A New and Comprehensive Analysis of Proton Spectra in Ground-Level Enhanced (GLE) Solar Particle Events

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***Abstract*. Proton acceleration to energies above ∼500 MeV is a controversial and poorly understood aspect of solar energetic particle (SEP) physics. We have developed a new technique for analyzing data from the world-wide neutron monitor (NM) network. We have used the method to derive absolutely-normalized event-integrated proton spectra for 53 of the 66 GLEs recorded since 1956. As a check on our results, we have compared the fluences from our NM spectra to satellite measurements at ∼300-700 MeV available from IMP8, SAMPEX, and GOES. We further show that the combined satellite and neutron-monitor measurements, ranging from ∼10 MeV to ∼10 GeV, can often be well-represented as a double power-law fit to the integral spectrum in rigidity, using the formulation given by Band et al. 1993. These comprehensive results are a useful starting point for investigations of the acceleration mechanism(s) in GLEs and for practical applications.**

***Keywords*: solar energetic particles, solar protons, ground level events**

I. INTRODUCTION

Although GLEs have been observed for more than 50 years, the physical processes responsible for accelerating protons to multi-GeV energies is still a matter of intense debate. (Compare, for example, [1] vs. [2] and [3].) Accurate knowledge of proton fluences and energy spectra in these powerful events also have important practical applications, such as the design of astronaut storm shelters [4], transient radiation exposures to aircrews and avionics [5], [6], and ionization rates in Earth's atmosphere [7]. The literature on GLEs is vast, with many detailed studies of onset timing and the evolution of anisotropies and spectral shapes, in most cases limited to the first half-hour or so of the event. But if one goes to this literature with very basic questions – What is the total proton fluence above 1 GV?; What is the spectral shape at neutron monitor energies?; How does that compare to the spectral shape at satellite energies?; Does the event-to-event variability in fluences and spectral shapes correlate in any meaningful way with particular features of the concomitant solar activity? – the answers are simply not to be found. Moreover, when addressing issues of event-to-event variability, it is useful to have results on many GLEs analyzed with the same technique.

These considerations have led us to develop a new and simplified method for extracting absolute proton spectra from the GLE database. We have applied our technique to both hourly-averaged and event-integrated spectra, but in this brief report, we we focus on the latter. This report necessarily omits many technical details, which will be explained in a future publication. Before we turn to a description of our methods, Fig. 1 displays our results for the GLEs of 1989-Oct-24 and 2001-Apr-15; our spectrum for 2005-Jan-20 is presented in [7]. Shown here are the power-law fits to the NM measurements. A noteworthy feature of our method is that fluences are extracted for individual NM stations, allowing quantification of the internal consistency of the results. In these two GLEs, the rms deviations of the NM fluences about the fitted spectra are 22.3 and 26.0%, respectively, levels of precision that should be adequate for many studies. Also shown in Fig. 1 are the Band function [8] fits that combine NM fluences with satellite measurements above 10 MeV. Differential spectra in energy, which are the starting point for many radiation-effect calculations, are easily derived from these fits.

II. METHOD OF ANALYSIS

We begin with pressure-corrected count rates from the world-wide neutron monitor network (available from online archives [9], [10], [11], as well as websites maintained for individual stations). In each GLE, for NM station *i* at vertical cutoff rigidity R_i, we define the *uncorrected* integral solar proton fluence as:

$$\tilde{F}_{SEP,i}(>R_i) \equiv F_{GCR}(>R_i, T_0) \cdot \left(\frac{\Delta N_{GLE,i}}{N_{GCR,i}}\right)$$

where $F_{GCR}(>R_i, T_0)$ is the integral Galactic proton fluence on date T_0 (taken from a semi-empirical model [12]) above cutoff R_i (evaluated using the code described in [13], which takes into account geomagnetic disturbances). The quantity in parentheses is the fractional increase in the neutron-monitor counts due to the GLE, corrected to sea-level using the method of [14].

