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Can the number of relativistic solar proton 1 AU crossings be determined from neutron monitor data?

Silvia Dalla,[a,*] **Alessandro Bruno,**[b,c] **Timo Laitinen,**[a] **Georgia de Nolfo,**[b] **Jim Ryan,**[d] **Adam Hutchinson**[a] **and Charlotte O.G. Waterfall**[a]

[a] *Jeremiah Horrocks Institute, University of Central Lancashire, Preston, PR1 2HE, UK*
[b] *Heliophysics Division, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA*
[c] *Department of Physics, Catholic University of America, Washington, DC 20064, USA*
[d] *University of New Hampshire, USA*
E-mail: sdalla@uclan.ac.uk

Energetic protons released during solar eruptive events experience scattering during their interplanetary propagation and may cross the spherical surface of radius 1 AU multiple times. Knowledge of $\overline{N}_{cross}$, the average number of 1 AU crossings per particle, is therefore important to deduce the total number of protons in interplanetary space during solar energetic particle events, for example for comparison with the number of interacting protons at the Sun during gamma-ray flares. It has been proposed that for relativistic protons $\overline{N}_{cross}$ can be obtained by comparing the relative fluences measured in the sunward and anti-sunward directions by the worldwide network of neutron monitors during ground level enhancements (GLEs). For five recent GLE events, we use neutron monitor data to derive $\overline{N}_{cross}$ using the latter approach and we compare the results with those of full-orbit test particle simulations of relativistic protons in a Parker spiral magnetic field, including the effects of scattering and drifts. We show that the approach based on neutron monitor data significantly underestimates $\overline{N}_{cross}$ during highly-anisotropic SEP events. This is due to the data sampling only a very small portion of the 1 AU sphere.

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[*] Presenter

1. Introduction

Energetic particles accelerated during flare and Coronal Mass Ejection (CME) events at or near the Sun may propagate through interplanetary space and be detected at distances of the order of 1 AU. Ions of the highest energies (e.g. $\sim 0.5-10$ GeV for protons) produce secondary particles when they hit Earth's atmosphere, allowing detection as sudden increases in neutron monitor (NM) counts on the ground, in events called Ground Level Enhancements (GLEs). At lower energies (e.g. ~1–500 MeV) Solar Energetic Particles (SEPs) are observed by spacecraft instrumentation such as solid state detectors .

In a number of different applications it is extremely useful to be able to estimate the total number N_{SEP} of SEPs accelerated during a solar event that reach 1 AU via propagation through interplanetary space. For example one might want to estimate how much of the energy released in a solar eruptive event goes into energetic particles [5]. In the analysis of solar Long Duration Gamma Ray Flares (LDGRFs) [12] knowledge of N_{SEP} allows one to compare the number of particles in interplanetary space with the number of 'interacting' particles generating the γ-ray emission [4].

In principle it is possible to derive N_{SEP} by producing observables from a full model that describes the 3D properties of the particles' acceleration and propagation, and fitting them to 1 AU measurements. In practice, because of the difficulty in developing such an all-encompassing model and of the large number of free parameters that could be adjusted, more empirical solutions have been used. In the latter N_{SEP} is derived by considering two main aspects: the first is the spatial distribution of SEPs at 1 AU, which needs to be evaluated from multi-spacecraft data, and the second is the so-called transport correction, describing the average number of times that particles cross 1 AU [4, 5]. The latter is required because energetic protons experience scattering due to turbulence in the interplanetary medium and may cross the 1 AU surface several times.

In this paper we focus on methodologies for evaluating the transport correction $\overline{N}_{cross}$, the average number of 1 AU crossings per particle. In some studies this parameter has been evaluated by means of test particle simulations [4, 5], while recently Share et al (2018) [13] (hereafter referred to as SH2018) proposed a method based on analysis of neutron monitor data. We compare these approaches by applying the SH2018 methodology to 5 GLE events (Section 2) and by using 3D test particle simulations (Section 3).

