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Interplanetary magnetic field fluctuations and the propagation of cosmic rays

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RESUMEN

El propósito de este trabajo de revisión es el de resumir y discutir los avances recientes en la investigación hecha en el campo de la propagación de los rayos cósmicos en el medio interplanetario. Se presentan los conceptos actuales acerca del viento solar y la heliosfera. Se analiza el problema de la propagación de partículas en el contexto de los eventos solares y su tratamiento bajo distintos enfoques, llegándose a una comparación de los distintos resultados para los coeficientes de transporte. Se revisa también el problema del transporte en la heliosfera exterior.

PALABRAS CLAVE: medio interplanetario, rayos cósmicos, partículas energéticas.

ABSTRACT

This review summarizes and discusses recent research done in the field of cosmic ray propagation in the interplanetary medium. Current ideas about the solar wind and the heliosphere are treated. Particle propagation from different approaches is discussed in the context of solar particle events and results on transport coefficients are compared. Transport in the outer heliosphere is also reviewed.

KEY WORDS: interplanetary medium, cosmic rays, energetic particles.

1. INTRODUCTION

Transport of energetic particles in the interplanetary medium remains an important topic in cosmic ray research. Since the first observations of the interplanetary magnetic field and the recognition that its existence established the anisotropic nature of the medium, particles became excellent probes to study the structure of the fields and the different ways in which test particle interactions occur with plasma irregularities.

Unfortunately, there is no way to observe the complete trajectory of an individual charged particle from its source to the point of detection. What is measurable is the intensity of charged particles of a given type as a function of time, energy and direction of incidence relative to the local magnetic field (i.e. pitch angle). To relate these observations to the characteristics of the medium a theoretical treatment should take into account its known properties and make some assumptions. Other approaches to the problem (i.e. numerical) can also be pursued.

This review summarizes and discusses recent research done in the field of cosmic ray propagation in the interplanetary medium. I briefly review the current ideas about the structure of the solar wind and the concept of the heliosphere, including a discussion about magnetic fluctuations and turbulence in the interplanetary medium. A theoretical treatment of particle propagation begins with the different forms of the transport equation in Section 3. Section 4 is dedicated to an outline of the Quasi-Linear Theory (QLT) approach to the problem of determining the transport parameters and the subsequent corrections to the original formulation. In Section 5 different investigations based on the solution of various forms of the transport equations are reported, the discrepancies of these results with QLT are discussed and a numerical calculation of particle trajectories is presented, from which transport coefficients can be obtained. A general discussion of the process of pitch angle scattering and the form of the pitch diffusion coefficient ($D(\mu)$) follows, with a presentation of comparative studies of propagation of solar particles using simultaneous field and particle data (Section 7). As the outer heliosphere has been reached by various space probes, new discoveries have been made about cosmic ray modulation. Current ideas about transport of particles in this region are discussed in Section 8. A final paragraph summarizes the main points reviewed, some personal conclusions and important questions still to be answered.

2. THE INTERPLANETARY MEDIUM

The existence of a certain kind of material flowing from the Sun was postulated since the early days of the 20th century by Birkeland (1908), in the report of his famous expeditions. The idea was left aside for a certain time until Biermann (1951, 1953, 1957) advocated the concept of a continuous solar wind to explain the observed acceleration of gaseous comet tails. Two opposite mathematical formulations about the expansion of the solar corona were produced shortly after (Parker, 1958 and Chamberlain, 1961), and a controversy developed until the findings of the Mariner 2 settled it in favour of the supersonic hydrodynamic expansion theory of E. N. Parker. The success of this theory is amazing considering the fact that it uses mathematical tools originally developed for a completely different kind of fluid where the dynamics is dominated by collisions and electromagnetic forces are absent.

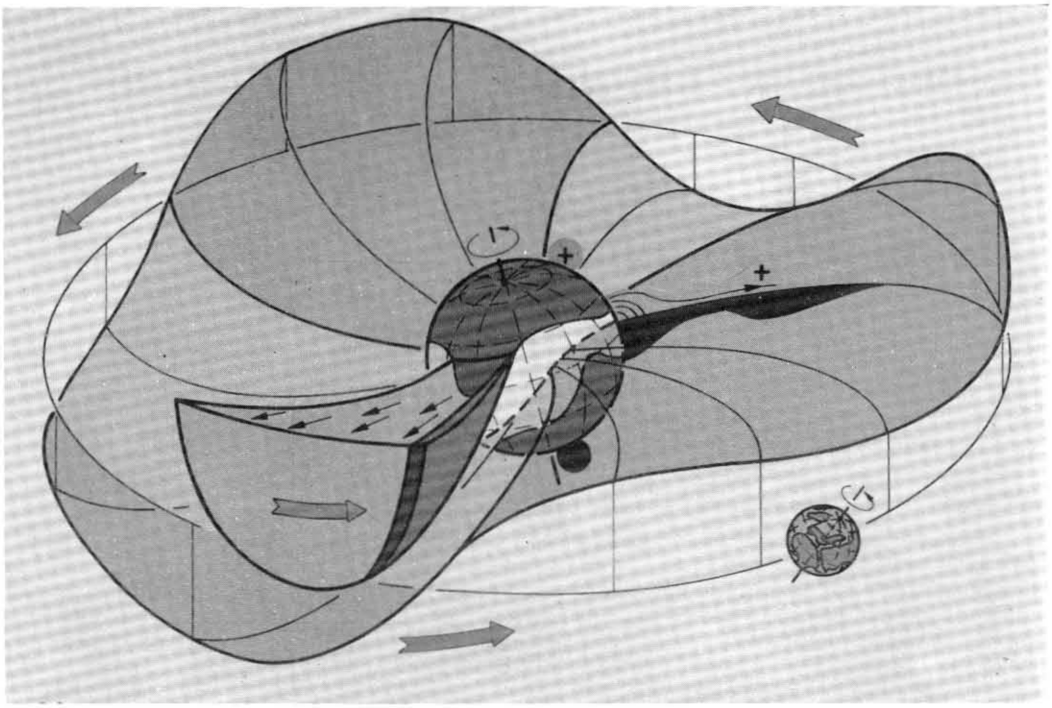

Fig. 1. Model of the heliosphere close to solar minimum. Coronal holes with opposite magnetic field polarity are shown over the poles. The "ballerina skirt" is a separation layer between positive and negative magnetic field lines. The whole structure rotates with the Sun about its somewhat inclined axis.

Space age data taken *in situ* began to accumulate and to pose new challenges to any theory of the solar wind. The picture we have now about the structure of the interplanetary medium is different of that envisaged by Parker in many respects which I assume to be common knowledge. I will not emphasize these differences here; rather I will try to summarize what is believed nowadays.

A highly conducting magnetized fluid in continuous expansion takes the field "frozen-in" with it. This fluid comes mainly from the divergent regions of open field lines known as *coronal holes,* one south and the other north of the Sun, during the solar minimum. These polar coronal holes have opposite field polarities. The gross magnetic field structure of the heliosphere is presented in Figure 1.

