# CORONAL PROPAGATION: VARIATIONS WITH SOLAR LONGITUDE AND LATITUDE*

N76-24133

G. Wibberenz

Institut für Reine und Angewandte Kernphysik der
Christian-Albrechts-Universität Kiel, 23, Kiel, FRG

**Abstract:**

Observational results on the East-West effect are summarized and discussed in the context of existing models of coronal propagation. The variation of the number of events with solar longitude is surprisingly similar for particles covering a large interval of rigidities. Over large longitudinal distances, time delays to the event onset and maximum intensity are independent of energy and velocity. This has important implications and will require probably a transport process which is determined by fundamental properties of solar magnetic fields, e.g. reconnection processes between open and closed field configurations.

A fit of Reid's model for diffusive propagation in the corona to the observed delay times gives a (two-dimensional) diffusion coefficient $\kappa_c$ corresponding to $r_c^2/\kappa_c \approx 100$ hours ($r_c$ = distance of the thin diffusing shell from the center of the Sun). Limitations of the diffusion model are given by the existence of a fast propagation region which may extend up to 40...50° from the flare site, by the possible existence of an energy independent drift process, and by the influence of solar sector boundaries. The relative role of open and closed field configurations is extensively discussed. Some evidence is presented that the acceleration of protons to higher ($\gtrsim$10 MeV) energies is related with a shock wave traveling in the solar atmosphere.

The importance of measurements performed from spacecraft out of the ecliptic plane is stressed, in particular with respect to the fundamental problems of particle acceleration in the flare process and for understanding fundamental dynamical properties of large-scale solar magnetic fields.

---

*Extended version of a talk presented at the "Symposium on the Study of the Sun and Interplanetary Medium in Three Dimensions", Goddard Space Flight Center, USA, May 15/16, 1975.

## 1. Introduction

The story of coronal propagation begins with the East-West-effect for solar cosmic ray events: with increasing longitude of the parent flare on the Eastern hemisphere of the Sun the number of events detected at the earth decreases considerably, and, for those events which are detected, the delay between the flare and the arrival of particles at the earth increases (see Burlaga, 1967, for asummary of some earlier results). The reason for the East-West-effect is obviously the asymmetric nature of the interplanetary magnetic field with respect to the central meridian on the Sun. For average solar wind conditions, a bundle of interplanetary magnetic field (imf) lines observed near the earth connects back to a point on the Sun which is close to 60° W. However, the controlling nature of the regions close to the Sun for the azimuthal propagation of energetic particles became only clear, when it was established that the propagation of energetic particles in space occurs preferentially along the imf. The arguments for negligible particle motion perpendicular to the imf have meanwhile been summarized by various authors. In addition to the arguments presented e.g. by Roelof (1974) we wish to point out that the variation of delay times with solar longitude is independent of energy, which is another strong argument against interplanetary perpendicular diffusion (Reinhard and Wibberenz, 1974, Ma Sung et al., 1975).

These effects of "coronal propagation" which depend on the relative azimuthal distance between a parent flare on the Sun and the point in space where the energetic solar particles are observed, could be studied so far only as a function of solar longitude. It is the purpose of this paper, (i) to summarize the observational results and to order them with respect to existing models, (ii) to point out which fundamentally new results we should expect by studying variations with solar latitude, i.e. by using observations in space out of the ecliptic plane.

We shall start in section 2 to summarize the methods, by which various transport processes can be separated. In section 3 we discuss the statistical methods, where the variation of characteristic parameters of solar events with solar longitude is studied for a large number of events. Different models have been developed to describe the average longitudinal variations. An independent method described in section 4 consists in detailed studies of individual events, including multi-spacecraft observations at different heliocentric longitudes, simultaneous intensity and anisotropy measurements, and the relation to observations of solar surface structures. Some indications to the acceleration process itself are treated briefly in section 5. Finally we summarize the open questions in section 6 and try to relate them to studies of solar particle events off the ecliptic plane.

## 2. Separation of various transport processes

In the sequence of events between the first acceleration of particles on the Sun and their final observation in space, we can ask different questions: How is the solar atmosphere filled up with energetic particles following the original acceleration process? How do the particles escape into space? How can the interplanetary propagation be separated from the solar transport processes? Let us start with some terminology related to the different steps.

(a) The acceleration process is visualized in many models as a pulse-like process limited in spatial extent to the flare area itself, approximated by a delta-function in space and time. In principle, the acceleration could also occur over an extended area in the solar atmosphere for long periods of time (see below).

(b) The accelerated particles spend a certain time in the vicinity of the Sun. We wish to make a distinction between propagation when they move away from the acceleration region and finally occupy a large area on the Sun, and storage when the particles remain confined to a certain region. The difference is depicted schematically in Figure 1. In reality, we may have a mixture of both processes.

(c) The number of solar particles observed in space is determined by the probability per unit time that a particle will leave the solar atmosphere by finally reaching an open field line leading out into space (Reid, 1964; Newkirk, 1973). This <u>release</u> mechanism has a very important influence on the azimuthal distribution of particles, because it also determines how many particles are left for further propagation along the solar surface.

(d) Sufficiently far away from the solar surface we only find open field lines which lead out into the interplanetary medium. Along this "source surface" (Newkirk, 1973) the processes (a) to (c) define an <u>injection function</u> $N(\phi, \theta, t)$. Measurements on a single spacecraft connect back to a certain solar longitude $\phi$ close to the solar equator ($\theta \approx 0$), and for a given solar wind velocity the connection longitude $\phi(t)$ as a function of time may be determined (see e.g. Nolte and Roelof, 1973).

A single satellite therefore "sees" an <u>injection profile</u> $I(t) = N(\phi(t), 0, t)$. Roelof and Krimigis (1973) have described an effective method to separate real longitudinal changes $\partial N/\partial\phi$ from changes in the injection function $\partial N/\partial t$. Since $dI/dt = (\partial N/\partial\phi) d\phi/dt + \partial N/\partial t$, the relative contribution of the two terms to the observed $dI/dt$ depends on the motion $d\phi/dt$ of the connection longitude. For a negative gradient in the solar wind velocity $V_w$, a solar wind "dwell", $d\phi/dt$ ist very small, so that $dI/dt \approx \partial N/\partial t$. For a positive gradient in $V_w$, $d\phi/dt$ is large, the second term can be neglected, and one may directly construct the coronal distribution $N(\phi)$. A more direct method for determining $N(\phi)$ is of course the use of multi-spacecraft observations (McCracken et al., 1971; Bukata et al, 1972), in particular if combined with actual solar wind measurements for determination of the connection longitude $\phi(t)$. Results of this method are summarized by Roelof (1974).

(e) It is clear that any attempt to determine the (coronal) injection profile I(t) or the related longitudinal distribution $N(\phi)$ has to start from observations in space, and, therefore, one first has to separate the effects of <u>interplanetary propagation</u>. Methods available to perform this separation are

(1) statistical studies in which the properties of solar particle events (maximum particle flux, times of onset and of maximum flux, shape of energy spectrum etc.) are ordered with respect to the longitude of the parent flare;

(2) multi-spacecraft observations. by which longitudinal and temporal changes can be separated;

(3) simultaneous intensity and anisotropy measurements, which allow to separate long-lasting solar injection processes from long-lasting interplanetary storage;

(4) the "mapping" of observed interplanetary particle fluxes to the high coronal source longitude, by using the simultaneously measured solar wind velocity.

We shall start with a summary of results obtained by method (1), since it makes use of the largest amount of observational data and gives insight into the average behaviour. Methods (2) to (4) can then be used to check predictions of models which have been developed and to provide additional insight into the relation with certain features observed on the solar surface.

## 3. Statistical studies of longitudinal effects

Let us first discuss how the total number of observed events varies with solar longitude. Figure 2 shows the longitudinal distribution of solar particle events for four different sets of observations. The dashed line is for non-relativistic electrons (after Lin, 1974), the dotted line for relativistic electrons (after Simnett, 1974a) plotted for longitudinal bins of 10° or 30°, respectively. The full line is the original curve of Van Hollebeke et al. (1975) for 20-80 MeV protons, and the hatched area indicates results for ground level neutron monitor data (GLEs), as taken from Pomerantz and Duggal (1974).

All four curves show the largest number of events observed when the parent flare is on the western hemisphere of the Sun, with a broad maximum somewhere between 30 and 90°W. The number of events clearly decreases as one goes to the Eastern hemissphere and beyond the West limb. Note that because of the difficulties of flare identification no electron data have been plotted beyond 90°W.