2. Analysis of neutron monitor data

2.1 Share et al (2018) methodology

In Appendix D of their paper SH2018 describe how they calculated N_{SEP} for >500 MeV protons by evaluating the average number of crossings per particle $\overline{N}_{cross}$, which they termed $C_{transport}$, via the formula:

$$C_{transport} = \frac{J_{forward} + J_{reverse}}{2\,(J_{forward} - J_{reverse})} \tag{1}$$

where $J_{forward}$ and $J_{reverse}$ are the forward and reverse GLE fluences at Earth, as observed by a network of neutron monitors. Although not defined in SH2018 we assume that 'forward' refers to particles propagating outward from the Sun, i.e. with pitch angle within 90° of an outward pointing

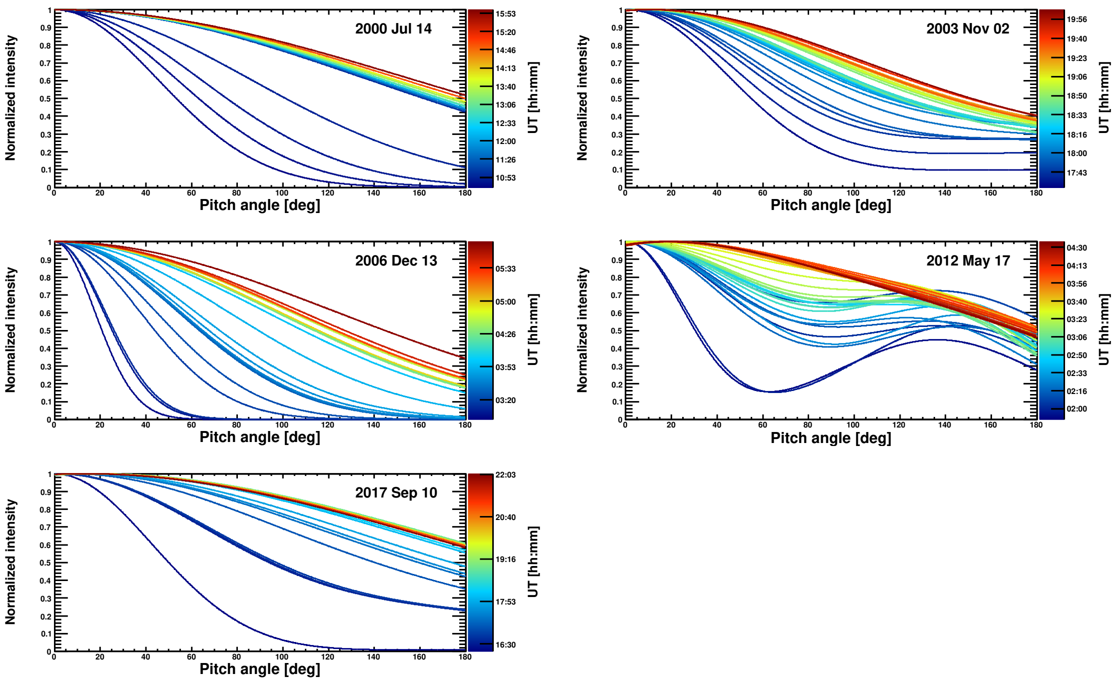

Figure 1: Time evolution of the >1 GV pitch-angle distributions for five GLE events based on neutron monitor observations [7–11].

unit vector along the direction of the interplanetary magnetic field at 1 au, and correspondingly 'reverse' to inward propagating particles.

The GLE events chosen by SH2018 to determine $\overline{N}_{cross}$ using Equation (1) are GLE #60, on 2001 April 15, and GLE #71, on 2012 May 17. Plots of the forward and reverse fluxes for the events are obtained, using the methodology of [14], and displayed in Figure 48 of SH2018. From the corresponding fluences, values of $\overline{N}_{cross}$ of 2.3 ± 0.1 and 1.9 ± 0.3 were derived for GLE #60 and #71 respectively.