From 1 to 10 GV, the NM yield function [15] increases rapidly, and the spectrum of solar protons is much steeper than that of GCR protons in this range. The *corrected* solar proton fluence must therefore be derived from the *uncorrected* fluence:

$$F_{SEP,i}(>R_i) = \tilde{F}_{SEP,i}(>R_i) \cdot C(\gamma, R_i, T_0)$$

where the correction factor is given by:

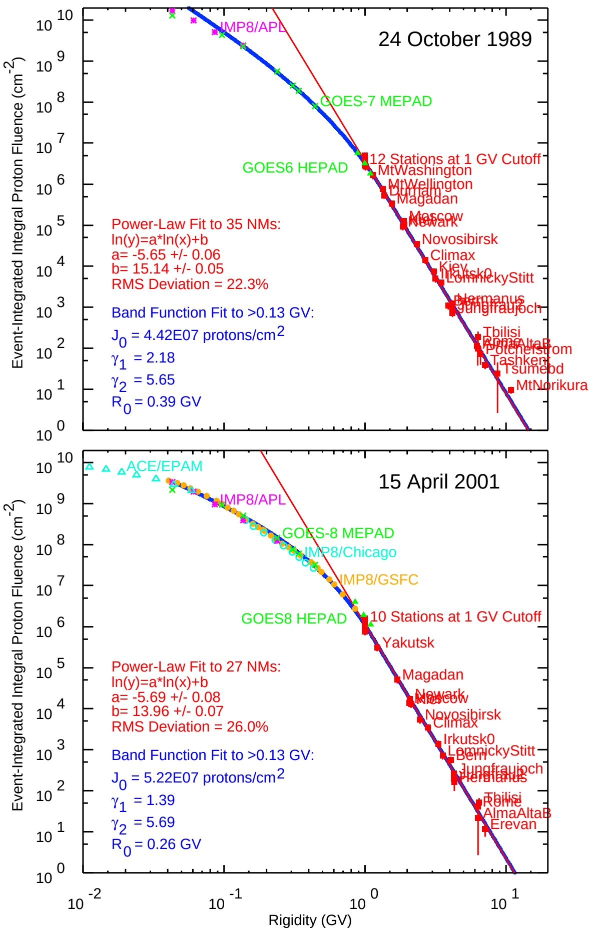

Fig. 1: Event-integrated integral proton spectra vs. rigidity for two GLEs. Noted are the parameters of the power-law fits to the neutron monitors and of the Band-function fits to measurements above 0.137 GV (10 MeV).

$$C(\gamma, R, T_0) = \frac{F_{SEP}}{\tilde{F}_{SEP}} = \frac{F_{SEP}}{F_{GCR}} \cdot \frac{N_{GCR}}{\Delta N_{GLE}}.$$

This correction factor depends on the solar proton spectral shape (here represented by a power-law index γ), the station's cutoff rigidity R, and the date of the GLE (through the solar-cycle dependence in the GCR flux). The correction factor can be evaluated numerically,

$$C(\gamma, R, T_0) = \frac{\int_R^\infty s(r)dr}{\int_R^\infty g(r, T_0)dr} \cdot \frac{\int_R^\infty y(r)g(r, T_0)dr}{\int_R^\infty y(r)s(r)dr},$$

where r is rigidity, $s(r)$ is the differential solar proton spectrum, $g(r, T_0)$ is differential GCR proton spectrum, and y(r) is the NM yield function [15]. The correction factors are only slightly sensitive to the upper integration limit on integrals involving $s(r)$; for convenience, we extend these integrals to infinity. If we now explicitly assume that the exomagnetospheric solar proton spectrum at Earth at NM energies can be represented as a power-law in rigidity,

$$s(r) = s_0 r^{-\gamma-1},$$

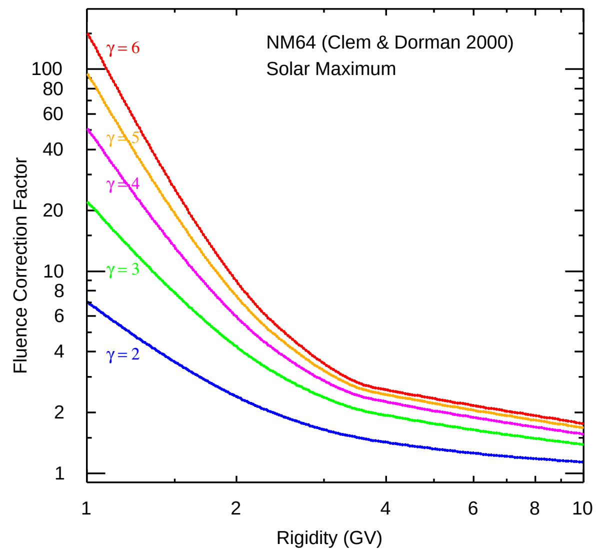

Fig. 2: Correction factor vs. rigidity for various solar proton spectral index values, using the NM64 yield function [15] and the 1990 solar-maximum GCR proton spectrum [12].