The overall similarity of the curves is rather surprising; only for the non-relativistic electrons the decrease in the number of events seems to start for a more westerly longitude. The similarity in the other three curves suggests a common propagation characteristics for the different particle species, which cover a range of Larmor radii of at least three orders of magnitude. Apart from the clear decrease of the distributions of Figure 2 east of about W30 solar longitude, the functional shape of the curves cannot be determined precisely. From a different set of data, Smart et al. (1975) have fitted a Gaussian distribution to the longitudinal distribution of 154 flares on the visible hemisphere of the Sun, which have produced proton events. They find the highest frequency of flares grouped between W30 and W40, and a standard deviation of the Gaussian of 55°. A Gaussian curve with these parameters supplies a rather good fit also to the three similar curves in Figure 2. From this fit, one can now extrapolate to the invisible hemisphere of the Sun, with the result, that roughly 20 % of all events should not be associated with a flare on the visible hemisphere of the Sun (for details see Smart et al., 1975). A similar result has been found by Van Hollebeke et al. (1975).

As we shall see below the decrease in the number of events is mainly determined by the escape rate of particles from the Sun, so that distributions of the type shown in Figure 2 can be used to determine the escape rate. We note then that the similarity in the distribution function for different particle species suggests escape rates which do not depend strongly on particle type and energy. Let us turn now to the variation of characteristic times of solar events with longitude. If the parent flare of a solar particle event is located on the Eastern hemisphere of the Sun, the arrival of energetic particles becomes more and more delayed with increasing solar longitude (Burlaga, 1967; Englade, 1971; Datlowe, 1971; Barouch et al., 1971; Simnett, 1972; McKibben, 1972; Lanzerotti, 1973; Reinhard and Wibberenz, 1974; Ma Sung et al., 1975).

As discussed above, azimuthal propagation of particles in the interplanetary medium cannot account for the observations. The first quantitative model for particle propagation in a surface layer around the Sun was developed by Reid (1964) and extended by Axford (1965). In Reid's model, the injection function can be written as

$$N(\chi, t) \sim \frac{1}{t \cdot \tau_L} \exp\left\{- \frac{\chi^2 \cdot r_c^2}{4 K_c t} - \frac{t}{\tau_L}\right\} \qquad (1)$$

Here $\tau_L$ is the loss time which describes the escape of particles into interplanetary space, $K_c$ is the coronal diffusion coefficient, and $r_c$ the distance of the diffusing layer from the center of the Sun. So $r_c^2/K_c = \tau_c$ is a characteristic time it takes the particles to diffuse by an angular distance of $\sqrt{2}$ rad = 81° from the flare origin. In what follows, we put the flare origin at $\chi$ = 0 and measure the angular distance $\chi$ from the flare to the root of a bundle of field lines leading out into space where an observer is located at longitude $\phi_R$ and latitude $\theta_R \approx 0$. Note that flares occur off the solar equator, say at longitude $\phi_F$ and latitude $\theta_F$, so that $\chi^2 = \theta_F^2 + (\phi_F - \phi_R)^2$. On the average $\theta_R \approx 20°$; in what follows, we shall disregard the dependence on solar latitude and put $\chi = \phi_F - \phi_R$. Observationally it is not possible to find systematic differences over a 20° angular interval.

Both $\tau_L$ and $\tau_c$ are assumed independent of $\chi$, but may vary with particle energy. Reid (1964) originally obtained an estimate of $\tau_c$ = 3.4 hours and $\tau_L \gtrsim 1.2$ hr. Applying Axford's (1965) version of the coronal diffusion model, Kirsch and Münch (1974) obtain values for the coronal diffusion coefficient of the same order of magnitude for the event of Nov 2, 1969. Lanzerotti (1973) used the Reid model to describe the variation of onset times for 0.6 to 25 MeV protons with longitude. He estimated 7 hr $\leq \tau_c \leq$ 16 hr. These values are probably underestimated because $\tau_c$ refers to the bulk of particles to diffuse and not to the "first" particles which define the event onset. It is remarkable that $\tau_c$ shows almost no energy dependence. This energy independence of the coronal transport times over large longitudinal distances is meanwhile firmly established (McKibben, 1972; Reinhard and Wibberenz, 1974; Ma Sung et al., 1975).

The most careful study so far in applying the Reid/Axford model to the East-West effect has been performed by Ng and Gleeson (1975). They have replaced the plane approximation by diffusion in a real spherical shell, and the coronal injection profile is then used as the boundary condition for interplanetary propagation, taking into account anisotropic diffusion along the spiral shaped imf, convection, adiabatic deceleration, and corotation of the flux tubes past the observer. With their two stage propagation model they reproduce many features of solar events. They have used in particular the results by McKibben (1972) on the variation of the time-to-maximum with longitude.

Their best estimates of the coronal parameters are $50 \leq \tau_c \leq 100$ hr and $10 \leq \tau_L \leq 15$ hr. For the interplanetary propagation they obtain a value of the (radial) mean free path, which corresponds to 0.03 AU for 10 MeV protons. This value is probably too small (see Wibberenz, 1974), since in many cases even for Western hemisphere events part of the delay is due to coronal, and not to interplanetary propagation (Reinhard and Wibberenz, 1974). But for the discussion of the East-West effect this difference is not critical.

In Figure 3 we compare the computations of Ng and Gleeson (1975) with $t_m$-values for $>10$ MeV protons (Reinhard and Wibberenz, 1974). For both curves (a) and (c) there is a well defined minimum close to W60, and a systematic increase on both sides of this ideal connection longitude. The apparent linear relation between $t_m$ and $\chi$ results from the escape term, which largely influences the coronal injection profile (1) for $t \gtrsim \tau_L$. The minimum value of $t_m$ is related to the interplanetary propagation and could be shifted downward by a factor of 2 or more, without changing the general conclusions. We can see now the limitations of the (modified) Reid model. For curve (a), a small value for the coronal diffusion time has been taken, $\tau_c \approx 13$ hours. This gives the desired flat longitudinal dependence for western events, but does not explain the large values of $t_m$ for eastern events. In model (c), the larger value for the coronal diffusion time, $\tau_c = 100$ hr, gives the larger increase of $t_m$ on the eastern hemisphere, but this increase now starts right away at W60 and is in strong disagreement with the bulk of data between 0 and W90.

It had already been pointed out by Reinhard and Wibberenz (1974) that observational evidence speaks against a well defined minimum in the propagation times somewhere between W40 and W60, and that very fast propagation with small or negligible coronal propagation times can be found for events where the parent flares are located between about 0 and W100. The horizontal lines in Figure 3 are meant to indicate the existence of a fast propagation region" (FPR) where minimal propagation times can be found. The extent of this FPR may vary from one event to the other. The existence of a very efficient solar propagation for certain longitude ranges had also been pointed out by Fan et al. (1968). The "open cone of propagation" for >40 keV electrons found by Anderson and Lin (1966) and Lin (1970), which also has an extent of about $100^{o}$, may be identical with the FPR. A "region of preferred connection longitudes" ranging from about W20 to W80 is defined by the work of Van Hollebeke et al. (1975). It may indeed be more appropriate to talk about a preferred connection to the acceleration region than about a fast propagation from it. We shall return to this point in section 5.

Let us return to the slow coronal propagation outside the FPR. One will obviously get a better fit to the data (see Figure 3) if e.g. curve (c) describing the coronal propagation does not start around W60, but with the same slope on both sides of the FPR. Clues to the possible nature of this slow coronal propagation may be found by a study of the dependence of $t_m$ on particle parameters. Reinhard and Wibberenz (1974) have studies time histories for 56 events in the energy range 10-60 MeV and found that the most probable travel distance $vt_m$ is a linear relation of velocity, or with other words, $t_m$ can be written as $t_m = c_1 + c_2/v$. The velocity dependent term in $t_m$ is found to be independent of solar longitude and describes interplanetary propagation. On the average, $c_2 \approx 4.5$ AU (with variations between about 2 and 10 AU). On the other hand, $c_1$ increases steadily with solar longitude East of central meridian and is independent of proton energy.

These results have been confirmed by Ma Sung et al. (1975) and extended to higher velocities (near-relativistic electrons) and to the inclusion of the event onset times $t_{on}$. They show that for the onset times a similar relation holds, namely $t_{on} = B_{on} + A_{on}/v$, with two additional constants $A_{on}$ and $B_{on}$, which have to be determined for each event in additional to $c_1$ ($\equiv B_{max}$) and $c_2$ ($\equiv A_{max}$). $A_{on}$ and $A_{max}$ do not vary systematically with solar longitude, so that they can be taken to describe interplanetary propagation. The numerical values ($\langle A_{on}\rangle$ = 2 AU, $\langle A_{max}\rangle$ = 4 AU) confirm that interplanetary propagation plays a relatively minor role up to the time of maximum particle intensity at 1 AU. $B_{on}$ and $B_{max} = c_1$ describe the onset time and the time of maximum of the solar injection profile, respectively. Both parameters are relative small on the Western hemisphere (of the order of 1 hour if averaged over many events), but increase systematically with increasing longitude on the Eastern hemisphere. Both parameters are independent of energy and/or velocity of the studied particles (0.5 to 1.1 MeV electrons, 4-80 MeV protons).