2.2 Corrected fluence formula

We have found that Eq. (1), for which a derivation was not given by SH2018, is incorrect, in that the factor 1/2 should not be present. This can be shown by deriving the equation itself via the equation of continuity [3] and by means of test particle simultations (see Section 3). Therefore we introduce a corrected fluence formula given by:

$$\overline{N}_{cross} = \frac{J_{antisun} + J_{sun}}{J_{antisun} - J_{sun}} \tag{2}$$

where $J_{antisun}$=$J_{forward}$ is the anti-sunward fluence and J_{sun}=$J_{reverse}$ the sunward fluence.

2.3 Application to five GLE events

The present analysis of the anisotropy observations from the worldwide NM network is based on the work by [7–11] in which the proton pitch-angle distributions were obtained. Here a Gaussian fit was used, relative to the instantaneous anisotropy axis which, in general, was assumed to have a

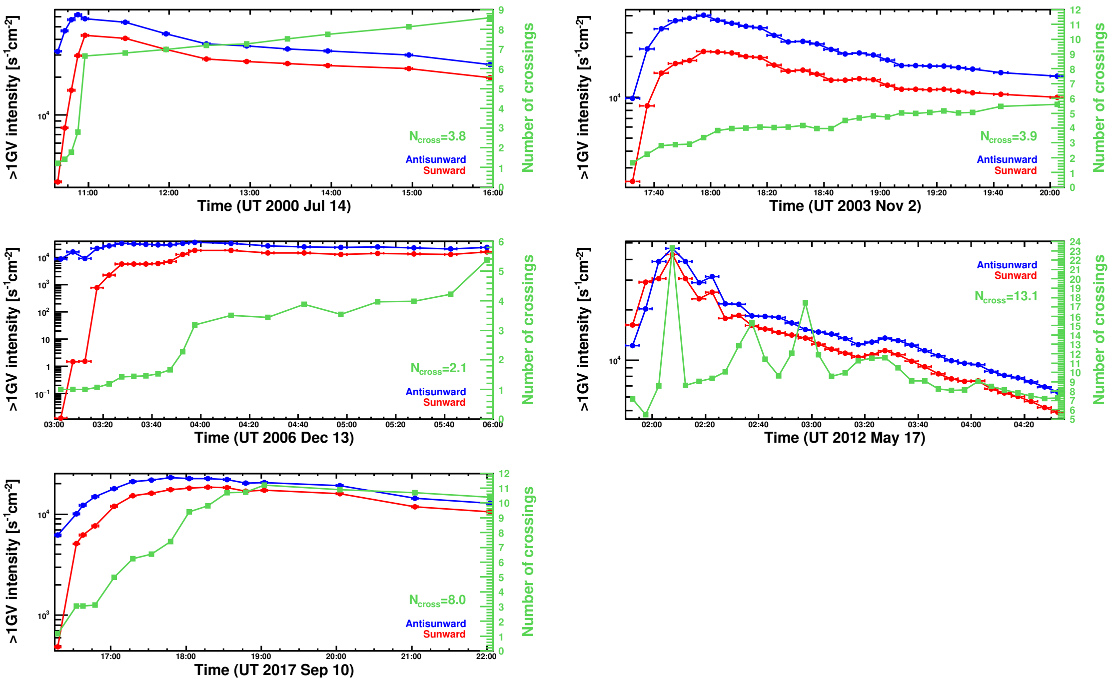

Figure 2: Temporal profiles of the >1 GV SEP intensities measured in the anti-sunward (*blue*) and sunward (*red*) directions during the five selected GLE events (see equation 3). For comparison, the green points indicate the instantaneous number of crossings (Eq. (4)); the event-averaged numbers of crossings (Eq. (2)) are also reported in each panel.