the correction factor then becomes:

$$C(\gamma, R, T_0) = \frac{R^{-\gamma}/\gamma}{\int_R^\infty g(r, T_0)dr} \cdot \frac{\int_R^\infty y(r)g(r, T_0)dr}{\int_R^\infty y(r)r^{-\gamma-1}dr}.$$

Fig. 2 shows sample calculations of the correction-factor for various values of γ. Above $\sim$4 GV, the correction factors are between $\sim$1 and $\sim$3 and have relatively flat rigidity dependence. But as we move toward lower rigidites, the correction factors become large and depend strongly on the value of γ. This dependence will become important when we turn to comparisons with the highest-energy satellite measurements, which are around $\sim$1 GV.

The rest of the procedure is straightforward. We calculate correction factors for a grid of γ values. For each γ, we apply the correction factors to the uncorrected fluences. We find the value of γ that gives the best least-squares fit to a power-law in rigidity. That is, let

$$\tilde{F}_i(>R_i) \cdot C(\gamma, R_i, T_0) = F_{0,\gamma} \cdot R_i^{-\gamma}$$

or equivalently,

$$\ln \tilde{F}_i = \ln F_{0,\gamma} - \gamma \ln R_i - \ln C(\gamma, R_i, T_0)$$

Now let
$y_i = \ln \tilde{F}_i$; $x_i = \ln R_i$; $A_\gamma = \ln F_{0,\gamma}$; $\sigma_i = \sigma_{\tilde{F}_i}/\tilde{F}_i$.

For each γ, find the best-fit value of A_γ by minimizing

$$\chi^2 = \sum \frac{(y_i - A_\gamma + \ln C(\gamma, R_i, T_0) + \gamma x_i)^2}{\sigma_i^2}.$$

Requiring $\partial\chi^2/\partial A_\gamma = 0$ yields

$$A_\gamma = \frac{\sum \frac{(y_i + \ln C(\gamma, R_i, T_0) + \gamma x_i)}{\sigma_i^2}}{\sum \frac{1}{\sigma_i^2}}.$$

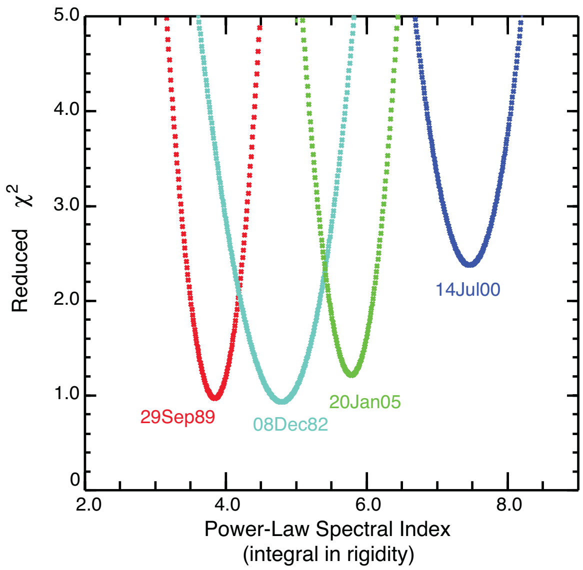

Fig. 3: Reduced χ^2 vs γ for four GLEs.

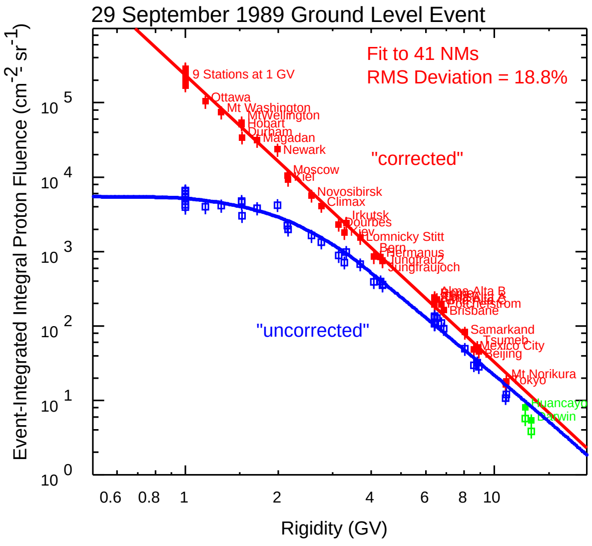

Fig. 4: NM fluences before and after correction in the 1989-Sep-29 GLE.

