RADIAL TRANSPORT OF ~1 MeV/nucleon IONS DURING THE 22 NOVEMBER 1977 SOLAR PARTICLE EVENT

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1. Introduction. Time-intensity profiles of solar flare energetic particle events carry information on the particle injection processes at the sun, as well as the transport of particles in interplanetary space. However, in order to help identify the individual processes of injection versus transport it is necessary to use observations taken at more than one radial location. We present here results of such a study concerning the 22 November 1977 solar particle event, observed with instruments at 1.0 and 1.55 AU. The observations are for particles of energies near 1 MeV/nucleon, considerably less than the ~10-20 MeV/nucleon energies typical of previous radial transport studies (e.g. 2,10). Thus, in the present work we are able to examine the validity of transport models to considerably lower energies than in previous work.

2. Observations. The 22 November 1977 event began at 0945 UT with a 2B flare at N24 W40. From this location it is reasonable to assume that particles had prompt access to the interplanetary magnetic field line connected to Earth. This solar particle event has been widely studied (e.g. references in 7). Figure 1 shows the time-intensity profiles for several species observed at 1 AU with the ISEE-1 ULEWAT sensor (5). Gaps in the profile are due to data removal around radiation belt passes. For He, the time of maximum (M) was about 36 hours after the flare (F), well before the passage of the flare-associated shock (S) late on November 25. Figure 2 shows time-intensity profiles for the same set of species observed at 1.55 AU (3) with the Voyager-2 LECP instrument (6). During this flare the Earth-Sun-Voyager angle was about 5°, and so this spacecraft was also well connected to the flare site. Although the Voyager profiles show some disturbance during the onset phase between 0000-1200 on November 23, it appears that the times to maximum can be identified, with a value of about 48 hours for He.

3. Model Fits. In modeling the time to maximum for low energy particles such as those in this study, it is essential to include the effects of convection and adiabatic deceleration (e.g. 9). Accordingly, we have used a model based on the spherically symmetric Fokker-Planck equation including diffusion, convection and adiabatic energy loss, numerically solved using the code of Hamilton (2). In the calculation we used a constant solar wind velocity typical for this period, an injection time at the H_α onset, and an assumed particle number density in the form of a power law in energy/nucleon with spectral index derived from the observed spectra at 1 and 1.55 AU. The interplanetary diffusion coefficient had the functional form typical in radial propagation studies: $\kappa = \kappa_o r^b = v_{particle}\lambda_r/3$. Finite injection time profiles used the form $I = I_o \exp(-t/\sigma_t)$. Following reference (7) it was assumed that κ_o scaled as $(A/Q)^{0.55}$ for this particle event.

With the model so specified, the adjustable parameters are λ_r, b,

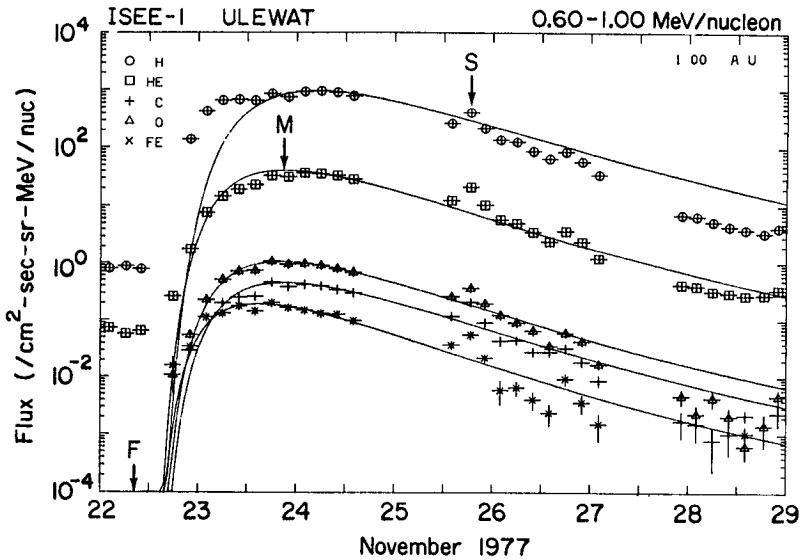

Figure 1

and σ_t; note that σ_t is a source characteristic while λ_r and b are properties of the interplanetary transport. Fitting the Helium time to maximum at 1 and 1.55 AU does not uniquely determine the 3 parameters: an additional observation was needed. This was chosen to be the time to 1% of maximum intensity at 1 AU (~10 hours) for Helium, thus fitting the early rise portion of the event.

Figures 3 and 4 show families of curves in the λ_r - b plane which provide the required T_{max} values at both sites: notice the wide range of values which are possible with an observation at 1 or 1.55 AU only. Overlaying Figures 3 and 4, an intersecting line is obtained, shown in Figure 5, which has the λ_r - b values which yield the observed T_{max} values at both 1 and 1.55 AU. The intersection of this line with the locus of values for $T_{1\%\ of\ max}$ = 10 hours (Figure 5) yields a unique set of values for λ_r, b and σ_t, which are listed in Table 1. The uncertain-