Polar coronal holes are also the sources of high speed solar wind streams which, when developed in the interplanetary medium, give rise to what is known as Corotating Interaction Regions (CIR's). A scheme of a situation with two CIR's in the interplanetary medium is shown in Figure 2.

In addition to these stable structures there are transients such as shock waves originating in solar phenomena which could be solar flares, eruptive filaments or unstable equatorial coronal holes. These transients propagate through the heliosphere causing, among other things, particle acceleration and magnetic disturbances in the planets of the solar system.

The overall structure sketched here represents the situation during the solar minimum. As the solar cycle progresses magnetic fields in the Sun become intrincate, causing a highly complicated structure of the solar wind, very difficult to describe even in drawings.

Most important for the topic of this paper is the presence of waves (mainly MHD) and discontinuities (rotational, tangential, etc.), since these are the disturbances which most strongly affect the transport of cosmic rays. Without entering into details on the nature of each of them, and because they are always present, IMF data can be analyzed as a fluctuating time series. Standard methods of time series analysis may thus be applied to obtain some of the characteristics of the IMF perturbations; in particular, a power spectrum can be calculated as a function of frequency or wavenumber.

Another property of the IMF influençing the particle transport is the magnetic helicity. The helicity spectrum yields a measure of wave polarization for different frequencies. The overall polarization can be calculated by normalizing helicity with the energy content of the series (Matthaeus and Goldstein, 1982). IMF fluctuations power and helicity spectra for a sample of data taken on board Voyager 2 at 2 AU from the Sun are shown in Figure 3.

Both spectra can be related to particle propagation by the use of quasi-linear theory (QLT). I will review this treatment in Section 4, but first I review a more phenomenological approach to the problem.

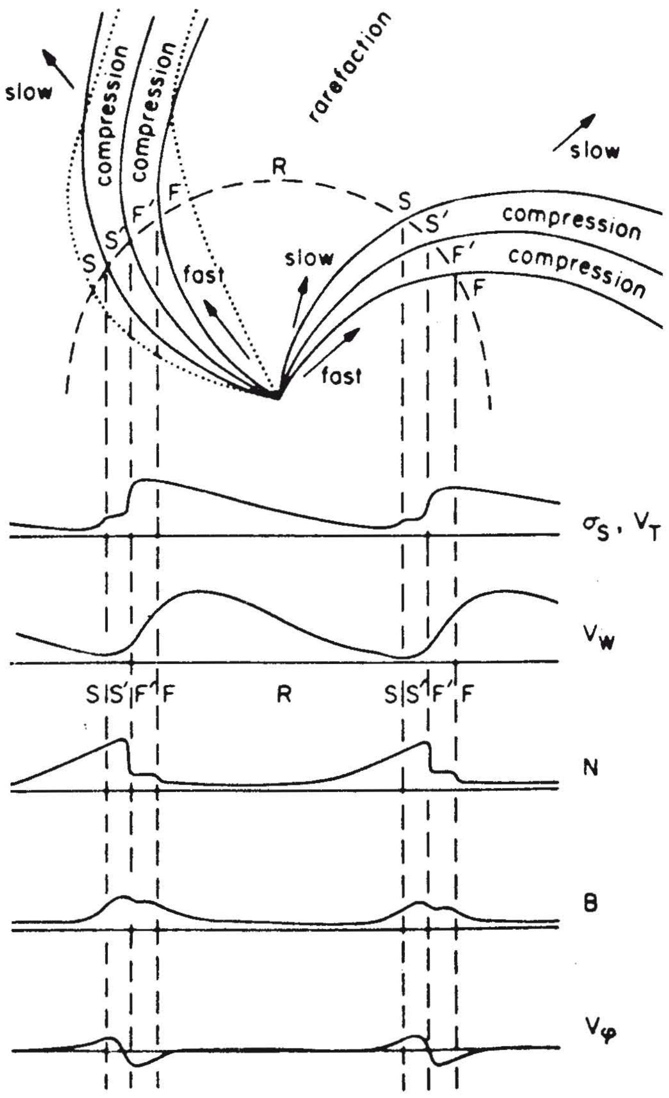

Fig. 2. Scheme of two CIR's and their effect on the solar wind. The upper half figure shows the encounter of two fast streams with the preceding slow solar wind. The solid curves represent the interaction or compression fronts which develop. The dotted curves are two representative magnetic field lines which are more strongly spiralled in the slow wind and less strongly spiralled in the fast wind. The vertical dashed lines leading to the lower half figure connect to profiles of various solar wind parameters influenced by the interaction. The solar wind speed and azimuthal velocity component are V_w and V_ϕ and the density is N. The magnetic field magnitude is B and σ_S represents the standard deviation in the superposed magnetic field fluctuations, which is correlated with the solar wind temperature or thermal speed V_T.

3. TRANSPORT EQUATION

The well defined overall structure of the IMF, namely the Archimedean spiral, gives energetic particles a preferential direction of propagation. On the other hand, irregularities present in the field cause the particles to scatter in pitch angle. As a result, the motion of the particles has two components: an approximately adiabatic motion along a smooth field and a random walk in pitch angle space. The equation governing the evolution of a particle distribution function f(μ, z, t) in the IMF can be obtained from the most general Fokker-Planck equation or from Liouville's equation (Jokipii, 1966, Hasselmann and Wibberenz, 1968). To account for the possible effects of focussing due to the divergence of the field, an additional term has to be considered (Roelof, 1969). The full equation can be written in pitch angle space as:

$$\frac{\partial f}{\partial t} = -\mu v \frac{\partial f}{\partial z} + \frac{\partial}{\partial \mu} D(\mu) \frac{\partial f}{\partial \mu} + \frac{v}{2} \frac{1}{B} \frac{\partial B}{\partial z} (1-\mu^2) \frac{\partial f}{\partial \mu} \qquad (1)$$

where $\mu = \cos\theta$ (pitch angle cosine), and v = particle velocity. The systematic effect of focussing is represented by the third term on the right hand side; it is characterized by the focussing length $L = B(z)/(\partial B/\partial z)$. The second term represents the stochastic forces causing pitch angle scattering with a pitch diffusion coefficient $D(\mu)$. Equation (1) does not take into account the effects of convection and adiabatic deceleration in the expanding solar wind. It should only be applied to particles with diffusive velocities much larger than the solar wind speed.

An extreme case represented by equation (1) is when $D(\mu) \cong 0$: the so called 'scatter-free' regime. In this case Liouville's equation states that the phase space density along a particle trajectory remains constant. Preservation of the first adiabatic invariant requires

$$\frac{\sin^2\Theta}{B} = \text{constant}$$

This means that the pitch angle Θ should decrease when particles are propagating outwards from the Sun as is the case of solar particle events. Charged particles injected isotropically at 0.05 AU would appear in a narrow cone of only 6° width to an observer situated at 0.5 AU. This situation is very rarely found, but some events have been observed in extremely quiet solar wind situations (Roelof *et al.*, 1973; Neustock *et al.*, 1985).