For each (γ,A_γ) pair, we now evaluate χ^2. Fig. 3 plots reduced χ^2 vs. γ for four events. For each event, the minimum is very well determined. Values of reduced χ^2 are generally acceptable, although the somewhat larger χ^2 for the steepest spectrum in this plot (2000-Jul-14) may indicate that another functional form, other than a power-law, would be better. (Other spectral forms will be investigated in future work.)

Fig. 4 shows this correction procedure applied to the 1989-Sep-29 GLE. The strongly rigidity-dependent way in which the the uncorrected spectrum has been "unrolled" is clearly seen. The distribution of fractional residuals about the power-law fit has an rms width of 18.8%. The measurements from Huancayo and Darwin indicate that the spectrum steepens above $\sim$10 GV. These two stations were not included in the fit.

III. Comparison with Satellite Measurements

Compared to other techniques for analyzing GLEs, our method has many shortcomings. Most importantly, we do not take careful account of anisotropies that are generally observed at the beginnings of events; instead, we rely on the world-wide network and wider time-binning to average out these effects, conceptually analogous to what happens with a spinning satellite. We also neglect other factors, such as rapid evolution of the spectrum in the initial stages of the event and careful numerical integration over each station's rigidity-dependent asymptotic viewing cone. Finally, we rely on a semi-empirical model of GCR protons to set our normalization. Given these and other approximations in our method, it is important to quantify the reliability of our results.

In that our NM analyses make no use of satellite data, comparison with satellite data provides a way of validating our results. In the left panel of Fig. 5, fluences measured by GOES/HEPAD at $\sim$400-700 MeV are plotted versus the fluences in the same energy interval evaluated from our NM fits. There is a strong correlation among events collected over 20 years and with fluences spanning nearly three orders of magnitude. The inset histogram shows the ratio of the HEPAD to NM fluences. The mean is 1.03 $\pm$ 0.07, and the rms width is 33%. The right panel shows a similar analysis, using the highest-energy channels from the Goddard instrument on IMP8 or from SAMPEX [16]. The correlation is again very good. The larger spread among the IMP8 datapoints is most likely due, at least in part, to incomplete correction for dead-time and/or saturation effects. In this panel, the average satellite/NM fluence ratio is 0.93 $\pm$ 0.09 with an rms width of 39%.

This good agreement between two completely independent measurements – from satellites and from NMs – is a critical validation of our method. As already noted, NM correction factors at $\sim$1 GV are very large and strongly dependent on the solar-proton spectral index (see Fig. 2). If our analysis technique were not fundamentally sound, we would not see the consistency demonstrated in Fig. 5. Our simplifications have not compromised the reliability of our results.

IV. Results

Fig. 6 shows fluences above 1 GV (top) and the integral spectral index in rigidity (bottom) for the 53 GLEs we have analyzed. (The other GLEs have too little NM data for our analysis.) The 1956-Feb-23 event has significantly larger fluence than any other GLE; but it does not have the hardest spectrum. The hardest spectrum is the 1989-Sep-29 GLE. The 1978-May-07 GLE is nearly as hard, but smaller in fluence by a factor of $\sim$30. The two most recent GLEs have nearly the same spectral index, but differ by a factor of 5 in