The energy independence of the coronal transport puts severe limits on the possible physical mechanisms. Any particle motion in a given static magnetic field configuration gives transport times with $(\text{velocity})^{-1}$ as one factor. This excludes e.g. gradient or curvature drift as one basic mechanism as well as the current sheet diffusion (Fisk and Schatten, 1972), since a diffusion mean free path $\lambda$ which varies inversely with velocity (to give $K \sim v\lambda$ = const) independent of the particle type is physically unrealistic. Ma Sung et al. (1975) propose a "leaky box model" with a diffusion coefficient $k_L \sim (\Delta L)^2/\Delta\tau$, where $\Delta L$ is the scale size of the boxes which open randomly on a time scale $\Delta\tau$. The leaky boxes could be idealized models of large coronal magnetic field loops, and the process of field line reconnection provides the random opening of the boxes. In this model, the direction and speed of transport processes is not governed by the particle parameters (like velocity or rigidity), but by fundamental properties of solar magnetic fields; it is the randomness of the reconnection process which would be responsible for a diffusion-like behaviour, whereas the particle motion is deterministic. Note that this concept might also lead to non-diffusive processes, if there is only a small number of boxes or channels along which the particles propagate. A more deterministic process, namely an energy-independent drift, which should act in addition to coronal diffusion, has been proposed by Reinhard and Wibberenz (1974). One of the original supports for this idea, namely the linear relationship between $t_M$ and $\chi$, can no longer be maintained, since because of the escape processes a quasi-linear relation can also be simulated in a diffusion model (Ng and Gleeson, 1975). However, the total injection time profile depends critically on the nature of the processes. Reinhard and Roelof (1975) have studied the relation between onset times and maximum times and confirmed the necessity to include solar drift processes. Their (linear) drift-diffusion model contains a drift rate $\tau_E$, a diffusion time $\tau_c = r_c^2/K_c$, and a loss time $\tau_L$. When the corresponding injection profile is convoluted with interplanetary diffusion processes, one gets a good description of the measured time profiles of 10-60 MeV protons. The parameters of the solar injection profile and the interplanetary scattering mean free path are independent of proton energy. From a fit to several Eastern events, Reinhard and Roelof (1975) determine average values for the coronal parameters as $\tau_E$ = 0.42 hr/grad, $\tau_c$ = 400 hr, $\tau_L$ = 13 hr.

This choice of $\tau_c$ takes care of the observed widening of the time profiles with increasing solar longitude, whereas it is essentially the drift which determines the increase of the absolute time delay with solar longitude. The corresponding dependence $t_m(\phi)$ for the drift-diffusion model is indicated by the dashed line in Figure 3. Here an extension of the FPR of $\pm$ 40° has been assumed, centered around W50 longitude, so the increase sets in East of W10 and West of W90°. The average contribution of the interplanetary propagation corresponds to a time delay of 4.4 hr for 10 MeV protons.

The loss time of 13 hours is within the range assumed to be realistic by Ng and Gleeson (1975). Let us see how the loss time $\tau_L$ can be determined observationally.

There are in general two processes by which for a given point on the solar surface the intensity is diminished, (1) the lateral spread of particles causes a corresponding decrease in surface density, (2) the injection into the interplanetary medium causes a general loss proportional to the number of particles present. These two points also determine the maximum intensity $N_{max}$ in the injection function. If we take the Reid/Axford model seriously, see equ. (1), we can derive the following predictions:

(a) For small distances $\emptyset$ the propagation times are small to that the escape term $\exp(-t/\tau_L)$ has no influence on the time of the intensity maximum $c_m$ of the coronal injection function. In this case $c_m = (r^2/4\kappa_c)\cdot\chi^2$ and we get from equ.(1)

$$N_{max}(\chi) = N(\chi, c_m) \sim \chi^{-2} \quad (2)$$

(independent of the coronal parameters). Thus, a strong dependence of $N_{max}$ in the coronal injection profile on angular distance from the flare is predicted by the Reid/Axford model. Its verification by observations in space is limited, (a) by the convolution with interplanetary propagation, (b) by the fact that most flares occur remote from the solar equator (see above, $\Theta_F \approx 20^o$).

In addition, the existence of the FPR will initially fill up an extended area close to the flare site, which will preclude the sharp dependence of $N_{max}$ on $\chi$ as suggested by (2). In any case, the relatively flat distribution of the number of events with longitude on the western hemisphere (see Figure 2) favors a model with a moderate variation of $N_{max}$ over small distances from the flare.

(b) For large distances $\chi$ , it is mainly the exponential term $\exp(-t/\tau_L)$ in equ. (1) which determines the decrease of $N_{max}$. (It should be noted that in the more realistic version of the Reid model treated by Ng and Gleeson (1975), at late times this is the only term in the temporal variation, because the whole solar surface is covered with particles, there is no 1/t-factor left).

Let us describe the average decrease of the number of particles at the maximum of the injection function with $P(\emptyset)$. $P(\emptyset)$ is allowed to vary with energy, but shall be the same for every event. Here we measure $\emptyset$ along the solar equator and let $P(\emptyset)$ be normalized to 1 for events close to $\emptyset \approx 0^o$. It is this variation

$$N_{max}(\emptyset) = N_{max}(0)\ P(\emptyset) \quad (3)$$

which determines how the number of events detected varies with solar longitude (Reinhard and Roelof, 1975). For normally an "event" is identified when the number of particles during the maximum phase exceeds a certain threshold, which is determined by detector background and counting rate statistics. Let the size distribution (the number W of events where the maximum intensity of particles exceeds a given value $N_{max}$) be a separable function of $N_{max}$ and longitude, i.e. the longitudinal distribution is independent of the size of the event,

$$W(N_{max}, \phi) = f(N_{max})\, g(\phi) \tag{4}$$

With $N_{max}$ = T = threshold for detection of the event type under study we get $W(T,0)$ = total number of events above threshold close to the preferred connection longitude around W40...W60, and $W(T,\phi) = f(T)g(\phi)$ is the longitudinal flare distribution (see Figure 2).

On the other hand, we have from equ. (3) $W(T,\phi) = W\left[T/P(\phi),\, 0\right]$. Equating the two expressions for W, we finally obtain

$$f\left(\frac{T}{P(\phi)}\right) = f(T)g(\phi) \tag{5}$$

Relation (4) has been verified by Reinhard and Roelof (1975) for protons >10 MeV, >30 MeV, and >60 MeV, and they showed that $f(N_{max})$ can be described by a power law $(N_{max})^{-\mu}$ with $\mu = 0.36$. Inserting this into (5) they get $g(\phi) = \left[P(\phi)\right]^{0.36}$ as relation between the longitudinal distribution g and the size variation P. Note that this relation implies that $g(\phi)$ is rather insensitive to the size variation $P(\phi)$. This is even more so, if we take an independent determination of the size spectrum from Van Hollebeke et al. (1[illegible]); they obtain for the differential size spectrum $dW/dN_{max} \sim N_{max}^{-\alpha}$ with $\alpha = 1.15 \pm .05$, which implies that the integral spectrum W is rather flat and $\mu \approx 0.15$ instead of 0.36 as above.

The longitudinal distribution has been determined by Reinhard and Roelof (1975) as $g(\phi) = \exp(m\phi)$ with $m = -0.01\ (\text{degree})^{-1}$. Insertion into the drift-diffusion model with the average parameters cited above leads to a loss time $\tau_L = 13$ hours, independent of energy. In contrast, Van Hollebeke et al. (1975) have concluded from a variation of the observed spectral shapes of proton spectra with longitude, that the escape rate should be energy dependent. They find an average loss time of $\tau_L = 1.85$ hours for protons with a mean energy of 40 MeV, and an increase in the loss rate of 35-45% from 20 MeV to 80 MeV. The smaller loss time for the higher energies would then be responsible for the observed steepening of the spectrum with longitude.