	GLE event				
	#59	#67	#70	#71	#72
$\overline{N}_{cross}$ =	3.8	3.9	2.1	13.1	8.0

Table 1: Event-integrated numbers of crossings (Eq. 2) for the five selected GLEs.

different orientation with respect to the local interplanetary magnetic field (IMF). In the case of GLE #71, a double-Gaussian functional form was used to account for a relatively large back-scattered particle component, possibly originated by magnetic-field structure effects [9].

We consider five recent GLE events: 2000 July 14 (#59), 2003 November 2 (#67), 2006 December 13 (#70), 2012 May 17 (#71) and 2017 September 10 (#72). Figure 1 shows the time evolution of the derived pitch-angle distributions, mostly limited to the anisotropic phase during the first ~3–6 hours of each event. The data refer to rigidity-integrated proton intensities above 1 GV, corresponding to the detection threshold used for GLE events.

The SEP solid-angle integrated intensities in the anti-sunward and sunward directions $I_{antisun}$ and $I_{antisun}$ were obtained by integrating the pitch-angle distribution $f(\alpha, t)$ as follows:

$$I_{antisun}(t) = \int_0^{\pi/2} f(\alpha, t) \sin\alpha \, d\alpha \quad ; \quad I_{sun}(t) = \int_{\pi/2}^{\pi} f(\alpha, t) \sin\alpha \, d\alpha. \qquad (3)$$

An instantaneous number of crossings can be obtained according to the formula:

$$N_{cross}(t) = \frac{I_{antisun}(t) + I_{sun}(t)}{|I_{antisun}(t) - I_{sun}(t)|}, \tag{4}$$

where the absolute value of the denominator accounts for the possibility that, for specific time intervals, I_{sun} might be higher than $I_{antisun}$.

The event-averaged number of crossings per particle was derived by calculating the fluences (SEP intensities integrated over the considered time interval):

$$J_{antisun} = \int dt\, I_{antisun}(t) \quad ; \quad J_{sun}(t) = \int dt\, J_{sun}(t) \tag{5}$$

and substituting these quantities into Eq. (2). The data by [7–11] are provided with a five-minute resolution; a logarithmic interpolation was used for estimating $N_{cross}(t)$ during the data gaps present at the end of the analyzed time intervals.

In Figure 2 the temporal profiles of SEP intensities in the anti-sunward (*blue points*) and sunward (*red points*) directions are given and the green points show the instantaneous number of crossings; the event-averaged numbers of crossings are also reported in each panel, and summarized in Table 1. We note that, as mentioned earlier, analyzed data do not include the event late phases.

As expected, $N_{cross}(t)$ is minimum during the initial phase, characterized by highest anisotropy, and then increases with time. The resulting $\overline{N}_{cross}$ are relatively low (~2–4) for the first three GLEs, while they are significantly higher for the two most recent events. In particular, a remarkably high value (14.5) was obtained for the 2012 May 17 GLE, for which the estimated anti-sunward/sunward fluxes were relatively close. In addition, as shown in Figure 1, the pitch-angle distribution of this event was characterized by a secondary peak at $\alpha \approx 130°$ caused by a relatively large component of reflected particles [9]. As a consequence, I_{sun} was found to be higher than $I_{antisun}$ during the intervals associated with the first two data points (UT01:50–02:00). Such results are in a clear disagreement with those of SH2018 (see bottom panel of their Figure 48), who reported much higher anti-sunward fluxes during the initial phase of the event. Indeed, by applying the corrected formula, Eq. (2), to their NM observations, $\overline{N}_{cross}$=3.8 is obtained, much lower than our value. It should be pointed out that the anisotropy analysis by in SH2018 also accounts for the event nearly-isotropic late phase (UT03:45–06:00), which is not included in our study.

3. Test particle simulations

We use a 3D test particle code [1] to obtain anti-sunward and sunward intensities and thus the number of 1 AU crossing per particle via the corrected fluence formula, Eq. (2). We consider simulations with monoenergetic proton populations and a unipolar magnetic field pointing outwards from the Sun (no heliospheric current sheet), with the total number of particles being 10,000. Particles are injected instantaneously from a region at r = 2 $R_\odot$ of angular extent 8 × 8°.