If pitch angle scattering is finite, particles diffuse in pitch angle space and arrive in a wider cone of directions. Approximate analytical solutions to this problem have been produced by Earl (1976, 1981), Kunstmann (1979) and Green (1984). The solution for an impulsive injection is a particle pulse which moves along the magnetic field with the 'coherent' velocity V_{coh} and widens at a rate given by a diffusion coefficient D_{coh}. These parameters are determined by the focussing to scattering ratio. Theoretical solutions of equation (1) were compared with observed solar particle data by Bieber *et al.* (1980), but restricted to a constant focusing length (exponential IMF dependence).

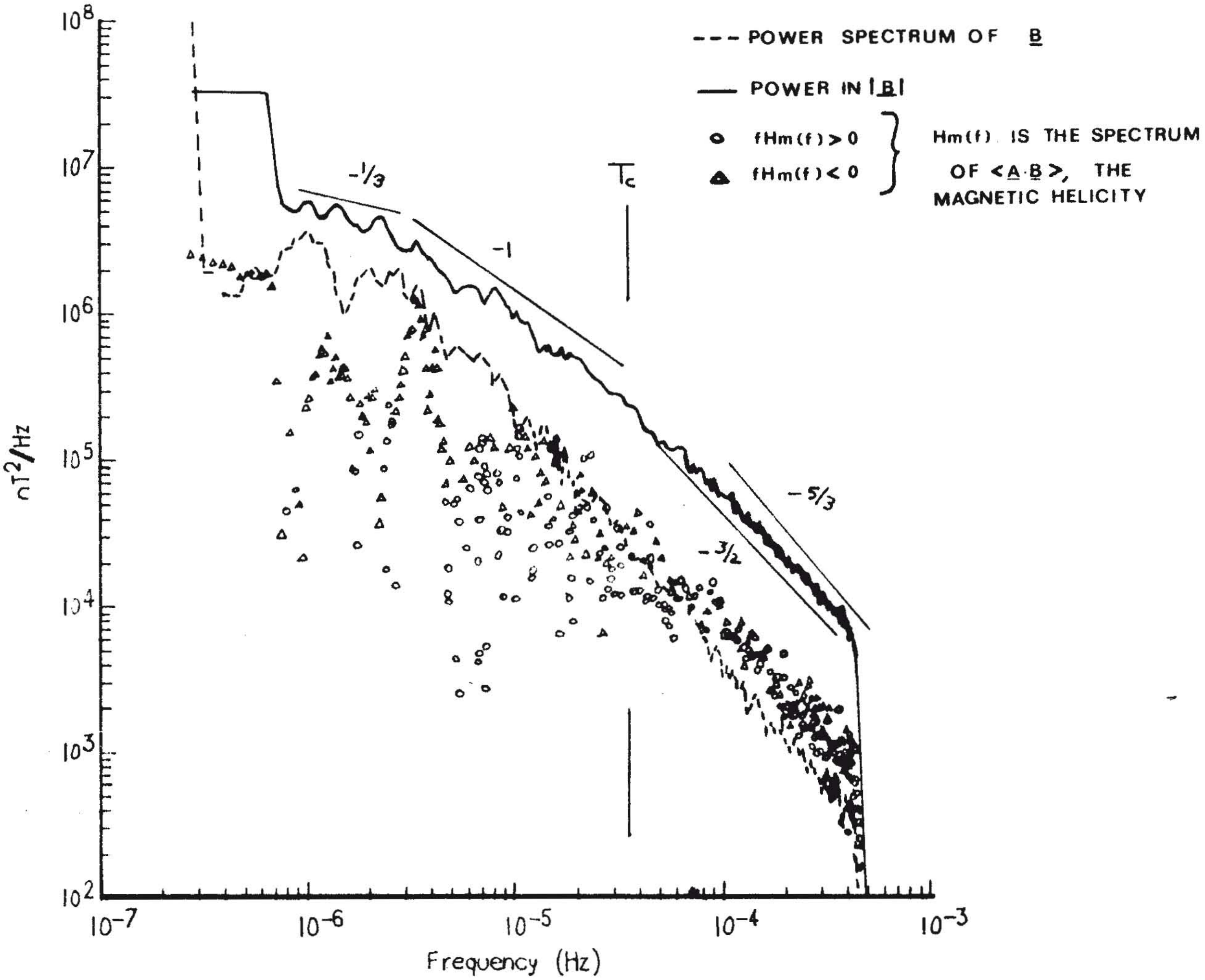

Fig. 3. Power and helicity spectra for a sample of IMF taken by Voyager 2 at 2.8 AU. Positive and negative helicities are shown separately. Straight lines are fits done "by eye" to show the changes in slope at different frequency intervals. Taken from Matthaeus *et al.* (1982).

Numerical solutions can overcome the above limitations (Ng and Wong, 1979). An example of this type of solution is shown in Figure 4, taken from Wong (1982). It corresponds to 9 MeV protons with a mean free path of 0.5 AU. Omnidirectional intensities correspond to observers at 0.5 and 1 AU left and right respectively.

The main feature of the solution is a strong coherent peak followed by a diffusive wake. For comparison, solutions of the purely diffusive equation are also plotted; these have been adjusted to give the same time to maximum as the full numerical solutions. It should be stressed that the striking differences of the two solutions arise only when there is a sufficiently brief solar injection. A long lasting solar injection leads to a profile where no coherent peak is present and thus the time-intensity profile will be indistinguishable from a purely diffusive case even for a large mean free path. A careful analysis of the anisotropy and angular distributions is required to understand the correct mode of propagation.

In the strong scattering regimes the transport equation (1) can be reduced to a diffusion equation for the omnidirectional intensity j (= $p^2 f$) or, equivalently, to the spatial particle density U. In this case the effects of convection and adiabatic deceleration due to the expanding solar wind have to be taken into account (see e.g. Jokipii, 1970). The effect of these phenomena are to shift the intensity maximum to earlier times; they may even steepen the decay substantially. They are of particular importance at solar distances beyond the Earth orbit (Hamilton, 1977, 1990; Beeck *et al.*, 1990). The complete equation assuming spherical symmetry reads:

$$\frac{\partial U}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 D_r)\frac{\partial U}{\partial r} + \frac{2}{3}\frac{V_w}{r}\frac{\partial}{\partial T}(\alpha T U) - \frac{1}{r}\frac{\partial}{\partial r}(r^2 V_w U) \tag{2}$$

where the radial diffusion coefficient D_r is related to the coefficient parallel to the IMF $D_{\parallel}$ as $D_r = D_{\parallel} \cos^2 \psi + D_{\perp} \sin^2 \psi$. This neglects the effects of perpendicular diffusion ($D_{\perp}$) as not being relevant for solar flare particles.