Reinhard and Roelof (1975) do not find a systematic variation of the spectral slope with longitude. The reason for the discrepancy is not clear, it should be partly related to the use of a different set of data (difference in the threshold T for event detection; different selection criteria for "solar events"). In any case, it appears that a loss time of about 2 hours is too small to be compatible with observations; the corresponding decrease in the injection function by a factor of 10 every 4.5 hours would make events from the Eastern hemisphere of the Sun praktically undetectable. Because of the intensitivity of the size distribution on $\tau_L$ (see the discussion following equ. (5) above) more direct determinations will be necessary (see section 4 for some indications).

Let us close this section on the variations of solar event parameters with solar longitude. We have discussed the delay times (onset and time-to-maximum), the general shape of the intensity-time profiles, and the distribution of the number of events with longitude. We have tried to relate the average behaviour of a large number of events to specific coronal propagation models. Let us summarize the essential aspects of the various models, in particular with respect to predictions of latitudinal solar variations.

(1) Propagation over small angular distances; existence of a fast propagation region?

In the Reid/Axford-model there is just one fundamental process acting thoughout the solar surface, characterized by a diffusion coefficient $k_c$. We had pointed out the difficulty to describe simultaneously, with a unique value for $\kappa_c$, the increase of $t_m$ on the Eastern disk and the small values of $t_m$ over the Western disk (see Figure 3). In principle, this difficulty might be overcome by assuming a large variability of $\kappa_c$ and by ascribing the small $t_m$-values to occasional large values of $\kappa_c$. Tests of the Reid model from measurements in the ecliptic plane are partly restricted because one never scans $\chi \approx 0$. A spacecraft measuring solar equatorial latitudes in the range 20-30$^\circ$ should see the strong dependence with distances from the solar flare predicted by the variation of $N_{max}$ (see equ. (2)) or a well defined second maximum related with the corotation for events East of the connection longitude (see Ng and Gleeson, 1975).

On the other hand, small latitudinal variations would be expected if the FPR (fast propagation region) exists. Reinhard and Wibberenz (1974) have suggested that the extent of the FPR is related to solar sector boundaries which have already been found to play an important role in determining the efficiency of coronal propagation (Roelof and Krimigis, 1973). The azimuthal distribution of the number of particles shows discontinuities at certain solar sector boundaries, so that is has become possible to assign "access probabilities" to individual unipolar solar cells (Gold and Roelof, 1974; Roelof, 1974). Studies on spacecraft off the ecliptic plane and the technique of mapping intensities back to the high solar corona (see Roelof, 1974) should allow to observe the very existence of the FPR, its latitudinal extent and the influence of the polewards sides of the unipolar solar cells.

(2) Propagation over large distances; dimensionality of transport?

A very schematic distinction between various models can be seen in Figure 4, where the broad time development over the solar surface is plotted for the pure diffusion model (left) and the drift-diffusion model (right). For simplicity, we neglect the influence of the loss term and merely indicate how a characteristic angular extent $\phi$ and the average particle density within $\phi$ are expected to vary with time.

C-4

The essential point in the "drift" process is that the transport process in the corona is not totally statistical (like in a diffusion process, where the net streaming of particles is simply proportional to the density gradient), but that there is a preferential bulk motion of particles into one direction superimposed. The filling up of one large "box" which was initially empty might be one such process (see the above discussion about the "leaky box concept"). A pure drift, where all particles move into the same direction, is depicted schematically in the outer right part of Figure 4. An $\underline{E} \times \underline{B}$-drift of the required order of magnitude (corresponding to velocities of 7 km/sec if $r_c$ = 1 solar radius) is not very likely. However, a very direct proof would be the systematic depletion of particles from the region close to the original flare (see Fig. 4, right part). The shift of time intensity profiles between spaceprobes separated in heliocentric longitude has been shown to be consistent with normal corotation for four individual solar events in 1968 (McKibben, 1973) and does not require an additional drift. Moreover, the azimuthal gradients are in general positive when one approaches the heliocentric longitude of the flare (see McCracken and Rao, 1970; McCracken et al., 1971).

So one should still regard the drift-diffusion model as hypothetical and a convenient mathematical description to describe coronal injection profiles at one longitude. The consequence of a depletion around $\phi \approx 0$ at late times has still to be confirmed.

Let us turn now to the question of dimensionality of transport. The distinction is shown in the two left schemes in Figure 2. The question is still open whether the coronal propagation is related to a fundamental solar process which acts similarly all over the solar surface, of if it is related to specific processes which are typical for the activity belts say. If the propagation is somehow related to large scale magnetic field loops, one should expect a preferential propagation along the East-West direction because of the preferential orientation of the loops in this way. This would favor a one-dimensional propagation in a limited latitudinal range (see second sketch from the left in Fugure 4). In this case, observations beyond about 40 or $50^{o}$ in latitude would hardly show an detectable amount of solar energetic particles, and the large coronal holes found sometimes at the solar poles would be totally free of solar flare particles.

On the other hand, coronal propagation might be related to a process which is occurring all over the Sun, similar to the supergranulation, or to the numerous current sheets and minute dipoles with average strength of 500 - 1000 Gauß and 12 hour lifetimes (see Newkirk, 1975, for discussion). In such a universal process, we should more expect a distribution sketched in the outer left part of Figure 4. It is clear that studies of particle populations at large heliocentric latitudes offer a unique opportunity to distinguish between the two fundamentally different possibilities.

## 4. Detailed studies of individual events

It is not intended to give a detailed account of the numerous studies of longitudinal effects for single events or for selected periods of time. We simply want to describe various methods and to describe a few results which give the necessary and important supplements to the statistical studies discussed so far.

McCracken et al. (1971) have studied data from four Pioneer spacecraft separated by $\approx 180^{\circ}$ in heliocentric longitude. At late times ($\gtrsim$ 4 days) in the events they still found strong gradients in longitude, with e-folding angles for 10 MeV protons of the order $\eta = 30^{\circ}$, and no temporal change in the relative gradient. This corresponds to a factor of 10 decrease every $70^{\circ}$. Note that this value of $\eta$ has only been directly determined for two events. Van Hollebeke et al. (1975) from the study of a much larger number of events conclude that on the average the event size for protons around 40 MeV decreases by about two orders of magnitude every $60^{\circ}$ away from the preferred connection region. This value is also consistent with an exponential gradient in longitude corresponding to a change of two orders of magnitude over a longitudinal distance of $40^{\circ}...60^{\circ}$ (Roelof et al., 1975) for MeV protons and alpha particles. A comparison of these gradients with specific coronal propagation models has not yet been performed.

Persistent anisotropies along the imf from the general solar direction have been among the first indicators that the solar source has to be described by a long-lasting injection instead of a delta-function in time (Bartley et al., 1966; Fan et al., 1968; Krimigis et al., 1971). The interpretation of these persistent large anisotropies depends on whether or not interplanetary propagation can be neglected. Schulze et al. (1974) gave an example where the simultaneous fit of intensity and anisotropy data for 22-60 MeV protons during the Nov 18, 1968, event allows to determine the approximate duration of the solar injection as well as the interplanetary mean free path. As pointed out later (Schulze et al., 1975) the interplanetary data are relatively insensitive to the form of the solar injection profile. A change in the form (not the characteristic duration) of the solar injection profile can be canceled by a suitable change in the interplanetary scattering mean free path without changing essentially the intensities or anisotropies.

The situation is different when interplanetary scattering within the inner solar system can be neglected. For the scatter-free proton event of April 20, 1971, Palmer et al.(1975) could directly determine the solar injection profile and obtained a solar decay time of about 7 hours for 7.6-55 MeV protons. Roelof and Krimigis (1973) have pointed out that for low energy protons ($\lesssim$1 MeV) scattering in the inner solar system is almost absent. Here the magnitude and the direction of the anisotropies are used to infer the small interplanetary scattering, and by use of the "mapping" technique conclusions can be drawn on the coronal injection profiles. Various time periods have been studies in a series of papers (Roelof, 1973; 1974; Gold et al., 1974; Krieger et al., 1975). Typical coronal profiles are ramp-like structures, which are relatively smooth as long as the observer is connected to the same unipolar cell on the Sun, and sharp changes in intensity when a neutral field line on the Sun is crossed. These results are seen with corresponding time delays at spacecraft widely different in heliocentric longitude, (Roelof and Krimigis, 1973) which confirms the spatial rather then the temporal structure of the profiles.