As a first test of the formula, we collect particle crossings over the entire 1 AU sphere to calculate $\overline{N}_{cross}$ for two levels of scattering, described by values of the mean free path λ=0.1 and 0.5 AU, for monoenergetic simulations at four proton energies. In Figure 3 values of $\overline{N}_{cross}$ obtained from the test particle simulations (*circles*) are plotted versus particle energy and compared with

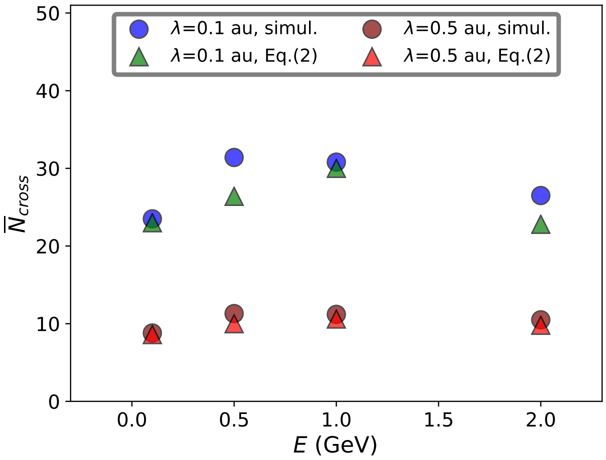

Figure 3: Average number of crossings per particles $\overline{N}_{cross}$ versus particle energy obtained by means of test particle simulations for two values of the mean free path λ. Values obtained via the test particle simulations and those from Eq. (2) (*triangles*) are compared.

those from Eq. (2) (*triangles*). There is fairly good agreement between the simulations and the equation, especially for the higher value of the mean free path. This agreement would be lost if values from Eq. (2) were multiplied by 1/2, as in the SH2018 formula (Eq. (1)).

The comparison shown in Figure 3 shows that in principle a fluence formula could provide a reliable methodology for deriving the average number of crossings. However fluences were derived by adding all crossings over the 1 AU surface. In a real situation it is not possible to have detectors distributed over the entire 1 AU sphere: the network of neutron monitors in fact provides the required fluences only at a single location on the 1 AU sphere.

It is interesting to use the test particle model results to simulate the fluxes that would be detected by observers at different locations on the 1 AU sphere and from these derive the average number of crossings. Figure 4 shows the profiles that would be seen by different observers for a population of 1 GeV particles when λ=0.1 AU. In each panel, in green, the value of $\overline{N}_{cross}$ that each observer would deduce is given.

It is clear from Figure 4 that at each location a completely different value of $\overline{N}_{cross}$ is obtained. At the well connected location, [0,0], where the largest difference between antisunward and sunward intensities is present (largest anisotropy) the average number of crossings is lowest, while it becomes much larger at other observers. When counts are collected over the entire 1 AU sphere one obtains $\overline{N}_{cross}$= 29.

Figure 4 shows that derivation of $\overline{N}_{cross}$ at a single point on the 1 AU sphere is not reliable as a measure of the global value of $\overline{N}_{cross}$, the quantity required to obtain N_{SEP}. At a well connected observer, the local value is a significant underestimate of the global value of $\overline{N}_{cross}$.

