RADIAL PROPAGATION OF SOLAR ENERGETIC PARTICLES ASSUMING LARGE SCATTERING MEAN FREE PATHS IN THE INTERPLANETARY MEDIUM

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Introduction

Progress in understanding the physical processes responsible for energization of solar energetic particles has long been hampered by the fact that details of the source function of the sun are obscured by the subsequent propagation in the interplanetary space to the observer. In practise, it is generally possible to trade off the effects of extended injection at the sun, with changes in the size of the interplanetary scattering mean free path $\lambda$ such that families of solutions exist which produce nearly identical results at, e.g., 1 AU. An exception to this is the case of the small, impulsive events rich in electrons, $^3$He, and heavy ions (Reames \textit{et al.}, 1985; Mason \textit{et al.}, 1989). For these events, one has an essentially unique solution consisting of nearly impulsive injection (<1 hour) at the sun, followed by propagation with $\lambda$~1 AU, as described by the Boltzmann equation in pitch angle scattering.

The question arises, can this picture also explain large solar particle events, which are typically described as diffusive, and can be often well-fitted by much smaller values of $\lambda$ (~0.1 AU)? We test this using two flares (November 22, 1977, and December 26, 1977) observed on multiple spacecraft, which can be well fitted by the diffusive model (Beeck \textit{et al.}, 1987).

Observations and fits to data

Both flares were observed on the Helios, IMP-8/ISEE-1 and Voyager S/C, with S/C to flare magnetic connection separations of less than 35\textdegree, except for Voyager in the November event, where the separation was ~70\textdegree. We proceeded as follows: (1) $\lambda$ was \textit{assumed} to be 0.8 AU, i.e. near the average value seen in $^3$He-rich flares, (2) propagation was calculated using the Ng and Wong's (1979) numerical solution to the Boltzmann equation, and (3) the solar source function was \textit{chosen} such that the Helios data (rise to just

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past time of maximum flux) was fitted. In a sense, then, the Helios data becomes the "source" term for the spacecraft further away from the sun.

Figure 1 shows the fits obtained for the November 1977 event for ~5 MeV protons. Note that Helios 2 fluxes were perturbed by a shock, but both Helios S/C agree well on the rise. At IMP, the calculated flux rises more sharply and 2-4 hours faster than the observations. While at first this might be evidence than our assumed value of \( \lambda \) is too large, this is negated by the fact that the rise and fit at Voyager is very good.

Note the extended injections used in these fits, where the full width at 1/10 max is about 15 hours. We emphasize that \( \delta \) function injections do not work for this event since their distinctive "pulse/ wake" shape is not at all close to the appearance of the time/intensity profiles we observe. We also compared these calculated fits with those obtained from a Fokker-Planck equation with \( \lambda \sim 0.1 \) AU (\( \delta \) function injection) and found that the differences were small.
compared to the differences between spacecraft not greatly separated.

The differences between the model calculations for large versus small mean free path become more important at low energies. Figure 2 therefore shows fits to the December 1977 event at energies near 1-2 MeV. The profile at Helios-2 is irregular, but the rise is well fitted as is the anisotropy. At IMP, the calculated rise is faster than the observations by a couple of hours; considering that Helios was at 0.9 AU and IMP at 1.0 AU, it is difficult to ascribe this difference to radial separation. The calculation in this case fit the Voyager-2 data reasonably well, but Voyager-1 rose earlier. Again, since the two Voyager were at essentially the same location this discrepancy seems to be due more to local effects, or longitudinal effects, than to radial separation. The source widths in these fits had a full width at 1/10 maximum of ~12 hours; as in the previous case fits calculated assuming δ function injection at the sun did not produce acceptable fits for Helios or ISEE; for Voyager, they were acceptable in form, since even with λ = 0.8 AU, the particles had scattered enough times to remove the "pulse/wake" shape at Voyager.
Discussion

We were surprised to find that for extended injections at the sun, the Boltzmann equation solutions did not differ drastically from solutions using the Fokker-Planck equation (FPE) with $\lambda$ values 1/10 as large. The anisotropies calculated with the Boltzmann equation were 2-3 times larger than those obtained with the FPE for Helios, but further out these differences blurred. The close similarity between the two solutions at greater distances occurs because at 1.5-2 AU, the distance along the field lines is ~2-3 AU, and so even with $\lambda = 0.8$ AU, the particles have scattered enough to destroy the distinctive "pulse/wake" feature. While the calculated forms were in fact different in all cases, we were impressed that these differences were of similar size to the differences between spacecraft whose relatively small separations yielded considerable flux differences. The anisotropy data, while yielding another parameter to test, has practical problems in interpretation, e.g., the presence of the magnetosphere for the IMP-8 or ISEE-1, and the fact that the Voyager probes were 3-axis stabilized. These considerations make it difficult to discriminate between the two models on the basis of anisotropy.

While the basic model fitting procedure here is markedly different from the approach taken by Beeck et al. (1987), we emphasize that the present work reconfirms one of the major conclusions of that study, namely that the injection of the particles at the source is extended in time, lasting $>10$ hours. We suggest that this time scale is due to the length of the interval over which large shocks accelerate particles within a few 10s of radii of the solar surface.

We speculate that the extended injection at the sun may explain why it is that large solar particle events never show the "pulse/wake" behavior seen in the small, impulsive events. Since these large events require shock acceleration for several hours to generate the large particle population, the spike-like profile is wiped out. Thus, even if the interplanetary medium is quiescent with large $\lambda$ values, a pulse-like large energetic event will not be observed.

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