CORONAL PROPAGATION OF FLARE ASSOCIATED ELECTRONS AND PROTONS

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ABSTRACT

A statistical study of characteristic times and intensities of 36 solar particle events observed between 1977 and 1979 by the Kiel Cosmic Ray Experiment on board HELIOS-1 and -2 has been carried out. For $\sim$ 0.5 MeV electrons we order the times of maximum and the absolute intensities with respect to angular distance from the parent flare. Discussion of coronal parameters in terms of Reid's model leads to typical time constants for coronal diffusion and escape.

1. Introduction. Particle intensities observed in interplanetary space are a superposition of coronal and interplanetary propagation effects which are difficult to separate. In this paper we use statistical studies of a large number of events to investigate the properties of solar transport of flare particles.

2. Coronal angular dependence of maximum times. Assuming only diffusive propagation in interplanetary space it can be shown that the maximum times of solar particle events can be approximated by (1)

$$T_{max} = t_{max}^{ipl} + c_m \tag{2.1}$$

in good agreement with the full numerical solution of the convolutional integral. C_m is the time-to-maximum of the coronal injection and t_{max}^{ipl} would describe the interplanetary propagation for δ-function injection.

Using the model of Reid (2) for solar particle transport and a simple model for interplanetary diffusion leads for sufficiently large angular distances ϕ to

$$T_{max} = t_{max}^{ipl} + \frac{\phi}{2}\sqrt{t_c t_L} \tag{2.2}$$

In this case c_m increases linearly with angular distance ϕ.

Maximum times versus ϕ for $\sim$ 0.5 MeV electrons with diffusive time intensity and time anisotropy profiles are shown in Figure 1. Only events were selected for which the coronal magnetic connection point of the spacecraft is west of the corresponding flare. The H_α-onset has been chosen as acceleration time. Apparently the nearly constant propagation times for small angular distances ϕ are described by a fast propagation region (3) with a mean extension of $\sim 26^o$. The time constants seem to increase linearly for larger angular distances as predicted in (2.2). A least squares fit to the data results in a geometrical mean of the two time constants for coronal diffusion and escape of

$$\sqrt{t_c t_L} \approx 7.5 \text{ h}$$

Coronal transport effects can be neglected within the fast propagation region, so that measured maximum times would only be determined by interplanetary propagation. For a radially independent diffusion coefficient K we obtain with

$$t_{max}^{ipl} = \frac{r^2}{6K}$$

an upper limit for the mean free path parallel to the average interplanetary field of $\sim$0.12 AU for $r = 1$ AU in good agreement with earlier work (4).

3. Coronal angular dependence of maximum intensities. In the 1977 - 1979 period we were able to obtain maximum intensities from both spacecraft HELIOS-1 and -2 for 12 events. Differences due to interplanetary propagation are corrected by assuming an r^{-2} dependence of the absolute intensities. Although the actual radial dependence can be derived only if coronal and interplanetary effects are taken into account in a combined propagation model, our statistical analysis shows that the coronal distance dependence is much stronger than the effects of different normalization factors $(r/r_E)^n$ for $2 \leq n \leq 3$. Radially normalized maximum intensities are therefore a measure of the number of particles at the injection maximum I_{max} for the respective angular distance. Using Reid's model in the range of large ϕ I_{max} is controlled only by the ratio of the time constants for coronal diffusion and escape:

$$I_{max} = I(c_m) \sim \frac{1}{\phi} \exp \left\{ - \sqrt{\frac{t_c}{t_L}}\, \phi \right\} \qquad (3.1)$$

Since the exponential term will dominate the ϕ^{-1}-dependence, this leads to

$$I_{max} \sim \exp \left\{ - \sqrt{\frac{t_c}{t_L}}\, \phi \right\} \qquad (3.2)$$

Comparing the normalized maximum intensities for the same event as observed by two spacecraft at different coronal connection distances from the flare allows to determine the ratio t_c/t_L:

$$\frac{I_{max}(\phi_2)}{I_{max}(\phi_1)} = \exp \left\{ - \sqrt{\frac{t_c}{t_L}}\, (\phi_2 - \phi_1) \right\} \qquad (3.3)$$

Figure 2 shows the amplitude variations with coronal angular distance for $\sim$0.5 MeV electrons. In order to disregard the different event sizes we normalize the respective maximum amplitudes to obtain $I_{max} = 1$ for $\phi = 0^o$.

The slope varies considerably, apart from a group of four events with similar behaviour. It is not useful to describe this amplitude variation with angular distance by an average value of t_c/t_L. Regarding individual events observed by at least two spacecraft at different solar longitude we always find intensity variations larger for protons than for electrons. Figure 3 shows an example for the event of April 11, 1978, as observed by HELIOS-1 and -2. The large difference in temporal delays for protons as compared to electrons is immediately evident. In general the difference in amplitude variation between the two particles is more pronounced than in this example (see e.g. 1).

4. Conclusions. For non-relativistic protons Ng and Gleeson (5) found $t_c = 50 - 100$ h and $t_L = 10 - 15$ h between 1 - 50 Mev. Mc Guire et al. (6) derived $t_c \approx 90$ h and $t_L \approx 9$ h for 3 - 60 MeV protons taking into account a typical extension of the fast propagation region of $\sim 25^o$.