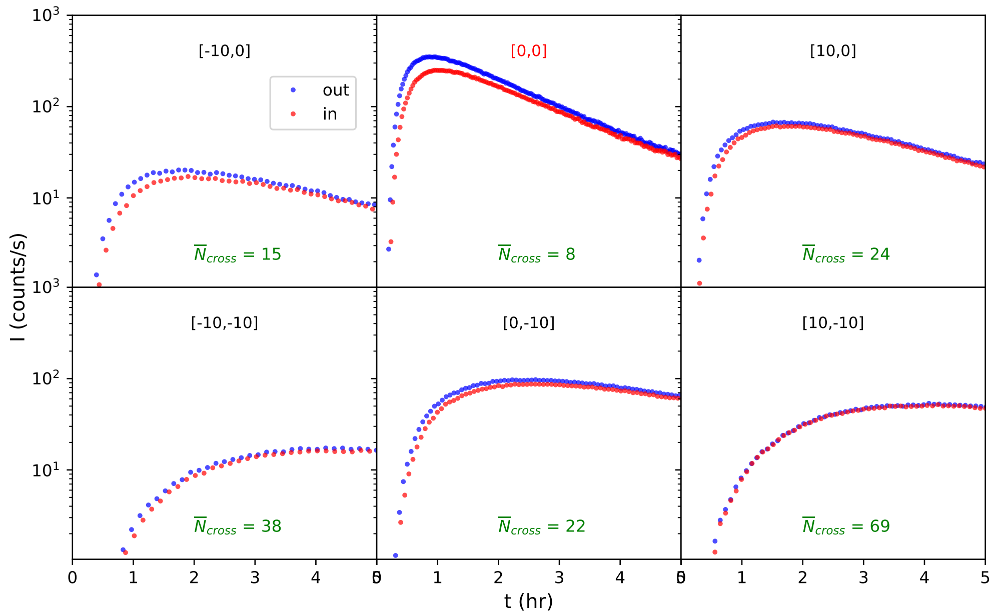

Figure 4: Antisunward (*blue*) and sunward (*red*) 1 GeV particle count rates from test particle simulations at a grid of locations corresponding to different observers. [0,0] is the observer with best connection. Latitude and longitude of the other observers with respect to the latter one are given in brackets. Here λ=0.1 AU. In green at the bottom of each panel the value of $\overline{N}_{cross}$ that would be derived by that observer based on the detected fluences and Eq. (2) is shown. Applying Eq. (2) to the entire 1 AU sphere gives $\overline{N}_{cross}$=29.

4. Conclusions

We have discussed possible methodologies for deriving the average number of 1 AU crossings per particle, $\overline{N}_{cross}$. In particular we have considered the method proposed by SH2018, based on analysis of neutron monitor anti-sunward and sunward fluences, to derive $\overline{N}_{cross}$ for >500 MeV protons.

Our main results can be summarised as follows:

- The formula used by SH2018 is incorrect in that the factor 1/2 should not be present. Values of $\overline{N}_{cross}$ obtained with this method therefore underestimate the actual values by a factor of 2 (at least).

- Application of the methodology proposed by SH2018 is complicated by the fact that pitch-angle distributions obtained from NM data are characterised by large uncertainties. Our independent analysis of one of the events considered by SH2018 resulted in very different profiles of antisunward and sunward fluences compared to the latter study, and a value $\overline{N}_{cross}$ = 13.1 compared to $\overline{N}_{cross}$ = 1.9 obtained by SH2018. The difference between these two values is due to: 1) SH2018 assuming that the IMF direction is the axis of symmetry for the anisotropy while the axis of symmetry was derived from the data in the derivation of the pitch-angle distribution we used [9] and 2) SH2018 assuming a gaussian fit while a double gaussian was used by [9].

- Even if pitch-angle distributions could be obtained reliably from NM data, analysis of 3D test particle simulations shows that values of $\overline{N}_{cross}$ at different observers have a strong dependence on observer location with respect to magnetic flux tube connected to the injection location. In general, local values of $\overline{N}_{cross}$ are not reliable estimates of the global value, needed to obtain the total number of SEPs in space, N_{SEP}.

We conclude that the number of 1 AU crossings cannot be reliably determined by using NM data via the procedure proposed by SH2018. The values of $\overline{N}_{cross}$ obtained in that work are an underestimate of actual values and as a result, since N_{SEP} is inversely proportional to $\overline{N}_{cross}$, the values of N_{SEP} they derived are an overestimate.

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