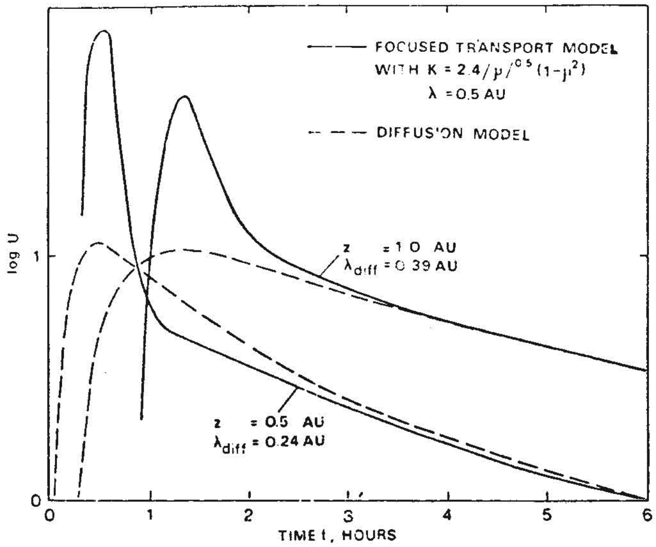

Fig. 4. Numerical solution of the transport equation (1) (solid line) for a mean free path $\lambda = 0.5$ AU and an observer at 0.5 AU (left) and at 1 AU (right). For comparison, the solution of diffusion approximation (dashed line) with a mean free path λ_{diffus} adjusted to give the same time to maximum (from Wong, 1982).

V_w is the solar wind speed, T is kinetic energy and $\alpha = T + 2T_o/T + T_o$, T_o is the rest energy of the particle. The second and third terms on the right hand side of equation (2) represent adiabatic cooling and convection generated by the continual expansion of the solar wind.

The transport equation (1) or its various approximations can be used to estimate the transport parameters involved by fitting the time intensity, anisotropy and angular distribution profiles of solar particle events thus improving our understanding of the propagation of energetic particles. However, it is also possible to derive transport parameters from the properties of the IMF relating the irregularities present in it to the fundamental process of pitch angle scattering.

4. QUASI-LINEAR THEORY AND CORRECTIONS TO IT

In Quasi Linear Theory (QLT), the basic cause for scattering lies in particle gyroresonance with waves in the IMF treated as stationary. Particles rotating around the field in phase with the scattering perturbation receive a resonance disturbance to their pitch angles.

Taking into account the particle relative motion with respect to the plasma, the resonant frequency is found to be

$$f_{res} = \frac{V w \Omega}{2 \mu v \mu}$$

where Ω, v, are the particle gyrofrequency and velocity. This diffusive process is related to spectral properties of the IMF. In the particular case of the 'slab' model of field fluctuations, a pitch angle diffusion coefficient can be obtained as (Jokipii, 1966; Haselmann and Wibberenz, 1968):

$$D(\mu) = A \mid \mu \mid^{q-1} (1 - \mu^2) \qquad (3)$$

where A is a constant depending on particle charge, mass, velocity and the level of field fluctuations, and q is the spectral index of the field power spectrum which is approximated by a power law for sufficiently low frequencies ($P \alpha f^{-q}$). QLT is based on the assumptions that particles follow approximate helical paths, that field fluctuations are small compared to the average field, and that particle distribution function changes are negligible over the scale of the IMF correlation length. If the field structure is different from the slab model (transverse fluctuations axially symmetric about the average field), equation (3) should be modified. The relation between the pitch angle diffusion coefficient and the parallel diffusion coefficient was found to be

$$D_{\parallel} = \frac{v^2}{8} \int_{-1}^{1} \frac{(1 - \mu^2)^2}{D(\mu)} d\mu \qquad (4)$$

where v is particle velocity.

This combination of a slab model for the magnetic field fluctuations with QLT has been used in many papers as a standard for comparison with experimental results and we shall refer to it as the 'standard model'.

It is well known that QLT breaks down for $\mu \cong 0$ in case of $q > 1$, a situation prevailing most of the time for IMF spectra. In this case equation (3) predicts no scattering at $\mu = 0$, and helical paths are no longer a good approximation for the particle motion. Nonlinear corrections to QLT lead to modifications near $\mu = 0$ where the scattering can be considerably enhanced, in particular for the large relative strength of fluctuations (Jones *et al.*, 1978). Magnetic mirroring due to changes in the field strength B is taken into account in most attempts to refine the theoretical model near $\mu = 0$ (Quenby *et al.*, 1970; Fisk *et al.*, 1974; Lee and Völk, 1975; Goldstein, 1976). This enhanced scattering reduces the corresponding diffusion coefficient and mean free path (λ), thus increasing the discrepancy of about an order of magnitude between predictions of QLT and mean free paths determined from solar particle observations (see next section). Therefore, other attempts to correct QLT have also been made.

Morfill (1975) considers the idea of waves propagating at an angle with respect to the magnetic field and Morfill *et al.* (1976) find that λ is larger by about a factor of 5 if the wave vectors tend to align with the radial direction in contrast to waves aligned with the average magnetic field **B** (slab model). Observations suggest that propagation vectors tend to align along **B** (Denskat and Burlaga, 1977), although some evidence exists for radially propagating waves (Mavromichalaki *et al.*, 1988).

Goldstein (1980) argued that the mean free path is essentially determined by a small amount of compressible fluctuations (5 - 10%) leading to a mean free path of the order of 0.3 AU, independent of rigidity.

Goldstein and Matthaeus (1982) include the effects of magnetic helicity considering only waves with the correct sense of polarization to produce cyclotron resonance. This also leads to $\lambda = 0.3$ AU, more in accordance with particle observations (see Palmer, 1982).

Dávila and Scott (1984) reduce the scattering near 90° pitch angle by collision damping of waves with high wave numbers and also add mirroring due to field compressions. Based on the average spectra for $\delta \mathbf{B}$ they obtain typically a mean free path of 0.04 AU roughly independent of energy. This value of λ is almost an order of magnitude lower than Goldstein's (1980) but still at least a factor of 3 larger than QLT prediction.

Schlickeiser (1988) and Dung and Schlickeiser (1990) assume superimposed parallel and antiparallel propagating transverse Alfvén waves taking into account magnetic and cross helicity. They conclude that the resulting mean free path can be larger than QLT predictions by a factor of 10 to 20. Note, however, that they used unrealistic forms of the power spectrum of magnetic field fluctuations.

A distinction between these various suggested modifications has not yet been possible. Most of the attempts to remove the discrepancy are related to the magnetic field structure. The combination of resonant scattering for large μ with different scattering processes at small μ may vary with particle rigidity. This would remove the coupling of the angular dependence of $D(\mu)$ from the rigidity dependence of λ (R) which was a characteristic feature of the standard model.