The ordering of solar energetic particle data by solar structures observable in $H_\alpha$-filtergrams becomes also clear in the large solar events of August 1972, where Roelof et al. (1974) have studied flux histories for protons $>$13.5 MeV from Pioneers 9 and 10 and IMP 5. The different access of particles to regions on both sides of a solar sector boundary is clearly established. The crossings of solar sector boundaries are therefore in many cases seen by abrupt changes in the intensities of solar energetic particles, but they can also lead to marked changes in the riese or decay times of the total profile (see Reinhard, 1975b). It is very remarkable that the solar sector boundaries, which are inferred from the $H_{\alpha}$-filtergrams (McIntosh, 1972) and which are found to play such an important role for the access probabilities of solar energetic particles, do not in each case coincide with <u>interplanetary</u> sector boundaries. A possible explanation by chromospheric neutral lines which are not continued into an interplanetary magnetic field sector boundary, has been given by Roelof (1974).

The irregularities which are related with the solar cells of different polarity certainly have to be superimposed on the overall dependence on solar longitude which we discussed in section 3. Formally this could be described by a variation of the coronal parameters with solar longitude. This scheme might offer an explanation for the observations of "anomalous" injection profiles of solar particles. Keath et al. (1971) have shown that the favored path for cosmic ray propagation in the March 12, 1969 event was about $40^{0}$ east of the nominal Archimedes spiral line of force from the flare location. Palmer and Smerd (1972) also found a deviation from the "classical" picture, where the best connection into space should be close to the flare site. They explain the appearance of a prompt low energy proton component far away from the original flare by the triggering action of a shock wave travelling in the solar atmosphere. Cherki et al. (1974) find by analyzing the March 29, 1970 event that particles of different rigidity are ejected at different longitudes on the Sun. Barouch et al. (1971) studied the onset times of 6-25 MeV protons for several flares from the same active region, and conclude that the magnetic fields close to the active region should be considerably distorted from the nominal Archimedean field.

These examples show that for individual events the release mechanism from the Sun may become very complicated, and that the models and coronal parameters discussed in section 3 only describe the average characteristics over many events.

In all cases, however, the unusual particle escape from the Sun is thought to be related to processes occuring in the vicinity of the Sun, in particular in the coronal magnetic fields. As discussed already in section 3, large coronal mf loops probably play a prominent role. Over which longitudinal range and how far up into the corona these loops extend is not yet clear. Simnett (1974b) in case of the August 11, 1970 event has suggested the existence of a stable loop extending several solar radii above the solar surface and about 100° in longitude. Two release points should exist for solar protons on both sides of this loop, with quasi-stable trapping inside the loop.
Observations from Skylab have cast some doubt on the existence of stable loops of this extent. Chase et al. (1975) have studied one hundred loops detectable in soft X-rays and show that the number of interconnections decreases steeply for longer distances; the longest interconnecting loop extends over an angular distance of 37°.

The question how far the loops extend and which portion of the solar surface is covered with "closed" or "open" configurations is crucial for the whole propagation problem. The energetic particles perform gyrations about the field lines, and the transport of particles from one field line to the neighbouring one does not depend on whether the field lines are closed (i.e. return to the solar atmosphere) or open (i.e. lead out into interplanetary space). However, the number of closed field lines determines the amount of trapping, and once particles have been transmitted to open field lines they will escape into space. This means that an efficient storage mechanism, and a transport which finally allows to fill practically the whole solar atmosphere (see McCracken et al., 1971; McKibben, 1972) ought to be only possible if a large fraction of the solar surface is "closed". This is confirmed by observational evidence; there should be a relative amount of open field lines of the order 10-15 % in equatorial regions, 25-40 % averaged over the whole Sun (Newkirk, private communication). These figures are based on the potential (current-free) coronal field calculated from the observed-line-of-sight fields at the photospheric level (Altschuler and Newkirk, 1969) and may have to be modified by the influence of the expanding solar wind.

Newkirk (1973) concludes that the ambient field configuration around active regions also determines whether or not protons escape from a given flare. It is found that among all flares proton flares have significantly more open field lines emerging from the vicinity of the active region. Newkirk assumes an "injection surface" of $36^{o}$ x $36^{o}$ centered on the flare and finds that the spread in longitude of open field lines is characterized by a full-width-at-50 percent of $10^{o}$ to $20^{o}$ which is insufficient to explain the observed longitudinal distribution of energetic particle events. One possible explanation for the discrepancy is that perhaps the original injection surface must be larger. This would occur if shocks are the principal sources of energetic protons in the corona. We shall discuss this point in somewhat more detail in the next section.

## 5. Relation to the acceleration process in solar flares.

Let us first summarize some of the properties of coronal propagation along the ideas of Simnett (1974) or McKibben (1973). There is a "prompt component" or "phase 1" of solar particle events. This is due to particles which either have been directly accelerated on open field lines or have been injected onto open field lines shortly after the flare. The longitudinal extent where these prompt particles are found should correspond to the "fast propagation region" discussed above. These initially injected particles give rise to a relatively short decay time (McKibben, 1973).
There is a "delayed component" or "phase 2" of solar particle events. It is very probable that these delayed particles have been accelerated on closed field lines. They then propagate in the corona, from one closed configuration to the next, maybe according to the concept of the leaky boxes discussed above, and from thereon there is only a gradual release of these particles into space. If this release were instead very fast and efficient, we would never observe that flare particles have finally occupied essentially the whole inner solar system!

There are two different solar decay times for the two types of particle populations. Wibberenz and Reinhard (1975) and Reinhard (1975a) show that by convoluting the solar decay processes with interplanetary propagation one can quite naturally explain the exponential or quasi-exponential nature of the interplanetary decay, and that no "free escape boundary" around 2...3 AU is required, which would be difficult to be reconciled anyhow with the Pioneer 10 and 11 observations.

We turn now to the phase-1 particles within the FPR. It has been shown that the injection profiles for these particles are not of the delta-function type in time, but finite in width (Palmer et al., 1975; Reinhard, 1975a). It is certainly difficult to distinguish whether these finite injection profiles stem from continuous release or continuous acceleration of particles. But if the decay in phase 1 is much steeper than in phase 2 (McKibben, 1973), then the particles cannot be replenished by the neighbouring storage region through the same process as the phase-2 particles. There might be a small storage region close to the flare with a different release mechanism for the phase-1 particles (this mechanism might exist because of the high degree of disturbance in the solar atmosphere following the flare). Or we have to assume that the injection profile directly gives the number of particles as they are accelerated.

The second possibility is very interesting with respect to the two-stage acceleration process, which is discussed in detail e.g. by Lin (1974). In the first phase non-relativistic electrons are accelerated. If a sufficiently large number of electrons is damped into the chromosphere and lower corona, explosive heating occurs and produces an ejection of material and a shock wave which accelerates electrons and protons to relavistic energies. This picture is confirmed by Svestka and Fritzová-Svestková (1974). They present convincing evidence that proton acceleration to higher energies ($\gtrsim$ 10 MeV) is closely connected with type II bursts, i.e. shock waves travelling in the solar atmosphere. Our above interpretation that the finite injection profiles might resemble the finite duration of the acceleration process itself would favor the shock acceleration model for protons, and it also explains, why protons may be found on a wide longitudinal range of open field lines.

The small longitudinal variation of the slopes of the proton energy spectrum discussed in section 3 implies that the particles of phase 1 and phase 2 have the same energy spectrum, which means that the acceleration process should work in the same manner on open as well as on closed field lines. In addition, any model of the acceleration proces should explain why the spectral slopes for high energy protons and relativistic electrons are roughly the same, $\gamma \approx 3$ (see Van.Hollebeke et al., 1975). It would also be interesting to see if the energy dependence of the decay times.as suggested by Reinhard (1975a) can be reproduced by a shock model acceleration.

We close with a remark which emphazises the role which the fast propagation region may play for the study of solar acceleration processes. The $He^3$-rich events which are a novel feature of solar cosmic rays (Serlemitsos and Balasubrahmanyan, 1975) appear to be observed only for sufficiently small events and are only found when the parent flare is on the Western hemisphere (McDonald, private communication). This might indicate a specific configuration near the Sun, where the acceleration process supplies $He^3$ nuclei only directly to open field lines.

## 6. Conclusions.

There are two important features of the interplanetary propagation which allow us to study coronal transport phenomena: (1) the motion of energetic particles perpendicular to the imf is small, (2) the scattering mean free path along the imf is large, so that details of the solar injection profiles can be regained from measurements in space.

We have tried to order the material by models for acceleration, injection, and propagation processes. None of these models has been proven to give the real physical picture, because the underlying processes could not yet be identified. In this brief summary we shall concentrate on those open points which could be further clarified by spacecraft measurements performed out of the ecliptic plane.

(1) What is the nature of the "fast propagation region" (probably identical with the "open cone of propagation" or the "region of preferred connection longitudes")? Is there also a region of preferred connection latitudes? If the latitudinal extent is limited, what is the nature of the boundary?

