DETERMINATION OF ENERGY SPECTRA FOR THE LARGE SOLAR PARTICLE EVENTS OF 1989[1]

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ABSTRACT The Bartol neutron monitor at South Pole is uniquely suited to the observation of solar energetic particles due to its high altitude and low geomagnetic cutoff. In addition we also operate unshielded BF_3 detectors at South Pole that respond to particles of lower average energy than those recorded by the standard neutron monitor. We are therefore able to estimate the spectral index as a function of time throughout the evolution of a solar particle ground level enhancement as well as the absolute flux level of the solar particles. We discuss the spectra of several large events that occurred in late 1989, and we note in particular spectral changes in the 19 October 1989 event that are relevant to an interpretation involving neutron decay protons.

INTRODUCTION Recent work has shown that there is more structure to the solar modulation of cosmic rays in the rigidity range 1-10 GV than many investigators would have supposed a few years ago. Moraal *et al.* (1989) note systematic variations in neutron monitor latitude surveys apparently linked to the 22 year solar magnetic cycle. Popielawska and Simpson (1990) discuss the different rigidity dependence of modulation in alternate cycles as exhibited in comparison of data from the Climax and Huancayo neutron monitors. Tuska, Evenson, and Meyer (1991) [See also paper SH 6.5.4, this conference] present data on cosmic electrons of several GV rigidity showing that these particles not only exhibit a much larger modulation amplitude than protons of the same rigidity but also fail to return to the same flux level at successive solar minima. We have therefore become quite interested in using the Bartol network of neutron monitors to study the cosmic ray spectrum in this interesting region.

The detectors available in the Bartol network are summarized in Table 1. This network is particularly suited to study of cosmic rays in the few GV rigidity range as it contains several low but distinctly different energy thresholds and a pair of exactly matched monitors (Thule and McMurdo) with different approach directions. At South Pole we actually have two stations, a standard neutron monitor and a set of "bare" NM-64 type neutron detectors (without the lead shielding). These "Polar Bares" have a lower counting rate and are much more sensitive to the environment than the standard monitor but, as they are at mountain altitude, they have an unusually low threshold. Our long term program is to use the station ratios in this network, normalized by latitude surveys and data from the ICE spacecraft to determine precise response functions and track cosmic ray spectra in quantitative detail.

SOLAR EVENTS Ground Level Enhancements (GLE) from solar events provide a particularly interesting perspective on this effort. Because the events are brief, to first order one can ignore systematic drifts in the stations and concentrate on the analysis of the excess flux. The events are also scientifically interesting in their own right. In Figure 1 we show our analysis of the energy spectra of five GLE that occurred in 1989. (The events are summarized in Table II.) For each event we present five determinations of the spectral index, where we assume power law spectra in momentum with a sharp cutoff at 10 GV. Three

STATION	ALTITUDE (meters)	CUTOFF (GV)
Newark (NE)	50	2.02
Thule (TH)	44	0.00
McMurdo (MC)	48	0.00
South Pole (SP)	2820	0.09
Polar Bares (PB)	2820 (no lead)	0.09

Table I: *Stations in the Bartol Neutron Monitor Network*

of these determinations are made from ratios of different stations. In addition, for each event we produce two determinations of the spectral index from the Polar Bare to South Pole monitor ratio alone. These two determinations are made using extreme cases of the Dorman functions determined by Stoker (1985), assuming also that the altitude correction is the same for Monitors and Bares. We note that whenever the determinations from station ratios form a tight cluster the determination from the PB(2)/SP analysis hits that cluster. (The PB(2) Dorman function has parameters alpha=7.846 and k=0.940.) We conclude therefore that with the proper choice of Dorman parameters the particle energy spectrum can be estimated using data from a single geographical location.

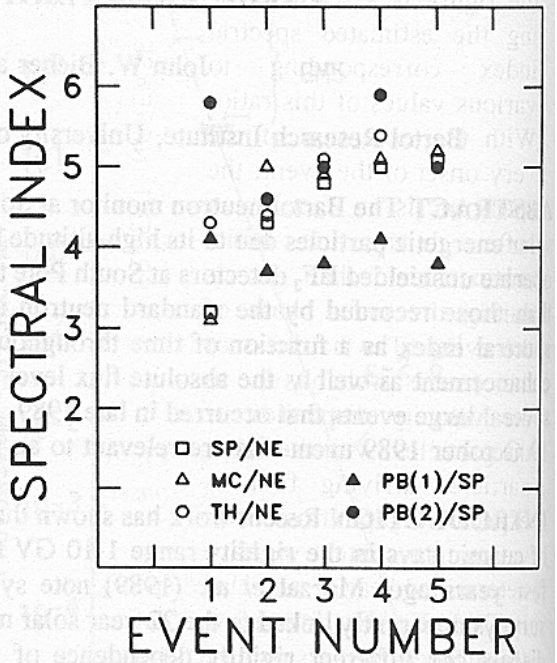

Figure 1: *Index of best fit power law determined during the late phase for five GLE in 1989 using station ratios from the Bartol Neutron Monitor Network. See text for details.*