5. SOLAR PARTICLE EVENTS

Most descriptions of solar particle propagation based on observations of particles have been confined to the determination of the scattering efficiency along the average IMF as expressed by λ and to the radial dependence of this parameter assumed of the form $\lambda \alpha r^b$ (see Palmer, 1982; Ng, 1986; Wibberenz *et al.*, 1989; Beeck *et al.*, 1990). The proper choice of b is important in order to determine the correct local value of λ at the point of observation. Studies based on observations between 0.65 and 5 AU led to values of b between 0 and 0.62 (Zwickl and Webber, 1977; Hamilton, 1977; Hamilton *et al.*, 1990). Nevertheless the radial variation of λ may vary from one event to the next and even a decreasing λ with solar distance is needed to fit some observations within 1 AU (Ng *et al.*, 1983; Valdés-Galicia *et al.*, 1988).

The global treatment presented in the preceding paragraph only specifies the level of scattering, not its variation with pitch angle which could give further clues to the nature of the scattering process. The elementary process of particle scattering and its dependence on pitch angle determines details of the pitch angle distribution of particles. As shown by Hasselmann and Wibberenz (1968), deviations from the isotropic particle flux can be related to the functional form of the diffusion coefficient $D(\mu)$. Based on a numerical solution of equation (1), Ng *et al.* (1983) obtained a reduced scattering near 90° pitch angle for a particular event. This may be restricted to conditions of weak overall scattering, as was suggested by Beeck and Wibberenz (1986). They studied an approximate solution of equation (1) and found that after proper normalization the anisotropic part of the distribution function became time invariant. The solution depends on the ratio between the mean free path λ and the focussing length L and on the shape of the pitch angle diffusion coefficient D (μ). I shall return to a more complete discussion of this point.

There is a large discrepancy between determinations of λ from solar particle events and the predictions made by QLT. Several attempts have been made to correct the theory, and some in fact provide clues as to the source of the differences. A summary of many different results is shown in Figure 5, taken from Palmer (1982). Dots of different shapes correspond to different carefully selected solar proton events. The data suggest that there is no systematic dependence on rigidity. A "consensus range" for λ between 0.08 and 0.3 AU seems to exist over a large range of rigidities. This small variation may be consistent with λ = constant which in principle would agree with Goldstein (1980), that the mean free path is mainly determined by a small amount of compressive fluctuations (horizontal line G). Other theoretical curves are also drawn, J corresponding to the 'standard model' already discussed and SM to Morfill *et al.* (1976) where they consider small resonant fluctuations superimposed on medium scale variations. This last idea also yields a constant λ over a considerable range of rigidities.

However, rigidity dependence of the mean free path can be substantially different from event to event. Figure 6 shows this dependence of the mean free path for several events observed with Helios satellites (Kunow *et al.*, 1990). The high variability in the scattering efficiency of the IMF is manifest, the limiting values of about two orders of magnitude corresponding to events only three days apart. A definite monotonic increase of mean free path with rigidity is also observed in 3 events, thus contradicting the idea of a constant λ. Curves G and J are as in Figure 5. Curve DS is based on Dávila and Scott (1984) where a certain mixture of resonant and nonresonant interaction is allowed.

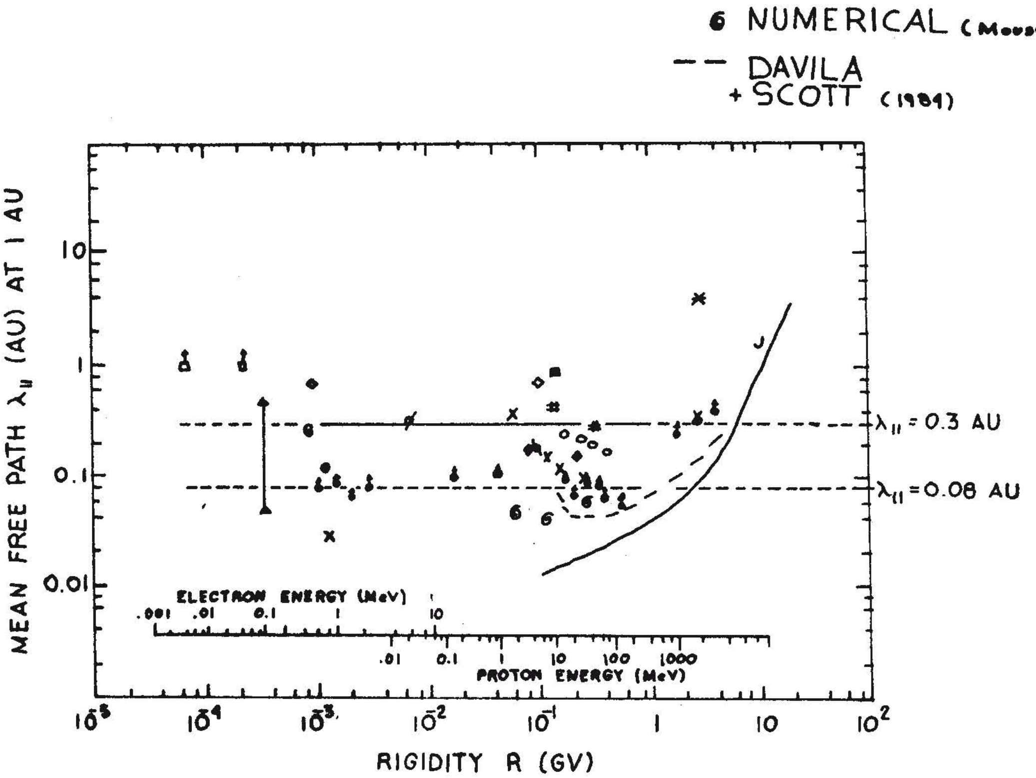

Fig. 5. Parallel mean free path as a function of rigidity for electrons and protons. The "consensus range" of Palmer (1982) is shown by the two dashed lines at 0.08 and 0.3 AU. Theoretical predictions are curves J (Jokipii, 1971), G (Goldstein, 1980) and DS (Dávila and Scott, 1984). Numerical simulations results are taken from Moussas *et al.* (1982).

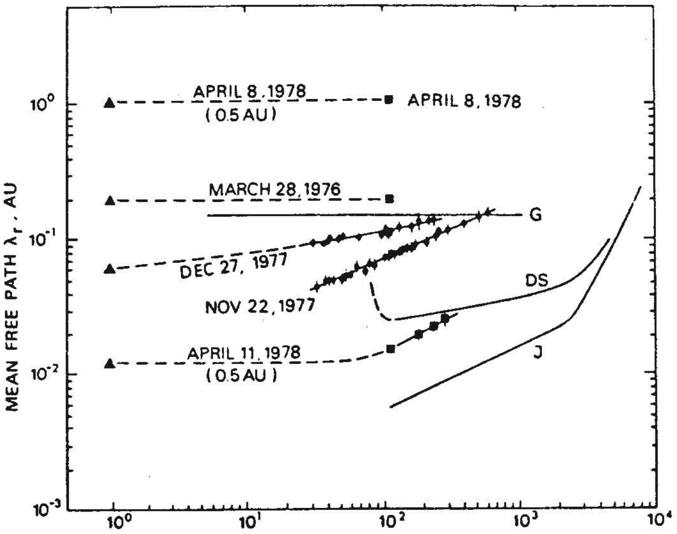

Fig. 6. The radial mean free path as a function of rigidity during several solar particle events.