(2) If there is a transport process involved within the fast propagation region, what is the nature of this process? Could it be a diffusive process with a sufficiently large diffusion coefficient? In this case one should be able to see the relatively strong dependence of the maximum intensity on angular distance Ø for small Ø as discussed in section 3, because the connection point of an ex-ecliptic spacecraft comes closer to the active regions.

(3) Is the acceleration process directly responsible for the longitudinal width of the FPR and for the fast access of particles to open field lines? If particles are accelerated on open field lines by a travelling shock and may then escape into space, the extent of this "prompt" region should be determined by the distance which the shock can travel in longitude and latitude. Will we see particles arrive very fast over the poles?

(4) Which role do the solar sector boundaries play? Is there a similar change in the access probabilities if one leaves a unipolar cell on the northern or the southern boundary? If there is one large unipolar cell (e.g. a coronal hole) extending from the pole to the equator, is there the same access probability all over this cell, or is there a gradual or drastic change with latitude? Would one detect $He^3$-rich events over the poles?

(5) What is the nature of the energy-independent slow coronal propagation over large distances in longitude? Is there a drift process (possibly related to electric fields) involved? Are the time delays and the intensity decreases merely a function of the absolute angular distance between flare and observer, or are the variations typically different into the East-West and into the North-South direction? If the large scale mf loops in the corona play an important role for the propagation, one would expect such systematic differences, and then the preferred direction of the propagation and the latitudinal

extent up to which particles are transported may vary with the solar cycle, because of the difference in the average orientation and location of the loops. If the interpretation in section 3 on the importance of magnetic reconnection processes is correct, the study of large scale coronal particle transport should give insight into a fundamental solar problem.

**Acknowledgements:**

I wish to acknowledge stimulating discussions with R. Reinhard, C.-G. Ng, M.A.I. Van Hollebeke, G. Newkirk, Jr., G. Simnett, and D. Smart. I also thank R. Reinhard, M.A.I. Van Hollebeke, and C.-G. Ng that I could make use of their results before publication.

References:

Altschuler, M.D. and G. Newkirk, Jr., Magnetic fields and the structure of the solar corona, Solar Phys. 9, 131, 1969

Axford, W.I., Anisotropic diffusion of solar cosmic rays, Planet. Space Sci., 13, 1301, 1965

Barouch, E., M. Gros, P. Masse, The solar longitude dependence of proton event delay time, Solar Phys., 19, 483-493, 1971

Bartley, W.C., R.P. Bukata, K.G. McCracken, U.R. Rao, Anisotropic cosmic radiation fluxes of solar origin, J.Geophys. Res., 71, 3297-3304, 1966

Bukata, R.P., U.R. Rao, K.G. McCracken, and E.P. Keath, Observation of solar particle fluxes over extended solar longitudes, Solar Phys., 26, 229, 1972

Burlaga, L.F., Anisotropic diffusion of solar cosmic rays, J. Geophys. Res., 72, 4449, 1967

Chase, R.C., A.S. Krieger, Z. Svestka, and G.S. Vaiana, Skylab observations of X-ray loops connecting separate active regions, Space Res., XVI (COSPAR-Meeting, Varna 1975), to be published, 1975

Cherki, G., J.P. Mercier, A. Raviart, L. Treguer, D. Maccagni, F. Perotti, and G. Villa, Effect of solar corona condition on flare particle propagation, Solar Phys., 34, 223 , 1974

Datlowe, D., Relativistic electrons in solar particle events, Solar Phys., 17, 436 , 1971

Elliot, H., Particle diffusion in the solar corona, in Dyer (ed.), Solar Terrestrial Physics, Part I, 1, 134 , 1970

Englade, R.C., A computational model for solar flare particle propagation, J. Geophys. Res., 76, 768 , 1971

Fan, C.Y., M. Pick, R. Pyle, J.A. Simpson, and D.R. Smith, Protons associated with centers of solar acticity and their propagation in interplanetary magnetic field regions corotating with the sun, J. Geophys. Res., 73, 1555 , 1968

Fisk, L.A., and K.H. Schatten, Transport of cosmic rays in the solar corona, Solar Phys., 23, 204, 1972

Gold, R.E., and E.C. Roelof, A prediction technique for low energy solar proton fluxes near 1 AU, Space Res. XVI (Cospar-Meeting Varna 1975), to be published, 1975

Keath, E.P., R.P. Bukata, K.G. McCracken, and U.R. Rao, The anomalous distribution in heliocentric longitude of solar injected cosmic radiation, Solar Phys., 18, 503, 1971

Lanzerotti, L.J., Coronal propagation of low energy solar protons, J. Geophys. Res., 78, 3942, 1973

Kirsch, E. and J.W. Münch, Intensities and anisotropies of low energy solar protons measured aboard the satellites AZUR, Explorer 35 and 41, November 1969- April 1970., Solar Phys., 39, 459, 1974

Krieger, A.S., J.T. Nolte, J.D. Sullivan, A.J. Lazarus, P.S. McIntosh, R.E. Gold, and E.C. Roelof, Relation of large-scale coronal X-ray structure and cosmic rays: 1. Sources of solar wind streams as defined by X-ray emission and $H_\alpha$ absorption features, Proc. 14th Intern. Cosmic Ray Conf., Paper SP 4-4, München 1975

Krimigis, S.M., E.C. Roelof, T.P. Armstrong, and J.A. Van Allen, Low energy (>0.3 MeV) solar particle observations at widely separated points (>0.1 AU) during 1967, J. Geophys. Res., 76, 5921, 1971

Lin, R.P., Observations of scatter-free propagation of ~40 keV solar electrons in the interplanetary medium, J. Geophys. Res., 75, 2583 , 1970

Lin. R.P., Non-relativistic Solar electrons, Space Sci. Revs., 16, 189 , 1974

Ma Sung, L.S., M.A.I. Van Hollebeke, and F.B. McDonald, Propagation characteristics of solar flare particles, preprint 1975

McCracken, K.G., and U.R. Rao, Solar cosmic ray phenomena, Space Sci. Revs., 11, 155 , 1970

McCracken, K.G., U.R. Rao, R.P. Bukata, and E.P. Keath, The decay phase of solar flare events, Solar Phys., 18, 100 , 1971

McIntosh, P.S., Solar magnetic fields derived from hydrogen alpha filtergrams, Revs. Geophys. Space Phys., 10, 837, 1972

McKibben, R.B., Azimuthal propagation of low energy solar-flare protons as observed from spacecraft very widely separated in solar azimuth, J. Geophys.Res., 77, 3957, 1972

McKibben, R.B., Azimuthal propagation of low-energy solar flare protons: Interpretation of observations, J. Geophys. Res., 78, 7184 , 1973

Newkirk, G.,Jr., Coronal magnetic fields and energetic particles, in High Energy Phenomena on the Sun, Symposium Proceedings, GSFC X-693-73-193, p. 453 , 1973

Newkirk, G. Jr., Solar activity, coronal observations, and composition, Proc. 14th Intern. Cosmic Ray Conf., Invited Paper, München 1975

Ng, C.-G., and L.J. Gleeson, A complete model of the propagation of solar-flare cosmic rays, preprint 1975

Nolte, J.T. and E.C. Roelof, Large-scale structure of the interplanetary medium. I: High coronal source longitude of the quiet-time solar wind, Solar Phys., 33, 241 , 1973

Palmer, I.D. and S.F. Smerd, Evidence for a two-component injection of cosmic rays from the solar flare of 1969, March 30, Solar Phys., 26, 460, 1972

Palmer, I.D., R.A.R. Palmeira, and F.R. Allum, Monte Carlo Model of the highly anisotropic solar proton event of 20 April 1971, Solar Phys., 40, 449 , 1975

Pomerantz, M.A., and S.P. Duggal,
The Sun and cosmic rays,
Revs. Geophys. Space Phys. 12, 343, 1974

Reid, G.C., A diffusive model for the initial phase of a solar proton event, J. Geophys. Res., 69, 2659, 1964

Reinhard, R., and G. Wibberenz, Propagation of flare protons in the solar atmosphere, Solar Phys., 36, 473 , 1974

Reinhard, R., and E.C. Roelof, Drift and diffusion of solar flare protons in the corona, Preprint, 1975

Reinhard, R., The exponential decay of solar flare particles. II. Western hemisphere events. Proc. 14th Intern. Cosmic Ray Conf. Paper SP 4-1, München, 1975a

Reinhard, R., Die solare Ausbreitung flareerzeugter Protonen im Energiebereich 10 - 60 MeV, Dissertation, Kiel, 1975b