The value from (6) for protons $t_c t_L \approx 810\ h^2$ in contrast to our value $t_c t_L \approx 55\ h^2$ quoted above for electrons shows that coronal transport occurs much faster for electrons for which the average rate of increase $\Delta T_m/\Delta\phi$ is almost a factor of 4 smaller. From the coronal transport models we can exclude electric field drift. This process proposed in (7) was based on (a) a linear rate of increase $\Delta T_m/\Delta\phi$ with ϕ and (b) the suggested independence of coronal transport from particle type (8). The simple Reid model leads to the observed linear dependence, based on the combination of coronal diffusion and escape, whereas diffusion alone would lead to $T_{max} \sim \phi^2$. We also find clear evidence that electrons are transported faster through the corona.

Any other process leading to coronal transport independent of particle type is also excluded by our observation (bird cage model (9) and coronal shock).

The considerable spread in the amplitude variation (Figure 2) precludes any simple classification scheme with coronal distance only. There is no apparent association of the size of the variation with the location of the coronal connection point inside or outside the fast propagation region. The observations suggest that we have no universal process for coronal diffusion as e.g. inherent in the Fisk and Schatten (10) model, but a process which varies highly with individual coronal magnetic field structures.

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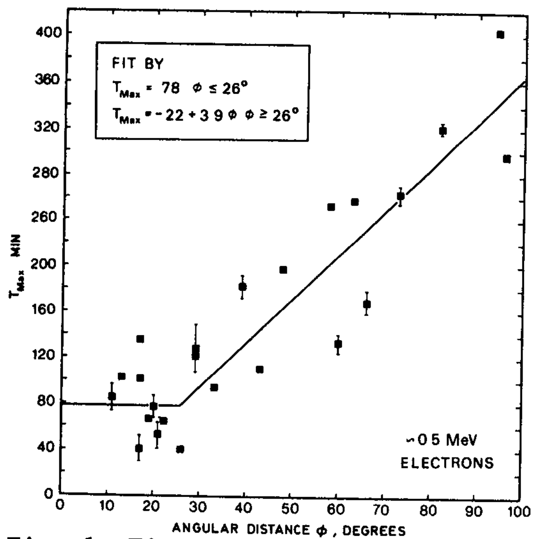

Fig. 1: Times to maximum of ∿0.5 MeV electrons versus coronal angular distance for events with magnetic connection west of the flare. Separate least square fits are qiven inside and outside the mean fast propagation reqion.

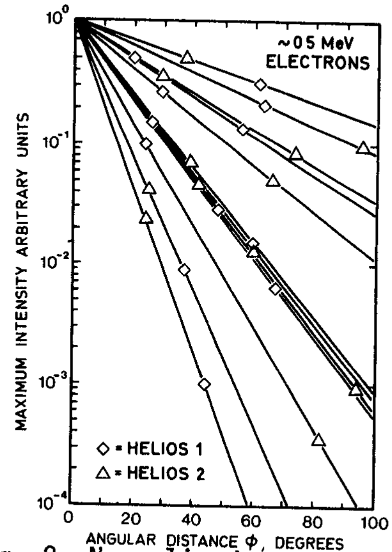

Fig. 2: Normalized maximum intensities for 1977 - 1979 ∿0.5 MeV electron events measured on 2 separate spacecraft versus coronal angular distance.

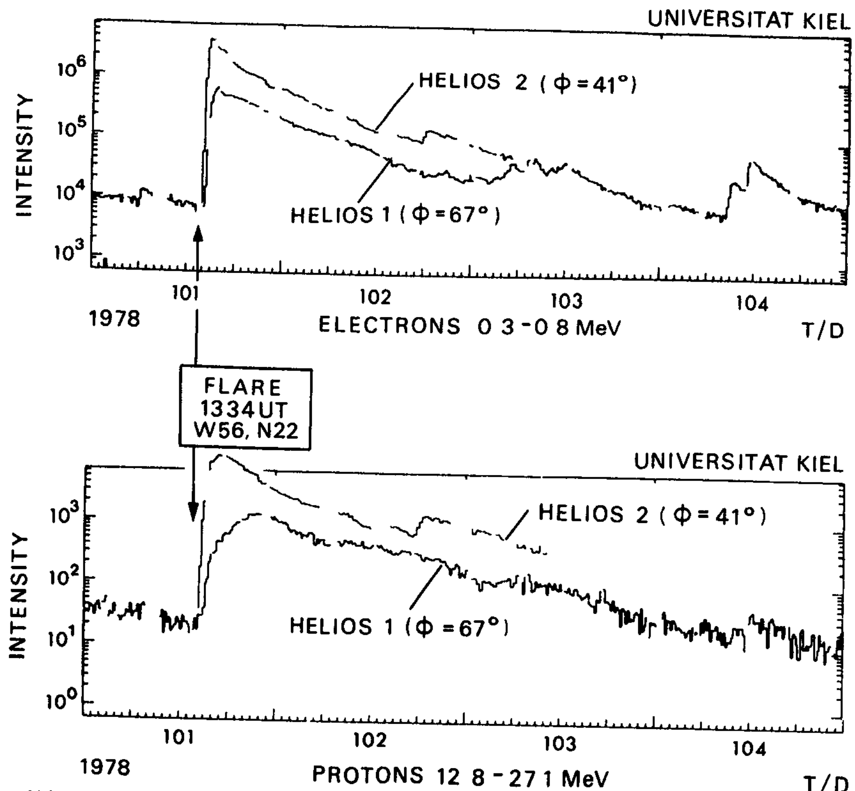

Fig. 3: Histories of the 11 April 1978 solar particle event are shown for protons and electrons as measured by HELIOS-1 and -2 at different coronal angular distances from the flare.