6. NUMERICAL TECHNIQUES

Numerical trajectory integrations in magnetic fields with a homogeneous component and fluctuations obeying Gaussian statistics were performed by Kaiser *et al.* (1978). Several different configurations of the field were explored and graphs of D(μ) vs μ were produced, but the power spectrum dependence was always limited to f^{-2} at high frequencies, a situation rarely observed in the IMF.

Moussas *et al.* (1978, 1982a) and Valdés-Galicia *et al.* (1984) have extended the numerical model of Kaiser *et al.* (1978) to use real magnetometer data from Heos, Pioneer and Helios spaceprobes. Resonant scattering, mirroring near 90°, non helical trajectories or specific helicity of the IMF are all automatically taken into account. Their model has been called the 'layer model'. It is based on measurements of all 3 components of the field taken on board satellites. Although various modifications must be made to best represent a particular set of data, the model can briefly be described as follows:

A string of data taken by a spacecraft (typically 24 hours) is assumed to consist of a series of layers in space. Each of these layers has a width given by the sampling time δt, times the solar wind speed (V_{sw}), which is assumed to be radial and constant. To each of these layers a value of the corresponding measurements of the magnetic vector is assigned. The basis of this method is to assume that, on a statistical average, the IMF sample taken by the spacecraft would measure the same sort of fluctuations that would be obtained if it could follow a flux tube. In this sense we can refer to the method as an approximation to a smooth line by a string of straight lines (cf. Figure 7). This model differs from the slab model in that power in longitudinal waves and the phase dependence of waves and discontinuities is retained.

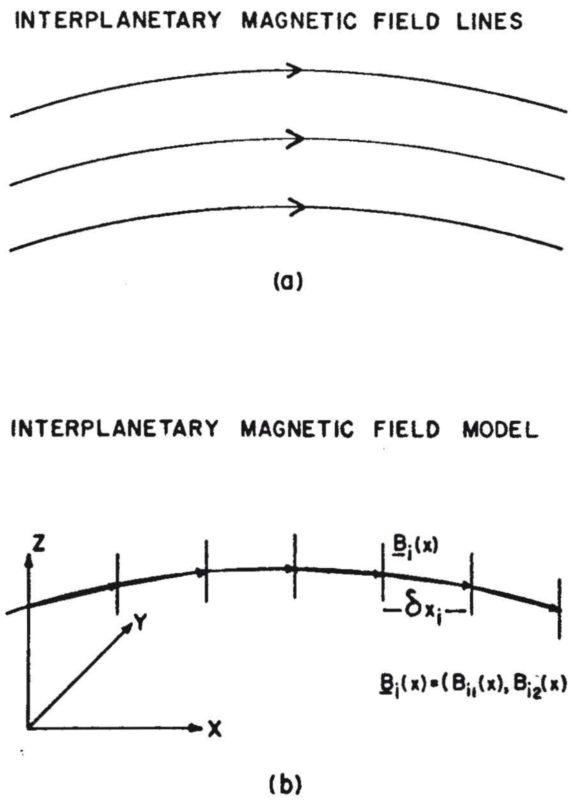

Fig. 7. Sketch of the IMF model used in Moussas *et al.* (1982) and Valdés-Galicia *et al.* (1988) to perform numerical simulation of particle trajectories.

Diffusion coefficients for any component of phase space can be calculated by injecting particles into the 'layer model' at a single point s_o and absorb them when they reach either of two present boundaries "left" (s_l) or "right" (s_r) of the injection point. A distribution function is built in *s* space and because of the absorbing boundaries there, a steady state situation is eventually reached and the flux equation corresponding to this is (Jones *et al.*, 1978; Moussas *et al.*, 1982a):

$$D(s)\frac{\partial}{\partial s}<F(s,\infty)>=J_{l,r} \tag{5}$$

If the fluxes $J_{l,r}$, are measured, we can evaluate D(s) from the slope of the distribution function. For the case where *s* represents pitch angle cosine, diffusion coefficients obtained for the periods of observation correspond (through equation (4)) to a mean free path of $\lambda = 0.03$AU in the range 1 - 100 MeV at 1AU, roughly independent of distance out to 5AU when perpendicular diffusion is taken into account far out. They also found some evidence of a decreasing λ between 0.4 and 1 AU.

These results for the mean free path are a factor of 3 higher than QLT predictions but still somewhat smaller than most determinations based on solar particle events. It should be noted that the numerical simulations have been performed with data sets which do not necessarily correspond to the IMF actually encountered by solar particles when they are released from flares. A comparative study has been carried out with magnetic data corresponding to times where solar particles have been observed at Helios spacecrafts. Analysis of particle pitch angle distributions has permitted not only a comparison of the resulting mean free paths but also of the pitch angle diffusion coefficients D(μ) which reflect details of the scattering process. I report on this study in the next section.

7. COMPARATIVE STUDIES OF PITCH ANGLE SCATTERING

Beeck and Wibberenz (1986) produced an approximate solution of the Fokker-Planck equation (1) in pitch angle space including the effects of focussing by divergent IMF lines. The observed angular distributions are described in terms of a Legendre expansion up to the fourth degree (Green, 1984). The normalized Legendre coefficients are related to the parameters of interplanetary propagation expressed by the ratio λ/L, by q' and by H in

$$D(\mu) = A\mu^{q'-1}(1+H)(1-\mu^{2}) \tag{6}$$

Here q' represents a measure of the deviation from isotropic scattering (q' = 1) and is not necessarily linked to the power spectrum of magnetic field fluctuations as in equation (3). The constant H simulates non-linear corrections to QLT. Although this approach does not give a unique D(μ) for a particular set of angular distributions, the main features of it can be well determined and also allow comparisons with the numerically obtained D(μ) which will mainly reflect features concerning the IMF structure at the time particles have been sampled in the same spacecraft. Such a study allows us to address the diffusion process directly, independent of any theoretical assumptions in QLT or its modifications. Theory can be considered after the determination of D(μ) to help us to decide whether the features of the field have been properly incorporated.