Roelof, E.C., Coronal magnetic fields and the structure of low-energy solar charged particle events, In: Symposium on High Energy Phenomena on the Sun, NASA Publ. X-693-73-193, pp. 486, 1973

Roelof, E.C., Coronal structure and the solar wind, In C.T. Russell (Ed.), "Solar Wind Three", Proc. Asilomar Conf., Los Angeles 1974

Roelof, E.C., and S.M. Krimigis, Analysis and synthesis of coronal and interplanetary energetic particle, plasma, and magnetic field observations over three solar rotations, J. Geophys. Res., 78, 5375 , 1973

Roelof, E.C., J.A. Lezniak, W.R. Webber, F.B. McDonald, B.J. Teegarden, and J.H. Trainor, Relation of coronal magnetic structure to the interplanetary proton events of August 2-9, 1972, In: D.E. Page (Ed.), Correlated Interplanetary and Magnetospheric Observations, Dordrecht 1974

Roelof, E.C., R.E. Gold, S.M. Krimigis, A.S. Krieger, J.T. Nolte, P.S. McIntosh, A.J. Lazarus, and J.D. Sullivan, Relation of large-scale coronal X-ray structure and cosmic rays: 2. Coronal control of interplanetary injection of 300 keV protons, Proc. 14th Intern. Cosmic Ray Conf., Paper SP 4-5, München, 1975

Schulze, B.-M., A.K. Richter, and G. Wibberenz, The influence of finite injection periods on anisotropies during solar particle events, Proceedings of the HELIOS Scientific Colloquium, Windberg 1974

Schulze, B.-M., A.K. Richter, and G. Wibberenz, On the influence of injection profiles and of interplanetary propagation on the time-intensity and time-anisotropy profiles of solar cosmic rays at 1 AU, Proc. 14th Intern. Cosmic Ray Conf., Paper 5. 1-9, München 1975

Simnett, G.M., Relativistic electrons from the sun observed by Imp-4. Solar Phys., 22, 189 , 1972

Simnett, G.M., Relativistic electrons events in interplanetary space, Space Sci. Revs., 16, 257 , 1974a

Simnett, G.M., A correlation between time-overlapping solar flares and the release of energetic particles, Solar Phys., 34, 337 1974b

Serlemitsos, A.T., and V.K. Balasubrahmanyan, Solar particle events with anomalously large relative abundance of $^3$He, Astrophys. J., 198, 195, 1975

Smart, D.F., M.A. Shea, H.W. Dodson, and E.R. Hedeman, Distribution of proton producing flares around the Sun, Space Res. XVI (COSPAR-Meeting, Varna 1975), to be published

Svestka, Z. and L. Fritzová-Svestková, Type II radio bursts and particle acceleration, Solar Phys. 36, 417, 1974

Van Hollebeke, M.A.I., L.S. Ma Sung, and F.B. McDonald, The variation of solar proton energy spectra and size distribution with heliolongitude, Solar Phys. 41, 189, 1975

Wibberenz, G., Interplanetary magnetic fields and the propagation of cosmic rays, J. Geophys. 40, 667, 1974

Wibberenz, G., and R. Reinhard, The exponential decay of solar flare particles.I.Eastern hemisphere events, Proc. 14th Intern. Cosmic Ray Conf., Paper SP 4-1, München 1975

## Figure Caption:

Figure 1: Schematic representation of "propagation" and "storage" processes. The main difference is in the lateral distribution of particles, whereas an observer close to the original acceleration region may see the same injection function in both cases.

Figure 2: Number of solar events as a function of solar longitude, for different particle types and energies. Data have been collected from Lin (1974), Van Hollebeke et al. (1975), Pomerantz and Duggal (1974), and Simnett (1974).

Figure 3: The time of the intensity maximum ($t_m$) as a function of solar longitude. The collection of experimental points taken from Reinhard and Wibberenz (1974) is compared with calculations. Curves (a) and (c) are based on the coronal diffusion model (Reid, 1964) in the extended version of Ng and Gleeson (1975), curve (DD) is based on the combination of a fast propagation region with the drift-diffusion model (Reinhard and Roelof, 1975).

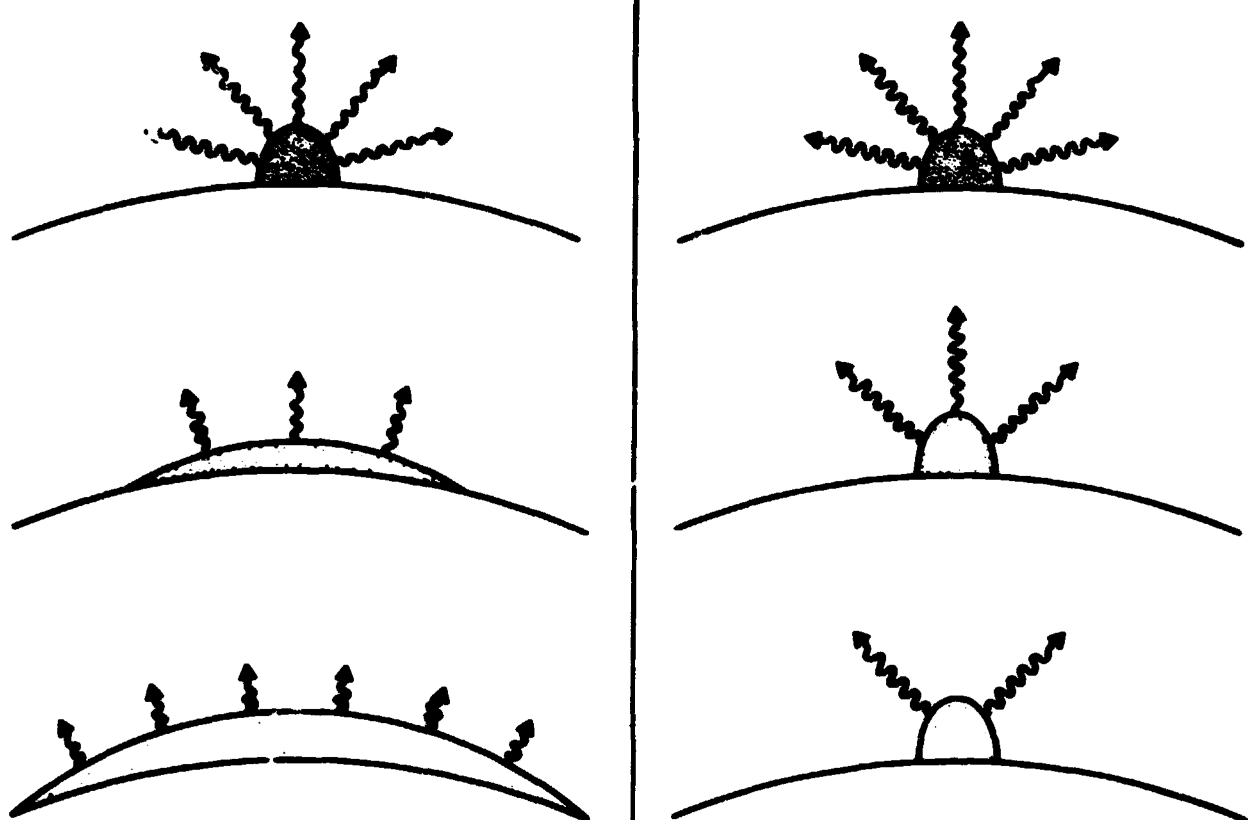
Figure 4: Angular spread over the solar surface for different coronal propagation models. Temporal development from top to bottom. The influence of the escape process is neglected. N is the average particle density within the cross-hatched area, $\phi$ is a characteristic maximum distance from the flare site reached after time t.

