates is not 1.00 for β = 0 because the two differential response functions for the 4NMD and that of the 3NM64 are normalized at P = 17 GV. The two curves in Figure 1 are considered to present the upper and lower limits of the ratio of the enhancements at a particular power β.

3. The GLE of 7 May, 1978. In Figure 2 the enhanced pressure corrected ten minute and hourly counting rates for the 4NMD are plotted as a function of the similar counting rates of the 3NM64, for the GLE of 7 May, 1978. The galactic contributions have been normalized to 100. From this Figure it follows that the first particles arrived at Sanae in the time interval 0335-0340 UT (signified by 0340) followed by a fast rise in counting rates during 0340-0350 UT. With $\Delta NMD/\Delta NM64 = 0.95$ for the enhancement until 0350 UT, $\beta \approx 1.3$, suggesting a flat initial spectrum, which presumably is the result of the earlier arrival of the more energetic protons. Subsequently the intensity of the slower particles are increasing, causing the displacement in the plot from 0350 to 0400, with the ratio $\Delta NMD/\Delta NM64$ changing to 1.49, giving $\beta = 3.4$-3.5 from Figure 1 for curves A and B respectively. After 0400 the solar proton spectrum becomes even softer. The average of the enhanced counting rates for the hour 0400-0500, indicated by 05 in the Figure, represents a ratio $\Delta NMD/\Delta NM64$ 1.63, giving $\beta = 3.8$-4.2. At 0450 UT $\Delta NMD/\Delta NM64 = 1.99$, and $\beta = 4.9$ for the upper curve A in Figure 1.

When the 7 May, 1978 solar proton spectra of Debrunner et al. (1984), for the rigidity interval of about 0.8 - 5 GV, are represented by the power law $J_S \propto P^{-\beta}$, the power values are $\beta \approx 3.3$, 3.6, 4.0 and 4.9 respectively for the time periods 0335-0345, 0345-0400, 0400-0415 and 0430-0500. These values are about the same as we have obtained from Figure 1.

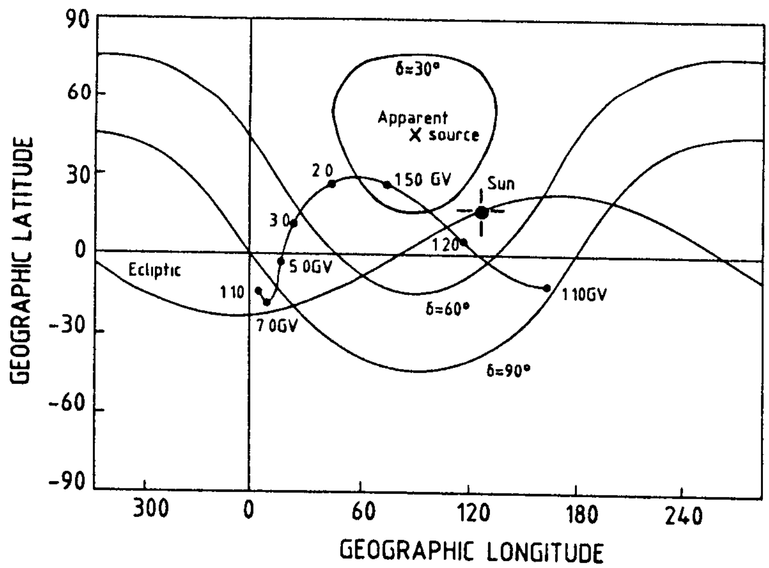
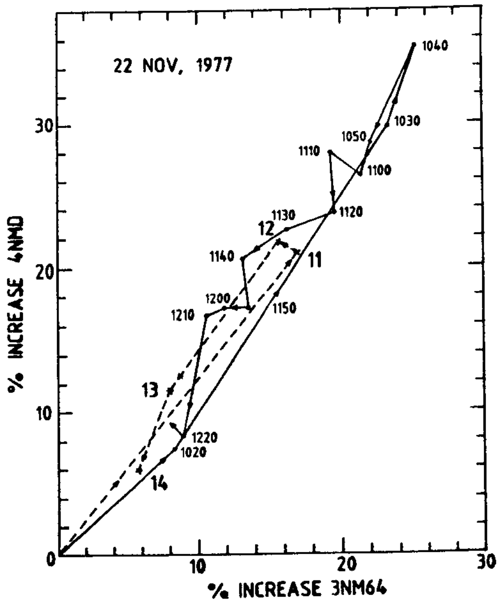


Figure 3 is in part a reproduction of Figure 3 of Debrunner and Lockwood (1980). The apparent source position and contours for angular distances of 30°, 60° and 90° are shown for the 7 May, 1978 event. Added to the Figure are the asymtotic directions of vertical incident particles for Sanae (Shea and Smart, 1971). From this Figure follows that the proton spectrum incident on top of the atmosphere at Sanae should be equivalent to the free space spectrum at 1 AU.

4. The GLE of 22 November, 1977. In Figure 4 the enhanced pressure corrected ten minute and hourly counting rates for the 4NMD are plotted as a function of corresponding counting rates of the 3NM64 for the GLE of 22 November, 1977. Here again the spectrum appears to soften from the eleventh to the twelfth hour UT. The ratio ΔNMD/ΔNM64 for the first ten minutes 1010-1020 UT is ~ 0.9, suggesting $\beta \gtrsim 0$, presumably again due to the earlier arrival of the more energetic protons. The ratio ΔNMD/ΔNM64 = 1.30 at 1030 which is also the average for the hour 1000-1100, implies $\beta = 2.7 \pm 0.1$. At 1040 the ratio of the enhancements = 1.41, with $\beta = 3.1$. For the decaying phase of this event the ratios of the enhancements show fluctuations around these values. For 1050-1100, ΔNMD/ΔNM64 = 1.23, and $\beta = 2.5$; 1100-1110, the ratio increased to 1.48 and β to 3.4. For the twelfth and thirtienth hour, the average ratio = 1.38 and $\beta = 3.0$.



When representing the 22 November, 1977 solar proton spectra of Debrunner et al. (1984) by a power law for the rigidity range ~ 1 - 6 GV, the power values are $\beta = 5.5$, 4.6 and 4.9 respectively for the time periods 1035-1046, 1055-1105 and 1200-1215. These values are larger than we found, but the fluctuations in hardness follow the same trend as we are observing. The lower power values deduced for Sanae may be attributed to an apparent source direction to the left 0° geographic longtitude in Figure 3, favouring the higher rigidity protons to enter the atmosphere. Thus a harder solar proton rigidity spectrum was possibly incident at Sanae comparing to the free space spectrum as 1 AU.

5. Conclusions. Spectra of relativistic protons recorded at Sanae may be deduced from the relative enhancements in counting rates of the 4NMD and 3NM64 detectors. For GLE solar proton spectra of 23 September, 1978, 8 December, 1982 and 16 Februarie, 1984 average powers $\beta = 4.5 \pm 0.2$, 2.8 ± 0.1 and 2.6 ± 0.1 were obtained respectively.

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