In Valdés-Galicia *et al.* (1988) three different methods for studying the strength and nature of particle scattering are compared for the event of 11 April 1978. The result for the shape of D(μ) is shown in Figure 8 for 100 MeV protons. The result denoted as "particle" is based on a fit of the particle data to a diffusion-convection model and on inspection of the angular distributions. They did not allow a direct determination of the parameters in (6) but they were consistent with isotropic scattering (q' = 1, H = 0). Beeck and Wibberenz (1986) have shown that electrons during the same event do not show any "dip" near 90° (μ = 0) with a value of q' = 1.2 ± 0.2. The "field" result in Figure 5 is based on the particle trajectory simulation in a field represented by the measurements of Helios 1, the date of the event. The close agreement with the direct particle observations is very encouraging. The remaining difference of about a factor of 2 could be explained by discontinuities which are measured by the magnetometer but not experi-

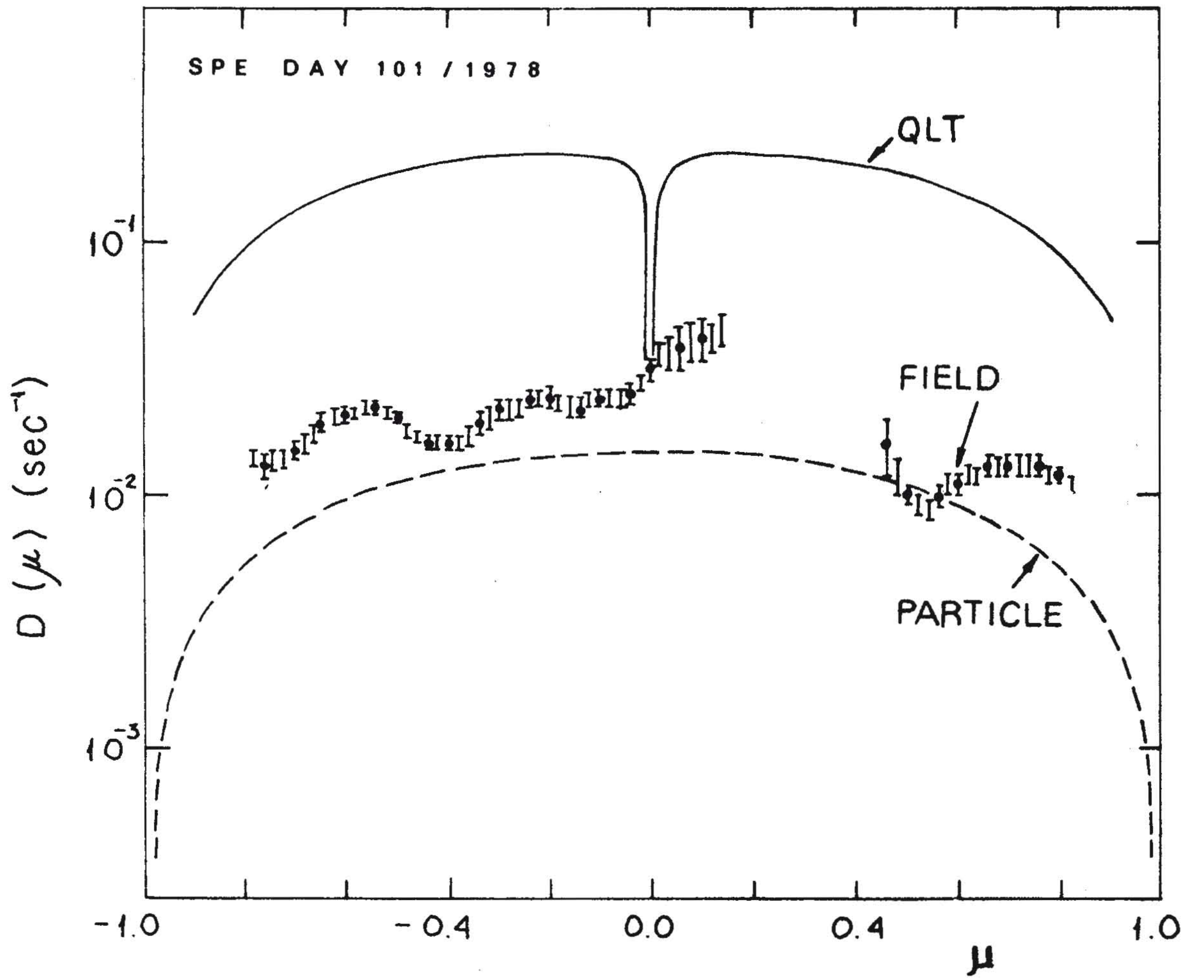

Fig. 8. Pitch angle diffusion coefficients from the standard model (QLT) and from numerical simulation (FIELD), for the event observed by Helios 2 on 11 April 1978. The dashed curve denoted PARTICLE corresponds to isotropic scattering for 100 MeV protons with λ = 0.029 AU. The QLT curve is under revision.

enced by charged particles travelling along a flux tube. The curve denoted "QLT" is based on the magnetic field power spectrum observed during the event and application of the standard model. What is interesting here is the relatively flat power spectrum with a spectral exponent q = 1.1. When applied to the standard model it leads to a very narrow dip at $\mu = 0$ which could be easily filled by particle mirroring caused by magnetic field intensity fluctuations, thus producing a D(μ) which closely resembles the other two determinations. However, the absolute value of this theoretical prediction leads to a degree of scattering considerably larger than in the other two cases. At the time this paper is written we have realized that it is perhaps not correct to use long data stretches to calculate power spectra and so the QLT curve is under close revision (Wanner and Wibberenz, 1991; Saulés *et al.*, 1991).

Mean free paths derived from results of Figure 8 are presented in Figure 9. "Particle" results are given for four proton channels and one electron channel. This result was already shown in Figure 6. The QLT curve is based on power spectrum of magnetic field data and the standard model. It shows a discrepancy of roughly an order of magnitude from the "particle" curve, which is the difference mentioned previously (Section 4). However, the result from QLT is also about a factor of 5 smaller than the "field" result obtained from the particle orbit simulation. This discrepancy, if confirmed, might well be due to the large degree of high frequency turbulence present in the field which destroys the resonance scattering and hence reduces the pitch angle diffusion rate.

The mean free path for the event of 11 April 1978 is around 0.03 AU which is smaller than most cases of solar particle event determinations reflecting the larger turbulence of the IMF. This is not surprising since the results of Jones *et al.* (1978) show that the gap D(μ) near 90° is filled according to the degree of turbulence <δB>/<B> so that isotropic scattering is to be expected in case of large fluctuations in the IMF. As a preliminary conclusion from this study it seems that the form D(μ) is not universal but will vary with the degree of turbulence of the field. Although it will have to be confirmed for a number of events it is important to notice that this is the first time an attempt has been made to determine propagation parameters from different sources of information leading to comparable results.

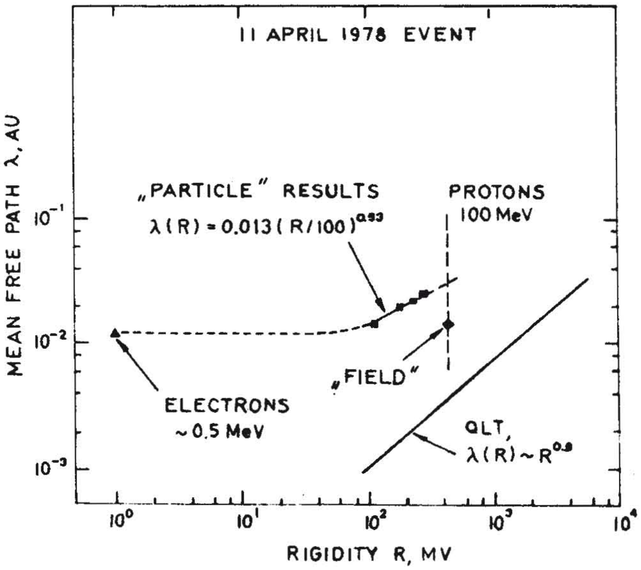

Fig. 9. Summary of results for the mean free path of the 11 April 1978 event based on three different approaches (see text).