In this analysis we have chosen data from the late phase of the enhancement, where the assumption that the particle fluxes have become isotropic due to interplanetary scattering and diffusion is likely to be a good one. The ability to produce a spectral determination from only one station is most valuable in the initial stages of a solar particle event, where the distribution of particles is far from isotropic, and where a simultaneous fit to spectra and anisotropies is required in a multi station analysis. Technically, this is of course necessary even in a single station analysis because the approach directions are energy dependent. We have investigated this effect numerically for the event of 19 October, with the conclusion that the error in spectral index would be approximately 0.3 for the anisotropy proposed by Shea *et al.* (1991), so we ignore this complication for the present discussion.

EVENT OF 19 OCT 1989 A particularly interesting event was that of 19 October 1989. This event has been identified by Shea *et al.* (1991) [See also paper SH 2.2-3, this conference] as possibly beginning with protons resulting from the decay of solar neutrons. Figure 2 illustrates the unusual feature pointed out by Shea *et al.* (1991), namely a small and highly anisotropic initial enhancement of the fluxes. In Figure 2 this enhancement is clearly present in our South Pole data but clearly absent in our Thule data. From their multi-station analysis, Shea *et al.* (1991) conclude that the initial event is anisotropic and contains primarily low energy particles.

Because the initial enhancement was well observed by our high time resolution station at South Pole in both the Monitors and the Bares we are in a position to investigate the event closely. Figure 3 shows the counting rate ratio (of the excess counts) of the Bare Counters to the Neutron Monitors at South Pole on the same timescale as that of

	DATE	LATE INDEX	EARLY INDEX
1	16 AUG	5.79	4.65
2	29 SEP	4.57	3.01
3	19 OCT	5.03	5.73
4	22 OCT	5.87	6.22
5	24 OCT	4.97	3.37

Table II: *Ground Level Enhancements Studied in the present paper. Power law spectral indices are determined from the PB(2)/SP counting rate ratio.*

Figure 2. To the right of the figure is a scale showing the estimated spectral index corresponding to various values of this ratio. With the exception of the very onset of the event, the spectrum is in fact much softer during the initial enhancement than it is during the main phase of the event. The hardness of the onset is probably due to the velocity dispersion of the particles, with the faster particles arriving first as expected. To put this observation into context we have determined "early" and "late" spectral indices for all of the events, and summarized the analysis in Table II. "Early time" was defined to be the twenty minute interval beginning eight minutes (to suppress dispersion effects) after the start of the first two minute reading in which both the Polar Bares and Pole Monitor observed an increase significant at the three sigma level. "Late time" was chosen by eye to be one hour of data late in the decay phase of the event, but before the fluxes were too low to permit an accurate determination.

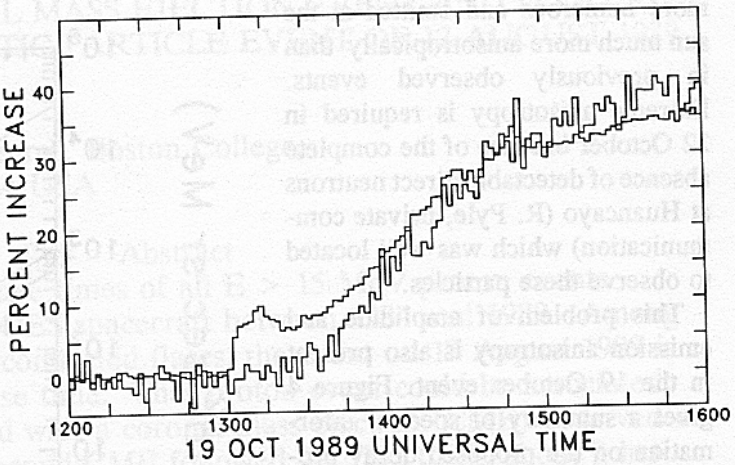

Figure 2: *Counting rate of the Thule and South Pole (earlier onset) neutron monitors during the GLE on 19 October 1989.*

DISCUSSION Our analysis confirms that the initial enhancement of the 19 October 1989 GLE has a much softer spectrum than that later in the event. Our results are therefore supportive of the idea that the 19 October event contains particles from two different sources, but say nothing directly as to whether one source is decaying neutrons. Spectra that soften with time, rather than harden, would probably be regarded as more typical of GLE's. In our detailed analysis of the February 16, 1984 event (Bieber, Evenson, and Pomerantz 1986) we showed explicitly that the higher energy particles went away faster than the low energies. Events 1,2, and 5 in the current study clearly show a softening. Even the 19 October event (Figure 3) shows a softening in the late phase.