**PROPAGATION**

(+RELEASE ⇝)

**STORAGE**

(+RELEASE ⇝)



-SMALL DENSITY GRADIENT (APART FROM INITIAL PHASE)

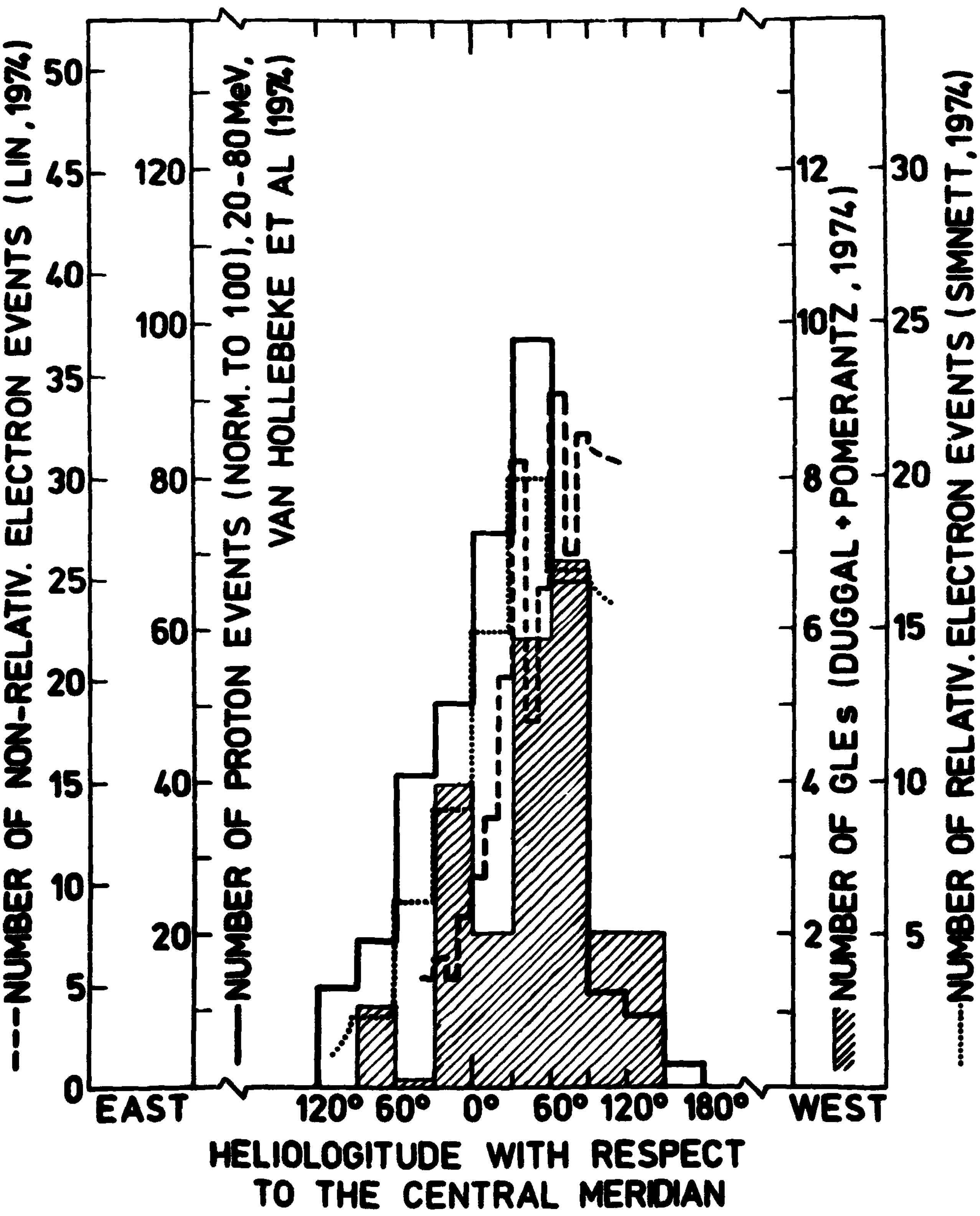
-GRADUAL WIDENING OF CONFINEMENT REGION

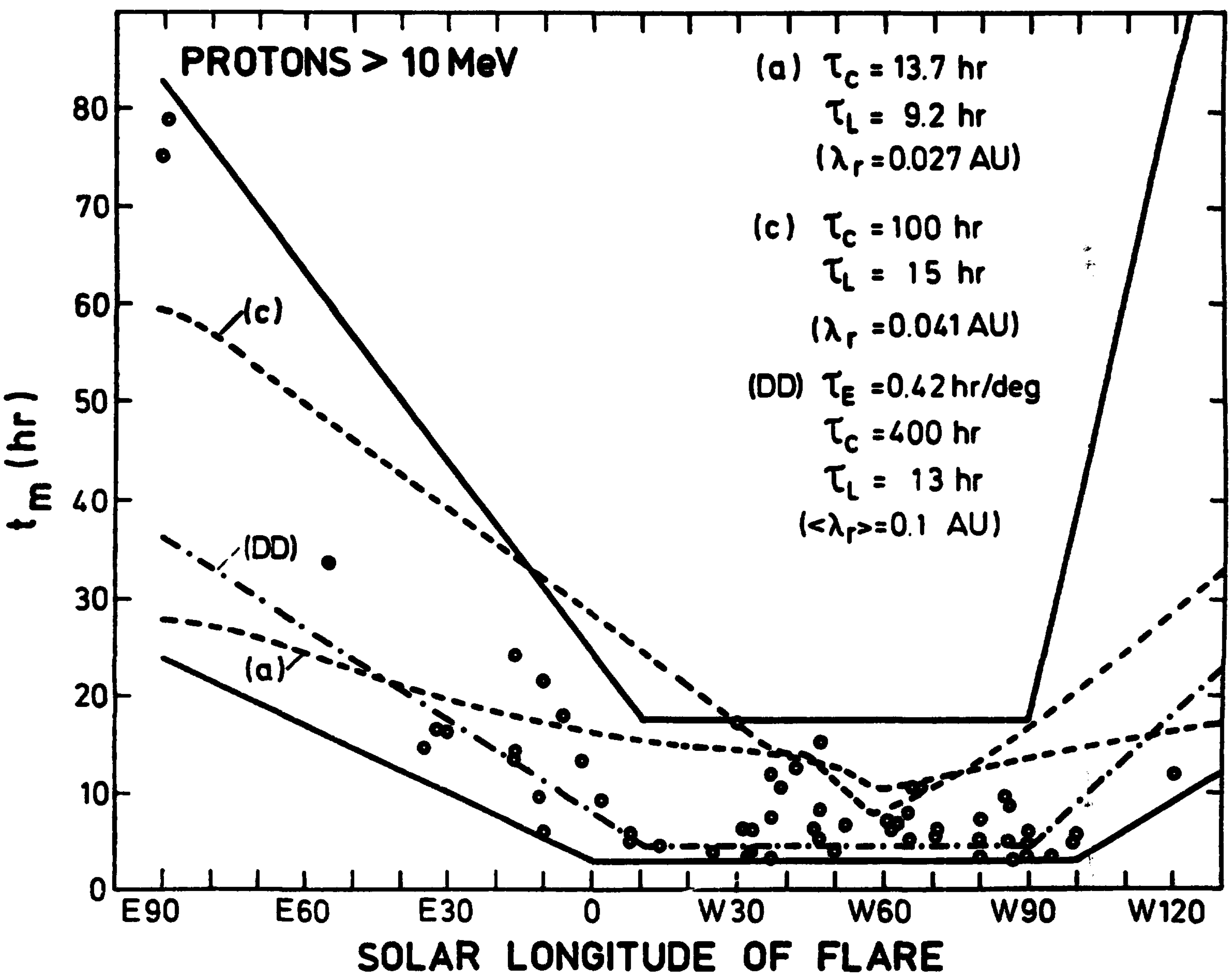
-REDUCTION IN DENSITY BY LATERAL SPREAD + LEAKAGE

-LARGE DENSITY GRADIENTS AT THE BOUNDARY OF THE STORAGE REGION

-NO OR SMALL WIDENING OF CONFINEMENT REGION

-REDUCTION OF DENSITY BY LEAKAGE


---NUMBER OF NON-RELATIV. ELECTRON EVENTS (LIN, 1974)
0
5
10
15
20
25
30
35
40
45
50
—NUMBER OF PROTON EVENTS (NORM. TO 100), 20-80 MeV, VAN HOLLEBEKE ET AL (1974)
20
40
60
80
100
120
NUMBER OF GLEs (DUGGAL + POMERANTZ, 1974)
2
4
6
8
10
12
······NUMBER OF RELATIV. ELECTRON EVENTS (SIMNETT, 1974)
5
10
15
20
25
30
EAST
120° 60° 0° 60° 120° 180°
WEST
HELIOLOGITUDE WITH RESPECT
TO THE CENTRAL MERIDIAN



PROTONS > 10 MeV
(a) τc = 13.7 hr
τL = 9.2 hr
(λr = 0.027 AU)
(c) τc = 100 hr
τL = 15 hr
(λr = 0.041 AU)
(DD) τE = 0.42 hr/deg
τc = 400 hr
τL = 13 hr
(<λr> = 0.1 AU)
(c)
(DD)
(a)
tm (hr)
0
10
20
30
40
50
60
70
80
E90
E60
E30
0
W30
W60
W90
W120
SOLAR LONGITUDE OF FLARE

MODELS FOR PROPAGATION OVER LARGE DISTANCES IN SOLAR LONGITUDE