Research in progress indicates that where magnetic field perturbations are smaller, large differences in pitch angle scattering strength and shape are found between the "particle" and "field" methods reported here. In this case, the role of tangential or rotational discontinuities is critical in the scattering process. These results might even question the assumption of pitch angle scattering as a completely diffusive process. This is also suggested from the results of Sakai (1990) where he finds different distributions of particles arising from Monte Carlo simulations as compared to solutions of Fokker-Planck equation in pitch angle space. Dissipative effects may also be present to steepen the power spectrum and make the integral in (4) divergent (Smith *et al.*, 1990). In this case, as in the previous ones, the need to account for second order effects appears to be obvious.

8. TRANSPORT IN THE OUTER HELIOSPHERE

Having discussed transport of particles in the inner Heliosphere which is mostly important when considering propagation of solar flare particles, we now turn to the outer Heliosphere where transport is most significant in the context of Cosmic Ray Modulation.

Measurements of cosmic ray intensity on board various spacecrafts out to 45AU have led to the revision of many early ideas concerning the modulation process. Modulation models contain a considerable number of uncertain parameters and several assumptions make direct comparisons difficult and somewhat artificial. On the other hand, measurements are done under circumstances which do not always produce consistent results by various groups (see e.g. Ng, 1986; Fillius, 1988).

The old stationary spherically symmetric diffusion-convection model for modulation (Parker, 1965; Quenby, 1965; Gleeson and Axford, 1967) has been refined to include several effects such as drift (i.e., Kota and Jokipii, 1987; Potgieter and Moraal, 1985), time dependent effects (Fisk and Perko, 1983) or more recently the existence of an external boundary layer (Potgieter and Le Roux, 1987, Quenby *et al.*, 1990).

Under these circumstances it is of paramount importance to have an appropriate knowledge of the transport parameters. Moussas *et al.* (1982 b, c) have calculated parallel and perpendicular diffusion coefficients and drift velocities at 5 AU from the Sun with numerical techniques similar to the ones described in Section 7. They concluded that even though $D_{\parallel}$ $D_{\perp}$ ~0 .5, perpendicular diffusion was an important factor in radial transport beyond 5 AU since there the IMF lines are almost azimuthal. Their findings revealed a constant radial mean free path in the range 1 - 100 MeV between 1 and 5 AU. They also found that the average drift velocity for 100 MeV protons at 5 AU was in accordance with the local gradient and curvature estimations with the sample used which were a factor of 5 larger than the nominal IMF.

More recent work by the same group (Valdés-Galicia *et al.*, 1989; Moussas *et al.*, 1990), employing Voyager data at 15 AU to calculate $D_{\perp}$ and Pioneer 10 at 20 AU to calculate $D_{\parallel}$, suggest substantial increase in both transport coefficients. They range from $D_{\parallel} \sim 10^{20}$ cm^{2} sec $^{-1}$ at 5 AU to $D_{\parallel} \sim 20^{23}$ cm^{2} sec^{-1} at 15 AU . These lead to a power law type radial dependence (r^{α}) where α is estimated between 0.6 and 1.2. High variability in the results of $D_{\parallel}$ at 20 AU was encountered when different IMF samples taken from days 14 - 56 of 1986 were used (up to a factor of 5 for the same energy) which roughly correspond to the level of field fluctuations. These results should be used with caution since a background constant field in the x direction was added to the original field measurements in order to avoid technical difficulties of the numerical model. This alters the fluctuation spectrum, making the actual contribution for every frequency somewhat lower. Voyager data at 15 AU did not suffer from this shortcoming where only a one-day sample (day 64, 1984) was used. Data resolution (13 secs) permitted the use only of 100 MeV particles. In any case, results coming from a limited amount of data should be taken as indicative only, since the outer heliosphere is rather complex and no small sample of IMF can be taken as representative (Burlaga, 1986).

Perpendicular diffusion becomes important for the radial transport of cosmic rays far out when the IMF lines become azimuthal. Therefore, the increase in $D_{\perp}$ between 5 and 15 AU obtained by numerical simulations would be in qualitative agreement with the need for a more efficient transport process, which would reduce the cosmic ray radial gradients as observed (see i.e. Fillius, 1988). Scaling of these numbers out to 50 AU allows appropriate diffusion parameters to be estimated for boundary layer models. 50% of the modulation is thought to take place either beyond the termination shock (Quenby *et al.*, 1990) or a zone of enhanced wave-particle interactions where wave growth occurs (Dorman *et al.*, 1990).

9. SUMMARY AND UNSOLVED PROBLEMS

The appropriate mathematical tools have been developed to solve the transport equation in cases of weak or strong scattering. Particular care should be taken to determine transport parameters from these solutions.

Modifications of the standard model are necessary to account for structures different from the slab structure, nonlinear corrections, nonresonant scattering (i.e. mirroring) and the reinforcement or attenuation of resonance caused by magnetic and cross helicity. Some efforts are being made in this respect (Jaeckel and Schlickeiser, 1990), where waves propagating at an arbitrary angle respect to the mean field are considered without restricting to the magnetostatic approximation or to first order resonance effects. However, there are indications that several of these corrections would not have dramatic effects on the transport coefficients derived (Wanner and Wibberenz, 1991, Saulés *et al.*, 1991).

The "consensus range" for λ between 0.08 AU and 0.3 AU proposed by Palmer (1982) seems to have no practical application in view of the differences found from event to event of: (a) size, and (b) rigidity dependence of the mean free path. At this stage only a case-by-case determination of λ would be reliable.

Particle trajectory simulations should be continued as a means to distinguish effects due to field structure from those due to inadequate theoretical treatment. Different field models should be used to disentangle the role of waves and discontinuities in the scattering process.

Angular distributions of particles can be used to determine the form of the pitch angle scattering coefficient and the local ratio between focussing and scattering forces. A systematic study of a large number of solar events where different methods are used seems to be in order. The mean free path over a large range of rigidities and particle species should be determined; multi spacecraft observations should be used whenever possible. Angular distributions analysis should be intensified, in particular with respect to possible effects of helicity or other mechanisms producing asymmetries (Beeck and Wibberenz, 1990). The relative importance of higher order terms in the theoretical treatment should be carefully assessed. An important element seems to be a good determination of the power spectral tensor of magnetic field fluctuations at the time of solar energetic particle observations.

A more appropriate knowledge of transport coefficients in the outer heliosphere is necessary to explore how the high variability of plasma conditions are reflected in cosmic ray propagation there and to give some clues to the relative importance of the different processes working to produce cosmic ray modulation.

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