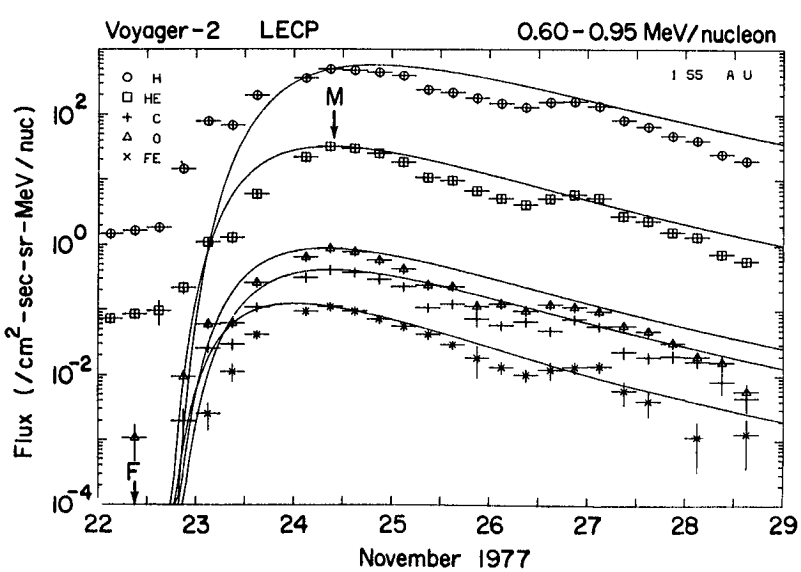

Figure 2

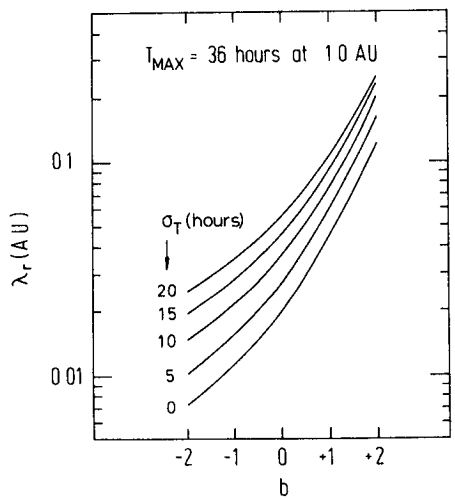

Figure 3

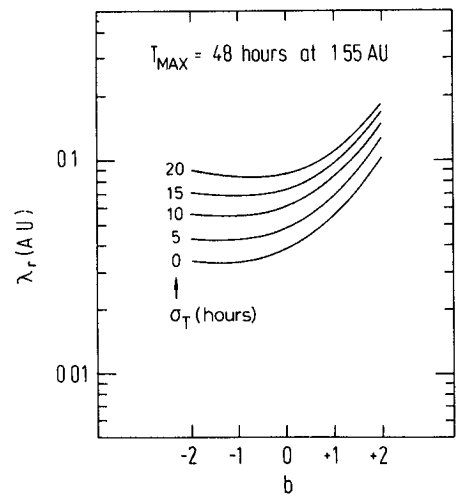

Figure 4

ties in the values are based on an estimated uncertainty of ± 20% in κ.

Table 1
Fit Parameters for 0.6-1.0 MeV/nuc Helium

λ_r = 0.10 ± 0.02 AU at 1 AU
b = 1.3 + 0.1
σ_t = 12 ± 3 hours

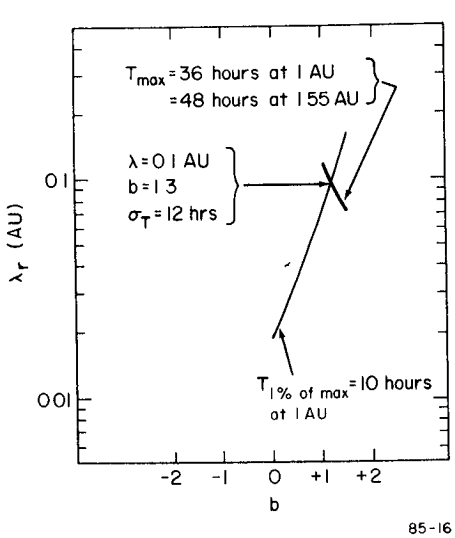

Figure 5

Time intensity profiles for all species using the Table 1 values for He, and assuming scaling in λ_r as $(A/Q)^{0.55}$, are shown in Figures 1 and 2. Considering the 1 AU data in Figure 1, the fits are generally satisfactory for He, C, O and Fe up through the early decay phase, and they reproduce the temporal variations of the heavy ion ratios such as Fe/O seen in this event (7). Protons, however, have a fast rise time which is not fitted by the assumed scaling. This may be indicative of interplanetary acceleration for the protons, which, as the lowest rigidity particles in the set would be expected to be the most susceptible to such effects. The 1.55 AU fits are reasonable for the times to maximum and the decay phases, although

of course the model does not fit the previously noted distortions in the rise phase. As is the case at 1 AU, the protons observed at Voyager have a fast rise-time which does not follow the $(A/Q)^{0.55}$ scaling used for the A/Z=2 species.

4. Discussion. Although the value of λ_r found here is similiar to previous studies (e.g. review in 8), the values found for b and σ_t are rather different from the higher energy studies (e.g. 1,2), which have generally yielded b ~ 0 and σ_t =0 (delta function injection). If we were to force such a choice on the present observations at 1 AU, it is possible to find the required λ_r value from the curves in Figure 3--however the resulting value (λ_r =0.015 AU) yields a T_{max} of 66 hours at Voyager: 18 hours beyond the observed value, and well outside the experimental uncertainties. It is possible that this result represents a disagreement with the previous work. More likely, it is due to the fact that the particle energies are lower, and also that the two spacecrafts are relatively close to 1 AU and thus the observations are more sensitive to σ_t and the behavior of λ_r out to 1 AU than the previous studies at generally much larger radial distances. It should be possible to resolve these uncertainties by considering additonal data such as anisotropies (4) and by analyzing additional particle events.

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