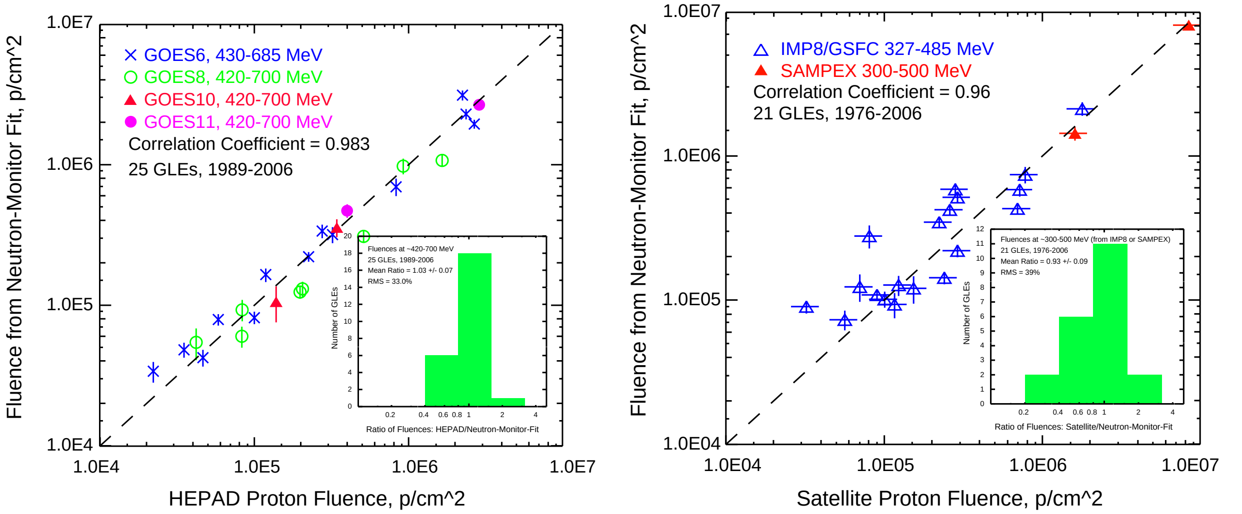

Fig. 5: Correlation of proton fluences from our NM analyses versus corresponding values from GOES/HEPAD (left) and from IMP8 or SAMPEX (right). Insets show histograms of the ratios of satellite-fluences to NM-fluences.

fluence. Although the 2005-Jan-20 GLE may have had the hardest spectrum ever recorded at satellite energies, its spectral index at NM energies is fairly typical. One noteworthy result of this survey is the (unweighted) mean integral spectral index among these GLEs, $<\gamma>$ = 5.9 $\pm$ 0.1, with $\sim$70% of the γ values in the range of 5-7. These numbers should be explainable by SEP models. Future work will involve more thorough studies of the variability shown in these results.

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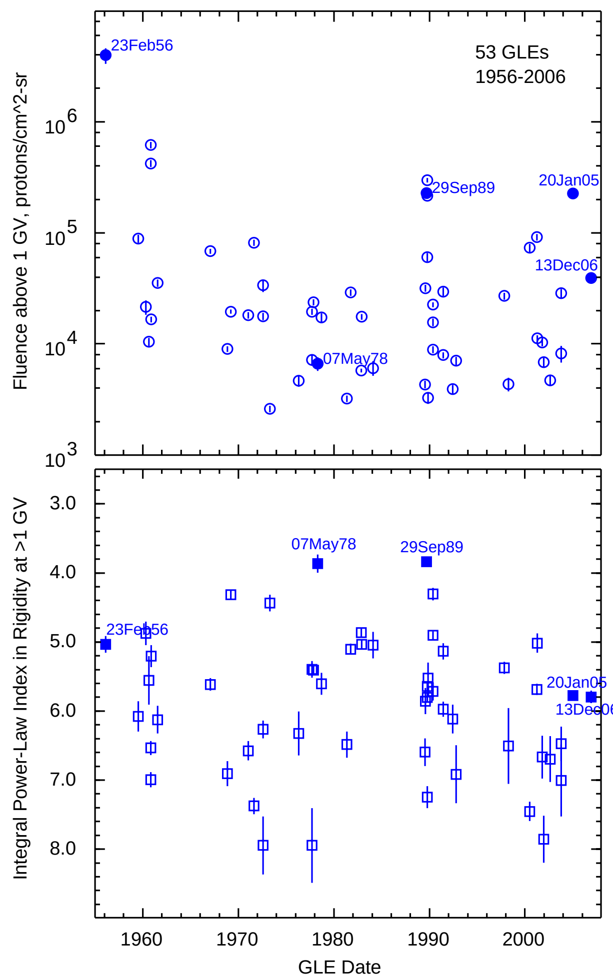

Fig. 6: Event-integrated proton fluence above 1 GV (top) and integral power-law index in rigidity (bottom) for 53 GLEs from 1956-2006. Some GLEs are labeled and represented as filled symbols for purpose of discussion. See text.

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