A soft initial phase is however not unique to 19 October. Event 4 (22 October) also shows such a feature. Like the event of 19 October, the 22 October event began with a highly anisotropic pulse of particles. In our initial discussion of the 22 October event (Bieber *et al.* 1990) we noted that such a spike could be produced by decay protons. We considered this explanation unlikely primarily because solar neutrons would have to be vastly

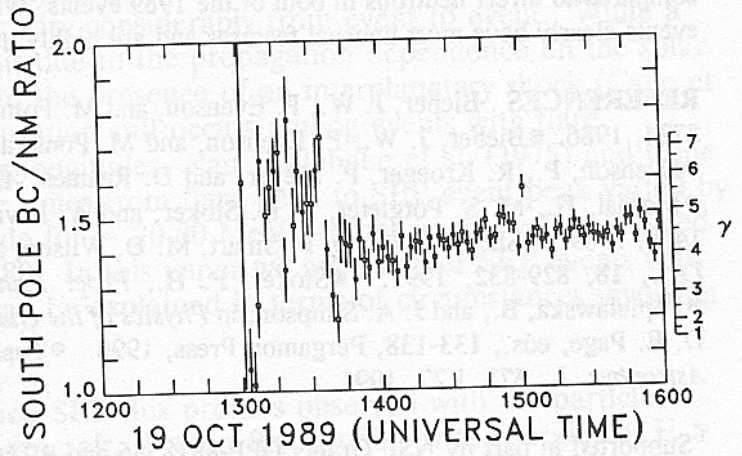

Figure 3: *Polar Bare to South Pole Neutron Monitor ratio for event on 19 October 1989. Scale gives inferred power law index using the preferred Dorman function (PB2) discussed in text.*

more numerous and emitted at the sun much more anisotropically than in previously observed events. Extreme anisotropy is required in 22 October because of the complete absence of detectable direct neutrons at Huancayo (R. Pyle, private communication) which was well located to observe these particles.

This problem of amplitude and emission anisotropy is also present in the 19 October event. Figure 4 gives a summary of spectral information on the proposed decay protons. Curve 1 is the spectrum of Shea *et al.* (1991) Curves 2 and 4 result from the PB/SP ratios using the "less favored" Dorman function. Curves 3 [151 exp(-P/0.27] and 5 [3.48 $P^{-5.73}$] use the function better fitting the late phase spectra. On the scale of the figure, all of these forms agree well in the few GV regime where the monitors are most sensitive. At lower energies, curve 3 is most consistent with the trend of preliminary GOES data (SESC PRF 738). For comparison we show decay proton measurements for the 25 April 1984 event (Evenson *et al.* 1990). This was the largest decay proton event observed in the previous solar cycle. Lack of detection by Tsumeb (Shea *et al.* 1991) puts less severe constraints on direct neutron detection than Huancayo does for 22 October, but one is probably dealing with orders of magnitude higher decay proton fluxes compared to direct neutrons in both of the 1989 events. Whatever the interpretation, these two events clearly have most unusual features and are highly interesting subjects for further study.

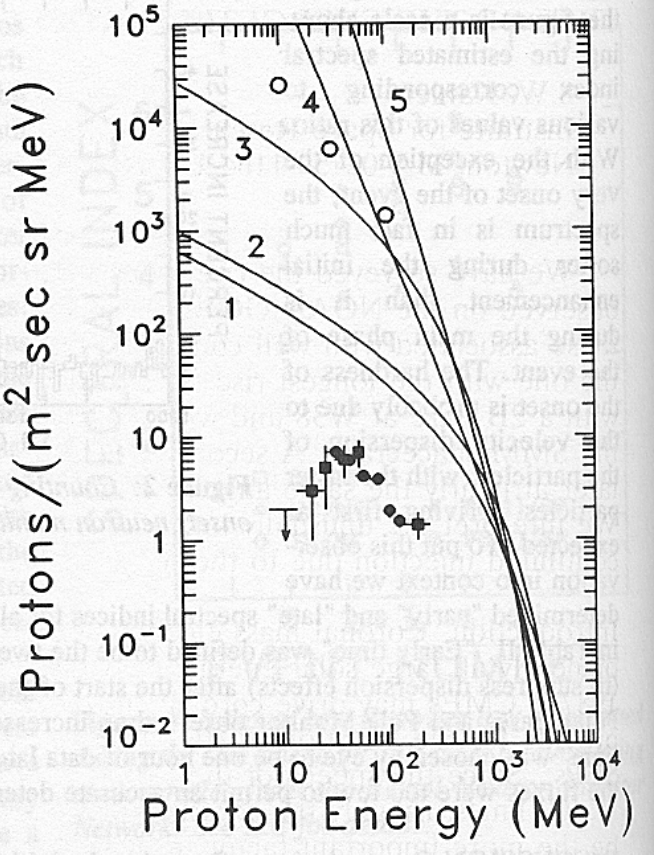

Figure 4: *19 October 1989 event spectra -- exponential form: (1) Shea et al. (2) PB1/NM (3) PB2/NM; Power law form: (4) PB1/NM (5) PB2/NM; GOES data: open circles. 25 April 1984 decay protons -- closed symbols.*

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